# Resolved Thermal Absorption: Characterizing the Unshocked Ejecta in the young SNR Cas A

Namir Kassim
(Naval Research Laboratory)

Tracey Delaney (WV Wesleyan)

Larry Rudnick (U of MN)

Rick Perley (NRAO)

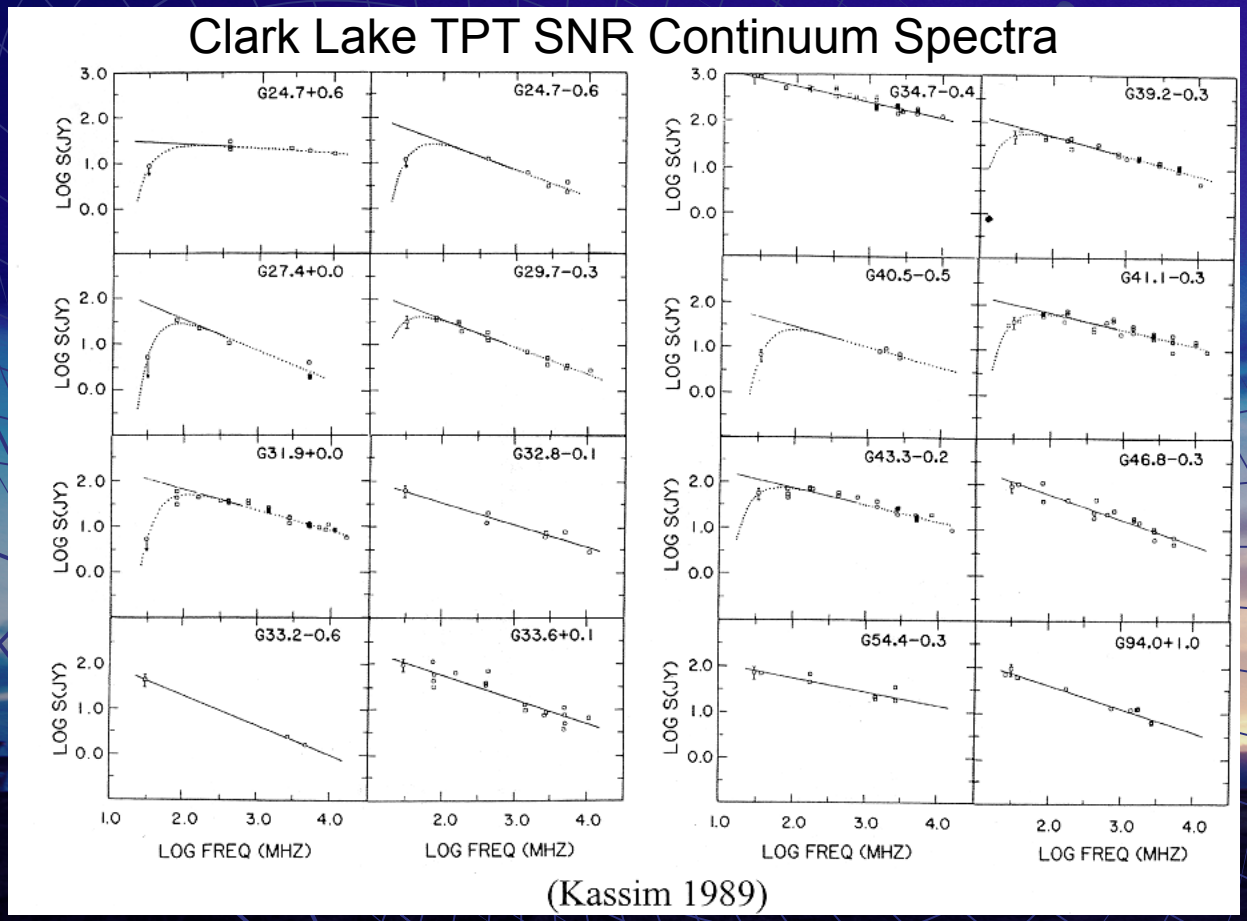
TD Acknowledgments:
Chandra grants: GO0-11089X and AR3-14007X
NASA - West Virginia Space Grant Consortium

