Low Frequency Observations of Supernova Remnants and HII regions

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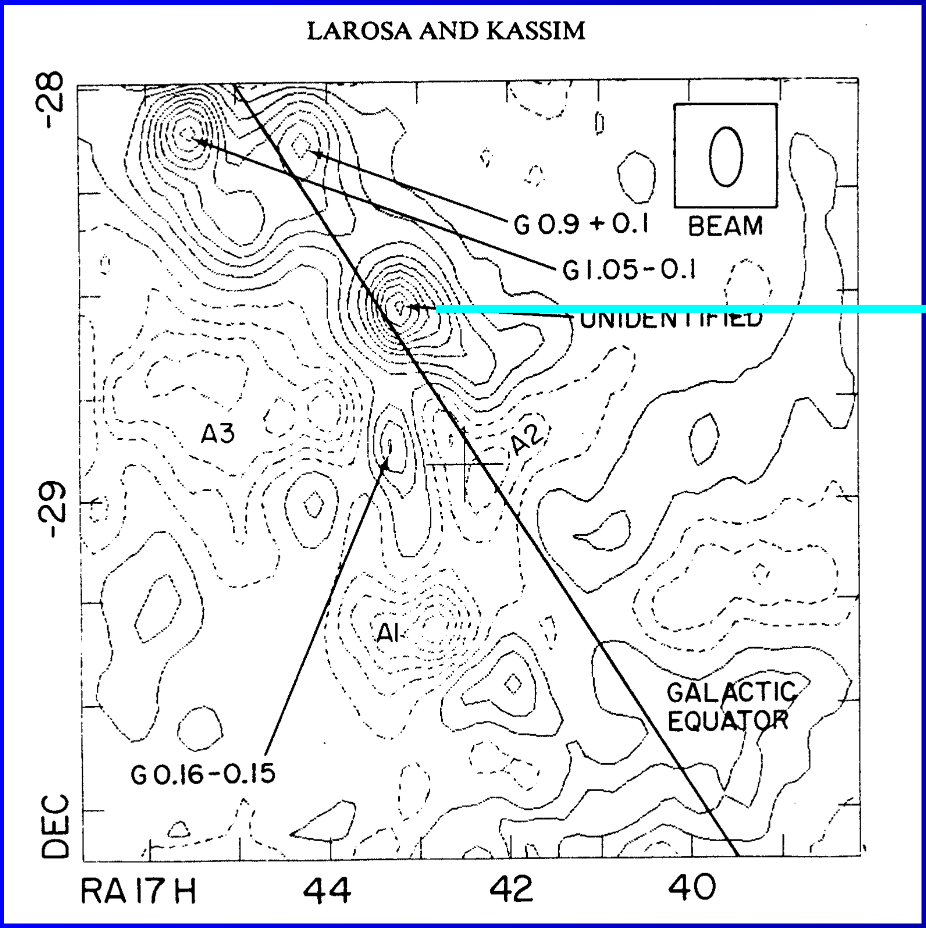
Why study SNRs at Low Frequencies?

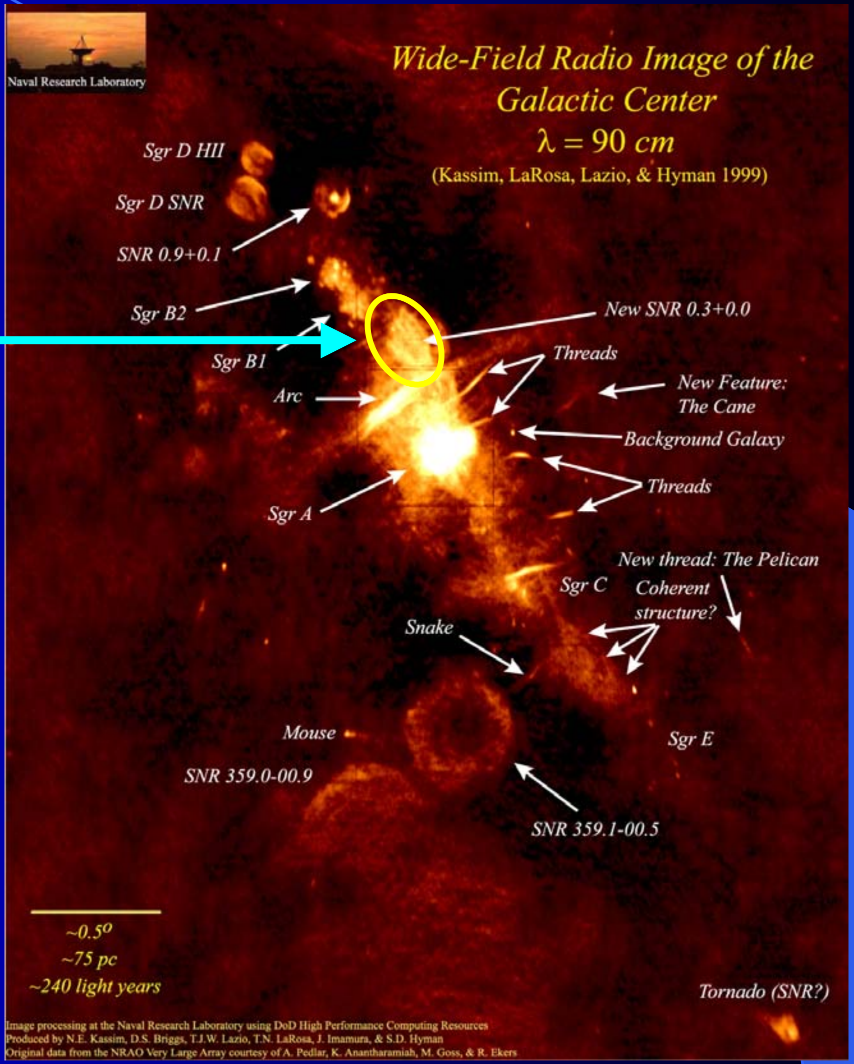
- They are nonthermal and hence brighter. Therefore:
  - It is convenient to study known ones
  - It is easiest to find new ones (in the radio at least)
  - Thermal absorption effects can be measured
  - Spectral studies are enhanced because of the increased lever arm in frequency space
- They are big: the FoV and angular resolution are generally well matched to SNR sizes

Finding New SNRs

- Low frequencies ideal for finding new SNRs
- Why is this important?
  - SNR catalogs incomplete
    - Catalogs severely limited by selection effects
      - Missing low surface brightness extended SNRs
        - Catalogs currently complete to $\Sigma > 8\times10^{-21} \mathrm{W m^{-2} Hz sr^{-1}}$
        - See Green 1991, PASP, **103**, 209
    - Also missing bright, compact "young" SNRs
  - Complete samples required for
    - SN/SNR birthrates
    - Energetics: Energy input by SN to ISM
    - Distribution: Comparison with distribution of progenitor population
    - PSR/SNR associations

