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A 5 GHz survey of the Galactic plane

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The CORNISH (Co-Ordinated Radio 'N' Infrared Survey for High-mass star formation) project is the radio continuum part of a series of multi-wavelength surveys of the Galactic Plane that focus on the northern GLIMPSE region ($10^\circ < l < 65^\circ$, $|b| < 1^\circ$), observed by the SPITZER satellite in the mid-infrared.

The survey was awarded over 400 hours of VLA time using B and BnA configurations at 5 GHz. This yields $\sim$1 arcsecond resolution and a root-mean-squared noise level of $\sim$0.4 mJy/beam, sufficient to detect UCHII regions produced by B3 stars or earlier right across the Galaxy. In addition, the survey will furnish samples of a wide range of radio sources, including planetary nebulae, ionised winds from evolved massive stars, non-thermal emission from active stars, high energy sources, active galactic nuclei and radio galaxies. Here we report the progress of the ongoing observations and present an initial sample of the data.

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1. Introduction

The observed progression of massive star formation, from cold collapsing core to young OB cluster, is largely understood via observations of discrete examples that have been ordered into an evolutionary sequence. Key to separating objects of different age and type are measurements of their spectral energy distributions (SEDs) at sub-millimetre, infrared and radio wavelengths.

The SPITZER GLIMPSE (Galactic Legacy Infrared Mid-Plane Survey Extrordinare) programme is the first of a number of sensitive infrared surveys covering the inner Galactic plane at high resolution and in an unbiased manner [1]. The northern half of GLIMPSE covers the region spanning $10^\circ < l < 65^\circ$, $|b| < 1^\circ$ at wavelengths of 3.6μm $-$ 8.0μm, which preferentially selects warm and dusty embedded sources. The companion SPITZER MIPSGAL survey [2] has imaged the same region at 25μm and 70μm, where the bulk of the energy from massive young stellar objects is emitted, and is hence sensitive to cooler and more deeply embedded young stellar objects. Completing the infrared picture of Galactic star formation is the UKIDSS[1] project (UK IR Deep Sky Survey) [3]. UKIDSS is a near-infrared survey operating in the J, H and K bands and is sensitive down to the 18th magnitude. The combined data from these surveys are driving the detailed characterisation of the Galactic population via their infrared colours (e.g., [4]). A complementary picture of the molecular and atomic interstellar medium (ISM) is being provided by the BU-FCRAO Galactic Ring Survey for CO [5] and the VGPS HI survey [6]. Similarly, the ongoing IPHAS H-α survey [7] probes H-α in emission towards nebulae and in absorption towards stars.

Conspicuous by its absence here is a comparable radio-continuum survey for compact ionised gas in the ISM. From a star formation perspective, the presence or absence of free-free emission is vital to distinguish evolved ultra-compact HII (UCHII) regions from their younger counterparts with similar thermal SEDs. The sheer number density of sources in the near and mid-infrared surveys necessitates complementary data at similarly high resolution to enable the full science potential to be fulfilled. This is particularly true in highly clustered star forming regions. It is important that any radio-continuum survey for UCHII regions be carried out at relatively high frequencies (>2 GHz) where thermal free-free emission is optically thin with a spectral inde of $S_\nu \propto \nu^{-0.1}$. High-frequency observations hence confer a signal-to-noise advantage and probe the structure of the ionised gas at all depths in UCHII regions.

No previous radio survey of the Galactic plane is comparable with the resolution or coverage of the SPITZER GLIMPSE data. A number of single dish surveys have been conducted at 5 GHz (e.g., [9]), however, their beams are several arcminutes across, compared to the arcsecond resolution of SPITZER. Most interferometric surveys have been carried out at a frequency of 1.4 GHz except for the catalogues of Becker et al 1994 [10], Giveon et al 2005 [11] and White et al 2005 [12], who surveyed the inner Galactic plane ($-10^\circ < l < 42^\circ$, $|b| < 0.4^\circ$) at 5 GHz. They used the VLA in C-configuration, which delivers a relatively large beam ($4'' \times 9''$) and the total survey area only covers 23 percent of the northern GLIMPSE region.

