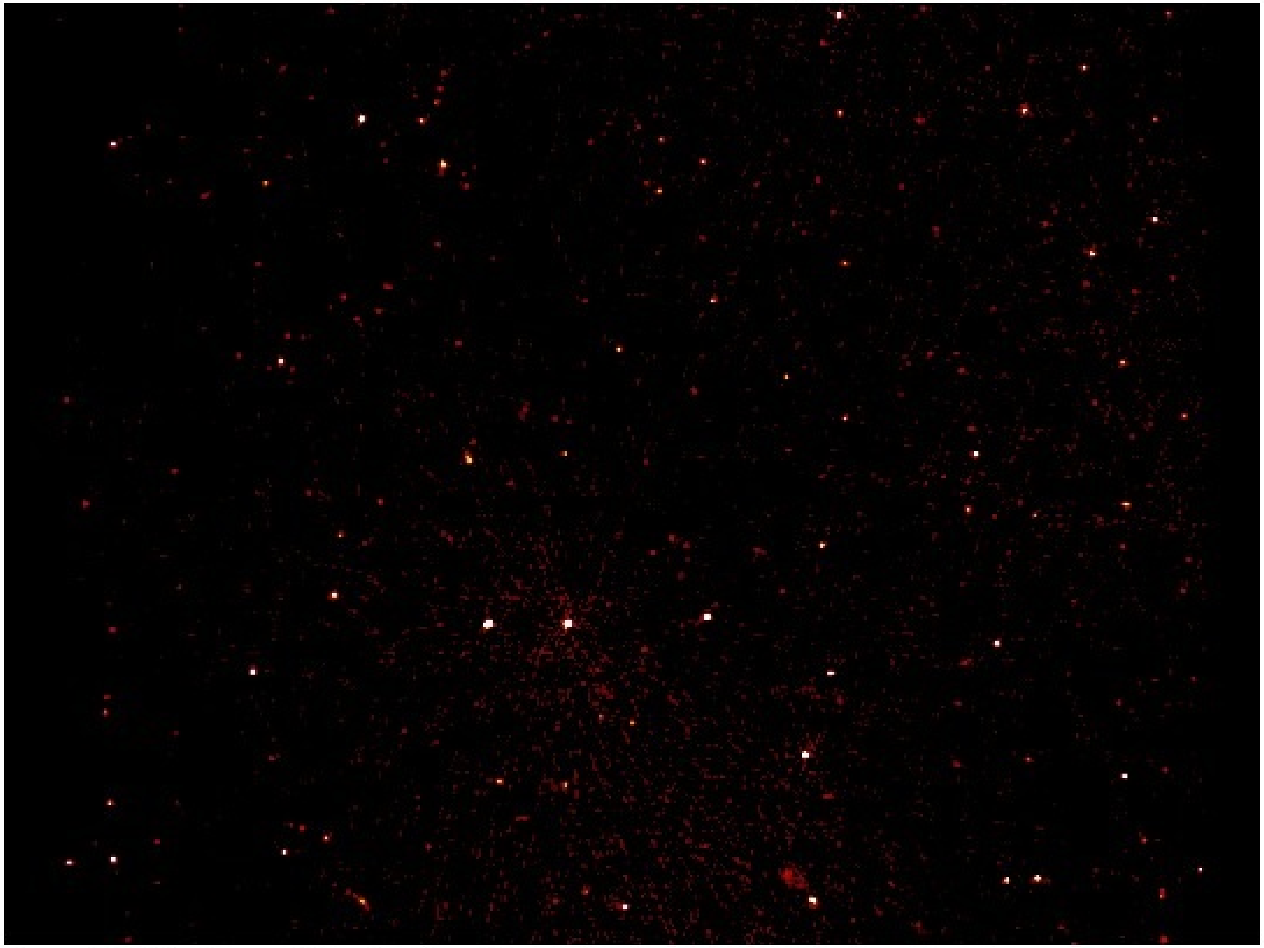
Galactic Radio Sky

Nimisha G. Kantharia
National Centre for Radio Astrophysics
RAS 19 August 2013

Galactic Radio Sky

radio sky at 150 MHz– TGSS



150 MHZ 45" R41D16 R=0

Bright/faint sources; constellations of sources.....

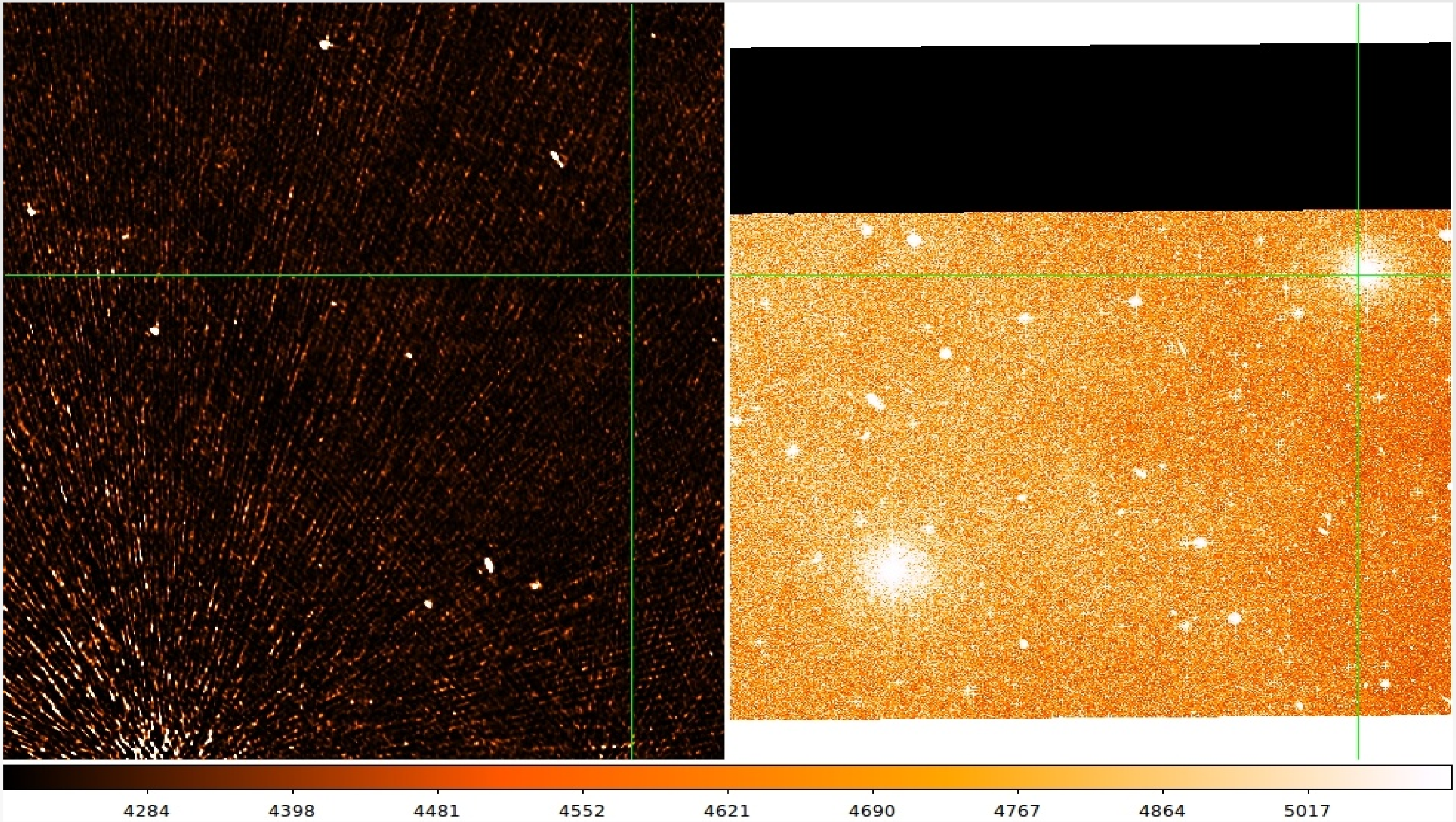
Mostly extragalactic sources – nearby to cosmological distances

TGSS: TIFR GMRT Sky Survey at 150 MHz using interferometric mode

Galactic Radio Sky

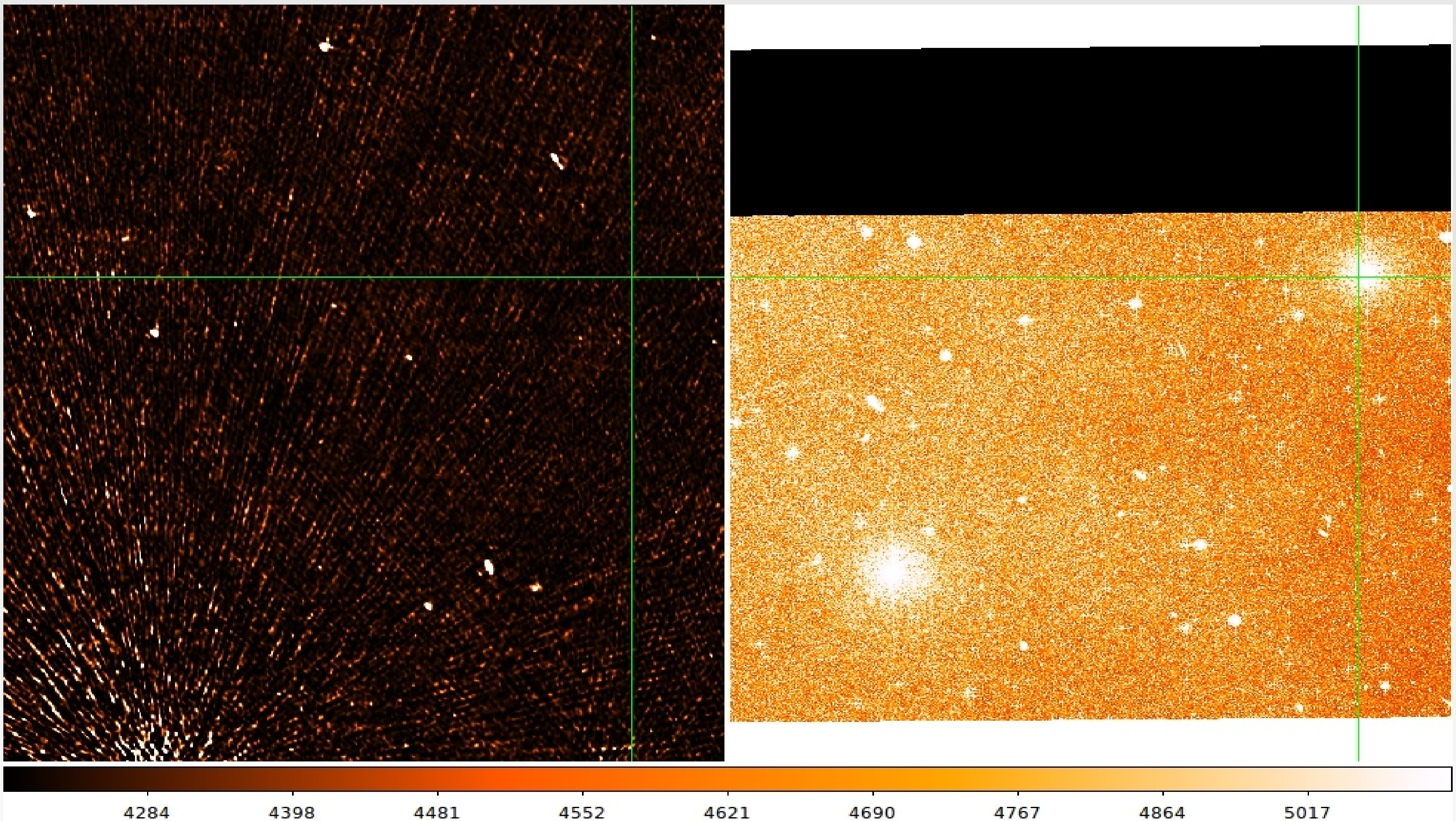
radio sky at 150MHz

optical sky - DSS



Galactic Radio Sky

radio sky *optical sky*



Mostly Extragalactic *Many Galactic - stars*

Galactic Radio Sky

- Radio Sky

Decametres to mm

Quasars, radio galaxies, clusters, supernova remnants, pulsars, HII regions

Probes Galactic to cosmogical distances – no dust obscuration

wideband emission :free-free thermal, synchrotron, narrowband emission

- Optical sky

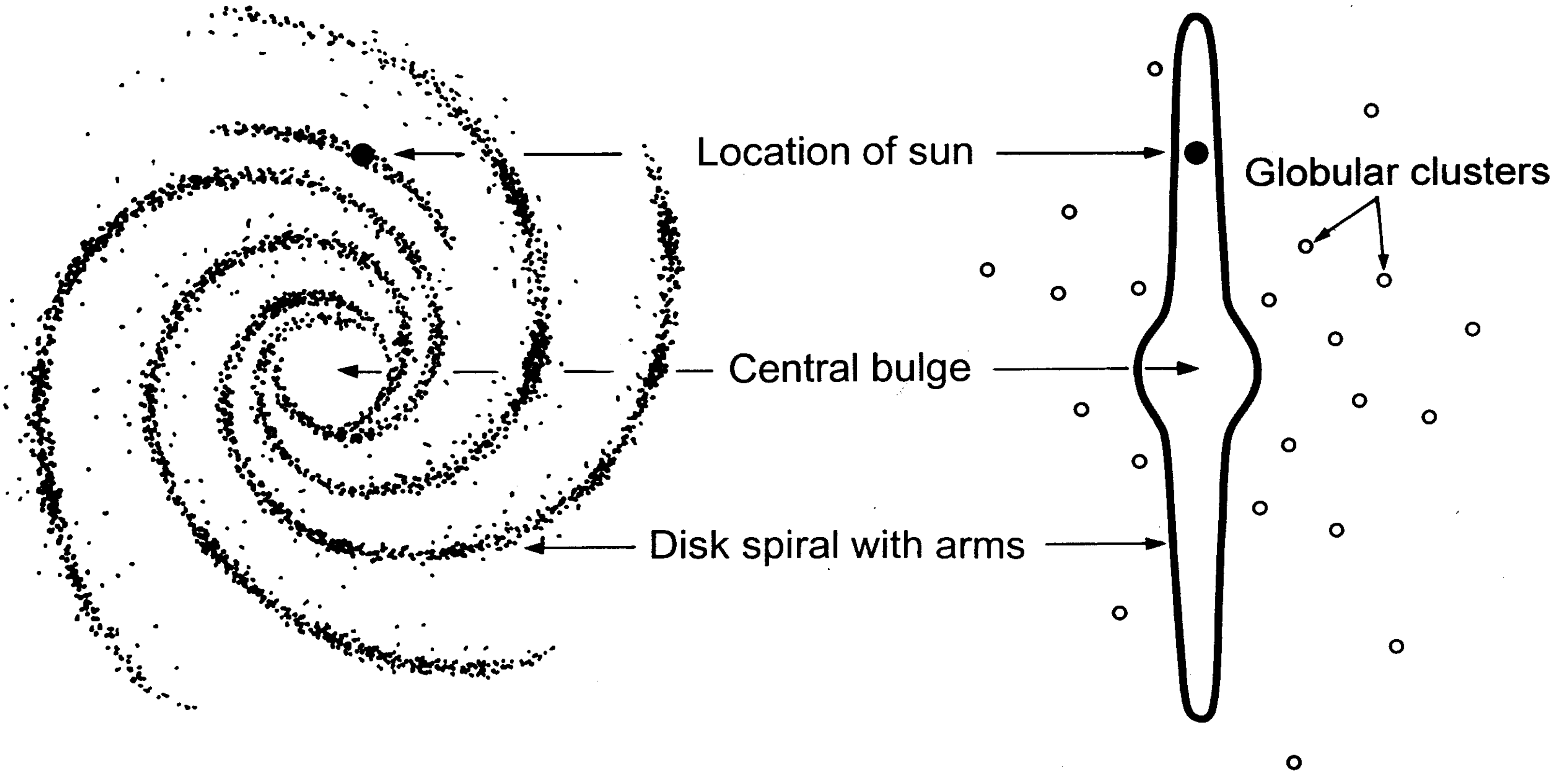
4000 – 8000 Angstroms

Stars, nebulae, galaxies, AGN

Nearby sky if in Galactic plane due to dust else can probe distant universe

Wideband emission: bound-free; narrow band emission

Galactic Radio Sky



Galactic Radio Sky

NGK 19August2013 RAS

Galactic Radio Sky

- Interstellar medium

Atomic clouds

Synchrotron Radiation field

Molecular clouds

Supernova remnants

HII regions

Planetary nebulae

- Galactic centre - SgrA*
- Stars including sun,pulsars.
- Planets – e.g. Jupiter
- Dark matter - indirectly

- Interstellar medium
- Stars and planets

Galactic Radio Sky

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- Galactic centre - SgrA*
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- Planets – e.g. Jupiter
- Dark matter - indirectly

- Interstellar medium
- Stars

- Radio emission allows study of physical conditions – temperature, magnetic fields, composition, densities, sizes, morphology, distances, kinematics, Galactic structure, physical processes......using radio continuum or spectral lines as diagnostics.

Galactic Radio Sky

Galactic luminous matter (< 10%) - Hydrogen clouds

- *Stellar mass ~ 10^11 solar mass; ISM ~ few % of stellar mass*
- *Stars occupy ~ 3 x 10^(-10) of Galaxy volume; rest filled by ISM*
- *mass abundance ~ 74% hydrogen; ~ 24% He; rest metals, dust.*
- *Rough pressure equilibrium in atomic phase of H -i.e.*

  nkT ~ constant → stable and long-lived

  e.g. Atomic HI - cold HI: T <~ 50K, nH ~ 50 /cc
  Warm HI: T~ 8000K, nH ~ 0.3 /cc - diffuse
  *nH *T ~ few thousand K/cc*

- *Molecular HI : T ~ 20 K, nH >~ 1000 /cc*
- *HII region T~8000K, ne ~ 1000 /cc - ultraviolet photons > 13.6 eV ionise H.*
- *Size ~ light years to several light years*

Galactic Radio Sky

NCRA • TIFR

Table 1.1 *Characteristics of the phases of the interstellar medium*

Phase	n_0^a (cm^{-3})	T^b (K)	ϕ_v^c (%)	M^d ($10^9\ M_\odot$)	$< n_0 >^e$ (cm^{-3})	H^f (pc)	Σ^g ($M_\odot pc^{-2}$)
Hot:							
intercloud	0.003	10^6	~50.0	—	0.0015	3000	0.3
Warm							
neutral							
medium	0.5	8000	30.0	2.8	0.1^h	220^h	1.5
					0.06^h	400^h	1.4
Warm							
ionized							
medium	0.1	8000	25.0	1.0	0.025^i	900^i	1.1
Cold neutral							
medium^j	50.0	80	1.0	2.2	0.4	94	2.3
Molecular							
clouds	>200.0	10	0.05	1.3	0.12	75	1.0
HII regions	1–10^5	10^4	—	0.05	0.015^k	70^k	0.05

All radio emitting except HIM/WIM

From Draine

Earth's atmosphere: 2.5×10^19 particles per cm3

Galactic Radio Sky

- *Stable Phases of ISM – large filling factor*
- *CNM, WNM, WIM – radio*
- *HIM - Xray*

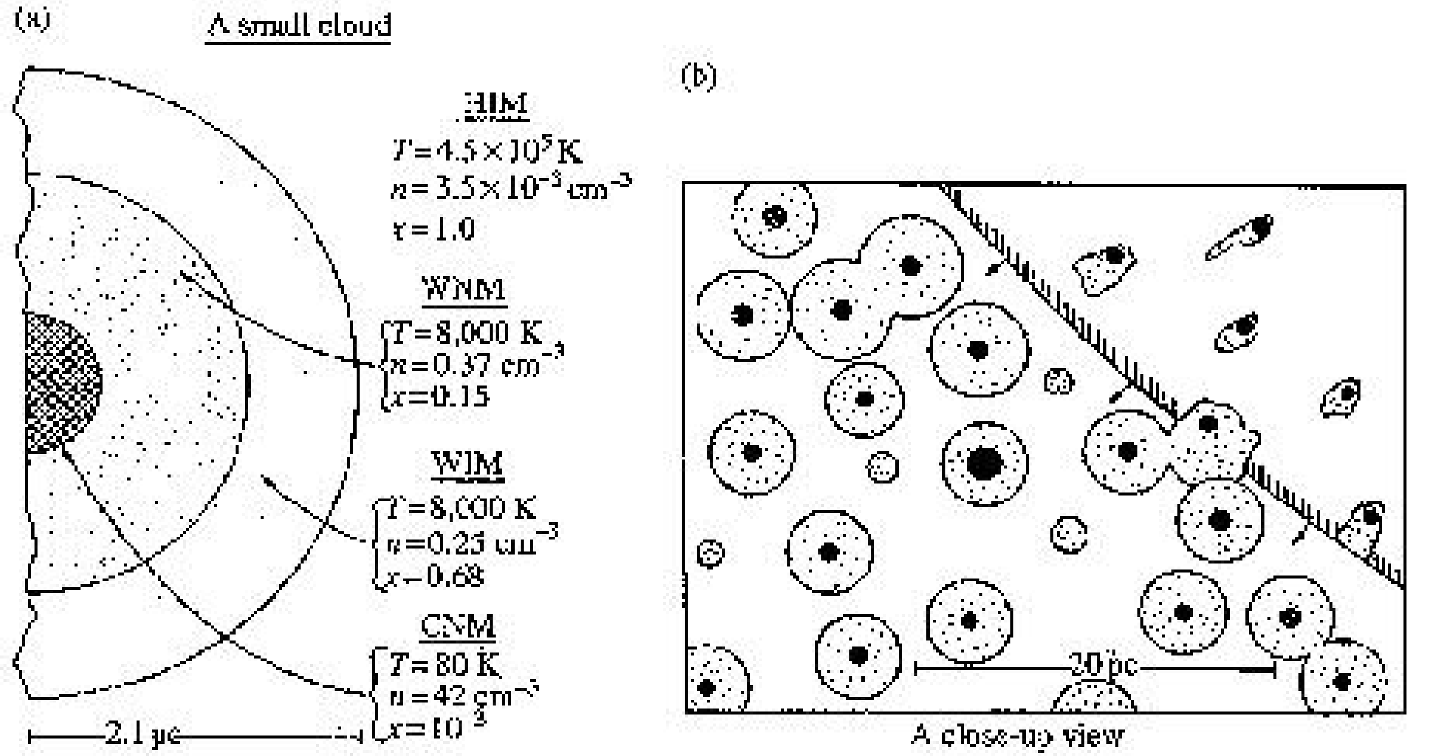

Figure 8.3 A schematic diagram of the three-phase model for the ISM stirred up by a supernova. (*a*) A blow-up of a cloud (CNM) surrounded by the warm intercloud (WNM and WIM) and embedded in the hot intercloud medium. Typical densities, temperatures, and degrees of ionization for these phases calculated in this model are also indicated. (*b*) The effect of an expanding SNR on the cloud population in the ISM (e.g., crunching and evaporating the warm intercloud media surfaces; cf. Section 12.4). Figure reproduced with permission from C. F. McKee and J. P. Ostriker, 1997, *Ap. J.*, **218**, p. 148.