# Outline

- Thermal absorption in the ISM
  - Towards SNRs
  - Presumed generally to be extrinsic
  - Finally resolved
- Low frequency observations of Cas A?
  - Extrinsic? Seems odd.
  - Constraints on the mysterious absorber
    - From theory
    - Correspondence with IR
    - Geometry
    - Physical parameters, including estimated mass
- Implications for LOFAR: thermal absorption is ubiquitous & rivals the power of HI because it constrains relative distances
  - Also for LWA, MWA, GMRT, VLA-LB, SKA-LO, etc …

# Thermal ISM Absorption

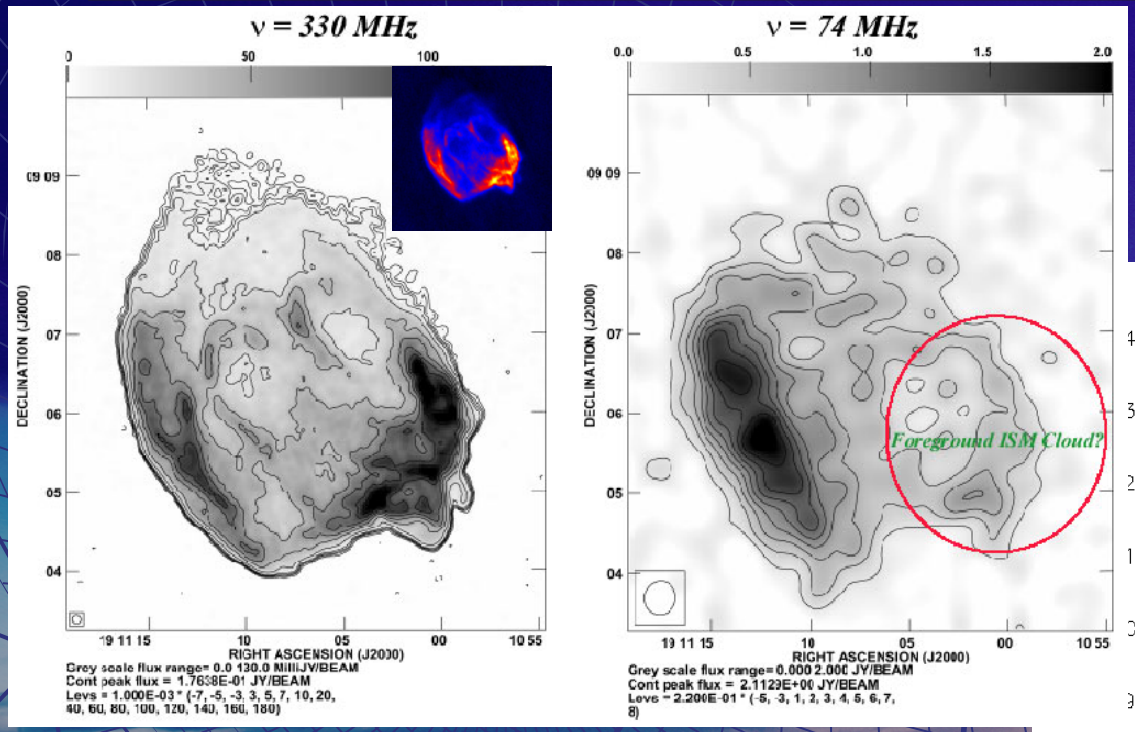
- A patchy distribution of low frequency ionized gas in the ISM - probably associated with normal HII regions (Dulk & Slee 1975 (SNRs), Anantharamiah 1986 (RRLs))



