# Radio Recombination Lines at Decametre Wavelengths

*Prospects for the Future...*

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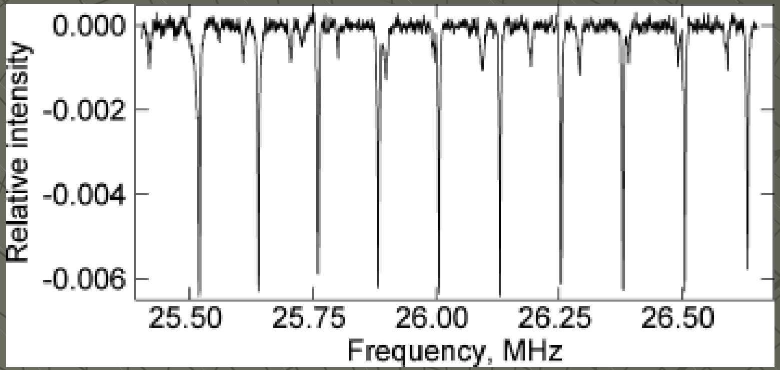
# What are Radio Recombination Lines? (RRLs)




**High resolution spectrum of Cas A showing multiple carbon radio recombination lines. (Stepkin et al. 2007 MNRAS 374, 852)**

Rydberg atoms, or atoms with a single electron at a high quantum number, occur naturally In the Galactic interstellar medium (ISM).

As the electron cascades to lower energy levels, each transition creates a radio recombination line, or RRL.

At frequencies above 200 MHz these lines appear in emission.

At frequencies below 150 MHz, the excitation temperature of the atoms approaches the typical gas kinetic temperature and the lines appear in absorption.

# Why do people study them?

At large n, the atoms are very big and fragile.

Variations in pressure, temperature and density as well as radiation broadening can all affect the line profile.

The lines can be used to estimate the cloud size and Galactic distribution.

When RRLs at multiple frequencies are combined with information from HI, molecular, and CII observations, a comprehensive picture of the absorbing clouds can be built.

The Parkes Radio Telescope which was used to survey RRLs at 76 MHz.