Galactic Radio Sky

Radio Emission Mechanisms

- *Non-thermal synchrotron from relativistic particles in B*
- *Free-free thermal emission from ionized media*
- *21cm spectral line from atomic hydrogen*
- *Spectral lines from molecules*
- *Radio recombination lines from atoms in ionised media*

First extra-earth radio emission reported from the Galactic centre direction in 1933 by Jansky !

Galactic Radio Sky

- Interstellar medium

Atomic clouds

Synchrotron Radiation field

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- Galactic centre - SgrA*
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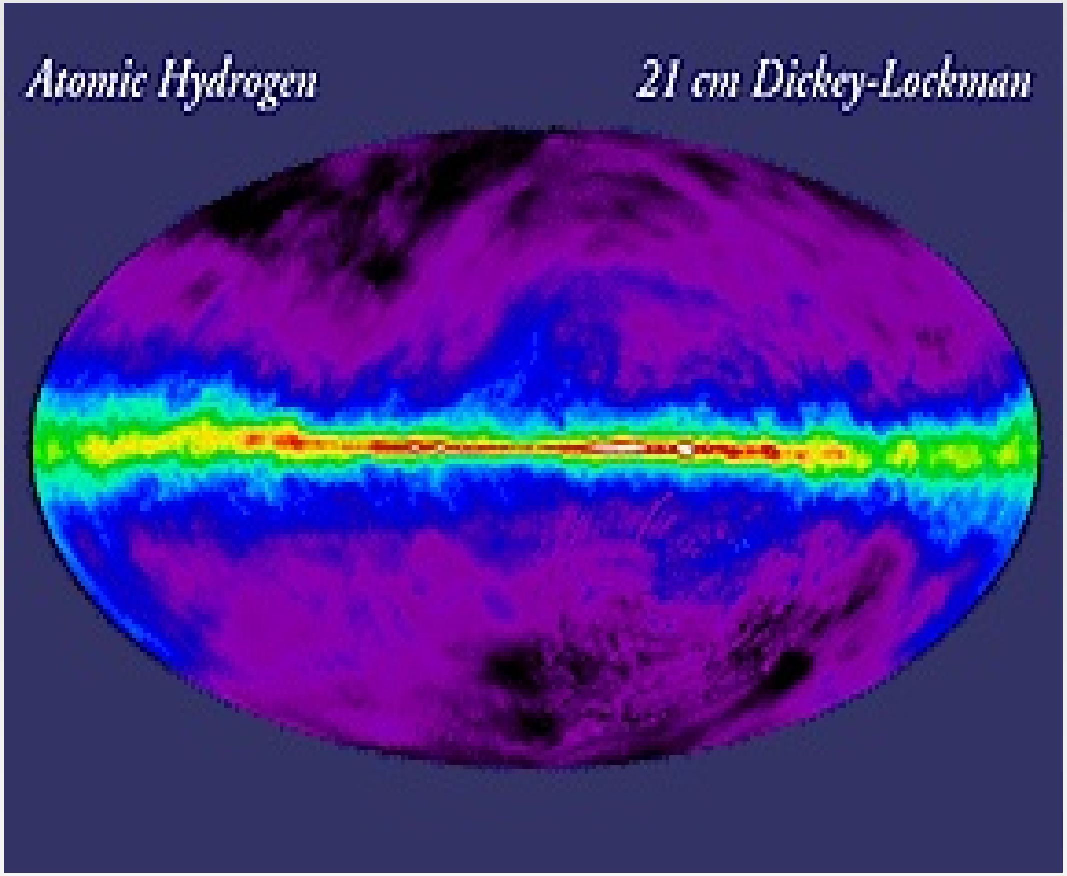
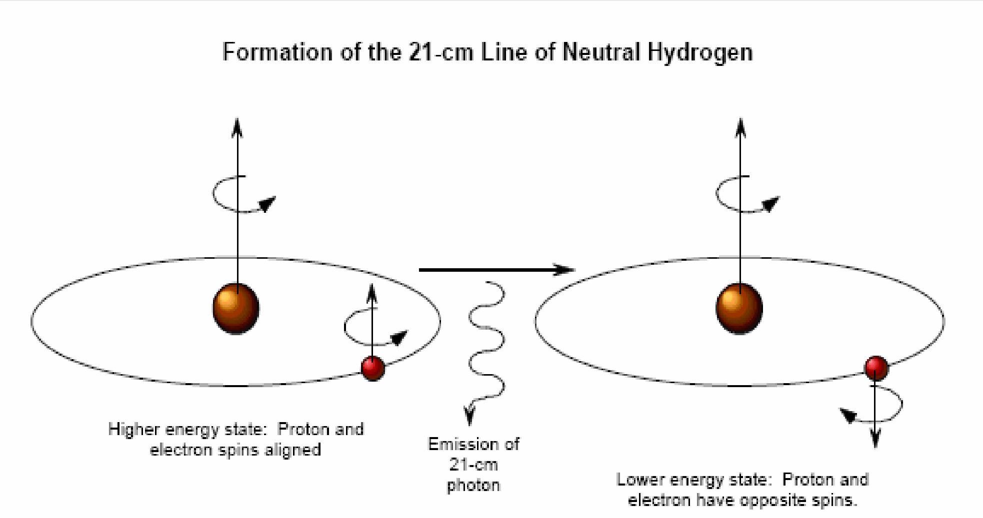
- Planets – e.g. Jupiter
- Dark matter - indirectly

- Interstellar medium
- Stars
- Radio diagnostics allows study of physical conditions – temperature, magnetic fields, composition, densities, sizes, morphology, distances, kinematics, Galactic structure, physical processes......using radio continuum or spectral lines as diagnostics.

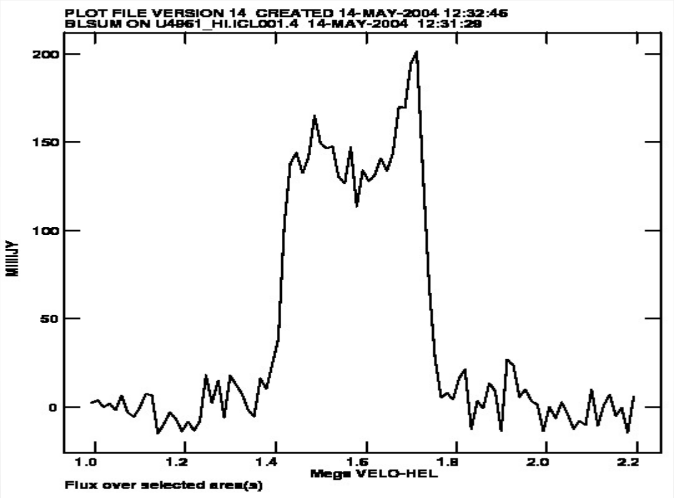
Galactic Radio Sky

Atomic Hydrogen in our Galaxy – spectral line



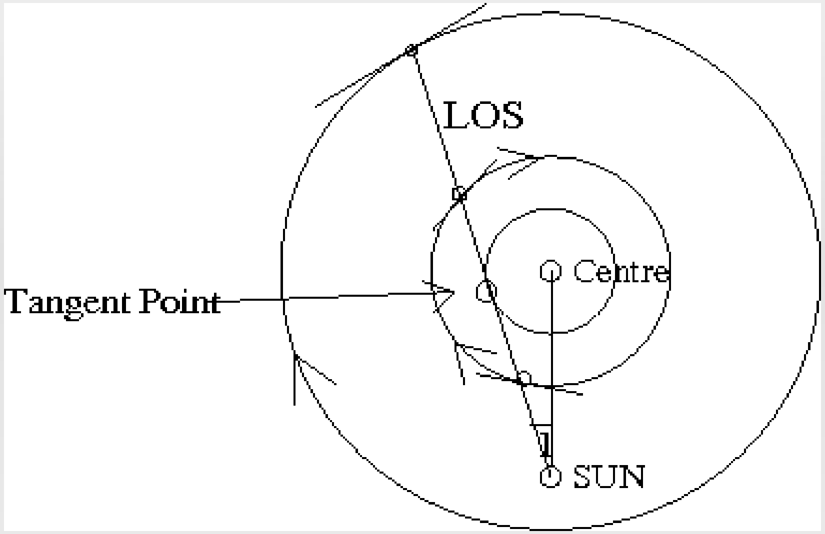


- A21~10^(-15) /sec; t ~ 10^7 yrs



- Rest frequency: 1420.403 Mhz
- Transition E~ 6micro-eV; T~ 0.068K

Galactic Radio Sky

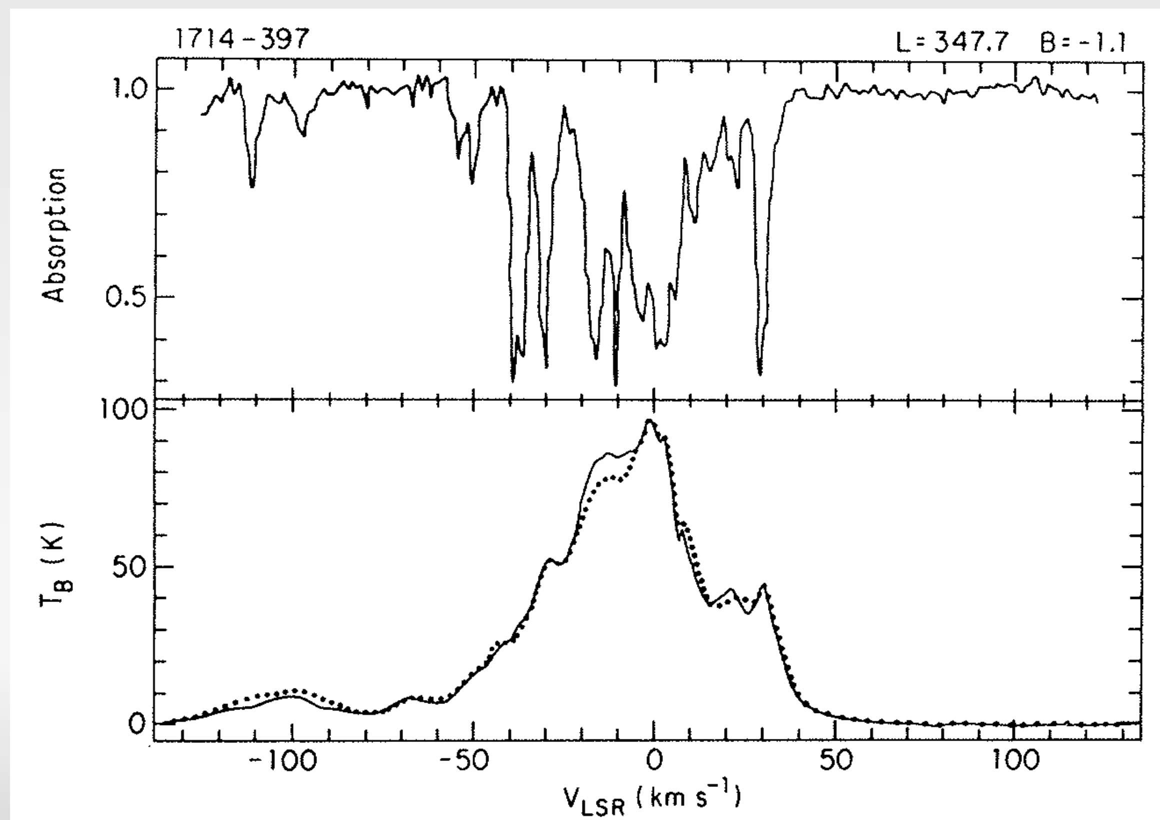


- Widths – temperatures, densities, global kinematics, atomic mass, dynamical mass
- HI absorption/emission profile (www.cv.nrao.edu/course/astr534)
- Column densities; temperature; low

Vrad= Rs(ω-ws)sin(l)

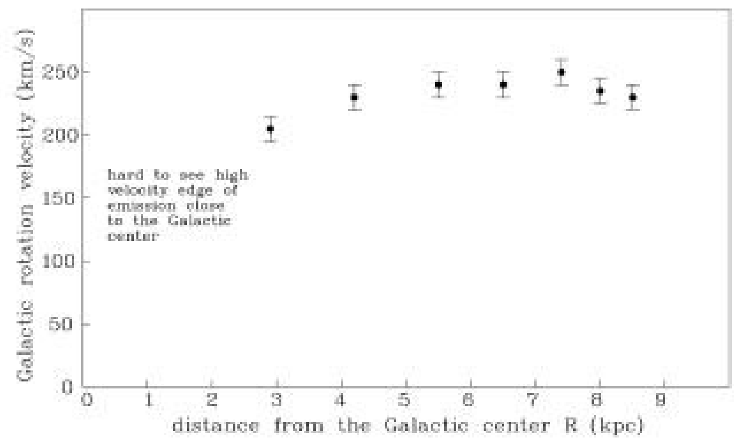
R(tangent) = Rs sinl

Rs~8.5kpc; wsRs~220 km/s
distance ambiguity
 for l < 90d, R< Rs.
Width – multiple
clouds along los ->
absorption-clumpy
emission - smoother



Galactic Radio Sky

Dark Matter

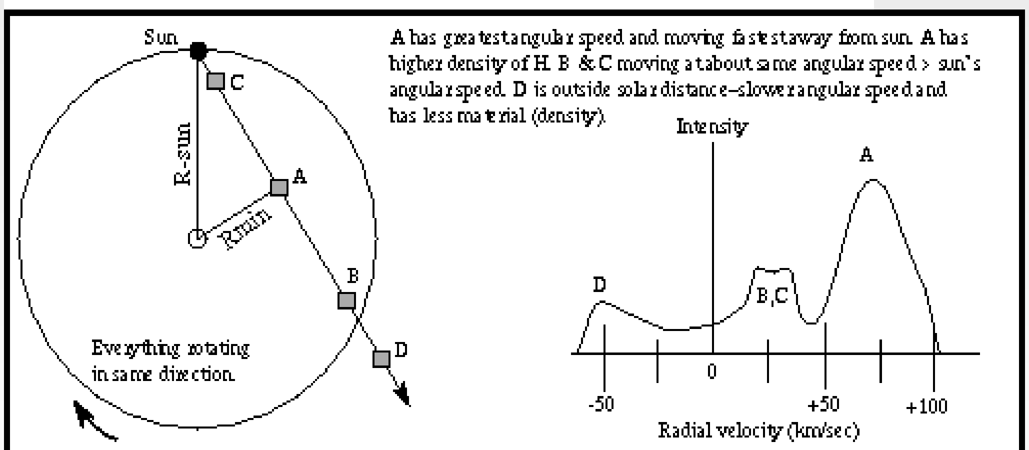


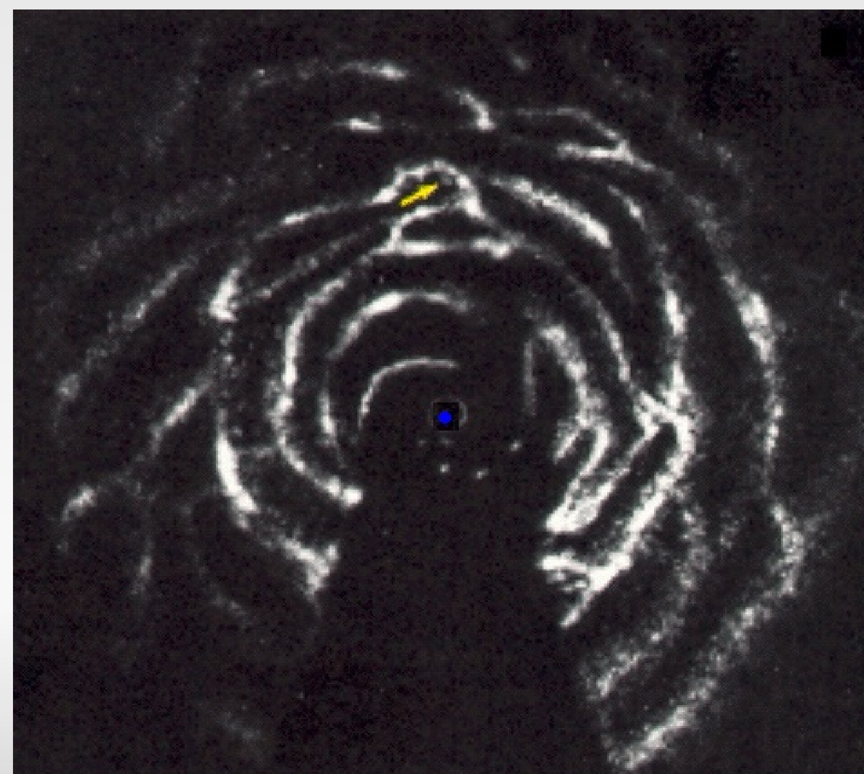
V_R = Vmax_observed (R) + wsR

V_R constant → Matter in outer parts → dark matter

If most of the matter was centrally located – Keplarian profile with V_R ~ R^(-1/2)