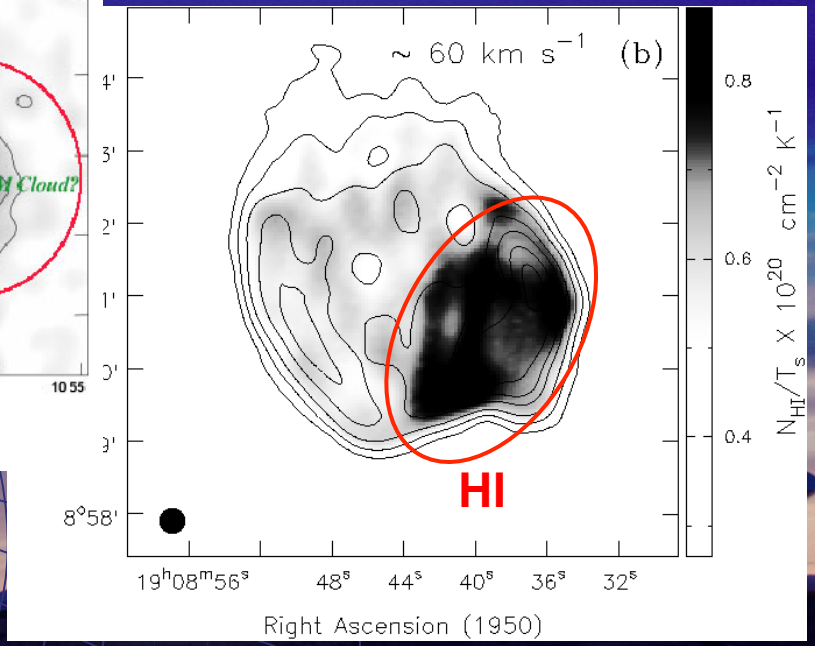

- Many, but not all, SNRs show LF continuum turnovers.
- Earliest studies limited to integrated spectra by poor angular resolution & sensitivity.

# Resolving the Confusion: Resolved ISM Thermal Absorption

We finally resolved the absorption towards a bright SNR (W49B) with the VLA at 20” resolution.



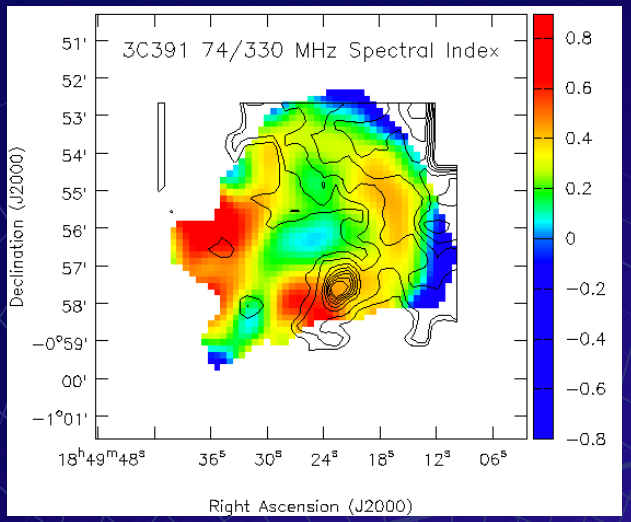

HI & radio recombination lines: what a big surprise!



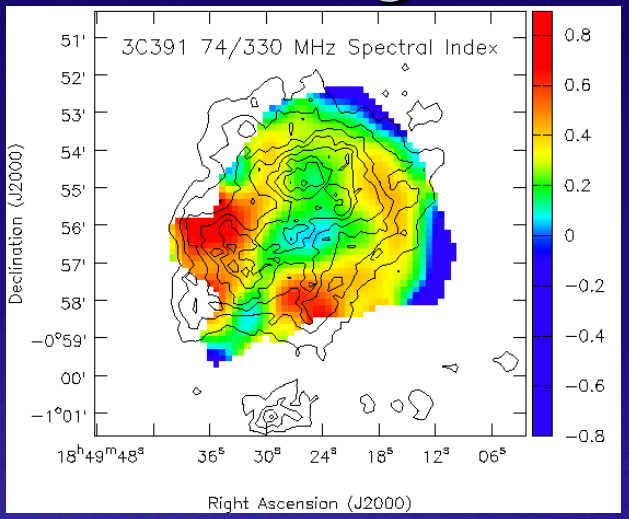

*Lacey et al (2001)*

*HI: Brogan & Troland (2001);* H134α RRL observed earlier at ~65 km/s (*Downes & Wilson 1974*)