# Why do we care?
# Planned 21cm Cosmological Measurements...

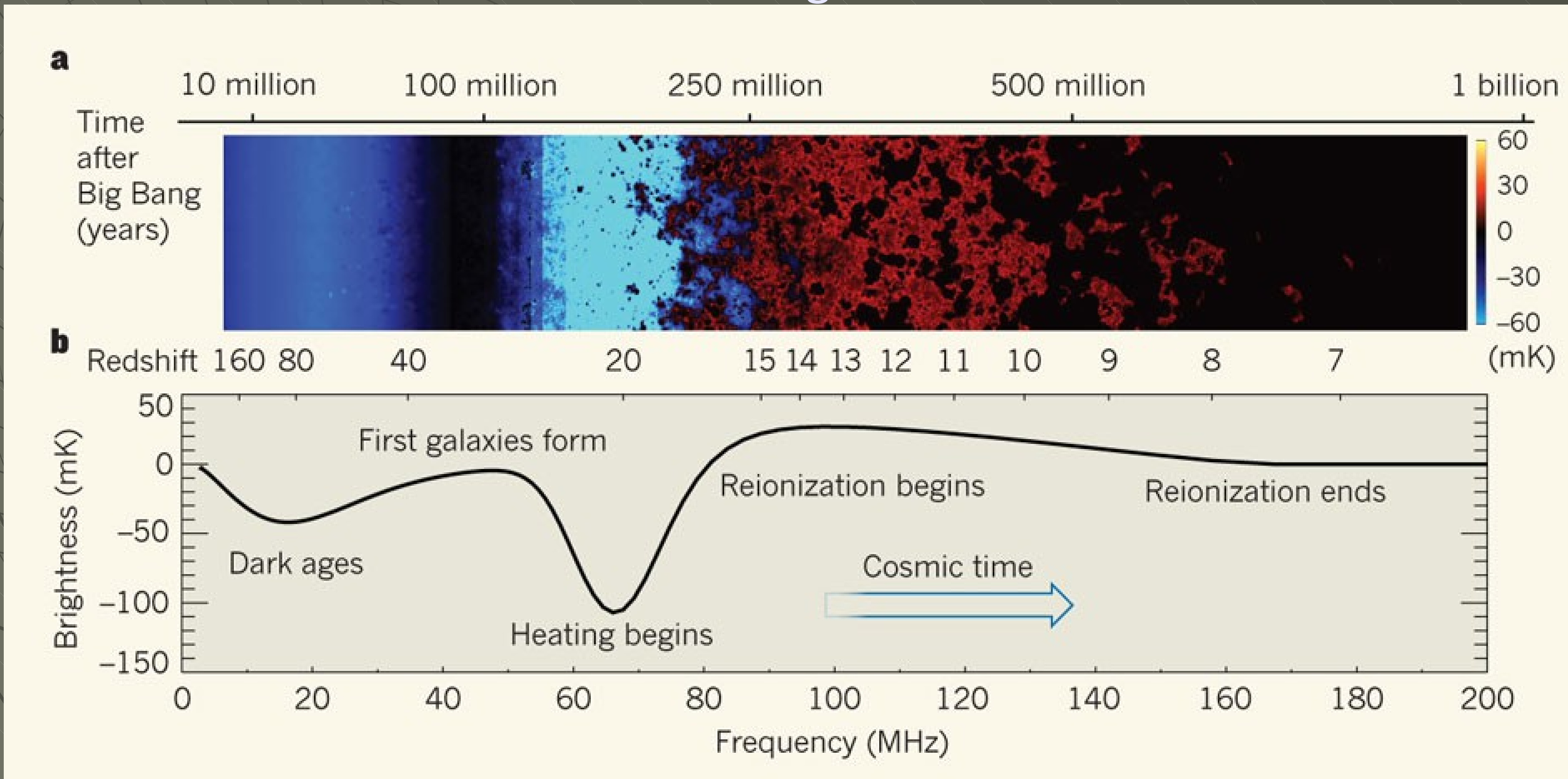
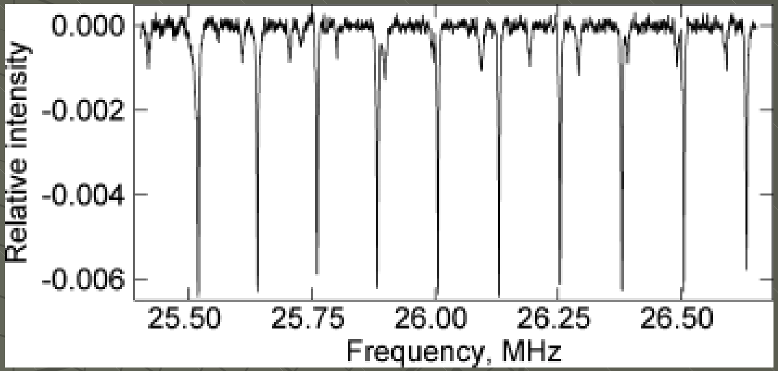



*Figure 1 From Pritchard & Loeb, 2010 Nature 469 772*

# Why do we care? (cont'd)




$\alpha$ lines appear roughly every 120 kHz.
**(Stepkin et al. 2007 MNRAS 374, 852)**

In order to detect any of these signals, foregrounds must be removed from the data.

Foregrounds can include radio frequency interference (RFI), ionospheric phase corruptions, Galactic synchrotron emission , and emission from extragalactic sources.

If present, RRLs represent a frequency-dependent foreground.

There are a lot of them -- the line spacing for the $\alpha$ lines is $\Delta \nu \sim 3 \nu/n$, and the other transitions may also be present.

# Will it really matter?

The magnitude of the spectral fluctuations expected from the HI signals for the dark ages, first stars and epoch of reionization is roughly in the range $10^{-4}$ to $10^{-5}$.

The magnitude of the spectral fluctuations from RRLs, based on known lines, would be of order $\tau$ to $2\tau$, or roughly $10^{-3}$ to $10^{-4}$.

