The ionised, radical & molecular Milky Way: spectroscopic surveys with the SKA

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SKA: a radio line survey machine

Dense compact core
Exquisite brightness temperature sensitivity
Push to higher resolution & higher core density with SKA-2
The Milky Way in 3D: HI

Galactic All-Sky Survey, McClure-Griffiths et al 2009
The Milky Way in 3D: H$_2$ (via CO)

Dame et al 2001

Milky Way in Molecular Clouds
The Milky Way in 3D: H$^+$ (via H$\alpha$)
Milky Way surveys present & yet to come

Very well served by sensitive continuum surveys at sub-arcmin & sub-arcsec resolution (*Herschel*, APEX, SCUBA-2, JVLA, VISTA, UKIRT...)

Most spectroscopic surveys are much more limited:
- Smaller spectral bandwidth makes it harder to detect lines
- Better $T_b$ sensitivity from single-dishes but poorer angular resolution
- Hα surveys limited by Fabry-Perot & interstellar extinction

**Prospects for spectroscopic surveys on the timescale of the SKA?**

HI:  ASKAP/SKA territory - see talk by Naomi McClure-Griffiths tomorrow

H$_2$: Single-dish CO at 10-30” resolution (Mopra, JCMT, LMT, CCAT, *ALMA*?!?)
But issues with optical depth, low critical density, excitation...

H$^+$: THOR JVLA & SIGGMA Arecibo surveys of 1.4 GHz radio recombination lines
THOR aimed at relatively bright HII regions & SIGGMA at the diffuse ISM
Peculiar faint radio phenomena discovered in the 1960s can be deployed as standard tools in the SKA era to study the ionised, radical and molecular components of the ISM.
“Mature” physics + SKA = new perspective

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Radio Recombination Lines:
- kinematics of the ionised ISM
- He$^+$, C$^+$ abundances & metallicities
- measure radiation field leaving HII regions
- detailed kinematics of compact HII regions
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Anomalous Formaldehyde Absorption:
- H$_2$CO “anti-maser” against the CMB
- molecular density tracer *par excellence*
- distance independent
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Hydride radicals
- not just OH but CH too
- excellent tracer of diffuse gas
Radio Recombination Lines (RRLs)
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Low energy recombination lines from high quantum numbers.

“Classical” lines - see Raymond Oonk’s talk on “Diffuse”
Faint: $T_L/T_C \sim 0.02 - 0.2$
Δn = 1,2,3... lines defined as α,β,γ...
H, He, C have similar frequencies
Lines are impact broadened:

$$\frac{\Delta \nu_i}{\Delta \nu_D} = 0.14 \left( \frac{n}{100} \right)^{7.4} \left( \frac{n_e}{10^4 \text{ cm}^{-3}} \right)$$

Faintness & impact broadening makes large scale studies difficult
- except with single dishes on diffuse ISM (Alves et al 2012, Liu et al 2013)
The SKA will be an RRL mapping machine

1. Broad bandwidths → multiple line stacking for detections
   Don’t need high resolution for RRLs - 10 km/s is sufficient
   50 Hα RRLs in SKA1-mid instantaneous Band 2 b/w, 25 in SKA1-sur
   SKA1-mid competitive with SKA1-sur due to wider b/w
   Band 2 RRL mapping speed of SKA1-mid & sur comparable to VLA continuum speed
   25 Hα RRLs in SKA1-mid Band 5 b/w

2. Broad frequency coverage → trace different electron densities
   Band 2 impact broadening negligible \( n_e \sim 100 - 1000 \text{ cm}^{-3} \)
   Band 5 impact broadening negligible \( n_e \sim 10^4 - 10^5 \text{ cm}^{-3} \)

3. Multiple lines → detailed modelling
   Directly measure line broadening & constrain non-LTE effects from \( \alpha, \beta, \gamma, \epsilon, \ldots \) lines

4. Multiple lines from multiple atoms → metallicity, abundance, radiation field
   Also have multiple He & C lines in the same band
   H/He line ratios constrain radiation field
A Band 2 RRL diffuse ISM survey

THOR detects RRLs toward bright continuum (> 70 mJy)

But in high densities & with pressure broadened lines

For diffuse unbroadened gas need to trace $n_e \sim 100$ cm$^{-3}$

Needs ~12 hours/tile with SKA1-sur or ~1 hour/pointing SKA1-mid w/ line stacking

Fully commensal with HI survey ~300 hours for Plane

Out of the box early science towards individual HIIls (~150 hours to map top 12 HIIls)
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Anomalous Formaldehyde absorption

Collisional pumping drives population to lower energy states (anti-inversion)

Shows up in absorption against CMB when $T_{\text{ex}} < T_{\text{CMB}}$

Evans et al 1987
First VLA detection
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Advantages of anomalous absorption

1. Distance independent tracer
   The Milky Way, nearby galaxies, starbursts... (Mangum et al 2013)

2. Excellent and unique tracer of gas density
   Line ratio between 4.8 GHz & 14.4 GHz fixes gas density to ~0.2 dex with good dynamic range: $10^3 - 10^6$ cm$^{-3}$ (Ginsburg et al 2011)

3. Unaffected by line trapping, sub-thermal excitation or high optical depths
   - unlike CO, where $n$(H$_2$) may not be constrained within 2 orders of magnitude

4. Removing the scatter in SF “laws”
   e.g. Krumholz 2014

Discontinuity shows where lines go into emission
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Band 5 Galactic Plane H$_2$CO survey

Anomalous H$_2$CO absorption is faint (-0.5 K) & too time-consuming for wide-area maps pre-SKA

But Phase 1 SKA-mid:
~0.1 K rms, 0.1 km/s, 20” in ~1 hour @ 4.8 GHz
(0.008 K @14.4 GHz)

200 square degree Galactic Plane survey would take ~500 hours at 4.8 GHz plus ~ 500 hours of targeted 14.4 GHz follow-up

Determine accurate H$_2$ density for every GMC in the Milky Way and more:
- synergy with SF from multi-λ surveys
- simultaneous deep high resolution continuum survey, ~0.4 μJy rms & 0.3” resolution
- Band 5 RRL detections of every compact HII > 0.7 mJy (25 Hα, 23 Heα, 23 Cα lines)
- other molecules (CH$_3$OH...)
Anomalous absorption is not the only absorption that will be measured.

Will also be able to measure absorption against continuum sources (HII regions, PNe etc)

All of these HII regions will have velocities (simultaneous RRLs) & ~100’s with accurate distances (Jimi Green’s talk)

Network of illuminating sources - constrain absorption to particular distances

Tomography of the molecular ISM
The SKA will be a radio line mapping machine from Phase 1

Band 2 RRLs to trace the low density ionised ISM - kinematics, metallicity, UV field

Band 5 RRLs trace denser gas in compact HII regions

Anomalous H2CO absorption important tracer of H₂ density in Band 5

Galactic tomography of the molecular ISM

What we need for effective line surveys:

Spectral zoom modes for velocity resolution & simultaneous broad-band continuum

Multiple processing of the data for lines (from core) & continuum (core + arms)

Band 5 as a Phase 1 priority - possibly even to 14.5 GHz or higher (UWB feeds?)

Commensal operations?

Phase 2 - the SKA

He, C RRLs at low electron density

Full Galactic Plane mapping at sub-15” resolution in H₂CO