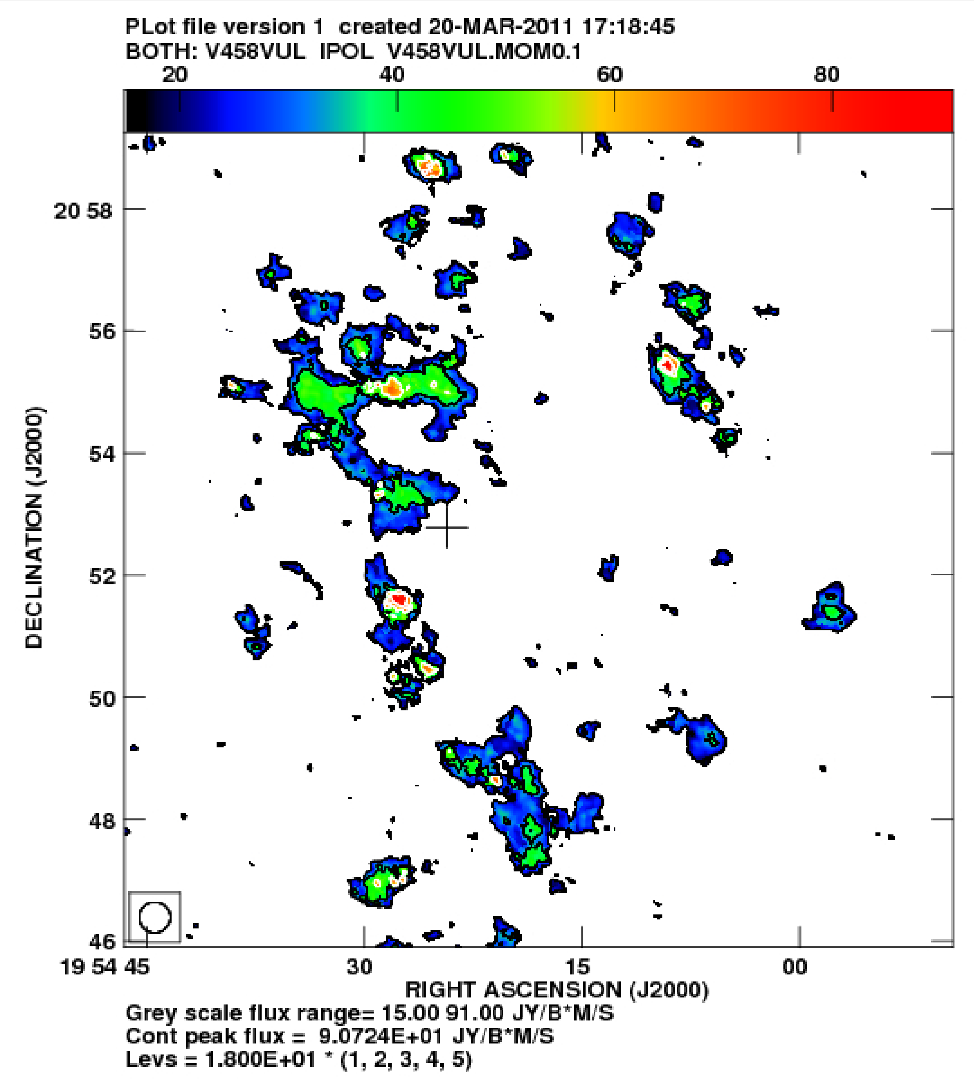
http://www.haystack.mit.edu/edu/undergrad/srt/SRT%20Projects/rotation.html

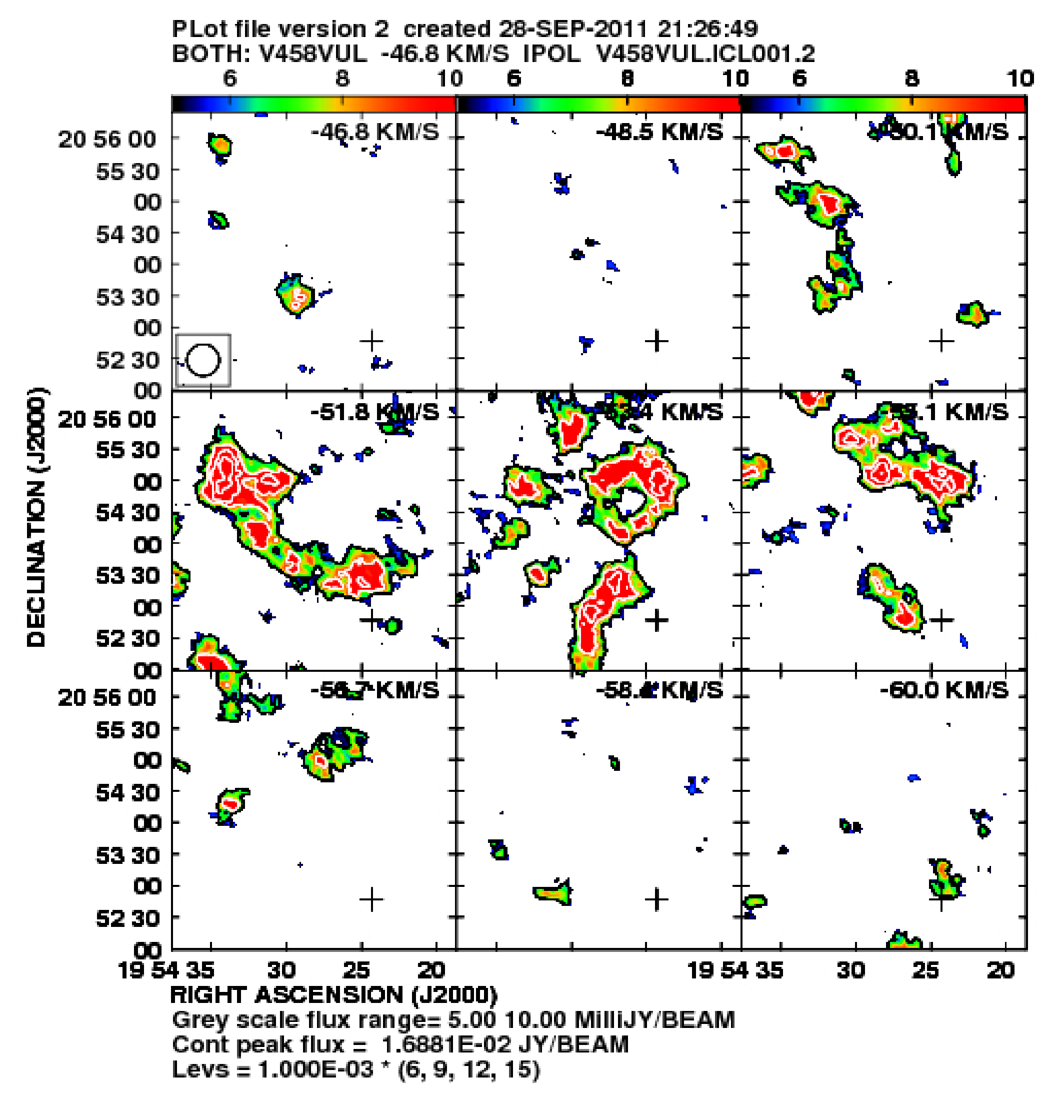




http://ircamera.as.arizona.edu/astr_250/Lectures/Lec_22sml.htm

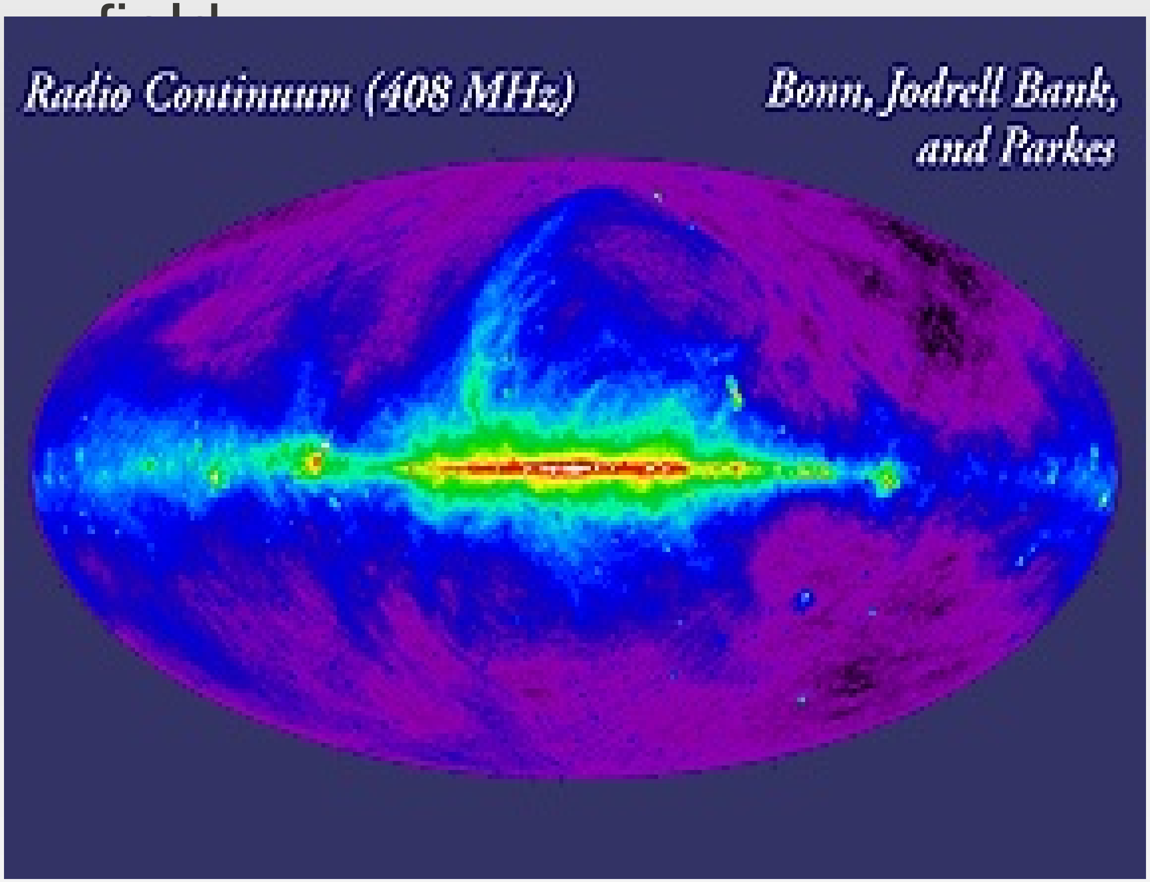
Galactic Radio Sky

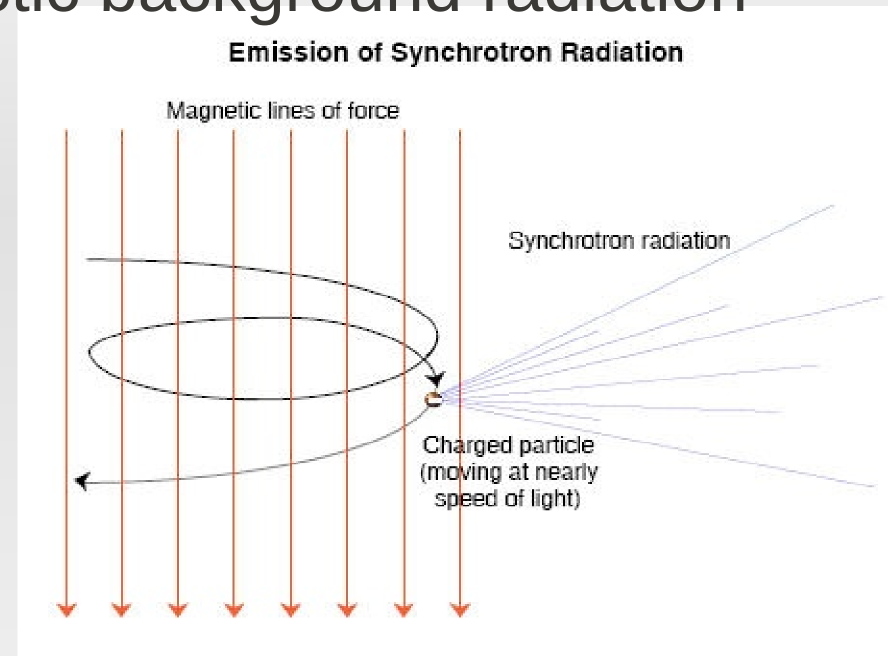




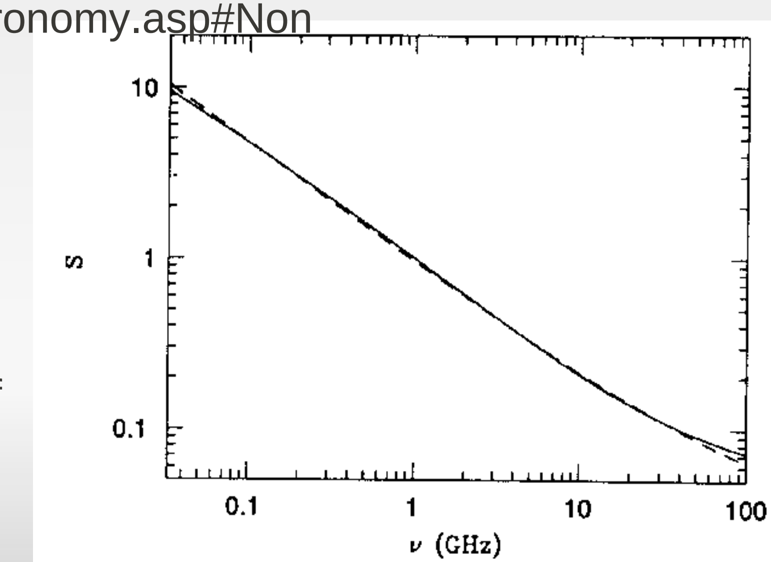
Galactic Radio Sky

- Radio continuum emission – Galactic background radiation field





http://astronomyonline.org/Science/RadioAstronomy.asp#Non



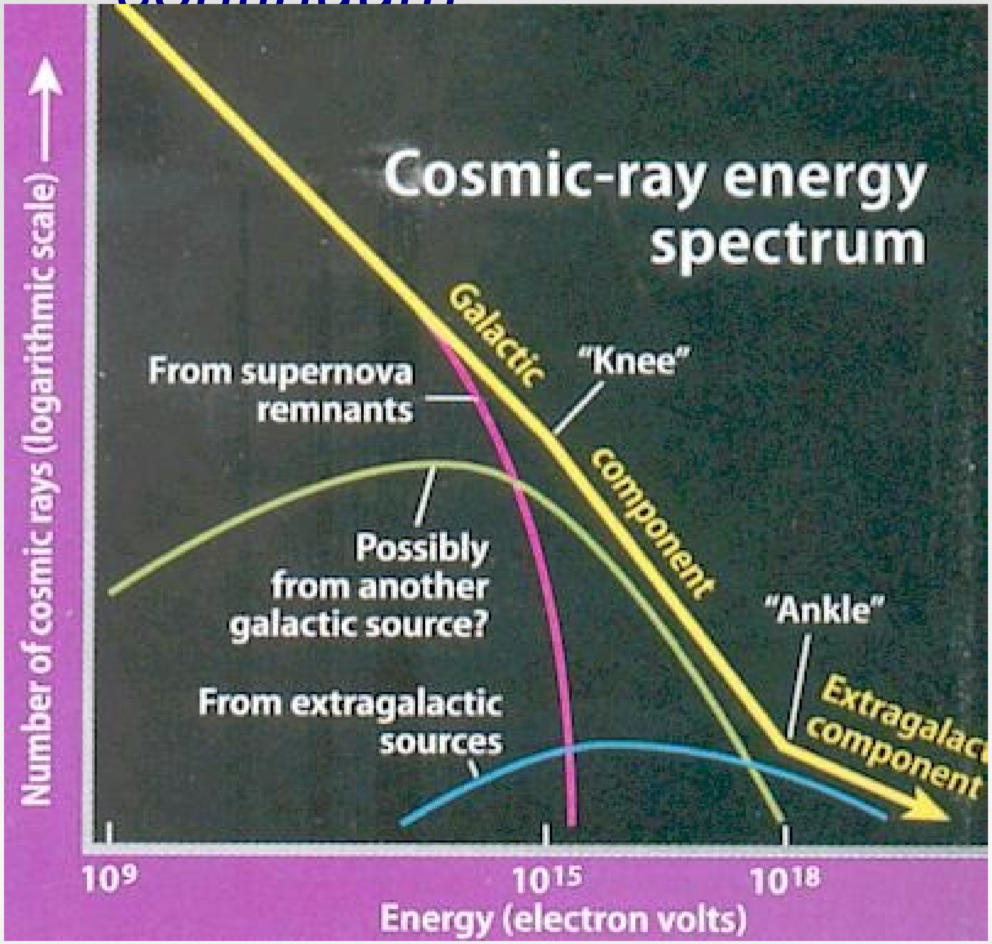
http://mwmw.gsfc.nasa.gov/ Alpha ~ 0.55 to 0.8

Synchrotron + thermal free-free

http://nedwww.ipac.caltech.edu/level5/Condon/fig6.gif

Galactic Radio Sky

- *Physical parameters from synchrotron radio continuum:*

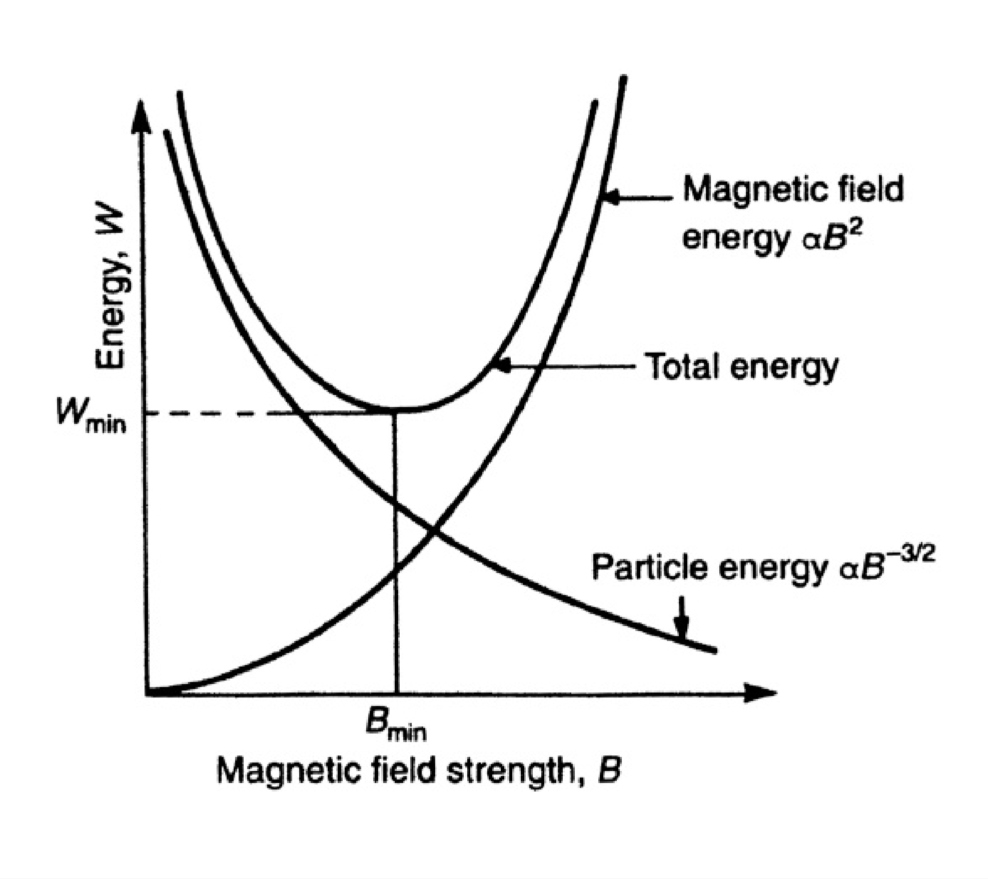


- S ~ freq^(-alpha) - Spectral index of radiation – energy spectrum of radiating electrons p = 2alpha + 1