*If there is RRL-hosting gas at high Galactic latitudes, the spectral fluctuations arising from RRLs could be comparable to or exceed those from the desired HI signals.*

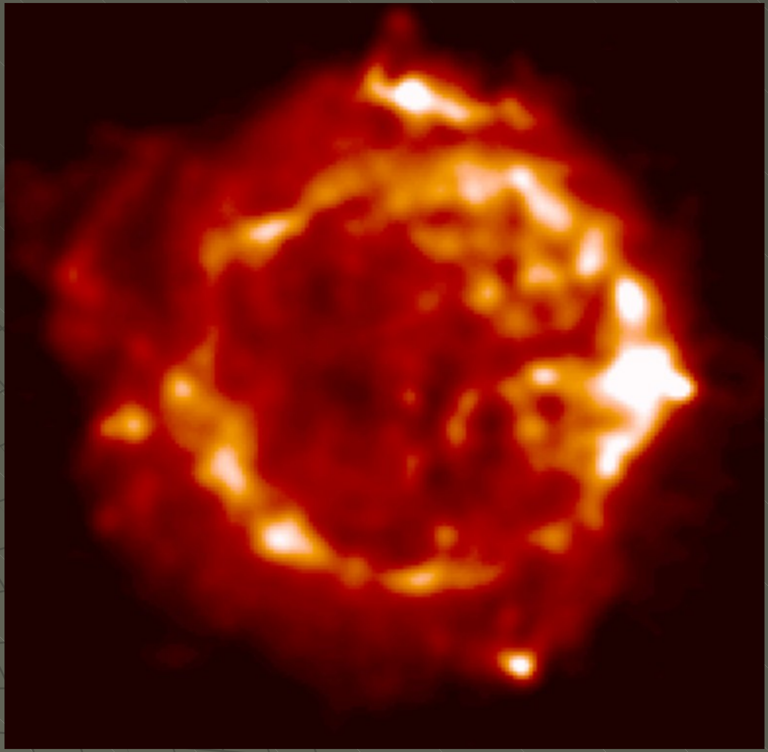
# The Cassiopeia A Lines

Decametre CI lines are seen towards Cassiopeia A (Cas A) at all frequencies.

These very well studied lines appear to arise in cold ($T_e$ ~75K) diffuse ($n_e$ ~ 0.02) HI clouds.

The lines are broadened by radiation and pressure and have Voight profiles.

The distribution across Cas A is a good match to the HI 21cm distribution.



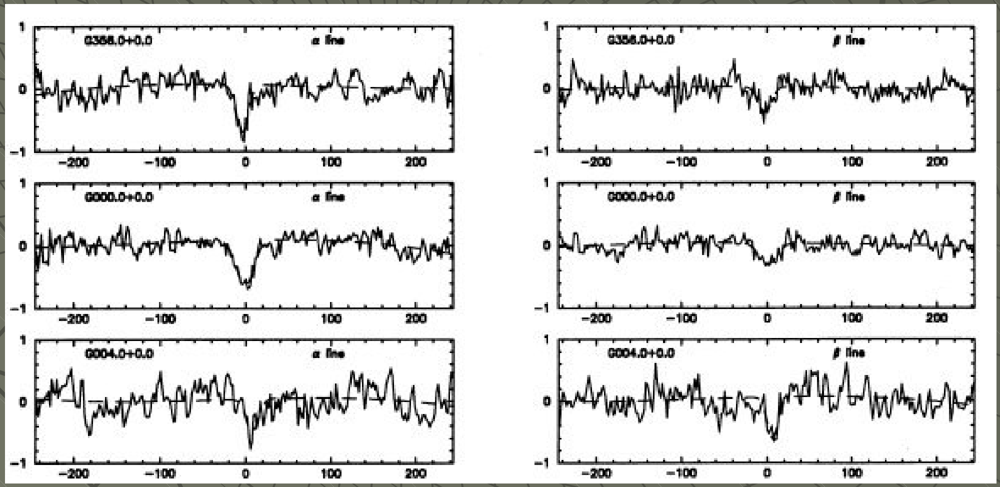
Cas A at 74 MHz. (VLA+PT-link image).