2. The CORNISH survey

The CORNISH (Co-Ordinated Radio 'N' Infrared Survey for High-mass star formation) project

[1] http://www.ukidss.org

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aims to deliver a uniform, sensitive and high-resolution radio survey to address key questions in high-mass star formation, as well as many other areas of astrophysics. The survey covers the 110 square degrees of the northern GLIMPSE region ($10^\circ < l < 65^\circ$, $|b| < 1^\circ$) using the VLA in B and BnA configurations at 5 GHz, resulting in a a $\sim$1$''$ synthesised beam. With a total integration time of 80 seconds per pointing, the root-mean-square (RMS) noise in the images is $\sim$0.4 mJy/beam - sufficient to detect a UCHII around a B3 star on the far edge of the Galaxy. As well as UCHII regions, the CORNISH survey will detect many other radio-bright objects: planetary nebulae, ionised winds from evolved massive stars, non-thermal emission from active stars, high energy sources, active galactic nuclei and radio galaxies.

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2.1 Observations and Data Reduction

VLA observations covering Galactic longitudes $21^\circ < l < 45^\circ$ were completed in October 2006. Remaining observations are due to finish in early 2008. The 110 square-degree target area is divided into 42 observing 'blocks', each of which contains 180 – 220 fields arranged in a hexagonal grid. This grid is a scaled version of the hexagonal NVSS pointing pattern (NRAO VLA Sky Survey, [13]), with a separation of 7.5$'$ between adjacent pointing centres, compared to the 8.5$'$ full-width half-maximum of the primary beam. During the reduction process individual fields are imaged out to an 8$'$ radius, resulting in a sensitivity uniform to $\sim$10 percent when combined into a mosaiced image. Each field is observed as two 50 second 'snapshots' separated by 4 hours, maximising the *uv*-coverage and minimising the elongation of the synthesised beam. Fields at declinations greater than -15° are observed using the VLA's B configuration, while fields at lower declinations are observed using the BnA configuration, which compensates for beam distortion at low elevations.

The data has been reduced using a combination of the NRAO AIPS and Obit[2] software packages. Calibration was performed using standard AIPS tasks, while the experimental Obit routines IMAGER and MOSAICUTIL were used to image and mosaic the fields, respectively. IMAGER implements an algorithm to detect and automatically clean emission in the fields[3] and also searches the NVSS catalogue for strong radio sources outside of the primary beam. Bright sources in the sidelobes may project artifacts into wide-field images and these regions are imaged and cleaned in parallel with the primary beam area. The basic data product of the CORNISH survey is a square image 'tile', measuring 20$'$ on a side and containing data from up to 30 fields.

3. Data Quality

Data from 2006 has been reduced and an initial assessment made of its quality. Approximately 5 percent of the fields are adversely affected by poor weather and are due to be re-observed in late 2007. Many fields towards the mid-plane of the Galaxy contain strong extended emission ($> 10''$), which is resolved out by the VLA. This has the effect of introducing stripes into the cleaned images

[2] Obit is experimental software developed by Bill Cotton at the NRAO. It is intended primarily as development tool, but also implements algorithms for handling radio astronomy data. Obit lends itself to building automated data reduction pipelines as it provides a Python-based scripting interface, which may also be used to control AIPS. For further information see http://www.cv.nrao.edu/ bcotton/Obit.html

[3] See the memo at ftp://ftp.cv.nrao.edu/NRAO-staff/bcotton/Obit/autoWindow.pdf

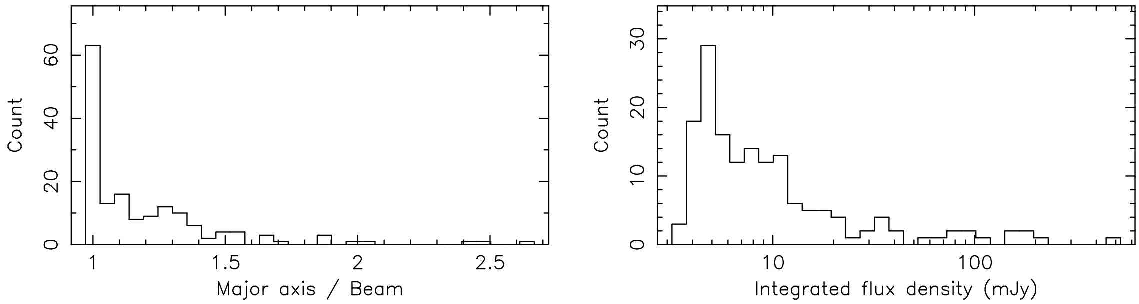

Figure 1: *Left:* Histogram of fitted source size compared to the restoring beam. *Right:* Distribution of flux densities for unresolved sources detected in a 2×5 degree area of the survey.

and requires careful flagging of short baselines on a case by case basis. The typical root-mean-square noise in a mosaiced tile constructed using 2006 data is $\sim$0.4 mJy/beam.