http://universe-review.ca/I15-33-spectrum.jpg

Galactic Radio Sky

- *Physical parameters from synchrotron radio continuum:*



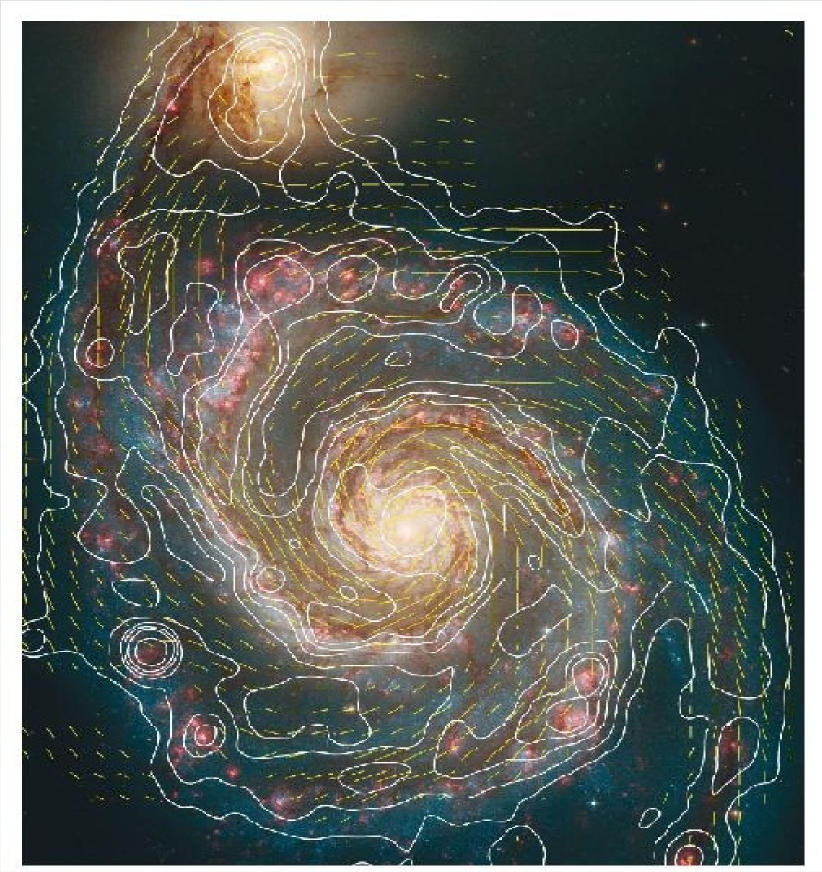
- S ~ freq^(-alpha) - Spectral index of radiation – energy spectrum of radiating electrons p = 2alpha + 1
- Equipartition magnetic field from minimum energy argument from observed luminosity

$$W_{\rm total} = V\varepsilon_{\rm e} + V\frac{B^2}{2\mu_0}$$

Longair

Galactic Radio Sky

- *Physical parameters from synchrotron radio continuum: M51*



- S ~ freq^(-alpha) - Spectral index of radiation – energy spectrum of radiating electrons p = 2alpha + 1
- Equipartition magnetic field from minimum energy argument from observed luminosity

$$W_{\text{total}} = V\varepsilon_{\text{e}} + V\frac{B^2}{2\mu_0}$$

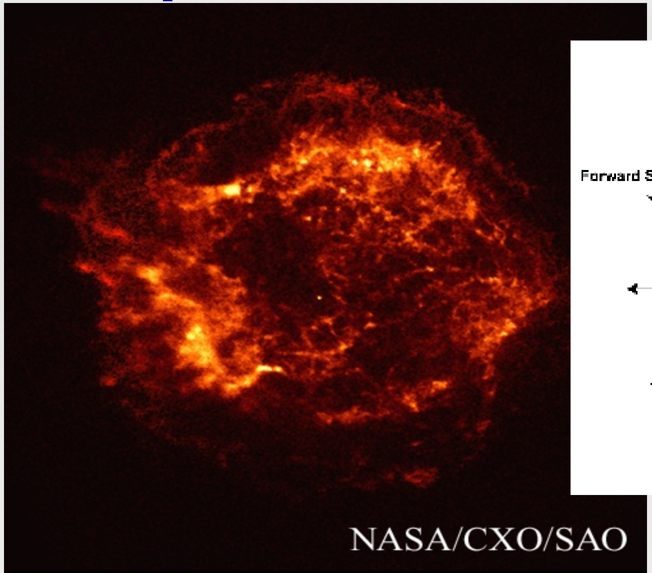
- Magnetic field from linearly polarised synchrotron emission

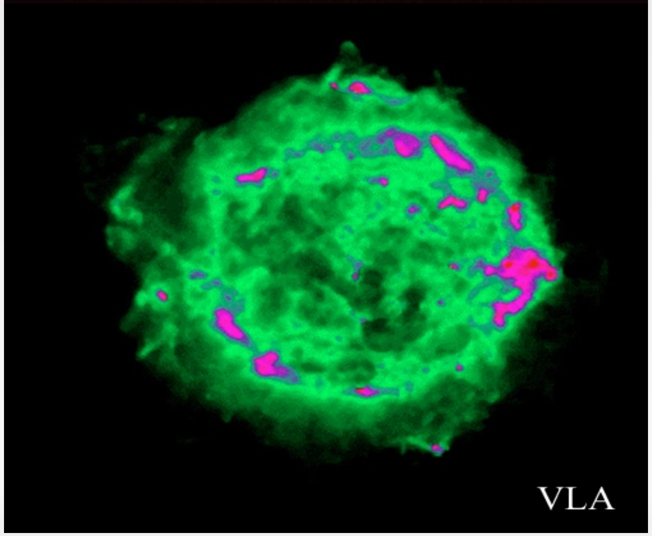
Fletcher etal

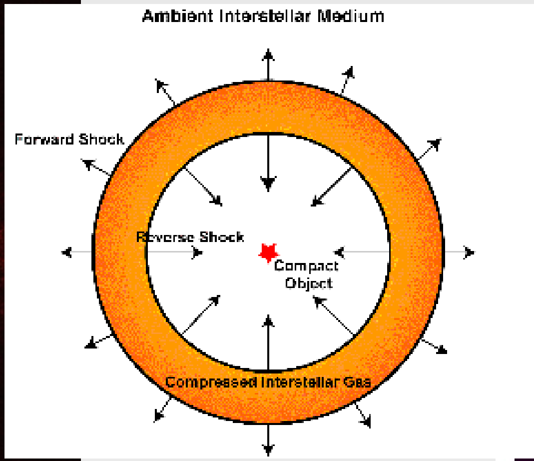
Galactic Radio Sky

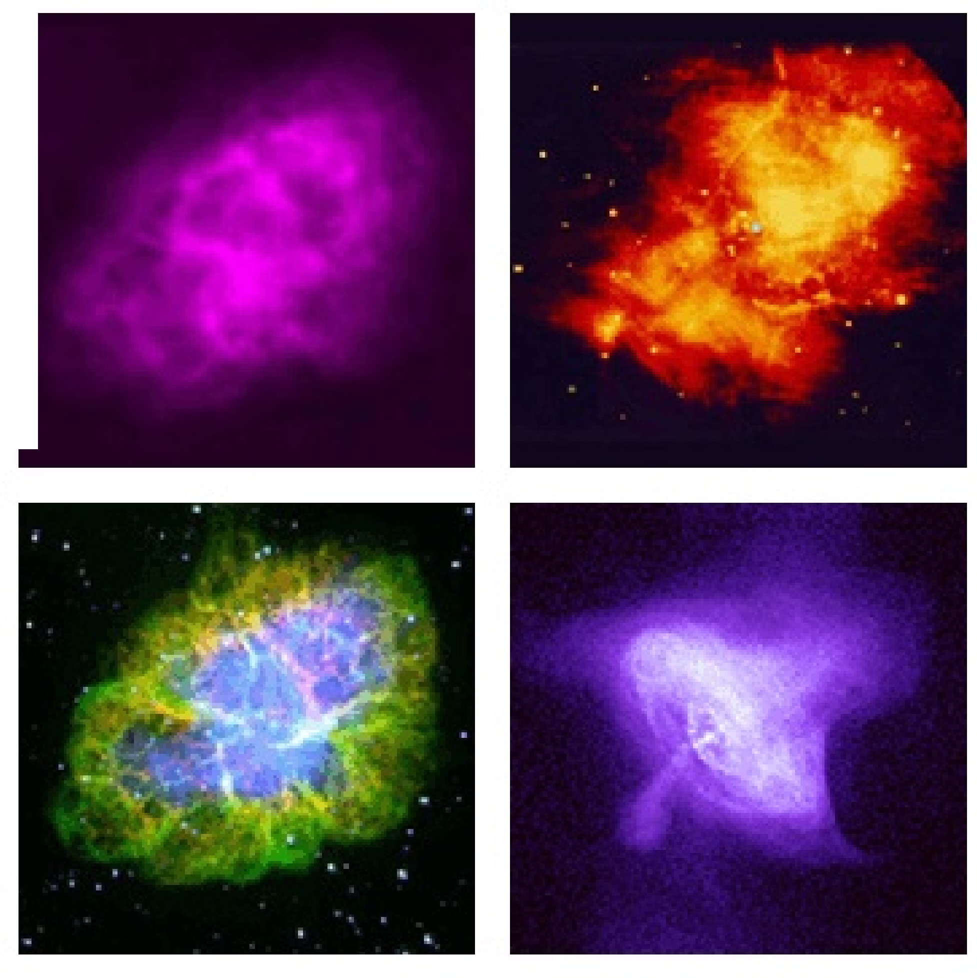
Supernova remnants

Crab in Radio, IR, optical, Xray









CasA: Xray
Radio
Energy and chemical input to ISM

http://chandra.harvard.edu/photo/0052/what.html

Galactic Radio Sky

Supernova remnants

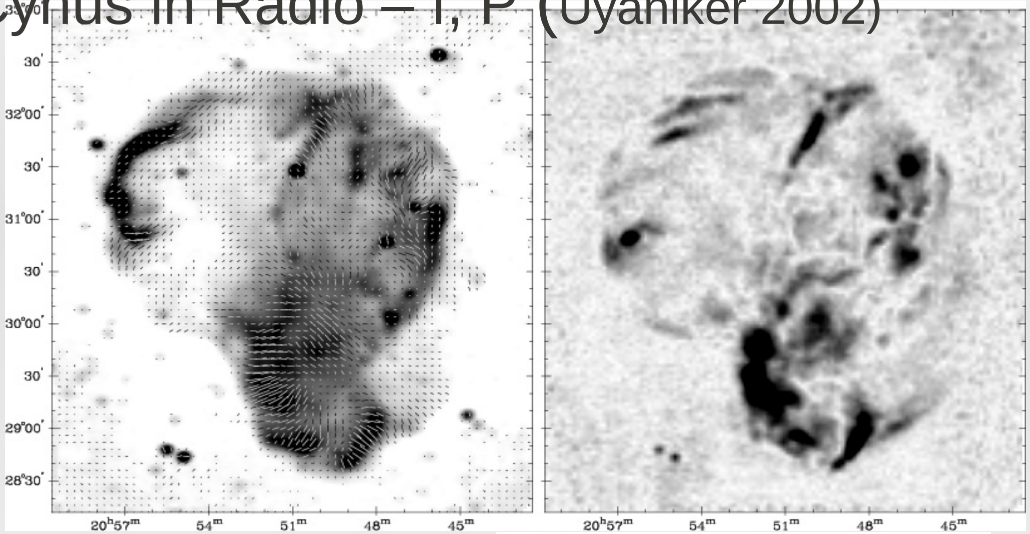
Star explosion – runs out of fuel

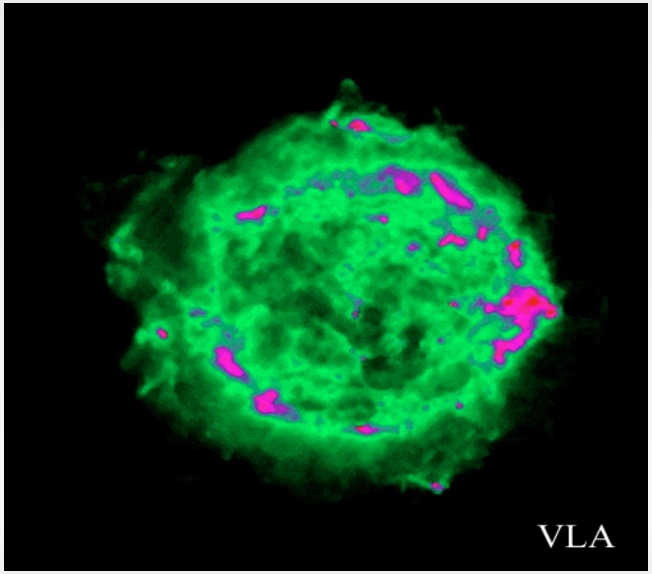
Core mass > 1.4 solar mass

10^51 ergs energy released; central star: neutron star

Acceleration of particles

Cynus in Radio – I, P (Uyaniker 2002)





Shell -type e.g. CasA; filled type e.g Crab powered by pulsar

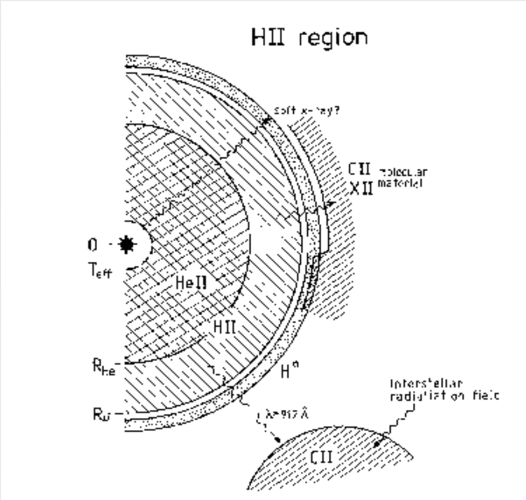
Different phases of evolution – all visible as radio objects - adiabatic

Crab in Radio

http://chandra.harvard.edu/photo/0052/what.html

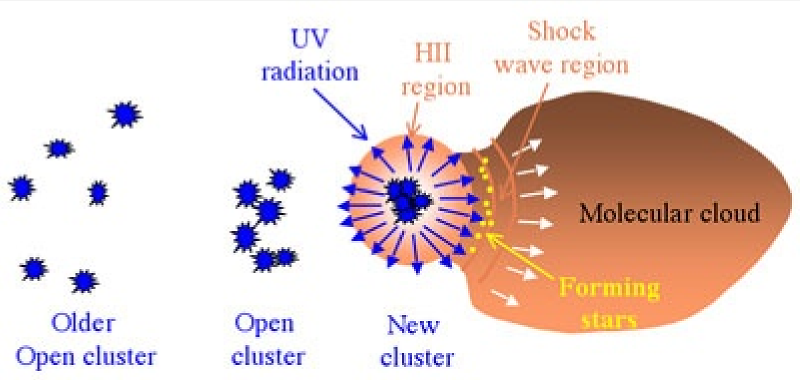
Galactic Radio Sky

- *Free-free thermal from HII regions – Halpha (optical)*

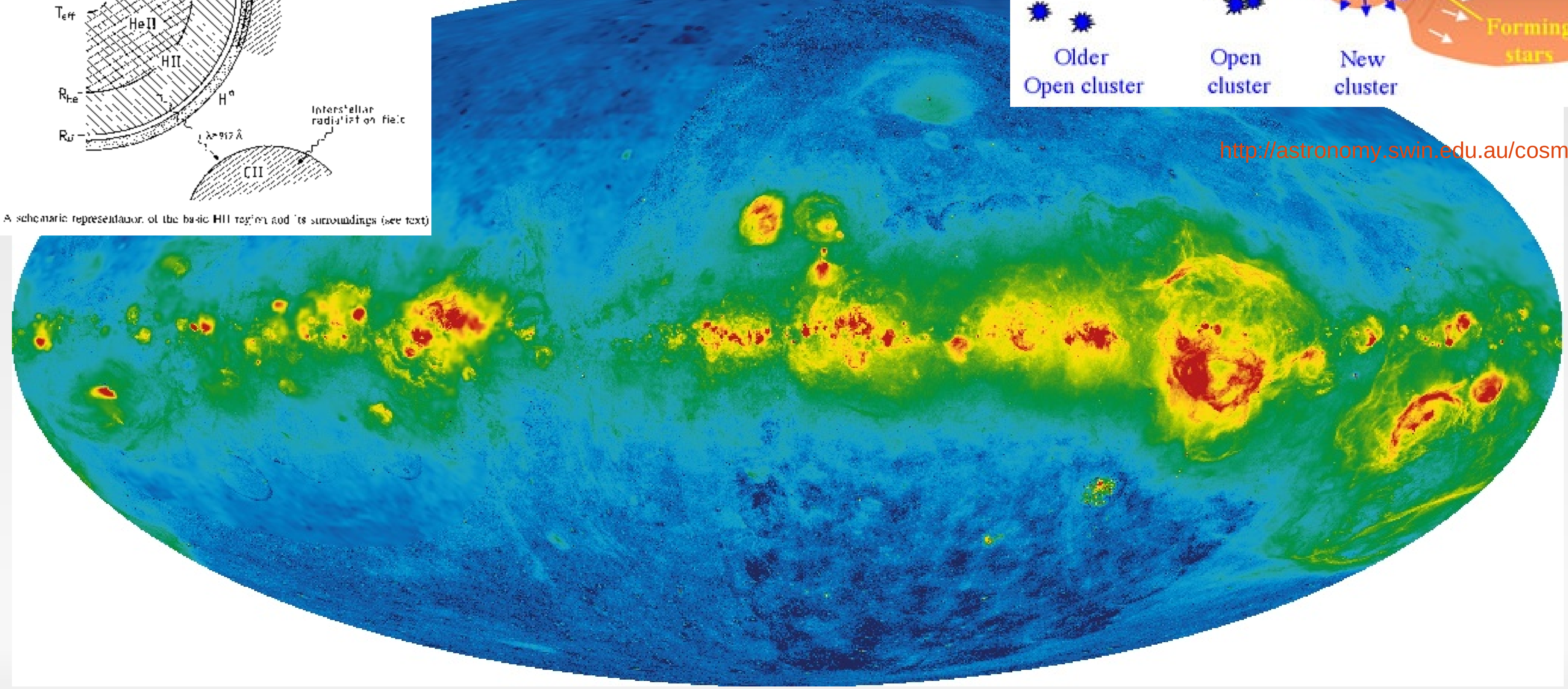


.4. A schematic representation of the basic HII region and its surroundings (see text)

O, B stars, Ionisation fraction~ 1 in R ~ pc Stromgren sphere



http://astronomy.swin.edu.au/cosmos/H/HII+Region



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http://lambda.gsfc.nasa.gov/product/foreground/fg_images/lrg_halpha_image.png

Galactic Radio Sky

- *Thermal free-free continuum – star forming regions*

Radio frequency approx to Planck's spectrum I ~ 2kT nu^2/c^2;
Optically thin regime: I ~ nu^(-0.1)
Optically thick regime: I ~ nu^2

Physics:
Average densities. Size, emission measure , exciting star, temperature

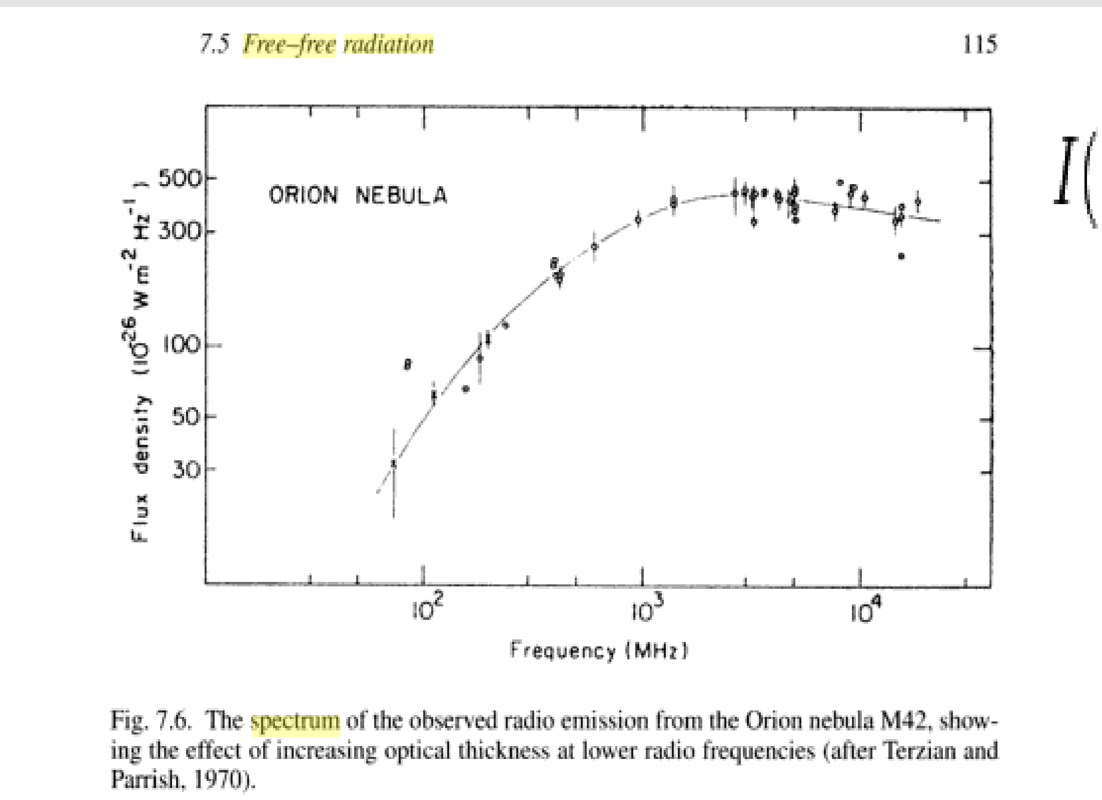
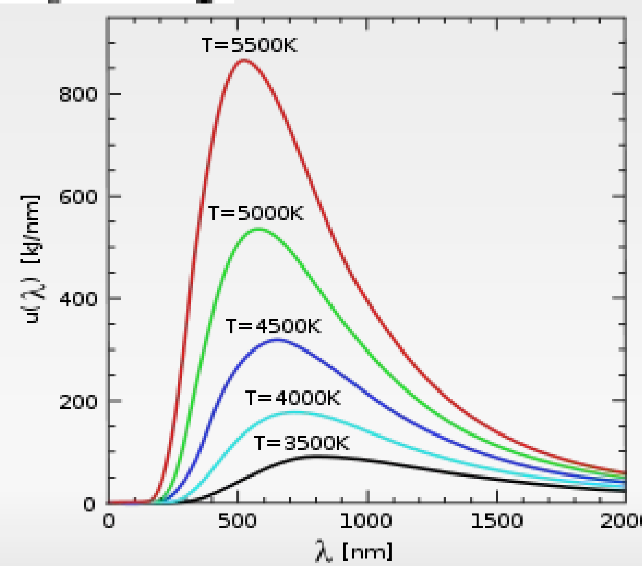