# Resolved SNR/MC Interactions: Smoking Gun!

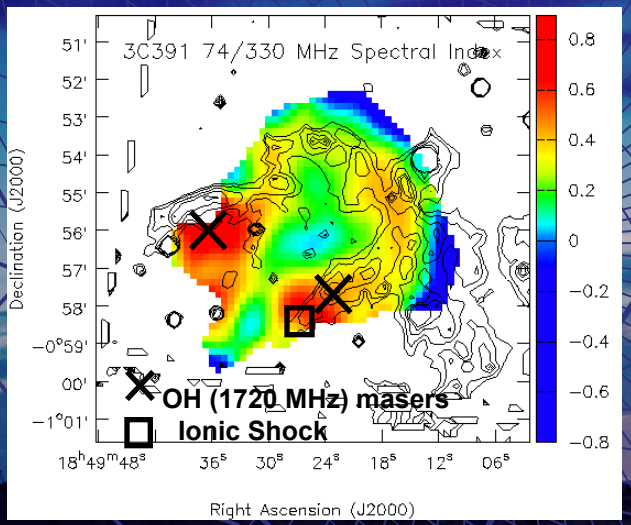



**CO (2-1)** integrated emission from **91 to 110 km/s** (*Reach & Rho 1999*).



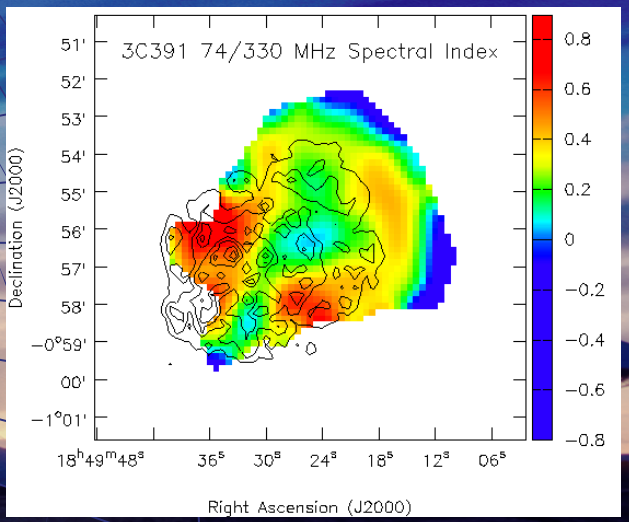

**HARD X-rays** from ASCA showing full extent of SNR (*Chen & Slane 2001*)

Surprising agreement between regions of greatest 74 MHz absorption – delineates sheath of absorbing ionized gas residing in the SNR/molecular cloud shock boundary!




Brogan et al. 2002

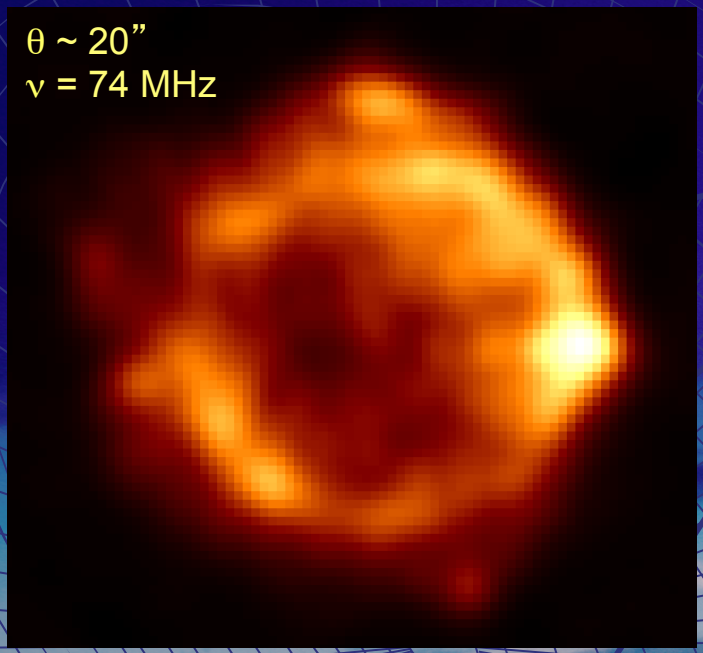
**IR** emission from 12-18 μm tracing shock boundaries (*Reach et al. 2002*).



