Unraveling the distribution of ionized gas in the Galactic plane with radio recombination lines.

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Science with ngVLA at JPL

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Science topic 1: Protostellar disks

- Explore disks using combination of observations and chemical models
- Different molecules probe different conditions and regions within the disk.
- Key species at radio wavelengths include:
  - ammonia - probes disk temperature
  - complex organics - probe grain surface chemistry, high temperature chemistry, desorption processes, and potentially disk turbulence

Science topic 2: Interstellar Medium

- What is distribution of the various phases of ISM gas in our Galaxy and beyond?
- Radio recombination lines probe ionized gas - a key unconstrained component of ISM
- ngVLA radio observations will complement our Herschel far-IR surveys of neutral gas
Goal: Understand the lifecycle of the interstellar medium

**Far-IR tracers:**
- [CII] 158um (Traces H$_2$, HI, and ionized gas)
- [NII] 205 and 122um (Ionized gas)
- [OI] 145 and 63um (Dense and warm H$_2$ gas)
  Etc.

**ngVLA tracers:**
- High density molecular tracers.
- Radio Recombination Lines
- Radio Continuum

**Diagram:**
- HII, NII, CII
- H$_2$, CO, CI
- Hi, CII
- PDR
- Cold Neutral Medium
- Warm Neutral Medium
- Warm Ionized Medium
- HII Region
- UV
- Cosmic Rays
Goal: Understand the lifecycle of the interstellar medium

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ngVLA tracers:

High density molecular tracers.
Radio Recombination Lines
Radio Continuum
GOT C+ is a volume weighted sample of ≈500 LOSs in the disk of the Milky Way.

We sample the Galactic plane every one degree in the inner galaxy and every two in the outer galaxy.

**GOAL:** Sample as many different clouds as possible over a wide range of physical conditions.

This allow us to obtain statistical information about the clouds in the Milky Way.
The rotation of the Milky Way
The [CII] distribution of the Milky Way:

The lines are projection of the Milky Way’s spiral arms into the Longitude-Velocity map.

Pineda et al. (2013) A&A 554, A103
Galactocentric Distribution

To derive global properties of population of clouds in the Milky Way we divide it into a set of rings and calculate the radially average distribution of different tracers.

Most of the [CII] emission in the galaxy comes from the inner galaxy (3-10 kpc). (We are 8.5 kpc away from the galactic center)
Galactocentric Distribution

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Knowing the distribution of the ionized gas in the Galaxy is fundamental for the interpretation of [CII] observations.
Galactocentric Distribution

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What about H^+?
The Herschel [NII] Galactic Plane Survey

- Nitrogen IP is 14.5 eV so found only in regions where H completely ionized. Electron collisions dominate.

- Herschel OT2 Project. PI: Paul Goldsmith

- 140 GOT C\(^+\) lines of sight at \(b=0^\circ\) observed in [NII] 205 um and 122um with PACS (897 s per observation)

- 10 selected lines of sight in [NII] 205um with HIFI (7041 s per observation)
Electron density distribution as a function of Galactic longitude (from [NII] 122um/205um)

- The [NII] 122um/205um gives the electron density.
- Typical $n_e = 10 - 50$ cm$^{-3}$. Much larger than WIM ($\sim 0.1$ cm$^{-3}$).
- Is the density the average along the line of sight? Or is dominated by a single source? **We need a velocity resolved, unobscured tracer of ionized gas.**

Radio Recombination Line Survey of the Galactic Plane

- RRLs are spectrally resolved, unobscured tracers of ionized gas.

- Provide unambiguous determination of the emission measure $EM = neN(H^+) = ne^2L$. It allows us to study the electron density distribution. (Continuum has to be separated between thermal and non-thermal emission).

- Hydrogen RRLs are the brightest, but Helium and Carbon RRLs can be detected in bright sources.

- Line to continuum ratio gives the electron temperature (e.g. Quireza et al. 2006)

- They trace the number of Lyman continuum photons and thus they trace the Star Formation Rate.

- There are 1 Hydrogen RRL per GHz. Observations with a broad instantaneous bandwidth can allow us to observe many RRLs simultaneously, thus significantly increasing the sensitivity (Balser 2006).
Radio Recombination Line Survey of the Galactic Plane

Alves et al. 2015 MNRAS 450 2025-2042

Parks survey
14’ angular, 20 km/sec velocity resolution.

Herschel GOT C⁺ survey: 15” angular, <1 km/sec resolution.

HRDS GBT Survey: Bania et al. 2010
Anderson et al. 2011.

80” angular, 2 km/sec velocity resolution.

Focus on 603 individual HII regions.
Radio Recombination Line Survey of the Galactic Plane

- We will observe 112 GOT C+ lines-of-sight in RRL with the NASA DSS-43 70m telescope (40” angular, <1 km/sec velocity resolution)

- Upcoming capabilities of the DSS 43 will allow simultaneous observations of RRL between 18 and 24 GHz (2 pol x 8 RRLs)

- Test observations are underway.
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Radio Recombination Line Survey of the Galactic Plane

Science Objective #1:

Follow techniques used in the GOT C+ survey to determine the distribution of ionized gas in the plane of the Milky Way.

Determine the contribution from ionized gas to the observed [CII] emission.
Science Objective #2:

Derive the distribution of the Star Formation Rate in the plane of the Milky Way.

Compare the RRL derived SFR with other tracers such as [CII].

Pineda et al. 2014 A&A 570, A121
Radio Recombination Line Survey of the Galactic Plane

**Science Objective #2:**

Derive the distribution of the Star Formation Rate in the plane of the Milky Way.

Compare the RRL derived SFR with other tracers such as [CII].

Pineda et al. 2014 A&A 570, A121
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Derive the distribution of the Star Formation Rate in the plane of the Milky Way.

Compare the RRL derived SFR with other tracers such as [CII].

Rigopoulou et al. 2015
Radio recombination line observations with the ngVLA

• The large collecting area of the ngVLA combined with large instantaneous bandwidths can provide extreme sensitive observations of RRLs.

• Our work in the Milky Way will pave the way for similar studies in external galaxies.

• We can learn about the properties of the ISM over different environmental conditions in galaxies as well as determine the star formation history of the universe.

• These data will have synergies with surveys of [CII] emission of high-Z galaxies with ALMA and future Far-IR observatories.