7.5 Free–free radiation 115

Fig. 7.6. The spectrum of the observed radio emission from the Orion nebula M42, showing the effect of increasing optical thickness at lower radio frequencies (after Terzian and Parrish, 1970).

$$I(\nu,T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}}-1}.$$



From wikipedia

An introduction to radio astronomy by Bernard F. Burke, Francis Graham-Smith

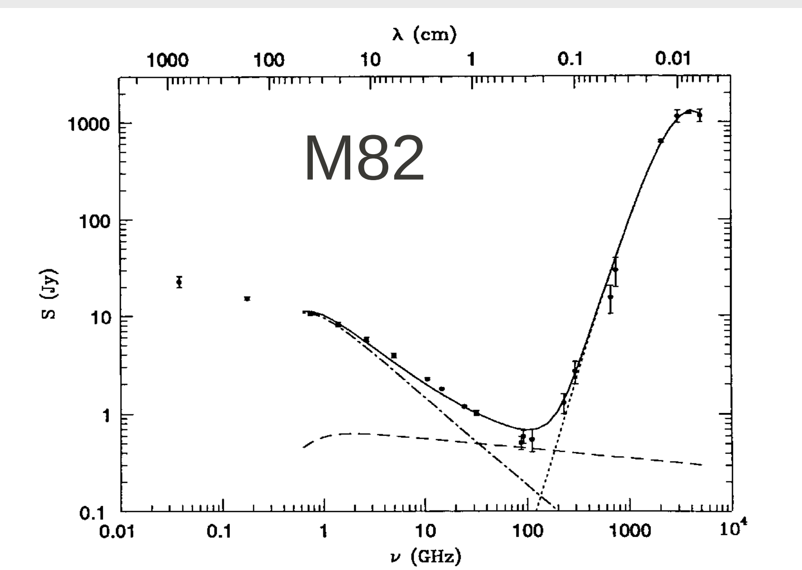
Galactic Radio Sky

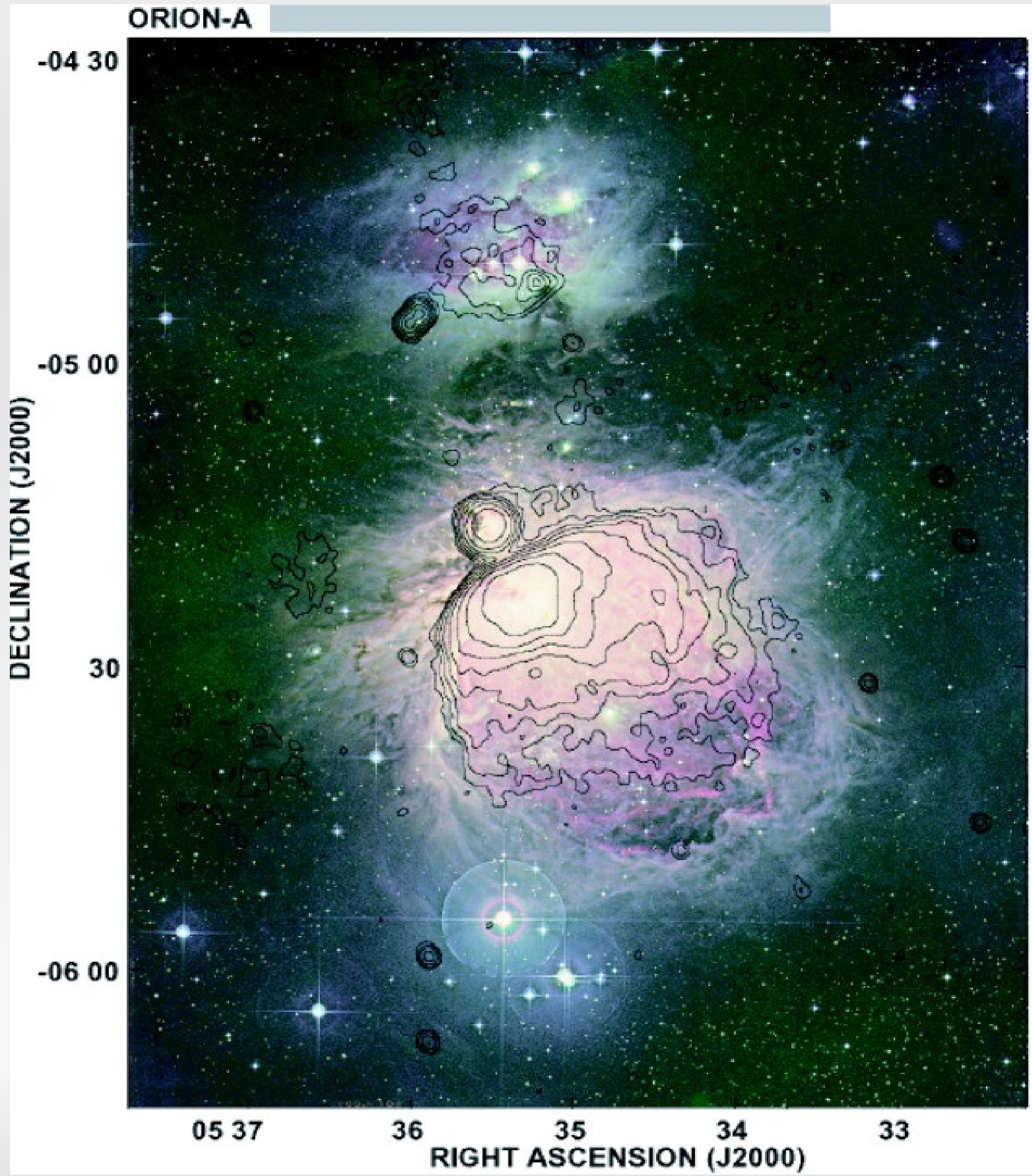
Orion (M42) nebula – optical with radio contours at 330MHz

Both are free-free thermal

Central 'star' in sword of Orion constellation

EM ~ density^2 * size





Subrahmanyan et al., AJ, 407, 121 (2001

Galactic Radio Sky

Thermal continuum:

Te ~ 10^4 K, ne ~ 1 to 10^4 /cc, size ~ sub-pc to pc, EM ~ 10^6 cm^-6-pc, high metallicity in inner Galaxy

Optically thick frequency: Tb ~ Te

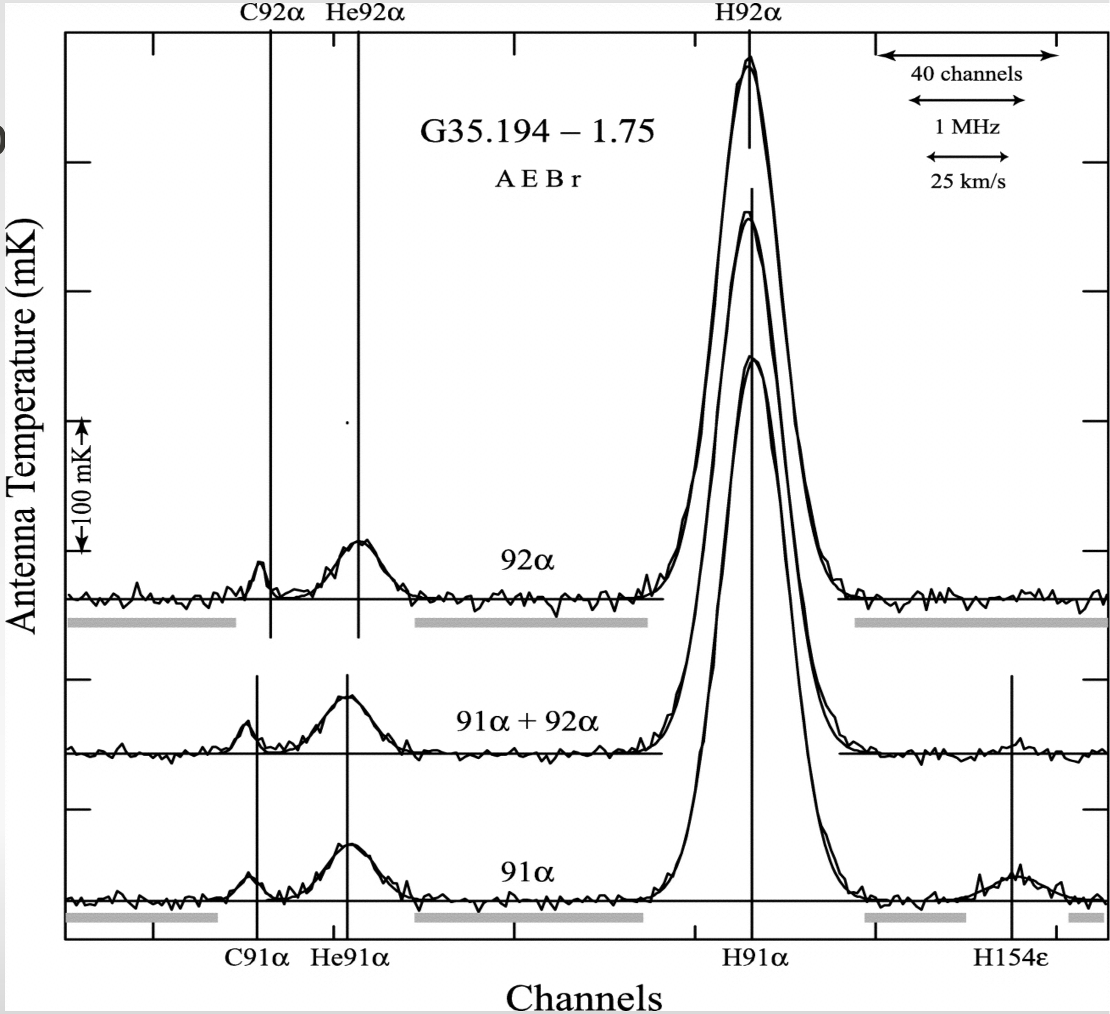
Turnover frequency → tau ~ 1; allows estimation of physical parameters

Optically thin regime: allows estimation of EM and densities

Radio Recombination lines

electronic transitions between principal quantum numbers - spans the em spectrum – ultraviolet to radio – from ionized thermal regions

Temperatures, densities, composition, abundances, size



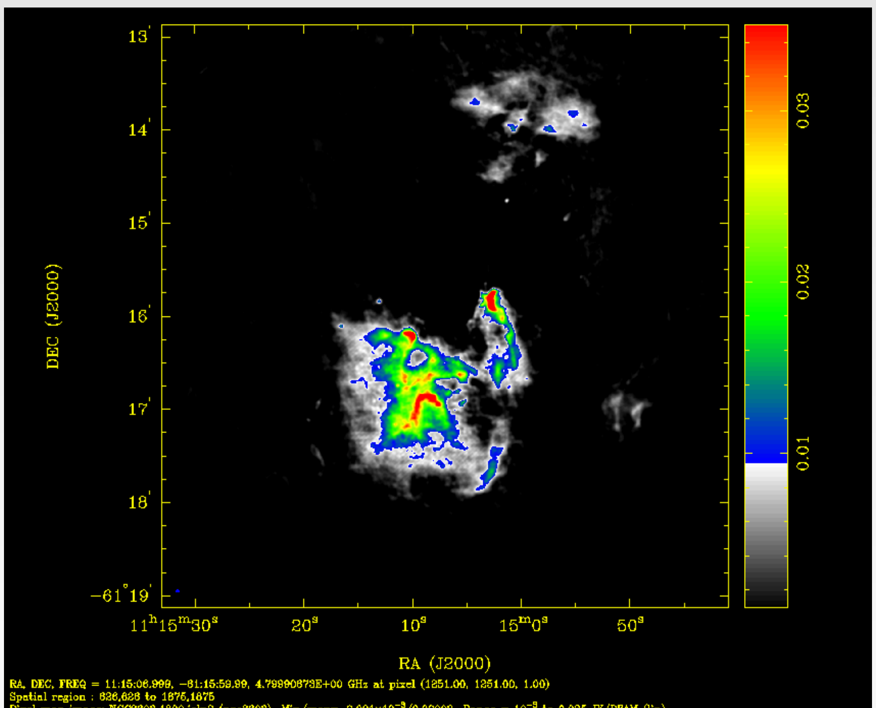
Galactic Radio Sky

- HII Regions

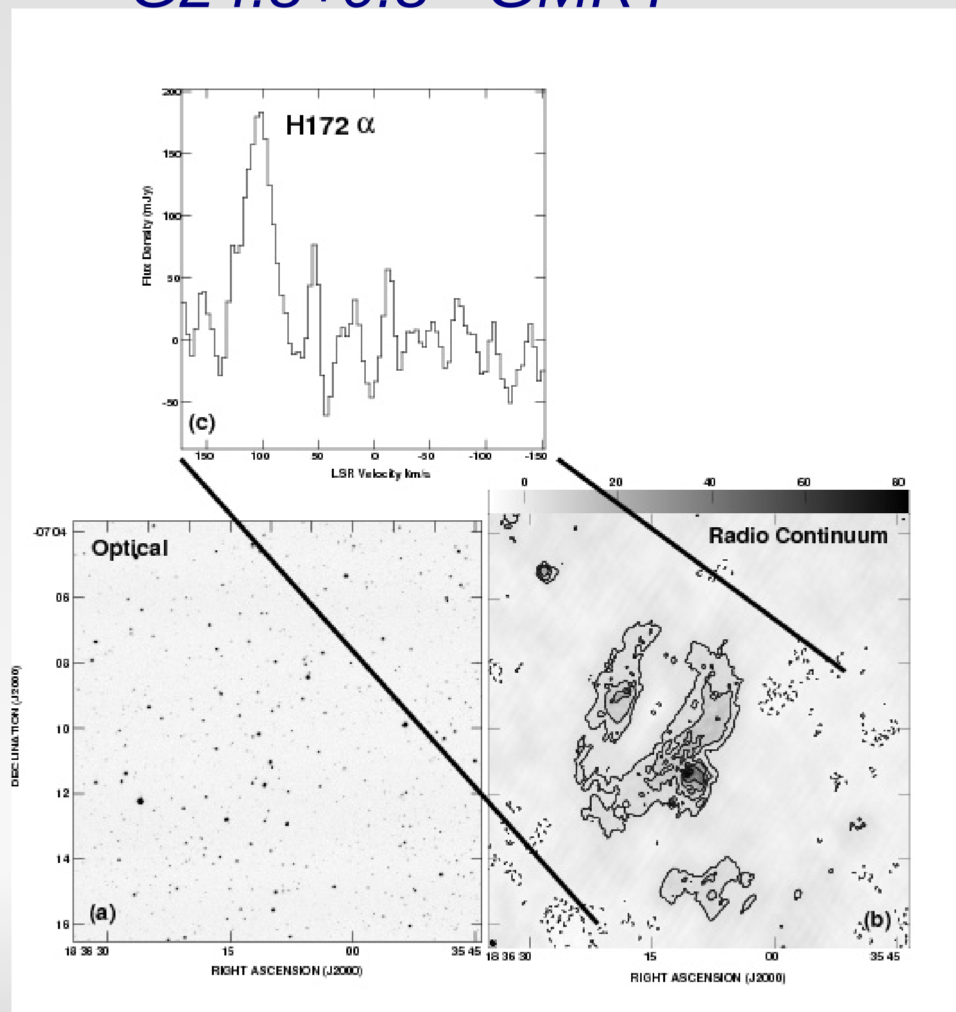
•tau_f ~ 8.24 x 10^(-2) T ^ (-1.35) nu ^ (-2.1) EM

- *G24.8+0.8 - GMRT*

NGC 3603 – thermal contm



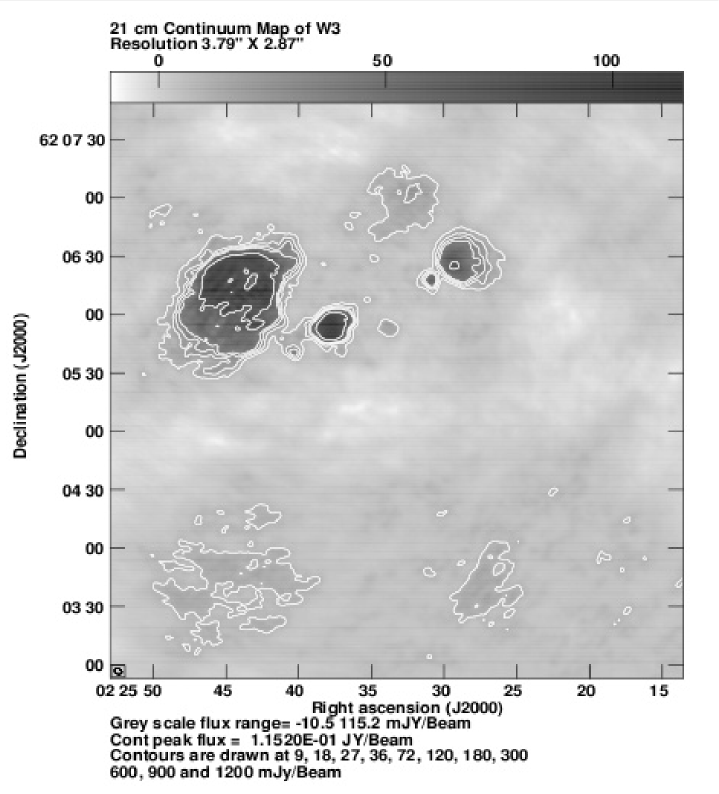
http://www.atnf.csiro.au/people/bkoribal/ngc3603/