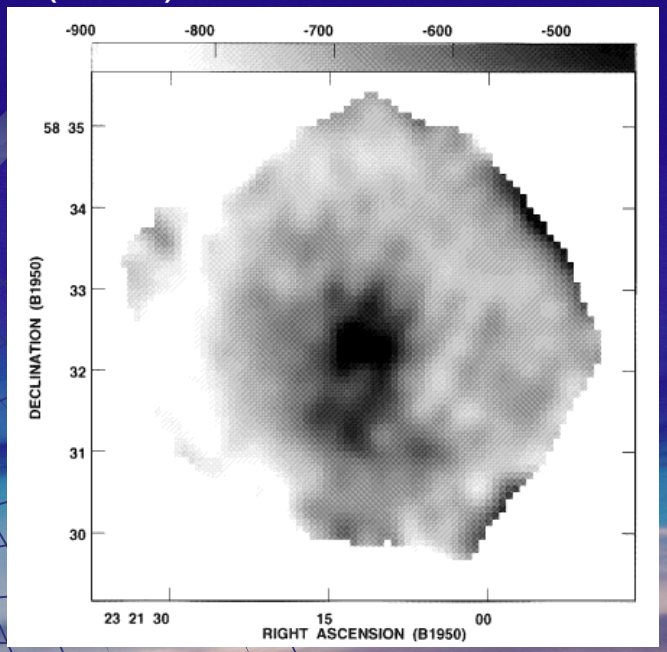

**SOFT X-rays** from ASCA showing X-ray absorption (*Chen & Slane 2001*)

# What's going on towards the center of Cas A – poor uv coverage?

74 MHz Intensity




74-330 MHz Spectral Index (x100)