Finding New SNRs





Studying Known SNRs

- Important for distinguishing shells-composites-plerions
  - Eg. Dwarakanath's 34 MHz Vela work (1991, J.Astrop.Astr., **12**, 1299)
    - Vela X: $\alpha \sim -0.16$ => Plerion, Vela YZ: $\alpha \sim -0.53$ ==>Shell
- Relative super-position of HII/SNRs in complex regions
- Useful for finding shells around known plerions?
  - E.g. the Crab
- Integrated & spatially resolved continuum spectra important for all theories of SNR emission

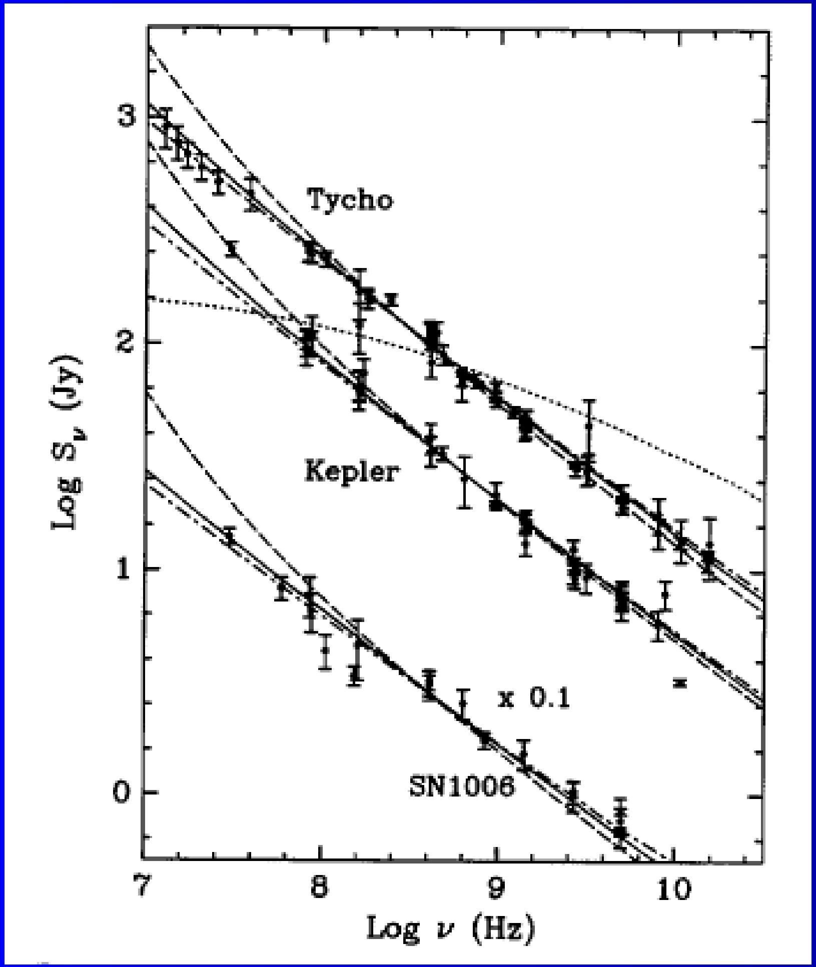
Radio Spectra of SNRs: Probes of Particle Acceleration Physics

- Radio spectral index measures the energy spectrum of the relativistic electrons accelerated in SNR shocks
  - Important to all theories of SNR emission (van der Lann & Fermi)
  - Reported variations have long been controversial
    - LF Imaging weak link in past studies
- Spatially resolved spectral index mapping
  - Possible source of variations:
    - Variations in parameters of ongoing particle acceleration
    - $\alpha=3[2(r-1)]^{-1}$: Weaker shocks, lower compression ratios, steeper α
  - Curved Electron spectra (CRs or PA with diffusion)
    - Regions of enhanced B field will shift break frequency up - convex
  - Cosmic-ray mediated shocks: Concave spectra
  - Mixed thermal population: Regions of flatter spectra
  - Very complicated, theory can predict anything!

SNR Spectra: Probes of CR Acceleration Physics

- Even accurate integrated spectra are important
  - Integrated spectra important test of DSA theory in young SNRs
    - Fermi theory predicts concave spectra – constrains magnetic field strength (Reynolds & Ellison 1992, ApJ, **399**, L75)
    - LF measurements key to determining integrated spectrum
      - LF flux densities are weak link in presently known spectra
  - Important for van der Laan emission in older SNRs
    - Spectral breaks in older SNRs linked to compression of CR gas with break at 200 MHz: -0.4 below, -0.9 above (Bridle 1967, MNRAS, **136**, 219)
    - Cygnus Loop (Green 1990, AJ, **100**, 1927; Sastry et al. 1981, J. Astrophys. Astr., **2**, 239)
- LF systems like SIRA with modest resolution – but powerful spectral dynamic range - can provide unique measurements

SNR Integrated Spectra



Reynolds & Ellison (1992)

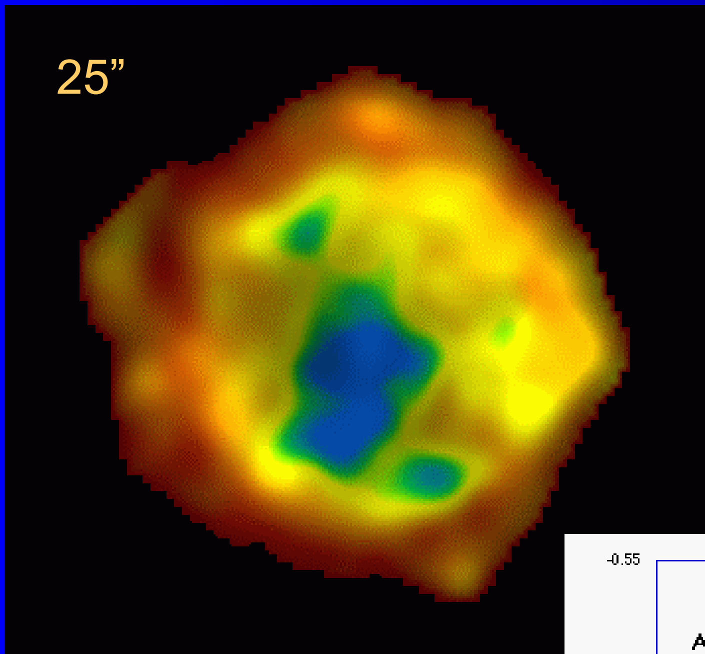
- Fermi acceleration predicts curved integrated spectra
- Large spectral dynamic range required to test this theory.
- Large spectral dynamic range can also determine magnetic field strengths.
- Ideal for SIRA

Absorption: Internal - Measure of thermal material inside SNRs

- Cas-A internal absorption at 74 MHz
  - Second case for unshocked ejecta inside young SNR (Kassim et al. 1995, ApJ, **455**, L59)
    - 1st case: SN1006: Hamilton & Fesen 1988, ApJ, **327**, 178
  - Important constraint for SNe/SNR theory
- Crab internal absorption at 74 MHz
  - Constrains location of filaments relative to nonthermal emitting material (Bietenholz et al. 1997, ApJ, **490**, 291)
  - Wets appetite for lower frequency measurements
- Internal absorption common? Even at this relatively "high" frequency?