# The Galactic Plane Lines

Observed on other Galactic sightlines, mostly through the plane around the Galactic center.

These lines are variously thought to be associated with cold diffuse HI clouds, cold molecular clouds, and/or HII clouds near photodissociation regions (PDRs).

Best fit models derive cloud temperatures $T_e$ ~ 20-300 K and electron densities $n_e$ ~ 0.03 – 0.8.




**Sample spectra on 3 Galactic sightlines show α (right) and β (left) carbon radio recombination lines. (Erickson et al. 1995, ApJ, 454, 125)**

# Where are they found?

The Gauribidanur telescope observes RRLs at 34.5 MHz.

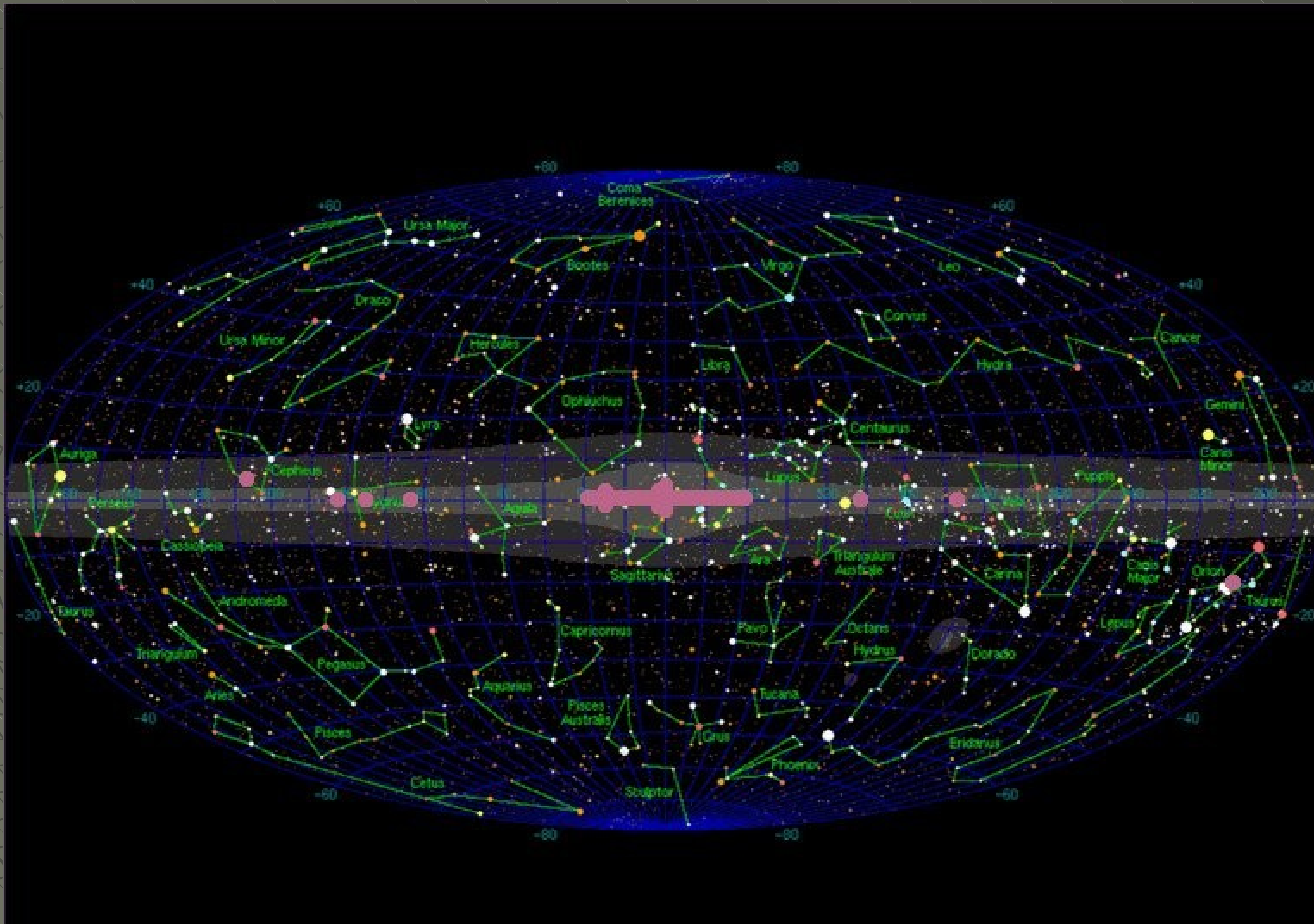
About 50 sightlines towards known bright background sources or passing through gas-rich regions in the Galactic plane.