3.1 Statistical properties

We have examined the statistical properties of a 2×5 degree sample region known to be mostly free of artifacts. The Gaussian source finder Obit SOUFIND (based on the AIPS task SAD) was used to search for sources down to a 5-σ cutoff. 625 sources were found, over a third of which are unresolved in the 1.5$''$ restoring beam. Figure 1 *left* illustrates the distribution of fitted source size compared to the beam. The distribution of detected flux densities for unresolved sources is shown in Figure 1 *right* and ranges from 3 mJy up to 500 mJy, with a mean of 7 mJy. The number of detections diminishes rapidly below 5 mJy as we approach the sensitivity limit.

To quantify the formal sensitivity limits of the 2006 data we conducted a completeness test on an tile from an 'empty' part of the sky. 100 artificial point sources were injected into the calibrated *uv*-data before running the imaging and mosaicing software. The flux densities of the injected sources were varied smoothly between 0.15 and 20 mJy, so as to bracket the expected sensitivity limit, and the positions were randomised. The SOUFIND routine was then used to find and fit Gaussians to the sources in the mosaiced image. After 10 injection-imaging iterations (1000 sources) the fit results were compared to the injection parameters. Figure 2 illustrates the percentage of sources recovered by SOUFIND as a function of the flux density. We recover 90 percent of the sources at a flux density of 4 mJy and 50 percent of the sources at 2.7 mJy.

4. Sample data

An initial cross-match between the CORNISH and GLIMPSE point-source catalogues reveals that the CORNISH detections are divided into red and blue populations when plotted on infrared colour-colour diagrams. Sample data from each catagory are presented in Figure 3.

A cursory inspections of the 'red' catagory reveal that we detect cometary UCHII regions whose morphologies agree well with 8 μm emission seen in the GLIMPSE images. Extended 8 μm emission is most likely due to fluorescing poly-cyclic aromatic hydrocarbons (PAHs). VLA observations using B and BnA configurations resolve out structures on scales larger than $\sim$10$''$, so PAHs emission is a useful tool in determining the large scale morphology of the PDRs surrounding

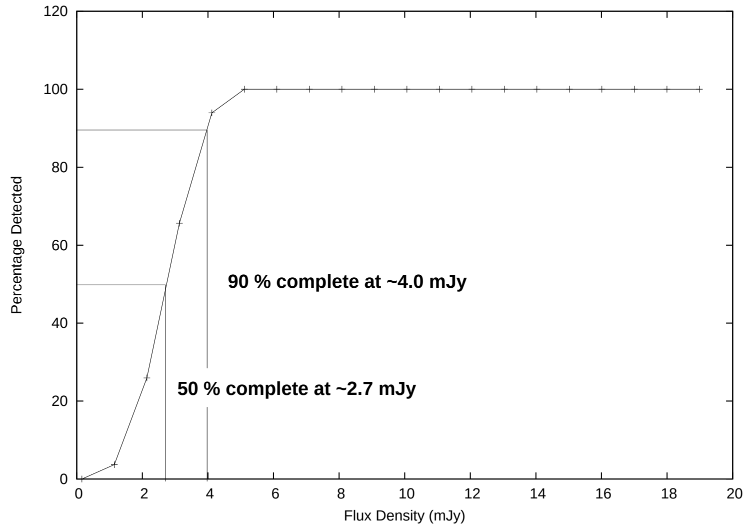

Figure 2: Percentage of sources recovered as a function of flux density. 1000 point sources were injected into the *uv*-data for a tile and recovered from the imaged data using the SOUFIND task. The plot is a measure of our completeness.

UCHII regions. The 'red' catagory also contains unresolved GLIMPSE sources surrounded by nebulosity; clearly embedded star forming regions.

The 'blue' catagory of sources appear to be associated with bright field stars. We also find a population of double-lobed objects, away from the Galactic mid-plane, which look like classical radio galaxies.

5. Future plans

A data reduction pipeline has been developed which largely automates the processing of raw CORNISH data into mosaiced image tiles. All the CORNISH data will be made public as soon as it has been reduced and verified to be of high quality. The calibrated *uv*-data and cleaned images will be available on the CORNISH web site (http://www.ast.leeds.ac.uk/Cornish/) via a query-driven user interface. In addition, a catalogue will be published containing the positions and flux-densities of detected sources and any SPITZER or UKIDSS counterparts. Where possible, the types of source present will be identified via their spectral energy distributions and any other associated detections (e.g., masers, H-α emission).

