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Probing obscured, high redshift galaxies using deep P-band continuum imaging with GMRT

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Abstract. We have carried out a deep (150 micro-Jy rms) P-band (325 MHz), continuum imaging survey of about 40 square degrees of sky in the XMM-LSS, Lockman Hole and ELAIS-N1 fields with the GMRT. Our deep radio data, combined with deep archival observations in the X-ray (XMM/Chandra), optical (SDSS, CFHTLS), near-infrared (UKIDSS, VISTA/VIDEO), mid-infrared (Spitzer/SWIRE, Spitzer/SERVS) and far-infrared (Spitzer/SWIRE, Herschel/HerMES) will enable us to obtain an accurate census of star-forming and active galaxies out to $z \sim 2$. This panchromatic coverage enables accurate determination of photometric redshifts and accurate modeling of the spectral energy distribution. We are using our large, merged photometric catalog of over 10000 galaxies to pursue a number of science goals.

Keywords : galaxies: nuclei galaxies: active radio continuum: galaxies galaxies: high-redshift galaxies: general galaxies: evolution

1. Introduction

Understanding the mass assembly history of galaxies remains a major challenge in astrophysics. This is because a major fraction of galaxy assembly happens at high redshifts, in intense bursts of star formation as well as black hole accretion. Therefore, disentangling starburst and AGN activity, and understanding why the peak in the comoving luminosity density of star formation coincides with that from AGN activity

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at $z \sim 2$, is vital for measuring the stellar/BH mass buildup. Since most of the energy from these activities is absorbed by dust and then re-radiated in the rest-frame infrared, comprehensive multi-wavelength studies are required to achieve this, with emphasis on far-IR/submillimeter observations which probe the peak in the IR emission from moderately warm dust, supplemented by radio surveys which can probe the inner regions of star formation and AGN activity, without being adversely affected by dust obscuration.

The last couple of years have seen the arrival of revolutionary FIR/submm surveys, on a large new FIR telescope – *Herschel*. Among those, the Herschel Multi-tiered Extragalactic Survey (HerMES[1]) is the largest (900 hr) guaranteed time program. It aims to chart the evolution of galaxies through cosmic history via a set of nested (wide and shallow as well as deep pencil-beam) surveys over twelve well studied areas of sky, in particular, those extensively studied by *Spitzer* at 24 and 70 μm, such as the ELAIS-N1, Spitzer FLS, CDFS, GOODS-N, Lockman and XMM-LSS fields (total area coverage of ~110 deg^2 plus 270 deg^2 of shallow survey).

As demonstrated by the results already published in about 40 refereed papers (see the HerMES website for a list of these papers), HerMES has provided new insight on distant dusty galaxies and AGNs. It seems that previous phenomenological galaxy populations need revision and it is now anticipated that HerMES will be able to catalogue over 100,000 galaxies with $> 5\sigma$ detections at 250 μm. HerMES will constitute a lasting legacy to the community, providing an essential complement to multiwavelength surveys in the same fields and providing targets for follow-up using many facilities for many years to come.

2. Our radio followup

These dramatically improved FIR data have only one limitation – their relatively poor resolution (18,25,36 arcsec FWHM for Herschel/SPIRE at 250, 350, 500 μm resp.). Radio interferometric observations with the GMRT at 325 MHz provide accurate (~ 1.5 arcsec) astrometry, even for faint sources, allowing matches to data at other wavelengths, and eventually redshift determination. With deep radio data, radio counterparts can be identified for many FIR sources because of the strong and tight radio-FIR correlation; FIR bright star-forming galaxies are invariably bright in the radio. We use the 325 MHz band of GMRT for our observations because it provides an optimal combination of good sensitivity (even more so for steep spectrum sources), moderate RFI, large field of view (half power beamwidth of 83 arcmin) and adequate resolution (beam size of ~10 arcsec and positional uncertainty of ~ 1.5 arcsec even for the fainter sources).