Resolved Spatial Spectral Index Variations

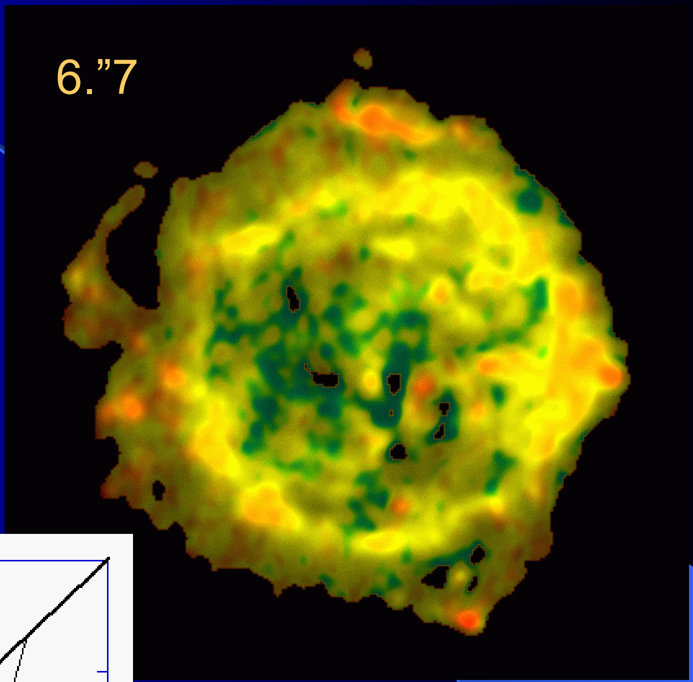
Cas A



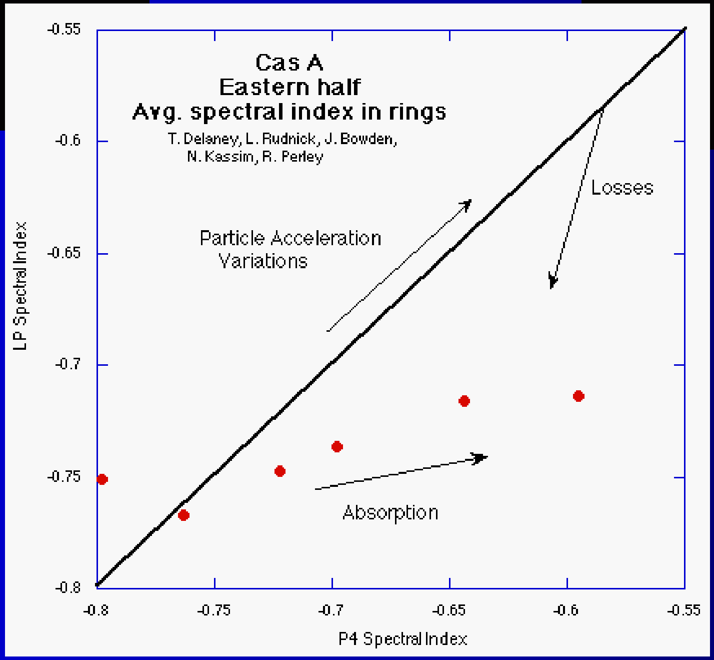
Spectral Index between 330 MHz and 74 MHz

