Radio Recombination Lines with the Lovell Telescope

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Introduction

Radio Recombination Lines (RRLs) are the radio counterpart of optical Balmer lines, which provide an accurate tracer for free-free emission without the need for substantial dust corrections required by Hα surveys. Independent models based on Hα data and Far Infrared data (which does not directly trace RRL gas but is uninhibited by dust) are used to derive the observable RRL flux from a sample of 43 galaxies expected to be strong thermal emitters. Integration times are established for the Lovell Telescope at Jodrell Bank. M33, M77 and NGC 1569 are established as promising candidate galaxies from which RRLs have not been detected. A new FPGA-based spectrometer is being developed for the Lovell Telescope, specifically for RRL measurements. This will have sub-km/s resolution over > 1GHz bandwidth, and will be expanded to include a GPU-processing element to further increase resolution and bandwidth. This system will initially be used to make new extragalactic RRL detections and add northern hemisphere RRL data to the HIPASS-derived Galactic-plane RRL survey by Alves et al. 2014.

The RRL calculations

1. The Hα model

Extinction and NII-corrected Hα data from Kennicutt et al. (2006, 2009, 2010) were used to calculate the thermal free-free using the equation from Niklas et al. 1997:

$$\left(\frac{S_{th}}{mJy}\right) = 2.238\times10^{-14}\cdot\left(\frac{S_{H\alpha}}{Jy{-}Hz}\right)\cdot\left(\frac{T_e}{K}\right)^{0.42}\times\left\{\ln\left(\frac{0.04995}{\nu_9}\right)+1.5\cdot\ln\left(\frac{T_e}{K}\right)\right\}$$

where the $H\alpha$ data can be corrected for inhibiting dust in the host galaxy using 24 μm emission as an $H\alpha$ tracer (K09)

$$S(H\alpha)_{corr} = S(H\alpha)_{obs} + a_\nu \nu\cdot S(24\mu m)$$

where $a_\nu \approx 0.02$.

2. The Infrared model

60 and 100μm data were used to estimate the thermal flux using equations from Marvil et al. 2014

$$\left(\frac{S_{th}(\nu)}{Jy}\right) = 1.4\times10^{10}\cdot\left(\frac{FIR}{Wm^{-2}}\right)\cdot\left(\frac{T_e}{10^4 K}\right)^{0.45}\cdot\left(\frac{\nu}{GHz}\right)^{-0.1}$$

where FIR is the estimated total infrared flux between 42.5 and 122.5μm, taken from Helou et al. 1985

$$FIR = 1.26\times10^{-14}\cdot\left(2.58 S_{60} + S_{100}\right)$$

3. Derived integration times

The above models give the thermal free-free flux. To find the RRL flux, the line-to-continuum ratio was used (Gordon et al. 2009). For the majority of our sample, RRL fluxes are ~ 0.01 mJy at 1.4 GHz. The strongest RRL emitters (eg. M82) are ~ 1 mJy

$$\frac{T_L}{T_C}\cdot\Delta v_{km/s} = 6995\cdot\frac{1}{a_\nu}T_e^{-1.15}\nu_9^{1.1}$$

Using specification for the 76m Lovell Telescope (T_{sys}=35K, η=0.6, ≈1 K/Jy), integration times were derived for galaxies in the local group expected to have high thermal flux, not yet detected in RRL. The table below lists 3σ integration times in hours, for the strongest candidates for new RRL detections, with each of the Lovell telescope's receivers. All times assume LTE, i.e. spontaneous emission.

Target	Hα model	
	1.4 GHz	5 GHz
M77	35.2	0.8
NGC 1569	44.6	1.3
NGC 4449	1100	5
II Zw 40	3300	94.1
NGC 6946	320	109
NGC 2366	5150	121

Target	FIR model	
	1.4 GHz	5 GHz
M77	1720	3.8
NGC 1569	877	19.2
NGC 4631*	1180	49
NGC 4102	2370	52.2
NGC 6946	707	75.5
M51	1030	105

* Tentative detection made by Churchwell & Shaver, 1979.