The GMRT field of view at 325 MHz is optimal for followup of the wide-shallow

[1] http://www.hermes.sussex.ac.uk

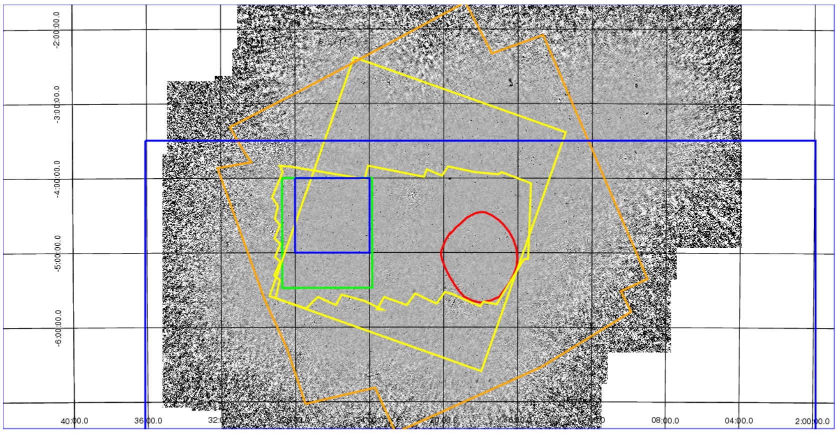

Figure 1. Our 325 MHz radio map of the XMMLSS field, originally observed in X-rays by the XMM/Newton telescope. The larger blue rectangle (only partially shown) is the area covered by the CFHTLS-W1 field. The small blue square corresponds to the CFHTLS-D1 field which also has deep radio observations with VLA/GMRT (Bondi et al. 2003, 2007). Overplotted as the green rectangle is the coverage of the VISTA Video XMM-3 field. The jagged yellow rectangle is the coverage of the Spitzer/SERVS survey. The inclined yellow square is the area with multiband observations from the Spitzer-SWIRE survey. The orange contour shows the coverage of the Herschel/HerMES observations in the 250,350 and 500 μm bands, while the red ellipse is the coverage of the deep 1.4 GHz VLA observations by Simpson et al (2006). A fraction of the Simpson coverage area is covered by HST imaging with CANDELS-UDS. Over 10^5 galaxy and quasar spectra are also available over our map.

component of HerMES. We have observed three such fields - XMMLSS, Lockman Hole and ELAIS-N1 (40 deg^2 in total) to a depth of $\sim$ 150μJy rms. In each field, we have covered the full area covered by the Herschel/HerMES and Spitzer/SWIRE surveys at uniform depth to maximise the scientific returns and legacy value. These well studied fields have a plethora of archival data (both imaging and spectroscopy) available in most bands from X-ray through radio (see Fig. 1)

3. Ongoing investigations

With this multiwavelength dataset, a number of scientific investigations can be carried out. We are currently working on the following projects.

- identify candidate high-z powerful radio galaxies using the $K - z$ relation and radio spectral index measurements and study their properties (see Singh et al. this volume).
- use image stacking of the HerMES and GMRT data explore the radio-FIR cor-

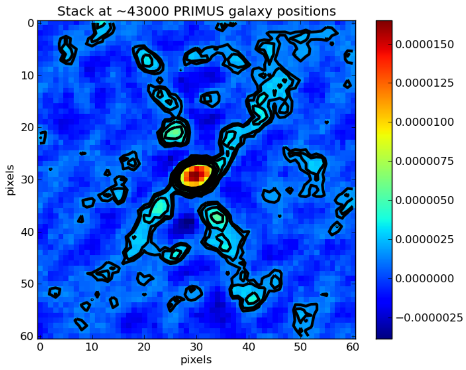

Figure 2. Median 325 MHz stack at the positions of ~ 43000 PRIMUS survey (Coil et al. 2011) galaxies in the XMM-LSS field. The peak flux is only 15μJy/beam and the image rms is ~ 1μJy/beam. The X shaped structure is the dirty beam of the GMRT from sub CLEAN-threshold sources contributing to the image stack. By careful image stacking in our radio image and the FIR data from HerMES, we hope to study the radio-FIR corellation in a hitherto unexplored region of parameter space.

relation in normal galaxies with $0 < z < 1.2$ well below the detection limit of the HerMES or GMRT images (see Fig. 2)

- separate starburst and AGN (Ibar et al. 2010) and identify powerful obscured AGN using e.g., the methods of Seymour et al. (2008, 2009)
- explore the radio/far-IR correlation in starbursts at high redshift. A recent study from the Herschel-ATLAS survey indicates that the correlation does not change over the redshift range $0 < z < 0.5$ (Jarvis et al. 2010).
- combine GMRT, HerMES and SERVS data (which probes rest-frame 1-3μm) to comprehensively test models of radio-mode feedback as a function of epoch and galaxy mass, with the GMRT data measuring feedback into the IGM by radio jets, HerMES data the current star formation rate and Spitzer data the stellar mass.

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