Red → Blue

- 0.9 → - 0.6

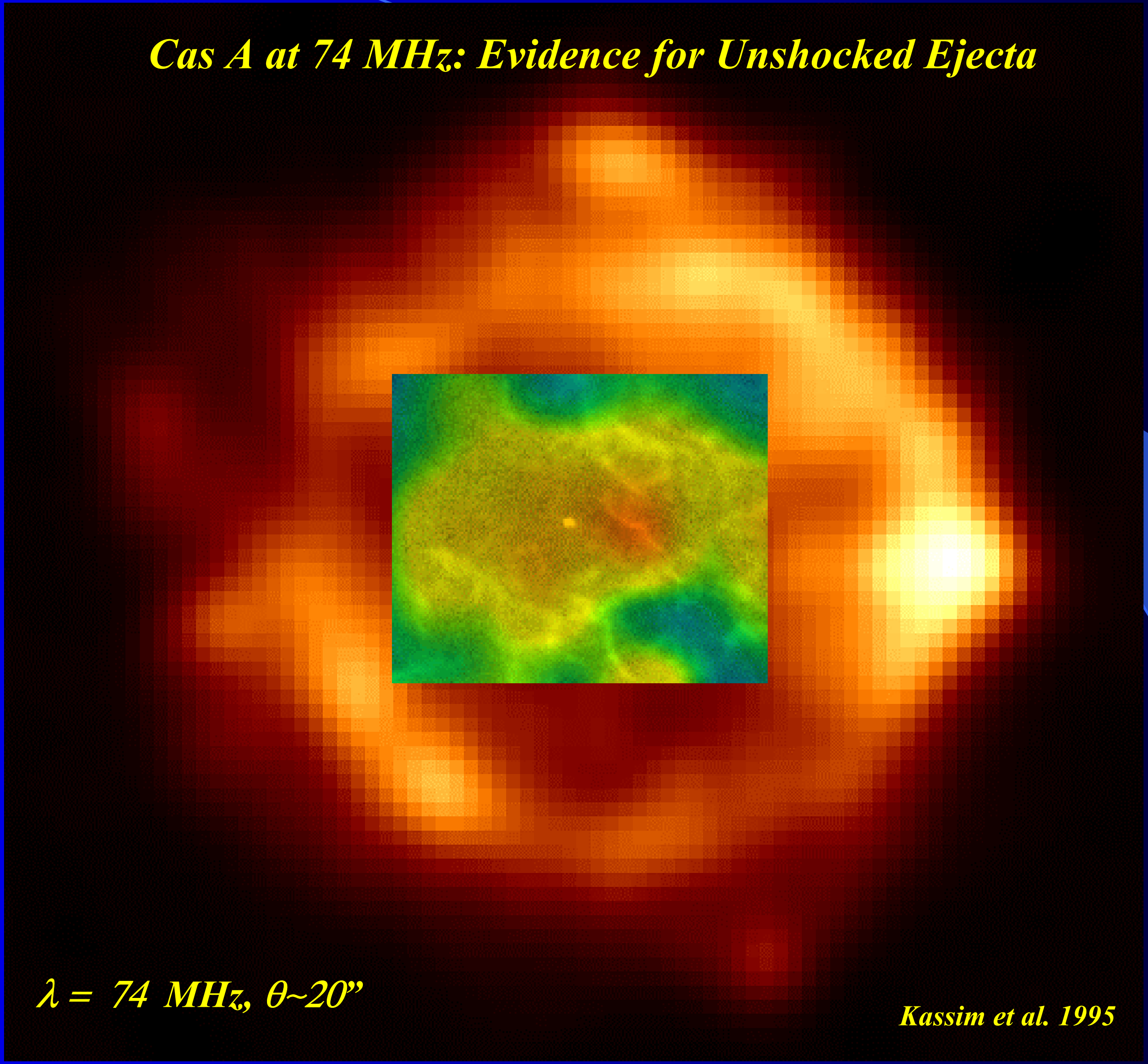


Spectral index between 1.4 GHz and 330 MHz



Courtesy L. Rudnick

SNR Cas A at 74 MHz



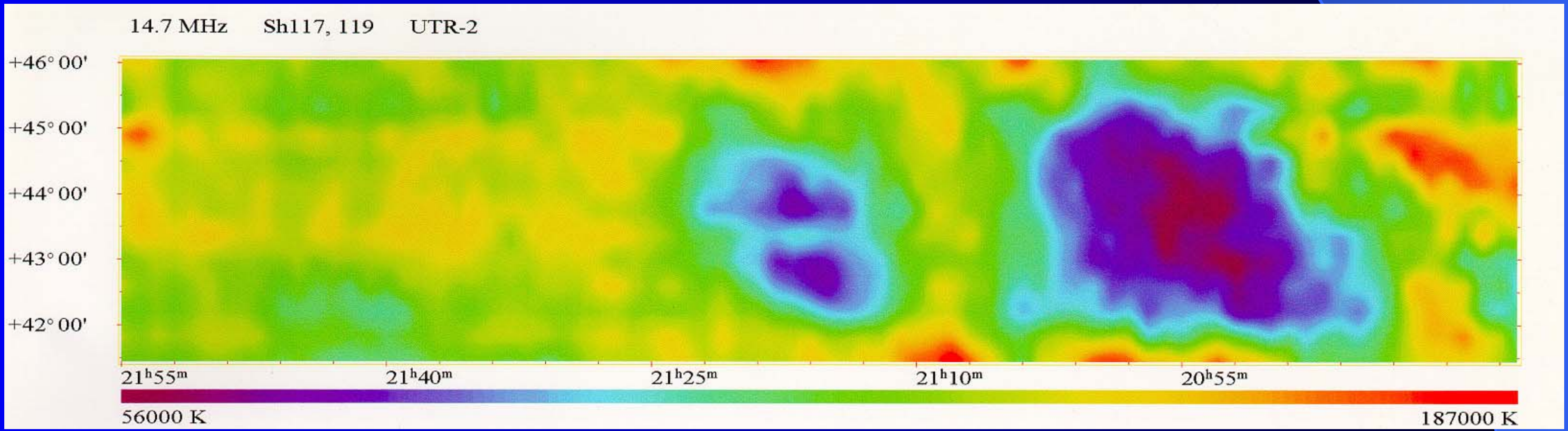
Low Frequency Observations of HII

- Discrete HII regions in absorption ($n>50\ cm^{-3}$)
  - Cosmic Ray tomography
- HII region Envelopes ($n \sim 1\text{-}10\ cm^{-3}$)
  - Patchy ISM component
- Warm Ionized Medium ($n \sim 0.1\ cm^{-3}$)
  - Widely distributed ISM component
  - Radio can probe entire galaxy
  - Optical depths ideal for SIRA

Discrete HII regions in Absorption: Cosmic Ray Electron Tomography

- Use Galactic synchrotron emission to trace CR electron gas
- High ν measure total column, confused with thermal & discrete sources
- Low ν see only the synchrotron emission, HII regions provide path lengths, allow determination of 3D distribution

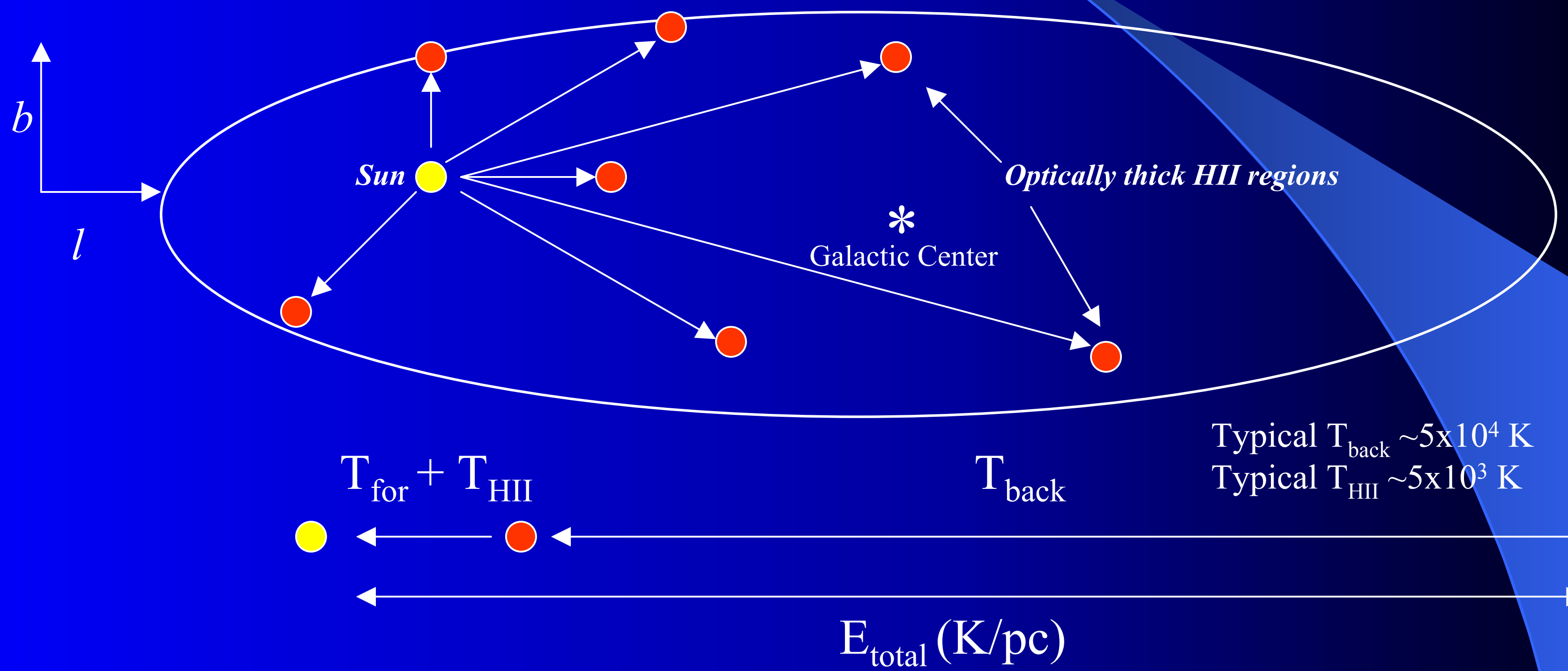
HII Regions in Absorption at Long Wavelengths