It should be possible to improve these times by a factor of 4 – 5 by stacking ~ 20 Hnα lines visible in each band, as recently done by Morabito et al. (2014), however this would remove any possibility of individual T_L and useful Δv measurements.

The spectrometer

1. **Hardware**

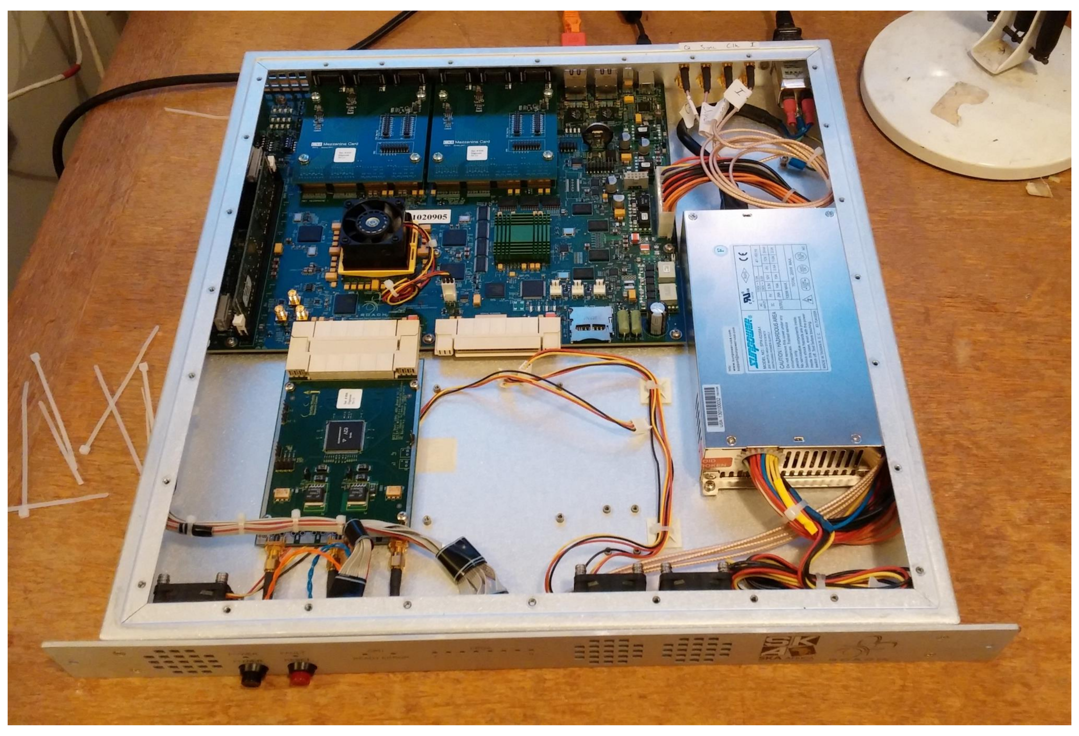
- Fully digitised system using ROACH2-2 control hardware with Xilinx Virtex-6 FPGA clocking 1.4 GHz, with 2000 DSP slices and 38Mb on-chip RAM.
- Fully shielded rack mount, SMA signal input. Ethernet/USB connected to control PC
- Initially using 2-input, 1 GS/s ADC for stokes I only, for use with dual-polarisation Lovell Super L-band and C-band receivers. May increase to 8-input dual ADC for use with Lovell multibeam receiver, depending on receiver condition and ADC availability.

2. Spectrometer design

- Wide band: 500 MHz on L-band, 4 GHz on C-band (ADC not yet available)
- High resolution: km/s after smoothing
- RFI suppression: polyphase filtering with many (>10) taps – currently under investigation

3. Implementation

- Matlab/Simulink used to construct designs, programmed to FPGA using Xilinx System Generator
- Data output to PC where telescope information is linked into data, FITS file created
- Survey data to be stored on dedicated network storage, expected data size ~ few TB



Summary

- Integration times for new extragalactic RRL detections estimated using two independent models.
- M77, NGC 1569, NGC 4449, NGC 4631, NGC 6946 promising candidates
- Spectrometer under construction to detect using Lovell L-, C-band receivers. Currently in primary design phase, RFI expected to be main design constraint
- Operational by Q2 2015.

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