Clouds on the Cas A sightline are associated with the Perseus arm of the Galaxy.

Galactic plane clouds are associated with the Sagitarrius and Scutum arms of the Galaxy.

Line strength does not diminish as Galactic latitude increases from 0 to 2 degrees.

Lines in the plane are seen from $-20 < l < 20$, but only on isolated sightlines elsewhere.




All-Sky View Toward Milky Way Center graphic from (http://openseti.org/OSPulsars.html)

# LWA-1 sensitivity

| $\nu$ (MHz) | $n$ | $f$ | $N_{\rm lines}$ | DF | $T_{\rm sys}$ ($\times 10^4$ K) | $\Delta t_{\rm int}$ (hr) |
|---|---|---|---|---|---|---|
| 20 | 683 | 0.92 | 10 | 0.26 | 29.5 | 50 |
| 25 | 640 | 0.87 | 8 | 0.41 | 18.3 | 28 |
| 30 | 603 | 0.76 | 12 | 0.59 | 12.4 | 6 |
| 35 | 572 | 0.63 | 10 | 0.8 | 8.9 | 5.5 |
| 40 | 548 | 0.5 | 8 | 1 | 6.7 | 7 |
| 45 | 526 | 0.4 | 6 | 1 | 5.2 | 15 |
| 50 | 508 | 0.33 | 6 | 1 | 4.1 | 23 |
| 55 | 492 | 0.27 | 10 | 1 | 3.3 | 10 |
| 60 | 478 | 0.23 | 10 | 1 | 2.7 | 14 |
| 65 | 466 | 0.2 | 8 | 1 | 2.3 | 24 |
| 70 | 454 | 0.17 | 8 | 1 | 1.9 | 32 |
| 75 | 444 | 0.15 | 6 | 1 | 1.7 | 56 |
| 80 | 434 | 0.13 | 6 | 1 | 1.4 | 72 |

$$\Delta t_{\rm int} = \left(\frac{m}{f \times DF}\frac{T_{\rm sys}}{\Delta T}\right)^2 \frac{1}{N_{\rm pol}\, N_{\rm lines}\, \Delta\nu}$$

We assume a 5σ detection, of $10^{-3}$ optical depth lines.

$T_{sys}$ is derived from GSM sky models along the Galactic plane.

The filling factor, *f*, was calculated using the dipole layout and accounts for overlaps and edge effects.

The dilution factor, *DF* assumes cloud sizes < 4 degrees.

$N_{lines}$ is based on 2 contiguous observing bands with roughly 2 km/s velocity resolution at all frequencies.

Multiple beams and wider bandwidths (lower spectral resolution) will lower the integration time.

Optical depths of $10^{-4}$ increase these values by a factor of 100x.

# RRLs with LWA-1

PI: Ylva Pihlström

Experiment planned for two stages:

1. Observe Cas A where lines are well-known to confirm system performance and develop necessary software
2. Observe 3 positions toward the Cygnus arm of the galaxy at two frequencies.

Planned setup:

- 3 beams (4th beam for ioncal)
- 2 x 2 MHz bands per beam
  - Combined 12 MHz
  - Many transitions to fold
- Observe at 26 and 74 MHz
- 15 hours per pointing per frequency
- Sensitivity: $10^{-4}$ optical depth at $5\sigma$

# Summary

Decametre RRLs uniquely probe cool, low density gas.

They are quite weak, and detection, except against a bright background source such as Cas A, depends strongly on a well-filled array or telescope.