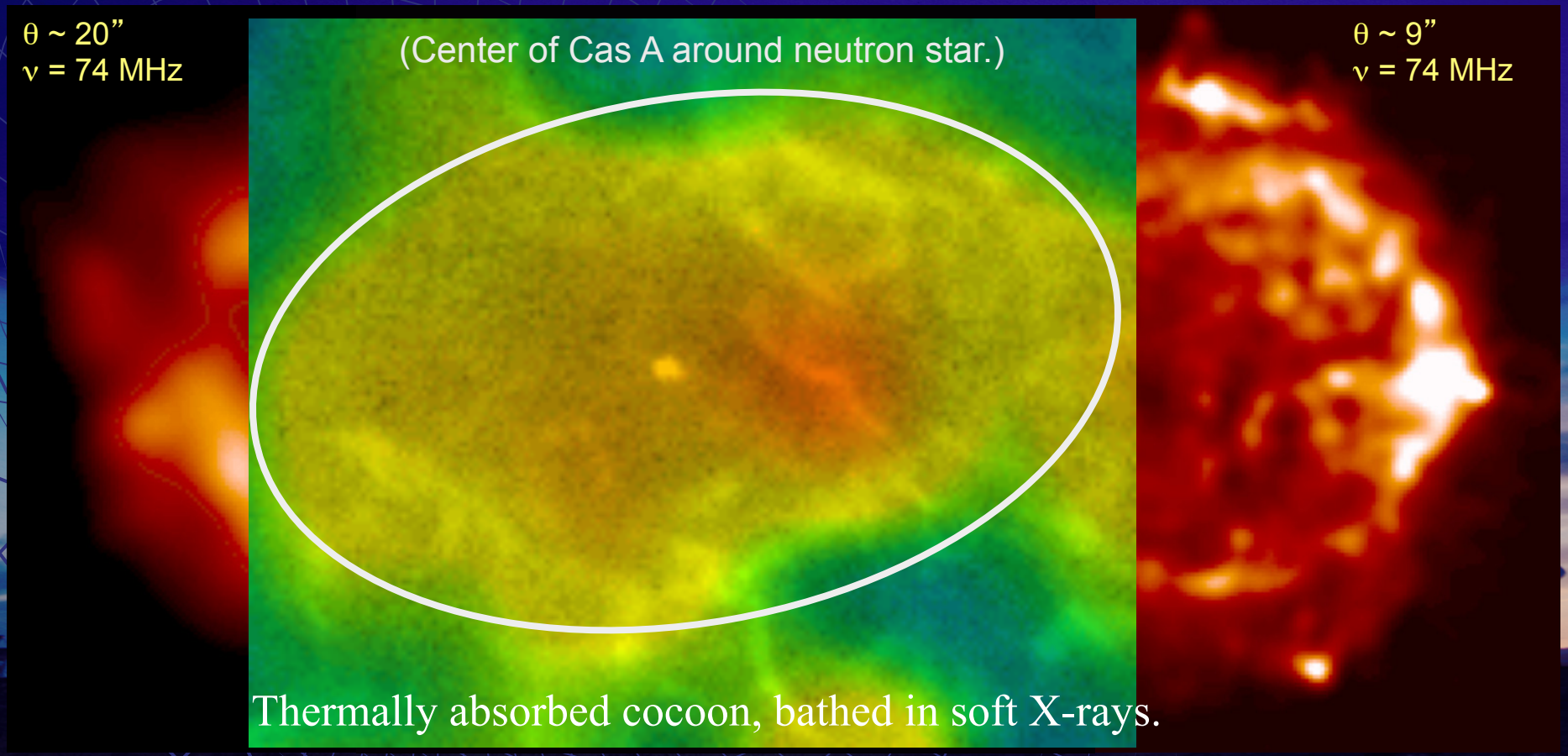



This 330 to 74 MHz spectral index map was initially a puzzle. Bill Erickson: "It's as if there were an absorbing cocoon inside Cas A."

# Let's try more antennas and higher angular resolution: It's still there!

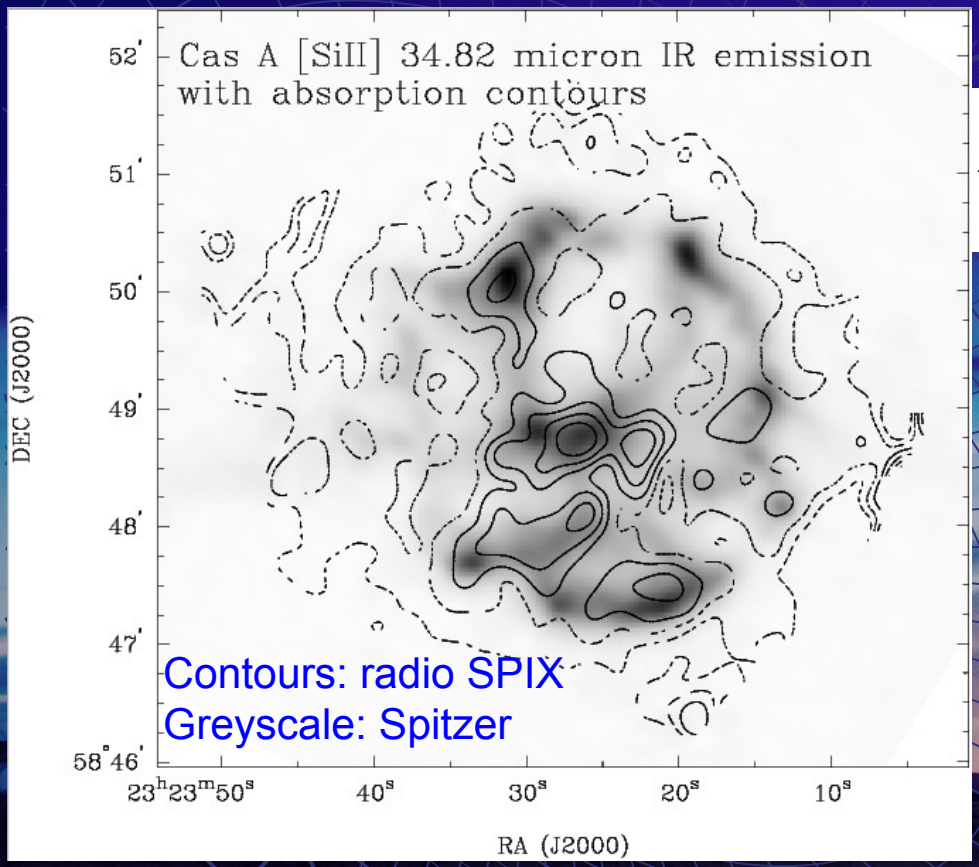
VLA (~35 km)