UTR-2 at 15 MHz: Sharpless 117 & 119, θ ~ 2 degrees

Mapping out the Cosmic Ray Electron Gas: Use Galactic HII regions at known distances

Measure foreground, background, & total synchrotron emission along many lines of sight

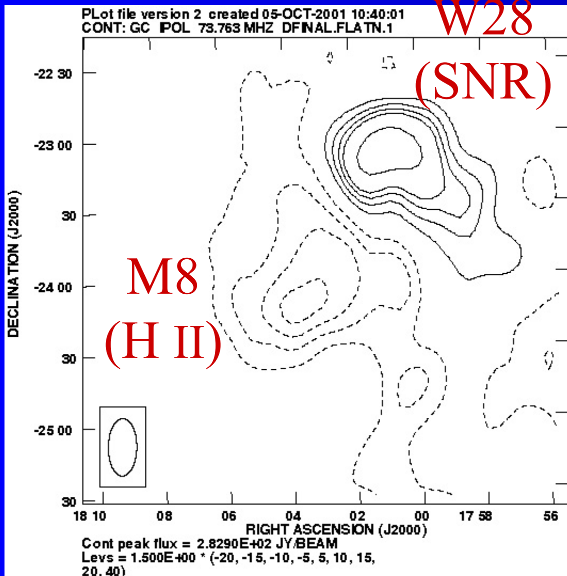


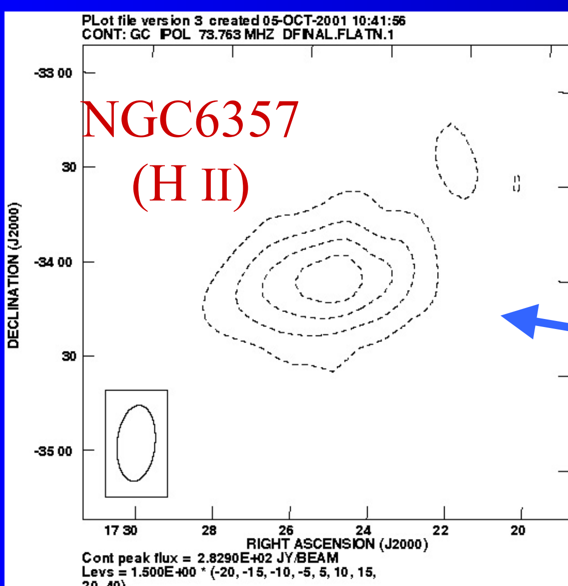
Typical 30 MHz absorption "hole" flux for 1' HII region: 25 mJy outer Galaxy, 100 mJy inner Galaxy
(at least 1000 Galactic HII regions of this scale)

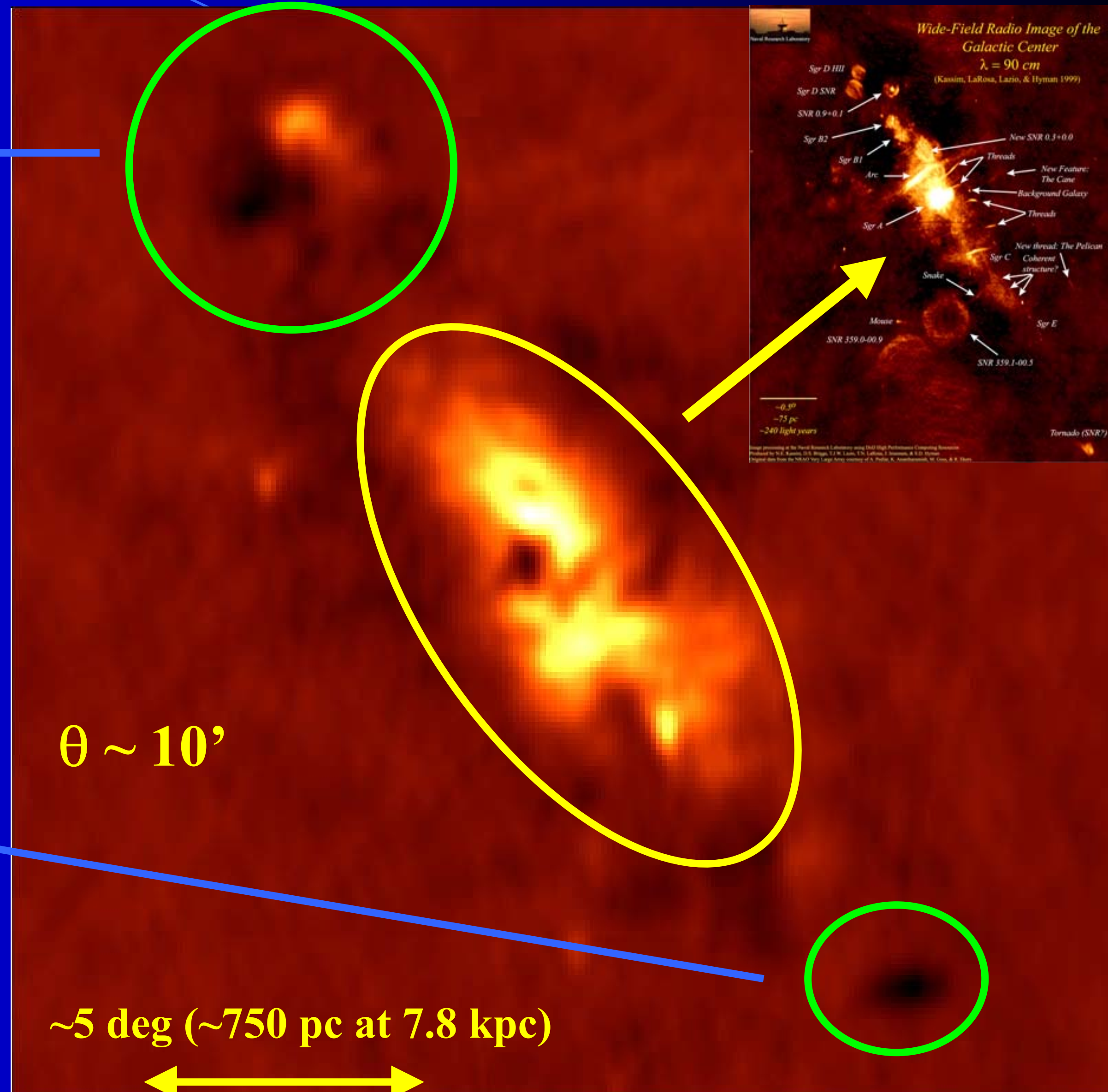
LOFAR inner Galaxy, distant HII – SIRA – larger, anti-center nearby HII