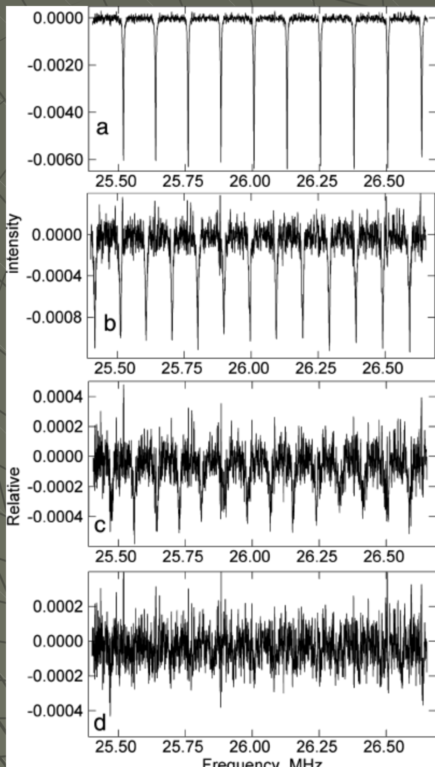
Current and past instruments struggle to detect these lines against the bright background of the Galactic center; their distribution in the larger Galaxy is very poorly known.

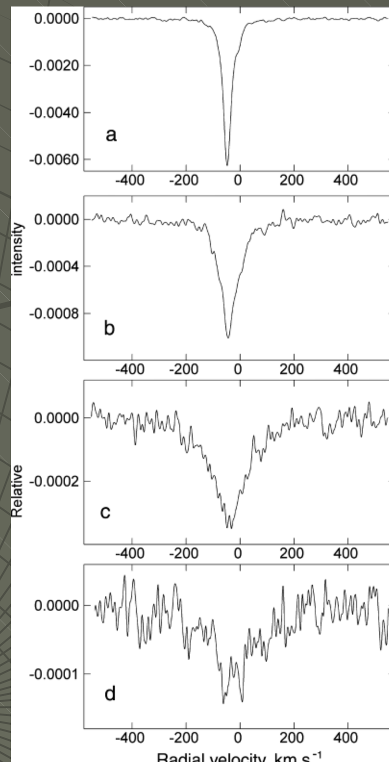
RRLs form a potential frequency-dependent astronomical foreground for cosmological line experiments.

We plan to observe RRLs towards Cas A and on 3 sightlines towards the Cygnus Arm with LWA-1. This project will test the LWA-1 spectral system, provide an opportunity to develop appropriate reduction software and potentially provide new RRL detections. All of the results can be used to plan a larger, more systematic survey of RRLs in the Galaxy.

Backup slides....

# Line-folding



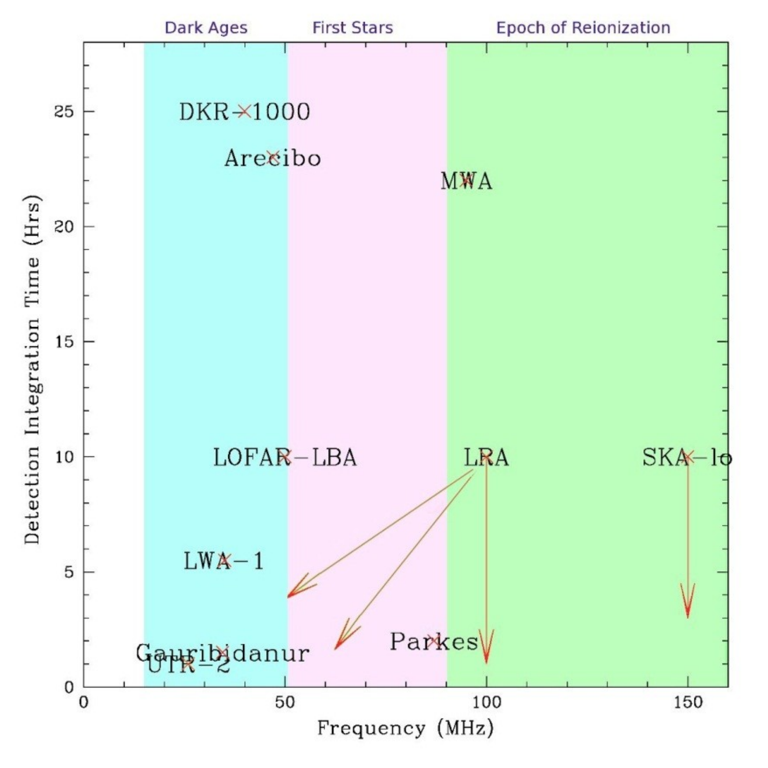

The line profiles vary slowly with quantum number, n.