VLA + Pie Town (~72 km)



# Intrinsic Free-Free Absorption!

Roger Chevalier: this is predicted by theory – cool thermal gas ionized by X-rays from the reverse shock. This "unshocked ejecta" was seen once before: via Fe absorption lines towards a white dwarf behind SN1006. We now also see this gas in emission with Spitzer.




## The Standard Formula

$$\tau = 8.235\times10^{-2}\left(\frac{T}{\mathrm{K}}\right)^{-1.35}\left(\frac{\nu}{\mathrm{GHz}}\right)^{-2.1}\left(\frac{EM}{\mathrm{pc\ cm^{-6}}}\right)$$

where $EM = \int n^2 dl$

Using this formula Kassim et al 1995, ApJ, 455, L59 published one of the most ridiculous estimates in Galactic astrophysics: 16 solar masses of ejecta on the inside!

# What Went Wrong?

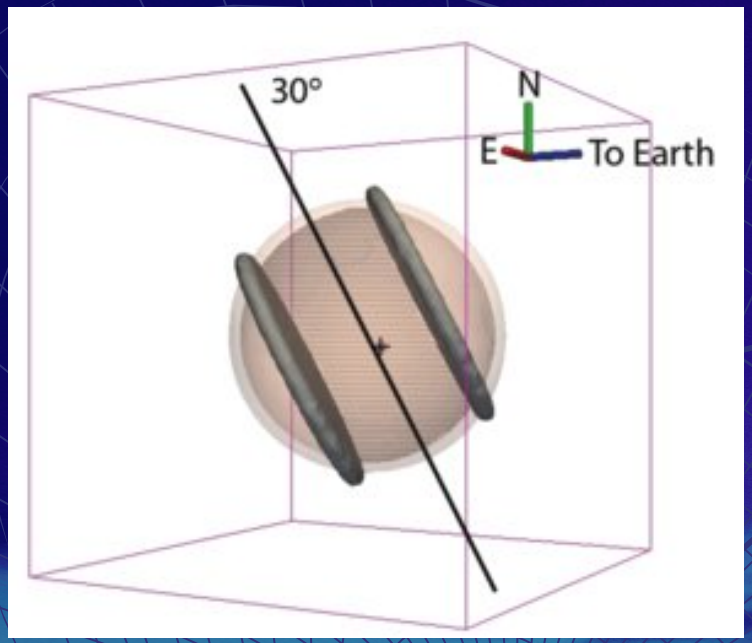
- Previous formula was for hydrogenic gas – works for most of the universe
- In SNR ejecta, oxygen a million times more abundant than hydrogen
- Must take into account Z and ionization state (electron/ion ratio)

$$\tau = 3\times10^{4}\left(\frac{T}{\mathrm{K}}\right)^{-1.5}\left(\frac{\nu}{\mathrm{MHz}}\right)^{-2}\left(\frac{EM}{\mathrm{pc\ cm}^{6}}\right)\left(\frac{Z^{2}}{f}\right)\ln\left(\frac{49.55T^{1.5}}{Z\nu}\right)$$

Tools of Radio Astronomy, 3rd ed., ch 9.4

# Density and Mass

(using the correct formula this time!)