74 MHz GC: HII Region Absorption

(Nord et al. 2002)





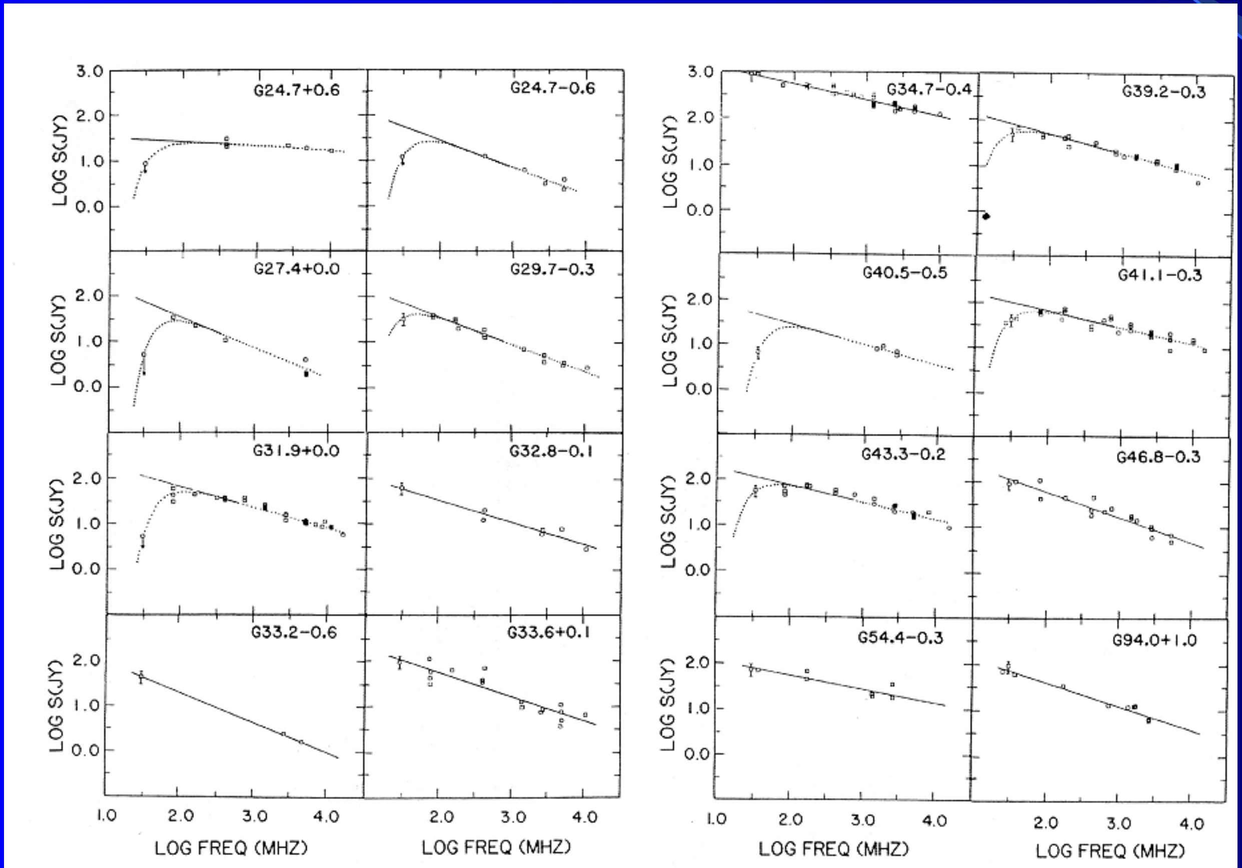


Probing Lower Density ISM HII: Absorption of Nonthermal Sources

- Many SNRs show low frequency turnovers
  - Dulk & Slee (1975 ApJ, **199**, 61), Kassim(1989, **347**, 915) work
  - Patchy absorption constrains distribution of low density gas in ISM
    - WIM density ≤0.26 cm^{-3} (for T~8000 K)
  - Consistent with absorption by Extended HII Region Envelopes
    - Inferred from 325 MHz RRLs (Anantharamaiah 1996, JApAstr, **7**, 131)
    - T~3000-8000K, n~0.5-10 cm^{-3}, Sizes~50-200 pc
    - Alternative interpretation: GRRLs may originate in old, evolved HII regions, not enough absorption seen at 34 MHz Dwarakanath thesis)
- This work in primitive state, the CLRO & Culgoora work was <u>severely</u> limited in frequency, angular resolution, & sensitivity (confusion)

Patchy Absorption Towards Galactic SNRs and the Distribution of Ionized Gas in the ISM