Thus when n >> ∆n, the lines are effectively identical and it is possible to combine adjacent lines.

This gives a huge boost in sensitivity.

500 Hrs of data -------> 5000 effective hours

# Old vs. New




New instruments generally not as well-filled as older instruments.

Dipole arrays less susceptible to RFI than single dishes.

New instruments (generally) have better spatial resolution.

Surveys needed!

# Why has nobody studied these?

...because they are hard to detect!!!

From the radiometer equation, the sensitivity of an experiment designed to detect RRLs is:

$$\Delta T = \frac{T_{sys}}{f} \frac{1}{\sqrt{N_{lines} N_{pol} \Delta t_{int} \Delta \nu}}$$

$\Delta$ T = rms noise
$T_{sys}$ = the telescope system temperature
*f* = the filling factor of the telescope or array
$\Delta t\_{int}$ = integration time
$\Delta\nu$ = frequency resolution
$N_{pol}$ = number of polarisations observed
$N_{lines}$ = number of simultaneous transitions observed

# Why has nobody studied these?

...because they are hard to detect!!!

If we are searching for a line of optical depth, $\tau$, then an "m-$\sigma$" detection implies $m\Delta T < \tau T_{sys}$. We can thus write:

$$\Delta t_{\rm int} = \left( \frac{m}{f \times DF} \frac{T_{\rm sys}}{\Delta T} \right)^2 \frac{1}{N_{\rm pol}\, N_{\rm lines}\, \Delta \nu}$$

A beam dilution factor, *DF*, accounts for potential mismatches between the angular sizes of the foreground absorber, the background source, and the observing beam itself.

If the absorber is smaller than the background source, and/or the observing beam is much larger than the absorber, unabsorbed background radiation will dilute the apparent line strength.

# Planned Instruments

| Name | Frequency (MHz) | Resolution | filling factor | $T_{detect}$ (hr) |
|---|---|---|---|---|
| LWA-1 | 20–80 | 9°–2° | 0.9–0.1 | ~ 10 |
| LOFAR-LBA | 30–90 | 2°–0.6° | ~ 0.1 | ~ 10 |
| LOFAR-HBA | 110–240 | 30′–15′ | ~ 0.1 | ... |
| SKA-lo | 150 | 7′ | ~ 0.1 | < 10 |
| LRA | 100 | 10′ | ~ 0.9 | < 10 |

The Long Wavelength Array first station (LWA-1) is under construction.

The Low Frequency Array – Low Band (LOFAR-LBA) is partially operational.

The Low Frequency Array – High Band (LOFAR-HBA) and Square Kilometre Array low-band (SKA-lo) cover a transition region between absorption and emission lines over which the lines become undetectable. It is unclear what could be detected in this regime.

SKA-lo and the Lunar Radio Array (LRA) do not have finalized designs; these numbers are indicative and not precise.

# Existing and Historical Instruments

| Name | Frequency (MHz) | Resolution | filling factor | $T_{detect}$ (hr) |
|---|---|---|---|---|
| UTR-2 | 26 | $40'$ | 1 | 1 |
| Gauribidanur | 34.5 | $21' \times 25°$ | 0.59 | 1.5 |
| DKR-1000 | 40 | $44' \times 1°$ | 0.2 | 25 |
| Arecibo | 47 | $80'$ | 0.25 | 23 |
| Parkes | 76 | $4°$ | 0.25 | 2 |

Filling factor tends to improve at lower frequencies for arrays.

Even single dish instruments are not "filled."

The beams for most of these instruments are quite large – arcminutes and degrees.

Single dish instruments are very susceptible to radio frequency interference and baseline instability.