6. Conclusions

The CORNISH project is poised to deliver a complementary radio view of the northern GLIMPSE region at 5 GHz wavelengths. With a resolution of $\sim 1''$ and a RMS noise level of $\sim$0.4 mJy/beam, the survey is tailored to search for UCHII regions across the Galaxy, but will also detect a wide range of radio-bright objects.

Observations are due for completion in early 2008 and the data will be available publicly as soon as the processing and quality control is complete. Detections will be cross matched with the

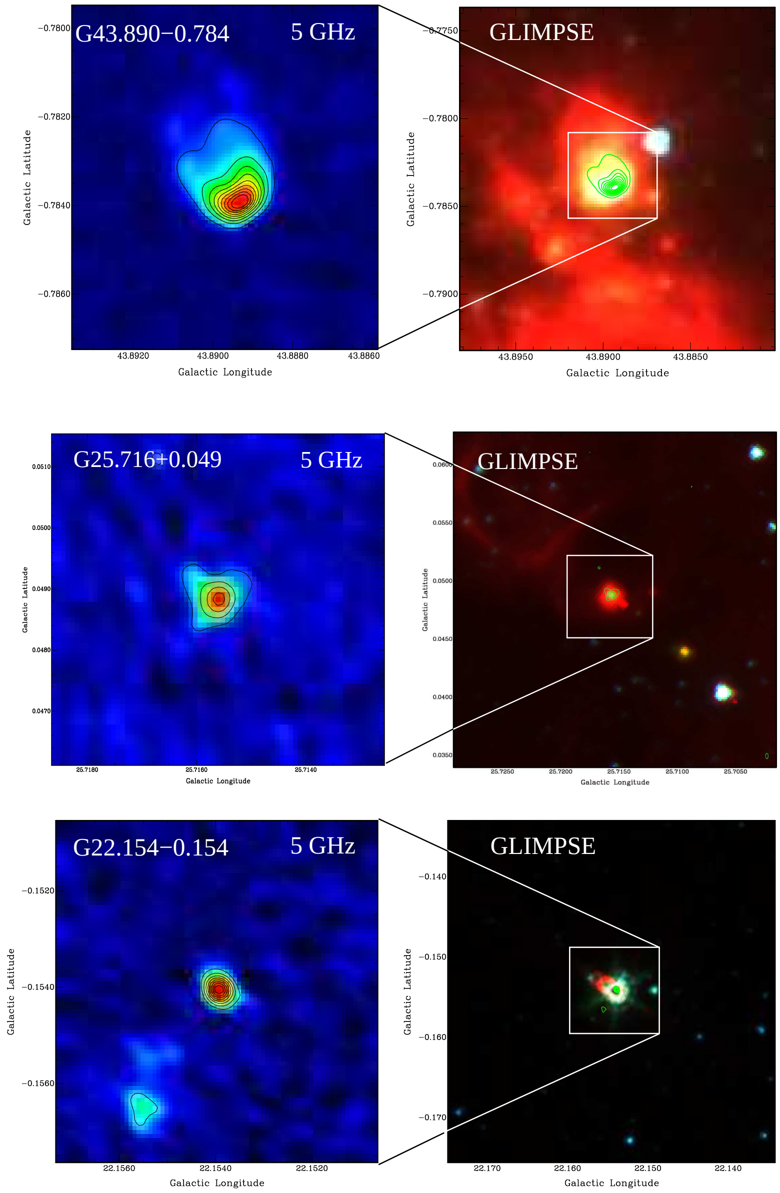

Figure 3: Examples of sources found in the CORNISH survey. Panels on the left present the 5 GHz VLA image. Panels on the right present a 3-colour GLIMPSE image, with red=8.0 μm, green=4.5 μm and blue=3.6 μm. *Top:* Example of a cometary UCHII region. The infrared image is dominated by 8 μm emission, most likely from poly-aromatic-hydrocarbons. The 5 GHz contours conform well to the brightest parts of 8 μm emission, however, structures larger than $\sim$10$''$ are resolved out by the VLA. *Middle:* Example of a compact source found in the 'red' GLIMPSE catagory. *Bottom:* Example an unresolved source from the 'blue' GLIMPSE catagory. The 5 GHz emission appears to be associated with a bright field star, which is saturated in all wavebands.

GLIMPSE and UKIDSS surveys, and the resulting catalogue will be an unprecedented resource for the study of galactic objects.

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