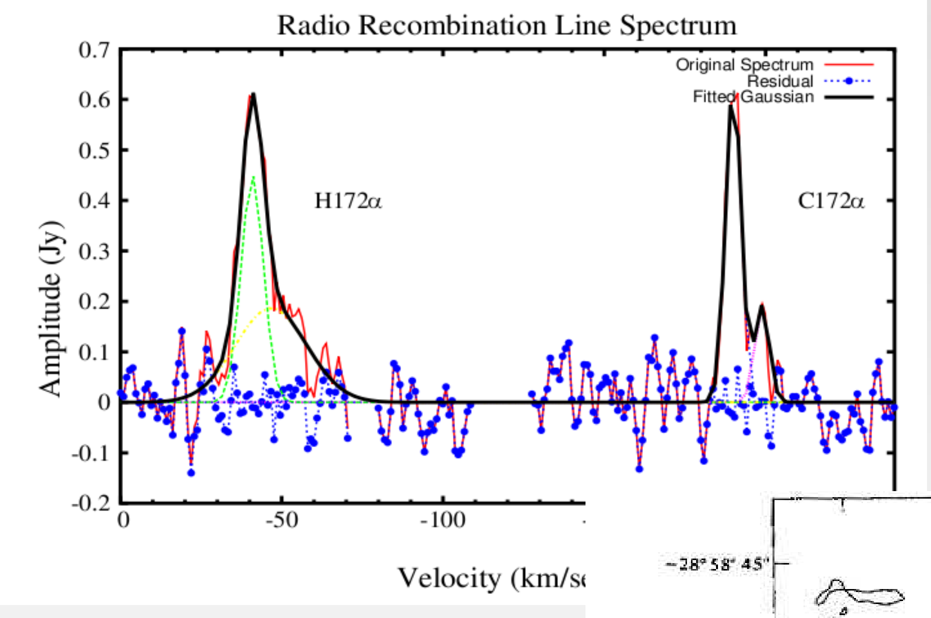
Galactic Radio Sky

- HII Regions – star forming regions - GMRT

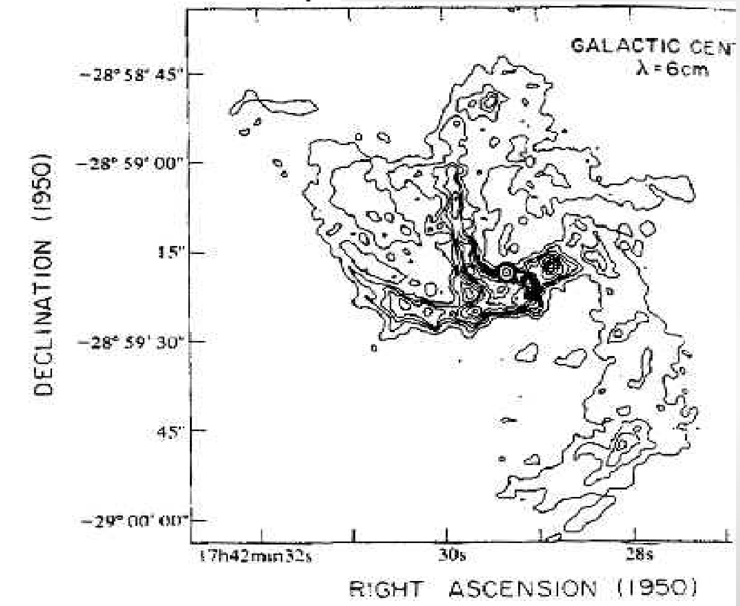
W3 star forming complex at 20cm



RRL from W3A

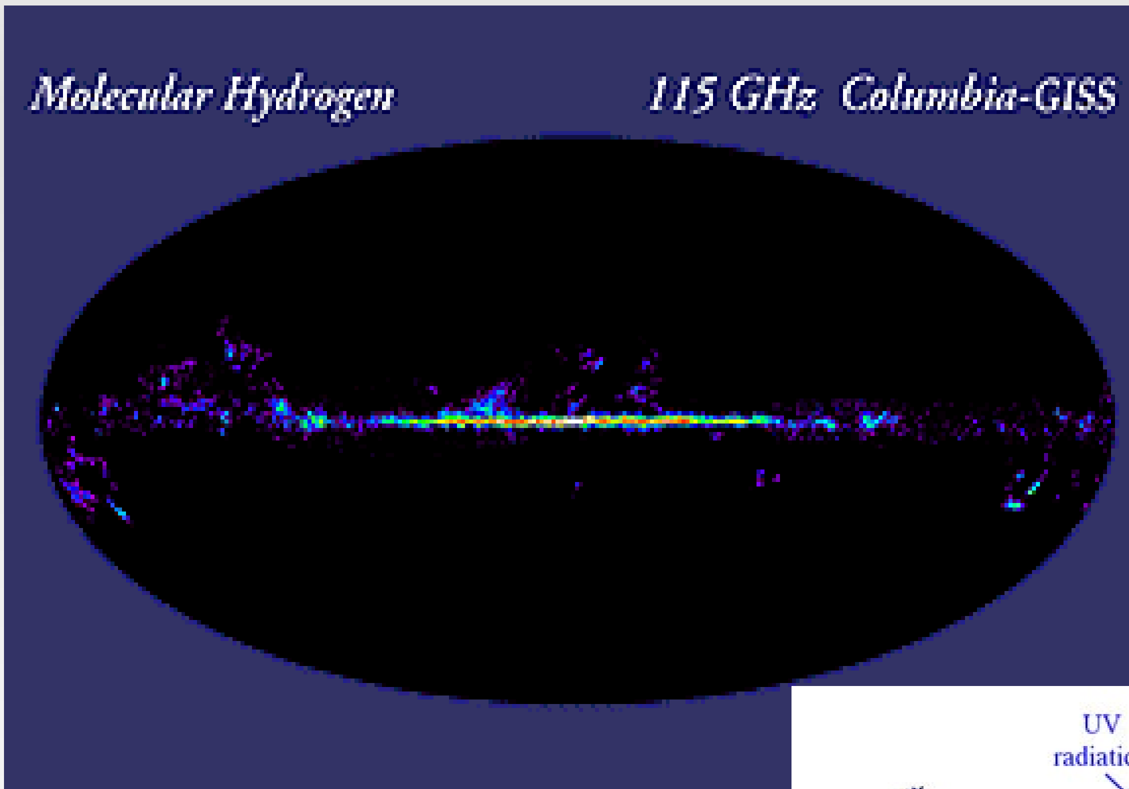


RRL emission near GC at 6cm



Galactic Radio Sky

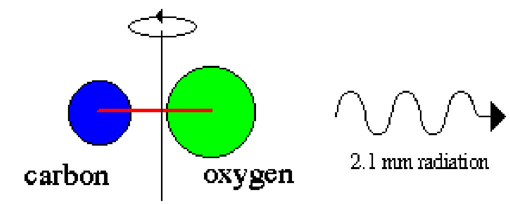
- Molecular clouds – radio spectral lines



Radiation from Interstellar Molecules

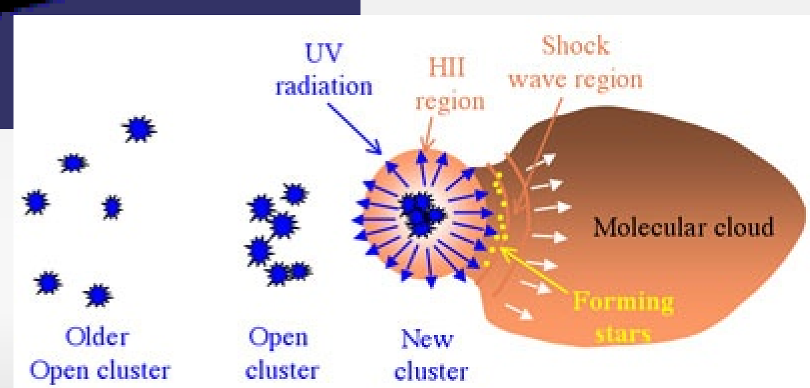
Interstellar molecules (such as H_2, CO, CN,) emit radiation by rotation rather than direct transition of their electrons

carbon monoxide molecule



The radiation emitted tends to be in the microwave region of the spectrum.

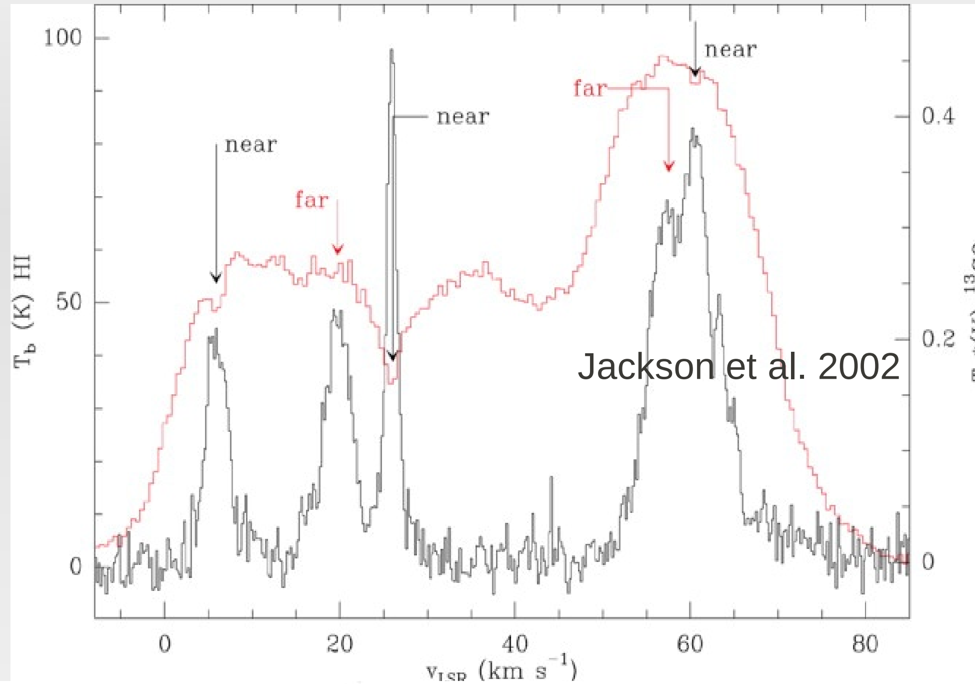
http://abyss.uoregon.edu/~js/ast122/lectures/lec22.html



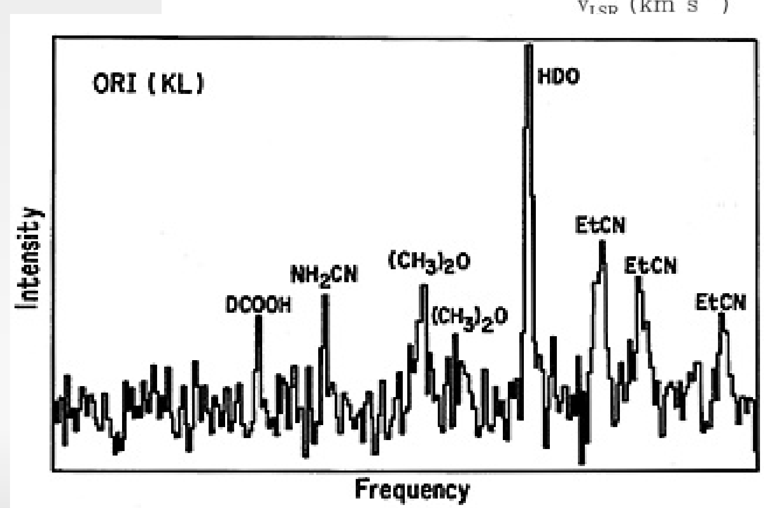
Galactic Radio Sky

- M42 in CO

http://aro.as.arizona.edu/docs/mm_astronomy.htm



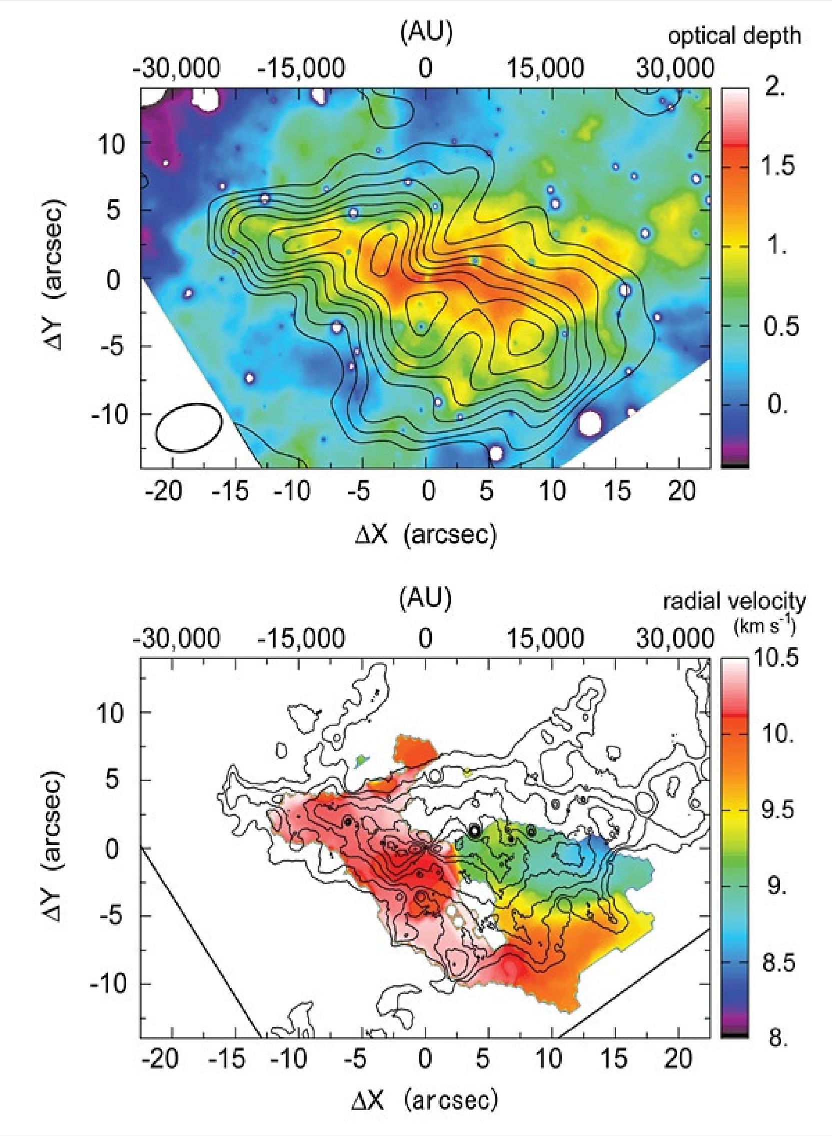
Jackson et al. 2002



Typical molecular line spectrum

Galactic Radio Sky

http://www.subarutelescope.org/Pressrelease/2005/04/20/



M17 SO1:
NIR colour
13CO
contours

Star forming
region

Temperatures ~ 10-20 K

Densities ~ > 200 /cc

Molecular clouds, cores....different tracers for different densities.

Sites of star formation

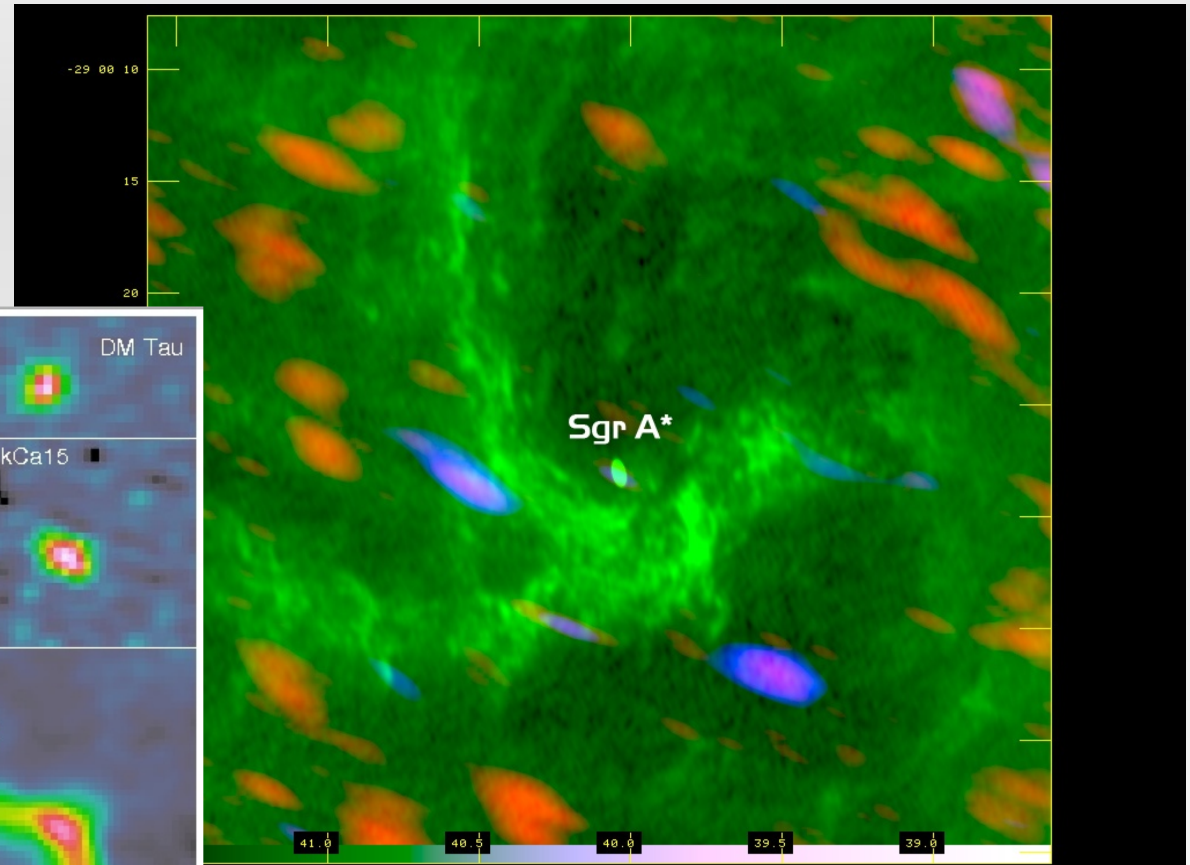
Galactic Radio Sky

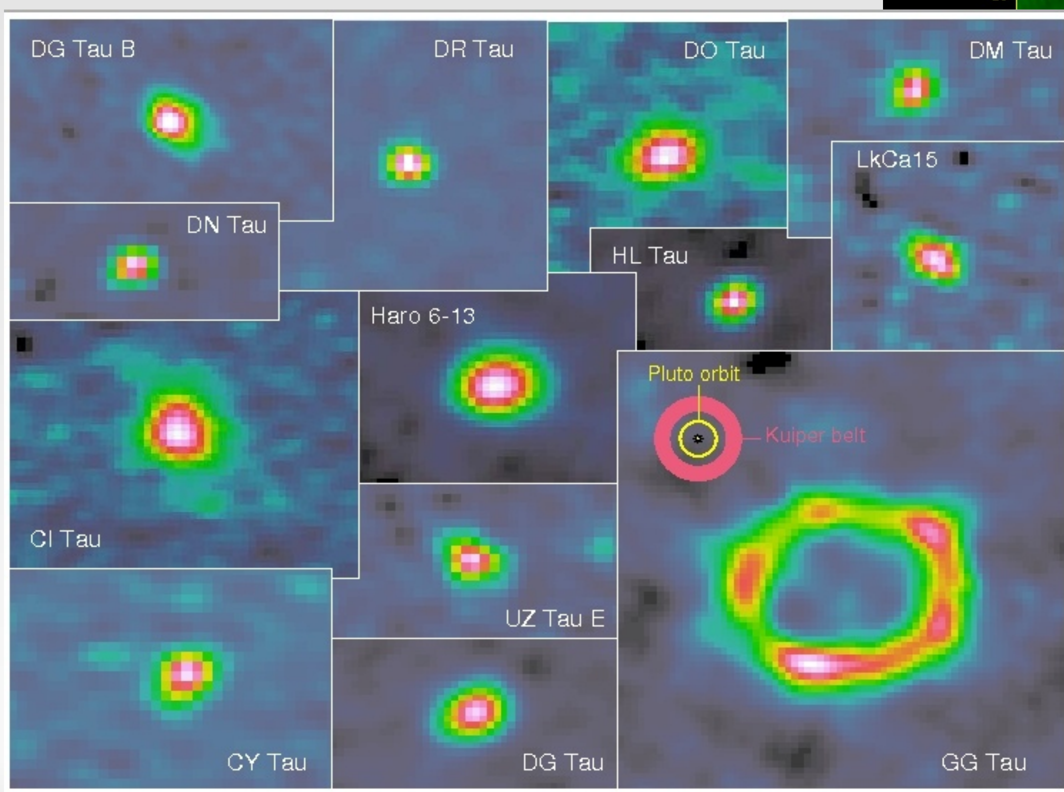
Young stellar objects

ALMA – SiO jets near GC

Formation of new stars very close to GC

http://www.almaobservatory.org



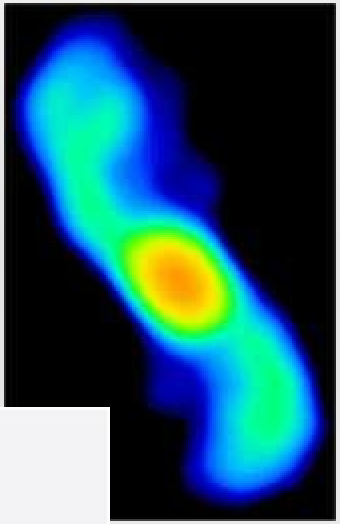


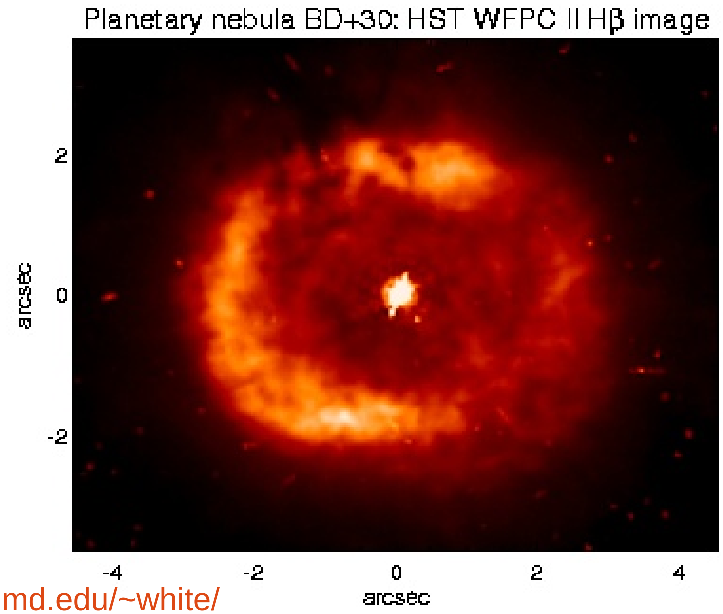
- *CARMA – mmwave continuum of circumstellar disks around young T Tauri stars*