- 0.15> $Tau_{FF}$ > 0.51 (74 MHz)
- Z=8.34: dominated by O
- f=2.5: [OIII] and [OIV]
- T=200 K
- Geometry=2 filamentary disks, thickness 10”=0.16 pc

$e^-$ density=4.2/$cm^3$, mass=0.39 Msun

In line with prediction of 0.18-0.3 Msun from Hwang & Laming, 2012, ApJ, 746, 130 based on hydrodynamic simulations.

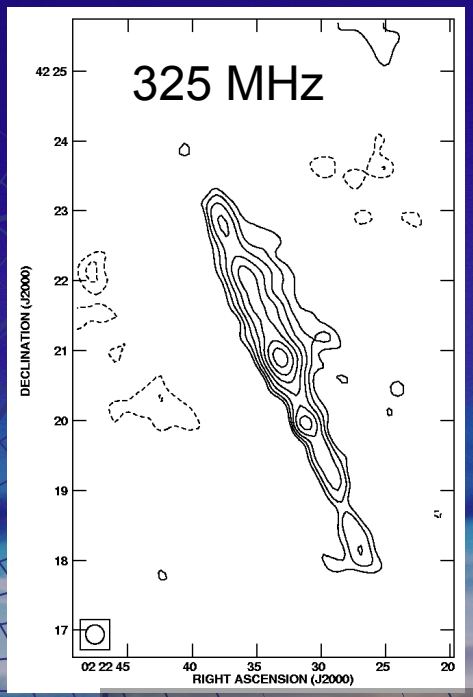
Note: there is not enough of this cold gas to cause the lower frequency turnover in the Baars et al. spectrum, but it plays a role.

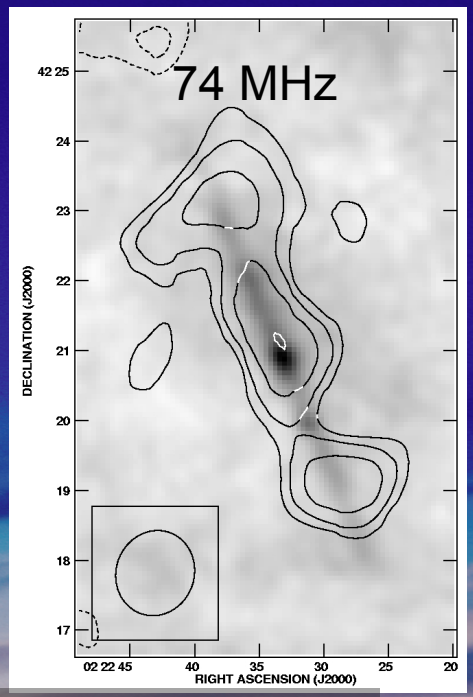
# Summary

- Thermal absorption by ionized gas in the Galaxy is ubiquitous
  - You see it along the line of sight
  - You see it in complex regions where nonthermal & thermal sources interact
  - You even see it in unexpected places, like SNR interiors
  - In Cas A we see it where we should and it matches the IR – but open questions remain (see our paper!)
  - *Thermal absorption has been seen towards nearly every SNR carefully observed below 100 MHz- must affect other sources*
- It's powerful because it tells you not only about the physical parameters of the ionized gas, but about the relative radial superposition of emitting regions – just like HI!
- The VLA lacked higher resolution for smaller objects & sensitivity for weaker ones, & most importantly frequency coverage
  - *LOFAR et al. can provide all of these things.*
- Next step in our story is for Ger: the extragalactic sky awaits!

# Resolved extragalactic thermal absorption? It must be there, and LOFAR can find it!

NGC 891: POSS II image




- Cohen, Israel & Kassim, 2004
- Hint of resolved spectral turnover in NGC 891 – spectrum flatter in disk – we need LOFAR to confirm!
  - EG thermal absorption has been predicted by Ger & others & seen at higher freq. (e.g. MERLIN @408 MHz) from higher density HII gas.