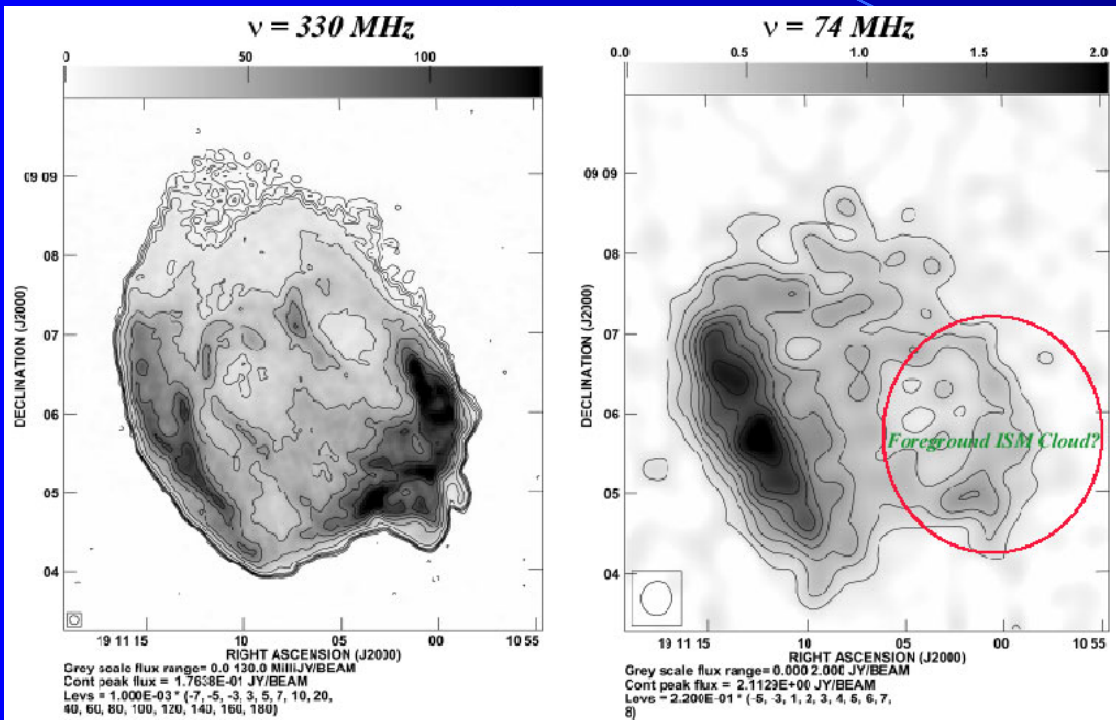
LOFAR inner galaxy, SIRA outer galaxy



(Kassim 1989)

- Many, but not all, SNRs show low ν continuum turnovers.
- Previous low ν studies have been limited to integrated spectra by the poor angular resolution and sensitivity.
- LOFAR will revolutionize these absorption studies and expand to utilize xgal background sources for scattering studies.

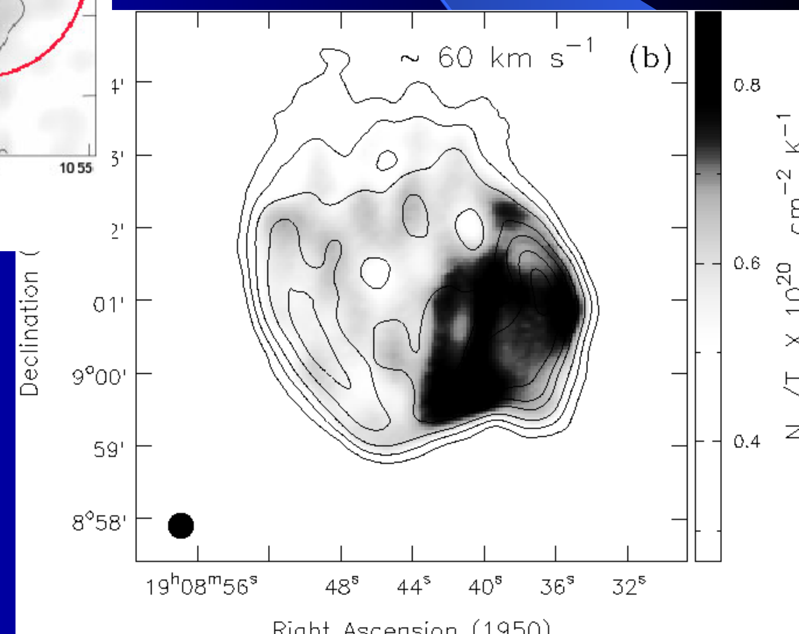
Free-Free absorption from the ISM: W49B



Lacey et al (2001)

First example of spatially resolved free-free ISM absorption

HI



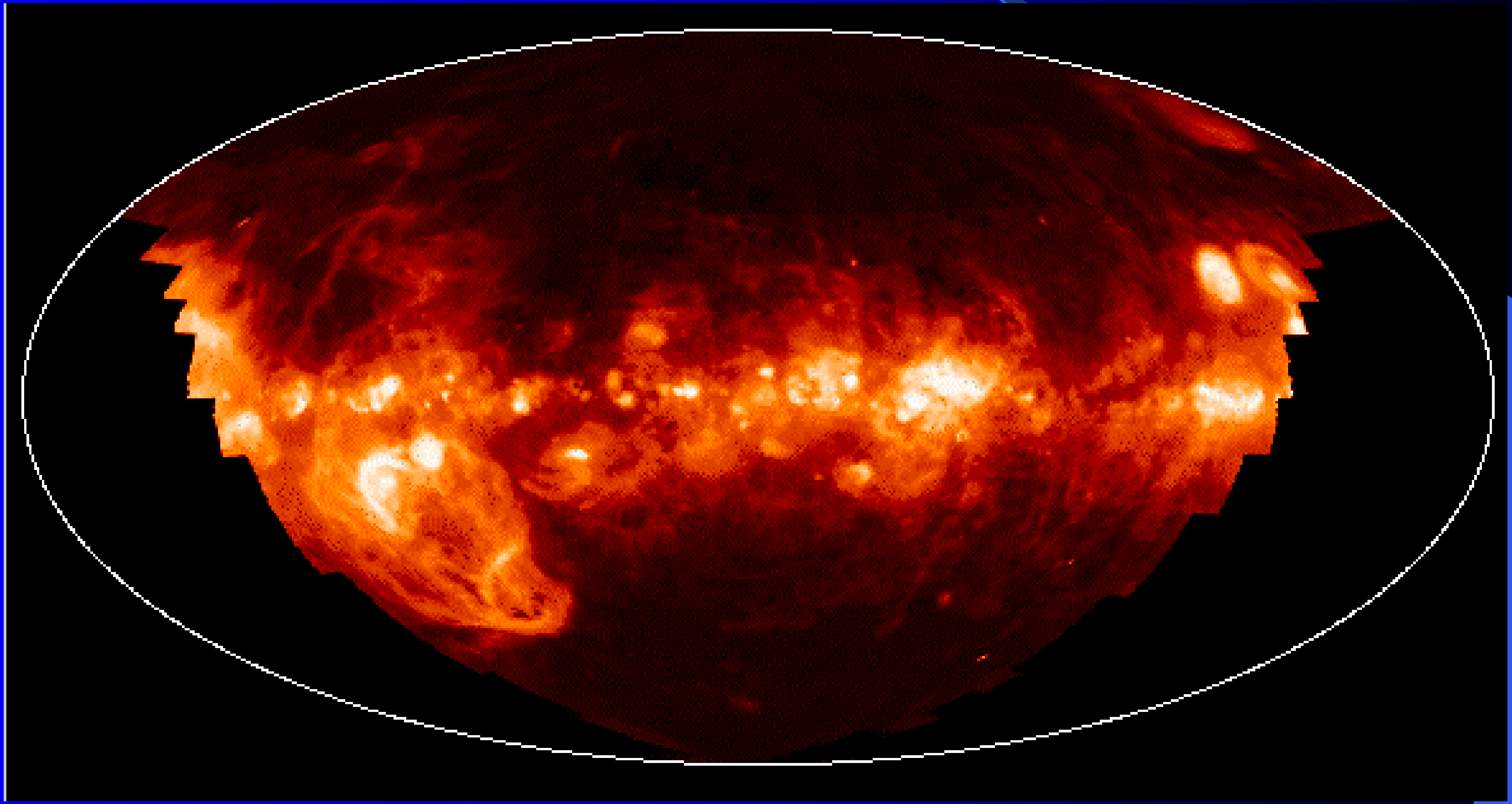
Brogan & Troland (2001)