Planetary Nebulae

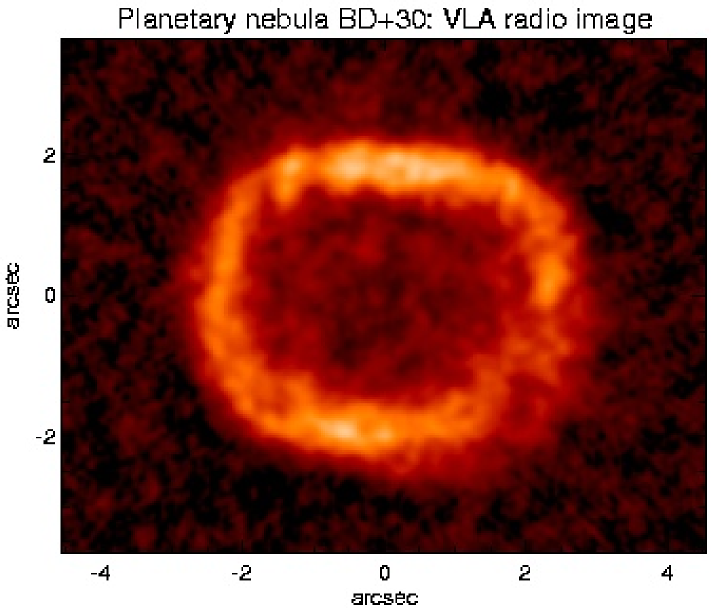
K3-35 – a planetary nebula in formation

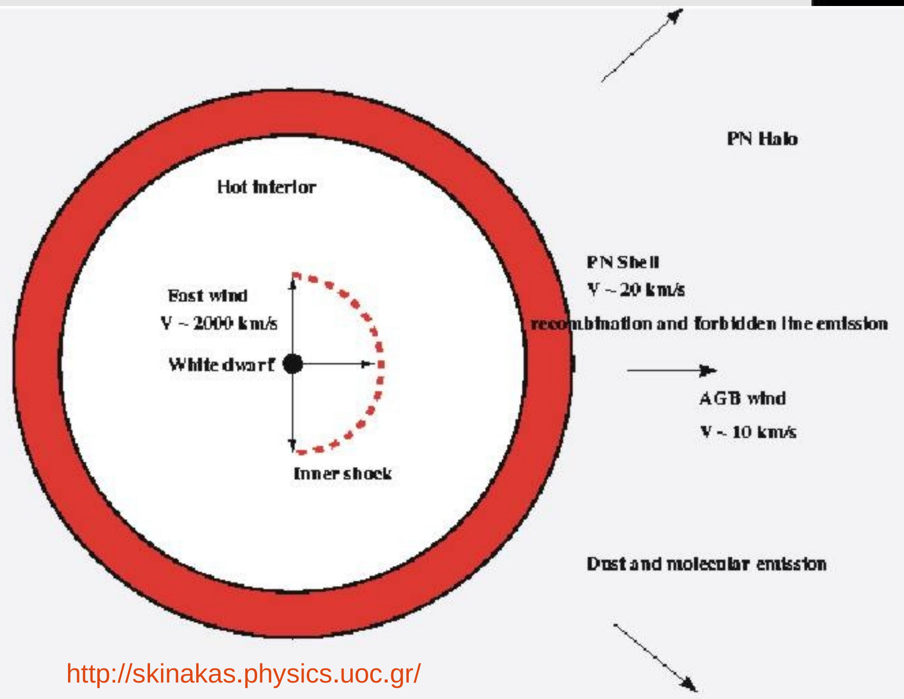
www.nrao.edu





http://www.astro.umd.edu/~white/





http://skinakas.physics.uoc.gr/

Galactic Radio Sky

Planetary Nebulae

Ionized thermal gas ejected from star Te ~ 20000 K

Stellar remnant after fuel exhausted in low mass stars (< 8 solar mass) – outer layers ejected in red giant phase and ionised by uv radiation from core which will become a WD.

Short-lived compared to star

Chemically important – returns metals to ISM e.g C, N, O, Ca

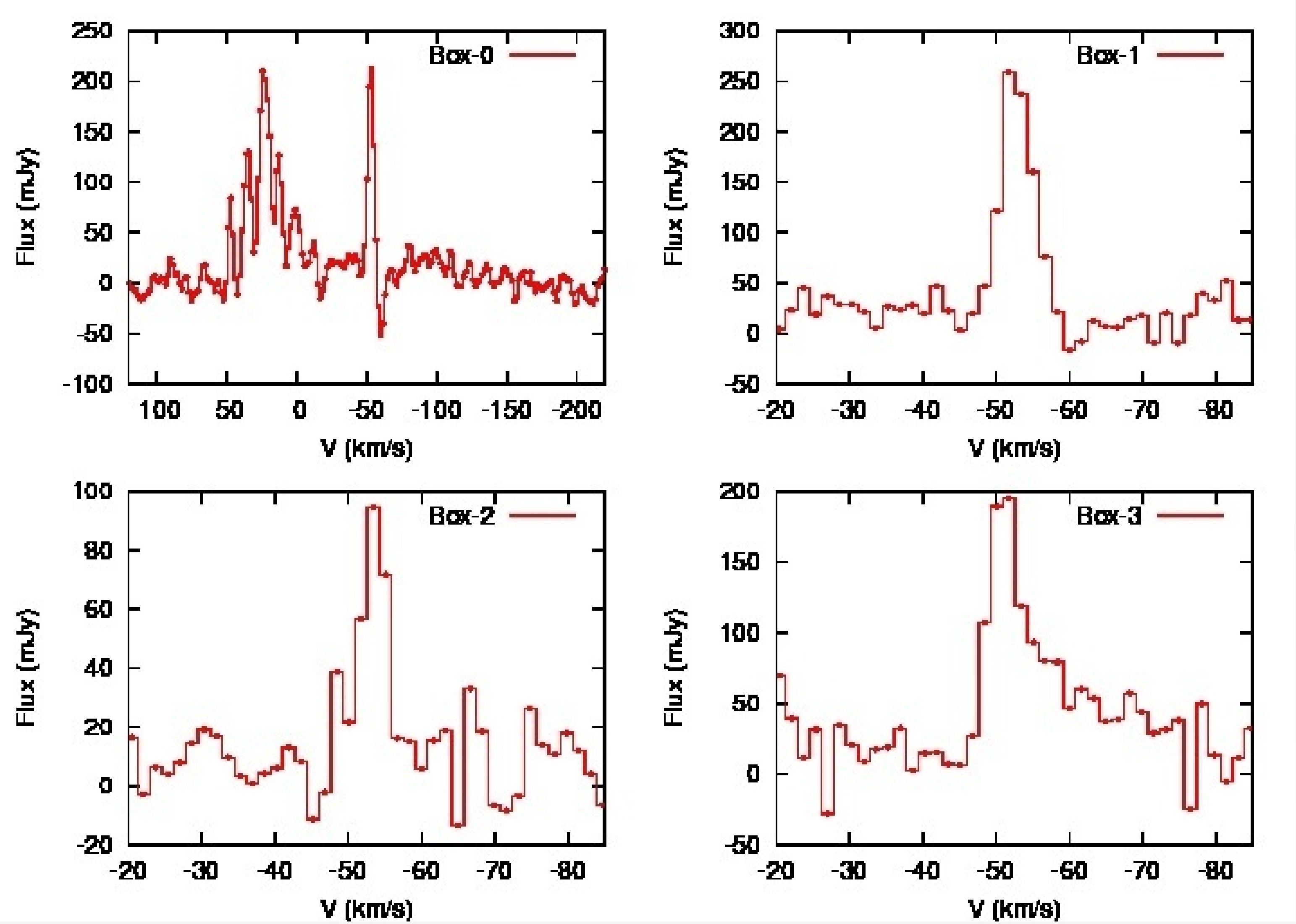
Complex morphologies – due to B, binary?

~ 1 pc, 100-10^4 /cc, 0.1-1 solar mass

NGC 6326, a planetary nebula with glowing wisps of outpouring gas that are lit up by a binary central star - Wikipedia

Galactic Radio Sky

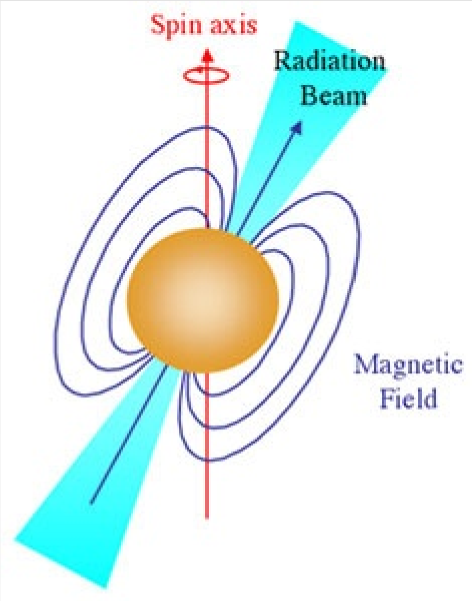
HI emission from planetary nebula - GMRT



Galactic Radio Sky

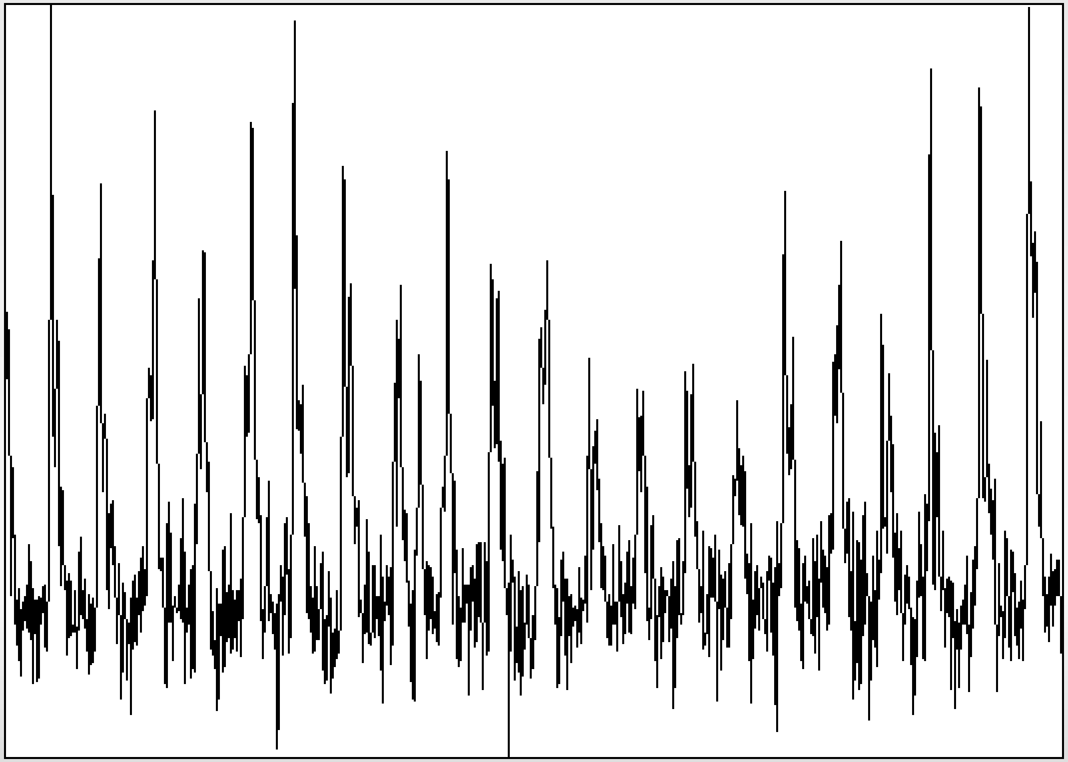
Pulsars – observable neutron stars as pulsating radio sources

End product of a massive star run out of fuel



B ~ 10^ 12 G; radius ~ 10 km; fast rotator period ~ ms to sec

Densites ~ 10^17 kg/m3 (earth ~ 5x10^3 km/m3)



Pulsed emission in radio when the radiation beam crosses LOS

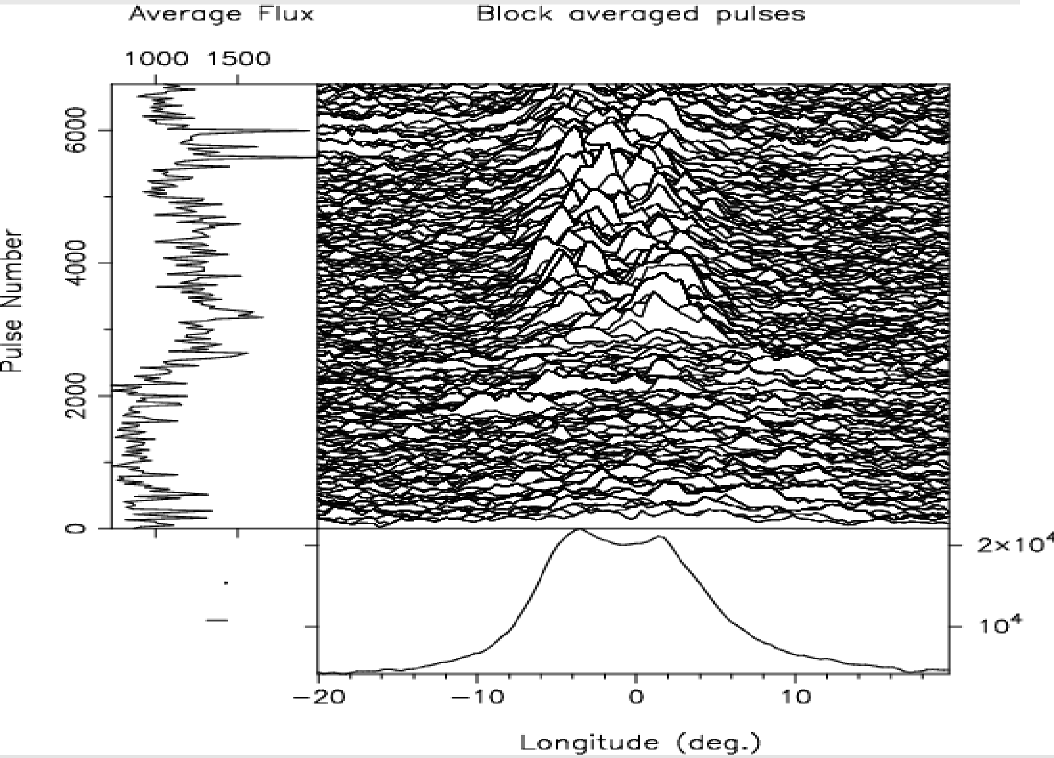
http://outreach.atnf.csiro.au/education/pulseatparkes/pulsar_properties.html