Published surveys were carried out by Gauribidanur and Parkes telescopes; other instruments have been used in targeted observations.

# Some known RRL absorbers

| Sightline | $\nu$ (MHz) | $n$ | $\tau$ ($\times 10^{-3}$) | $V_{LSR}$ (km $s^{-1}$) | $\Delta v$ (km $s^{-1}$) | Reference |
|---|---|---|---|---|---|---|
| G0+0 | 34.5 | 575 | 1.16 | 5.3±0.8 | 20.5±1.1 | 5 |
| | 75 | 443 | 0.57±0.04 | −1.0±0.5 | 14.8±1.2 | APE88 |
| | 76 | 441 | 0.73 | −1 | 24 | 1 |
| G0−4[b] | 76 | 441 | 0.33 | −6 | 13 | 1 |
| G0−2 | 76 | 441 | 0.57 | −10 | 30 | 1 |
| G0+0 | 34.5 | 575 | 1.16 | 5.3±0.8 | 20.5±1.1 | 5 |
| | 76 | 441 | 0.73 | −1 | 24 | 1 |
| G0+2 | 76 | 441 | 0.70 | −2 | 26 | 1 |
| G0+4 | 76 | 441 | 0.68 | −2 | 31 | 1 |
| G2−3.5[b] | 76 | 441 | 0.52 | 7 | 5 | 1 |
| G2−2 | 76 | 441 | 0.97 | 5 | 9 | 1 |
| G2+0 | 76 | 441 | 0.90 | 2 | 25 | 1 |
| G2+2 | 76 | 441 | 0.61 | 6 | 11 | 1 |
| G3+0 | 76 | 441 | 0.90 | −1 | 14 | 1 |
| G4+0 | 76 | 441 | 0.54 | 8 | 17 | 1 |
| G5+0 | 34.5 | 575 | 0.74 | 10.2±1.4 | 21.2±2.0 | 5 |
| G6+0 | 76 | 441 | 0.73 | 9 | 25 | 1 |
| G6.6−0.2 | 76 | 441 | 0.87 | 10 | 28 | 1 |
| G8+0 | 76 | 441 | 1.09 | 11 | 22 | 1 |
| G10+0 | 34.5 | 575 | 0.81 | 14.3±1.7 | 37.5±2.5 | 5 |
| | | | 0.93 | 9.6±1.5 | 24.9±2.3 | 5 |
| | | | 0.47 | 40.2±2.6 | 18.4±3.7 | 5 |
| | 76 | 441 | 0.72 | 17 | 26 | 1 |
| G12+0.0 | 76 | 441 | 0.91 | 12 | 20 | 1 |
| G14−2.0 | 76 | 441 | 0.88 | 11 | 32 | 1 |
| G14+0 | 34.5 | 575 | 0.66 | 37.8±2.7 | 54.0±3.8 | 5 |
| | 76 | 441 | 0.85 | 16 | 25 | 1 |

Most experiments only detect $\alpha$ transitions.

Optical depths are generally from $10^{-3}$ to $10^{-4}$

Most of the detecting instruments had beams of a few degrees; estimated cloud size is 2-4 degrees.

Velocity widths ~few tens of km/s.

# Why do we care?

The HI 21cm hyperfine transition serves as a cosmological and astrophysical probe of the distant Universe.

There are 3 distinct epochs with corresponding spectral windows for the redshifted HI signal:

*The Dark Ages* ($100 < z < 30$,  15 MHz $< \nu <$ 50 MHz)
The kinetic temperature of the gas falls below the CMB temperature.  This is thought to occur before stars form or any other heating sources arise, so the evolution of the signal should depend purely on cosmological parameters.

*First Star Formation* ($30 < z < 15$, 50 MHz $< \nu <$90 MHz )
Ly$\alpha$ photons from the first stars couple the HI Kinetic and Spin temperatures creating a second absorption feature.

*Epoch of Reionization* (EoR; $15 < z < 7$, 90 MHz $< \nu <$ 200 MHz)
Stars and black holes heat the HI gas, creating an emission feature which persists until reionization completes.

Estimated signals strengths are in the range 10-100 mK