Radio Recombination line H134α observed at ~65 km/s (*Downes & Wilson 1974*)

Absorption by the WIM

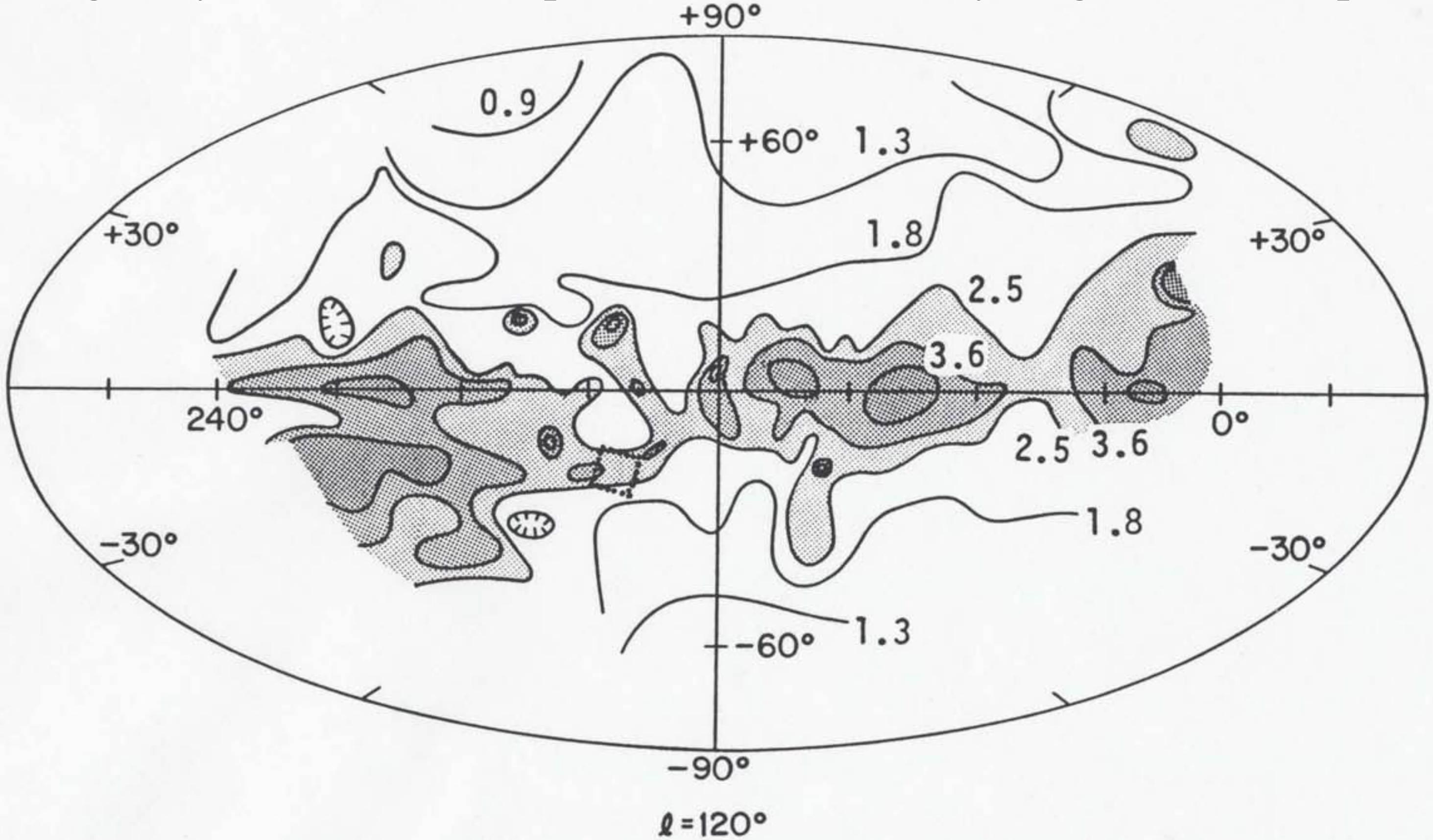
- Major component of ISM
  - 20% of volume
  - Scale height 1 kpc
  - Energetically important
    - Requires 1/6 of ionizing flux from O star population
      - Puzzle: incompatable with scale height well above stars and HI
  - Key diagnostic: H-alpha
    - Ron Reynolds work with WHAM
      - H alpha limited to probing ~1 kpc from the sun
      - Radio can probe entire galaxy
  - Frequency range ideal for SIRA
    - Low SIRA frequencies: probe outer galaxy and halo WIM
    - High SIRA frequencies: probe inner galaxy WIM

Wisconsin H-Alpha Mapper Survey
(Ron Reynold's group)



WIM Absorption Frequencies for $\tau \sim 1$

Outer galaxy: low SIRA frequencies Inner Galaxy: high SIRA frequencies



Summary

- SIRA should provide unique observations of Galactic nonthermal and thermal sources
  - SNRs - good for SIRA – non-thermal & big
    - Find new SNRs, Spectrum of known SNRs
      - Even integrated spectra important for testing Fermi acceleration theory - SIRA to provide powerful lever arm in frequency space
      - Cas-A like internal absorption
  - Discrete "classical" HII regions ($n>50\ cm^{-3}$)
    - Probes of 3D distribution of CR electron gas
      - Study acceleration, diffusion, propagation, origin of Galactic CRs
  - Extended HII region envelopes?? ($n \sim 1\text{-}10\ cm^{-3}$)
    - Map distribution through observations towards discrete nonthermal sources – compliment to LOFAR
  - WIM ($n \sim 0.1\ cm^{-3}$) – SIRA brings unique capability to map distribution of this important ISM constituent across the galaxy
- with LOFAR: probe complimentary regions of ISM phase space