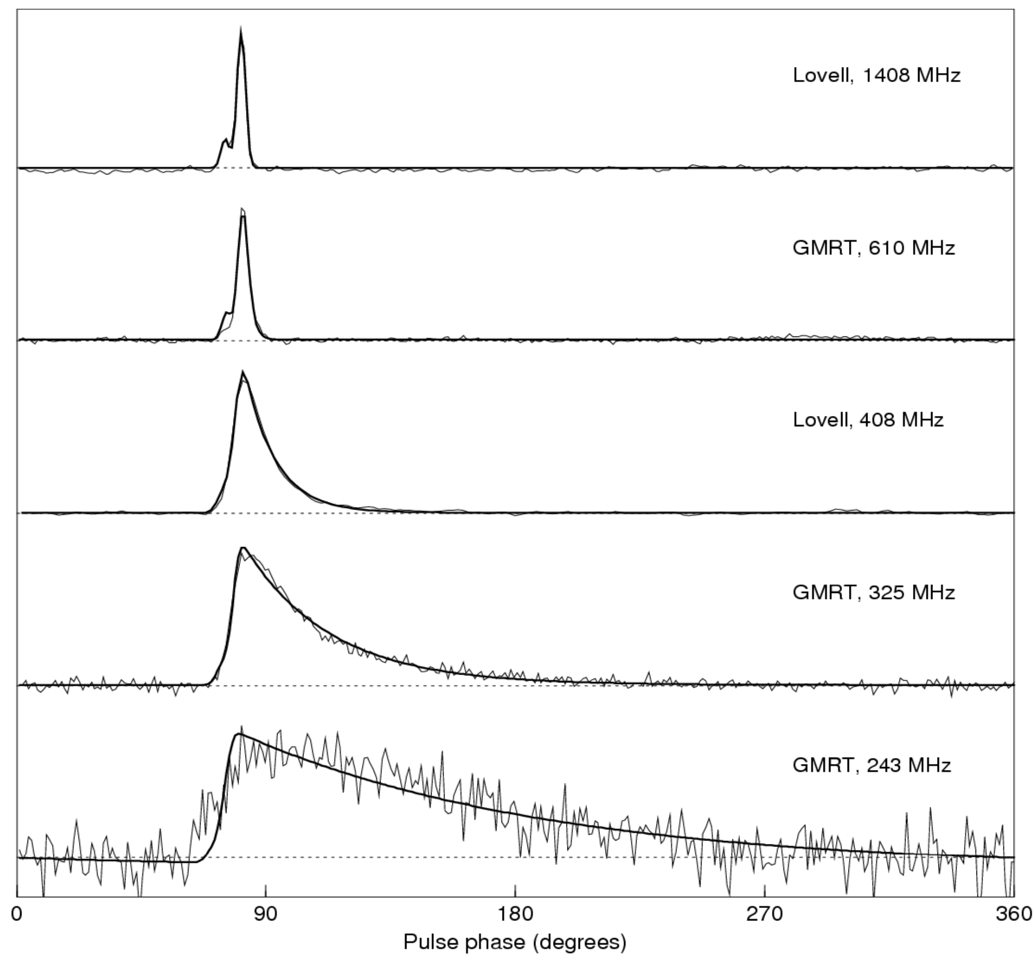
Galactic Radio Sky

IS scattering causes the long tail at low frequencies

DM causes low frequency pulses to arrive at a later time

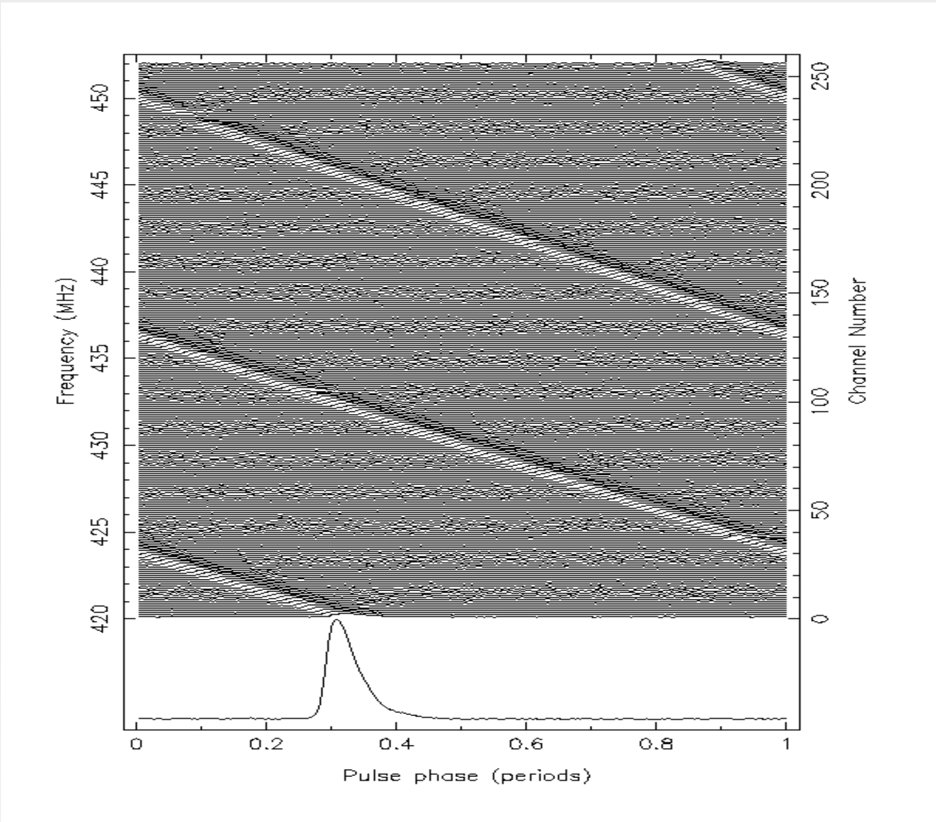
DM ~ ne L

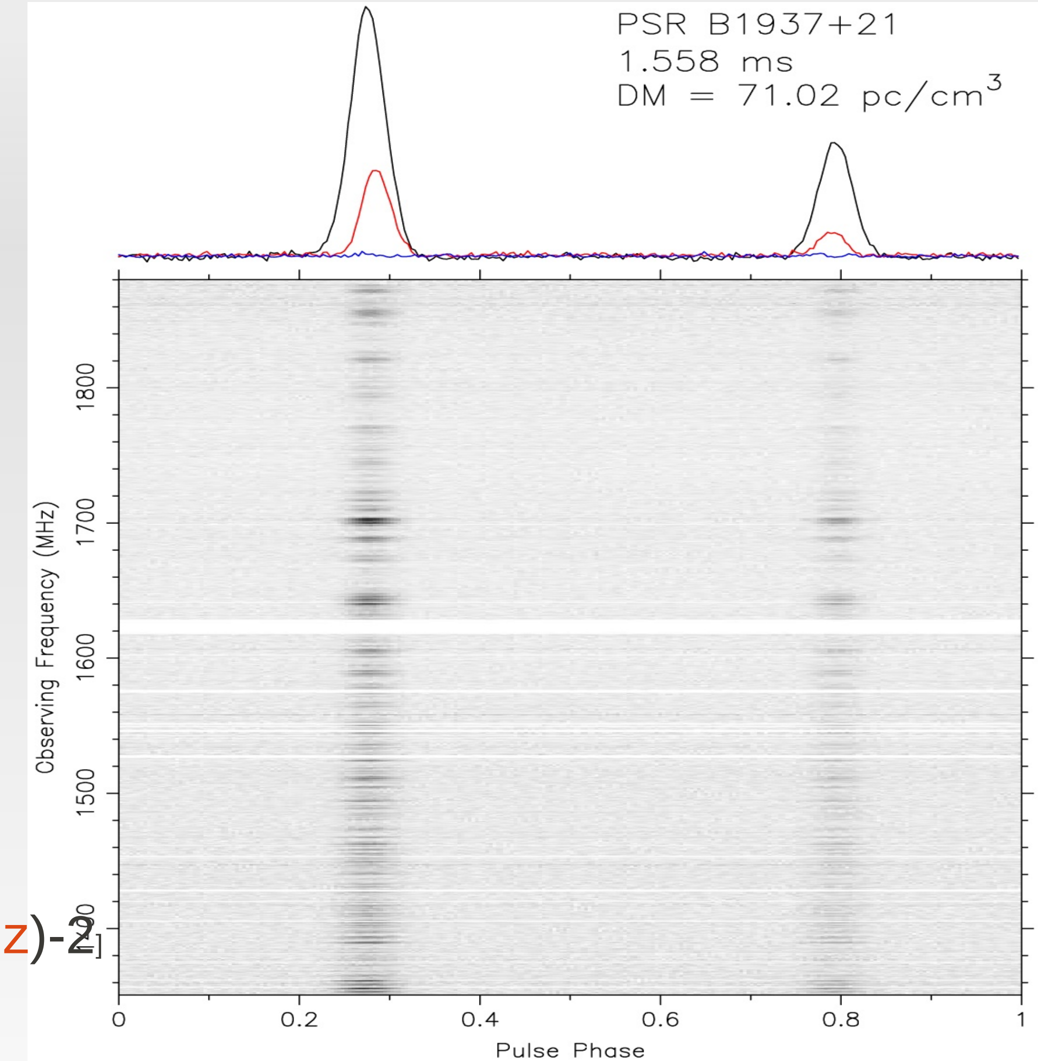




scattering(t) = exp (- t/tsc).
tsc ~ nu ^ (4.4) and DM ^ (2.2)

Galactic Radio Sky





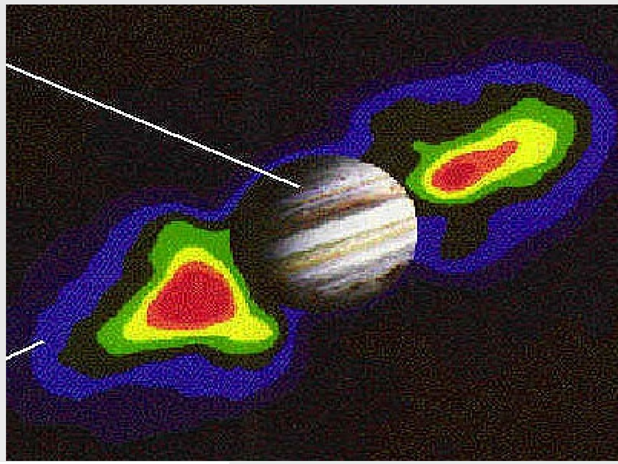
$t_2 - t_1 = 4.15\ \mathrm{ms}\ DM\ [(\nu_1/\mathrm{GHz})^{-2} - (\nu_2/\mathrm{GHz})^{-2}]$

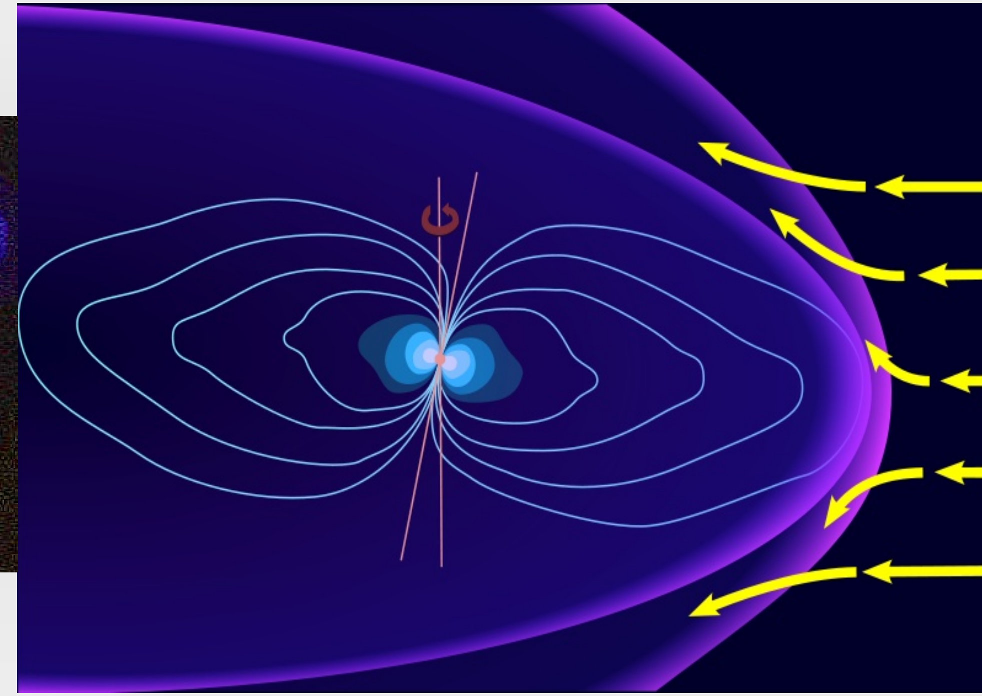
Pulsar emission mechanism,
interstellar medium physics,
extreme physics

Galactic Radio Sky

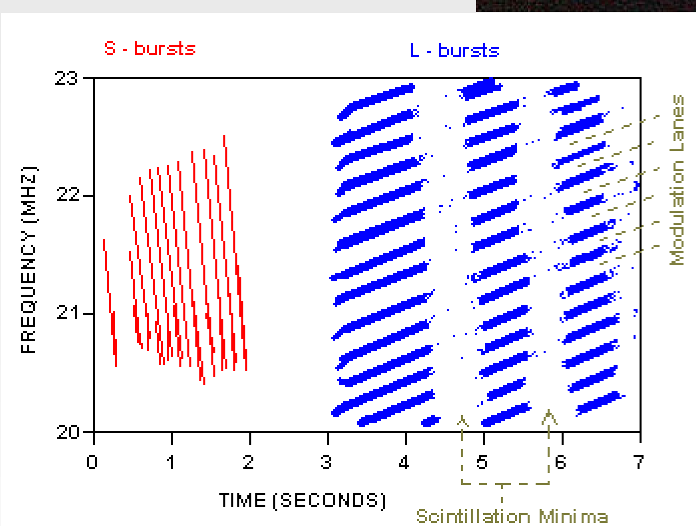
Jupiter

Jupiter's magnetosphere – cavity in solar wind by Jupiter's magnetic field, rotation and Io's plasma.





From Wikipedia



http://www.spaceacademy.net.au/spacelab/projects/jovrad/jovrad.htm

Variable radio emission – cyclotron, synchrotron emissions

Decametric radio bursts – related to IO which has > 400 active volcanoes – responsible for plasma around Jupiter

Galactic Radio Sky

Sun at radio wavelengths

Solar activitiy

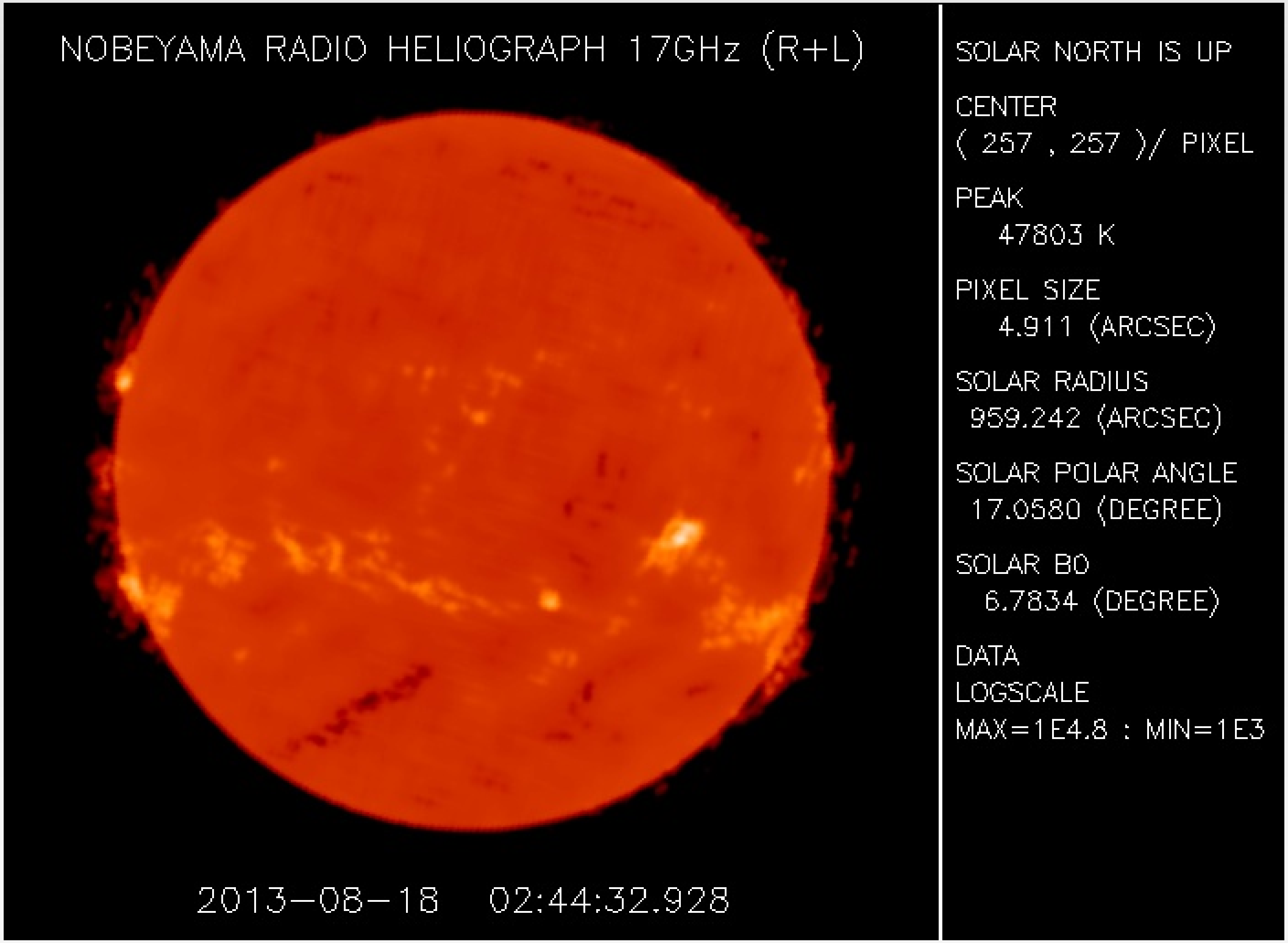
Radio flares

Noise storms

Quiet sun/active sun

Radio emission well-correlated with the sunspot 11yr cycle

Thermal + synchrotron emission



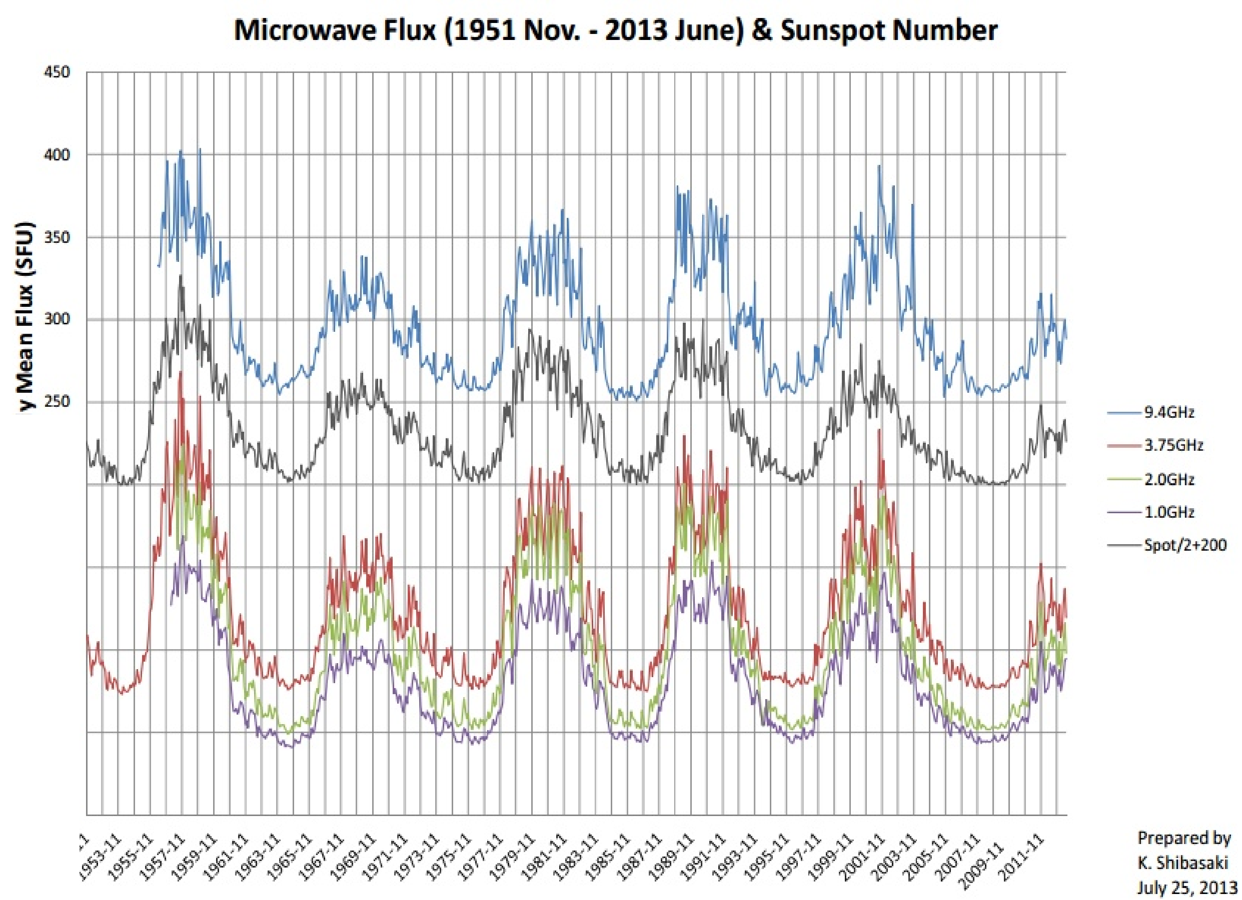
http://solar.nro.nao.ac.jp

Galactic Radio Sky

Sun at radio wavelengths

Helps us understand radio emission from other stars

Most stars – radio quiet – fev are flare stars – radio bright



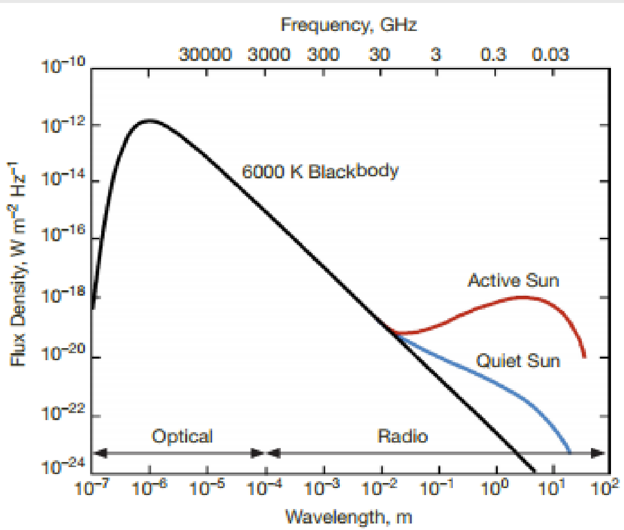


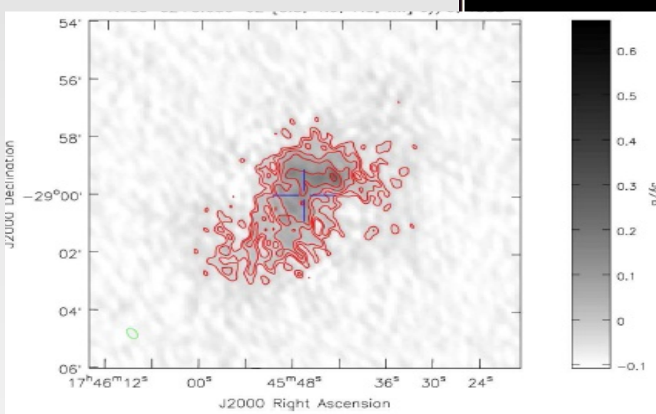
Figure 1. The solar radiation spectrum at optical and radio frequencies. At wavelengths greater than 1 cm, the radiance from an active Sun is much larger than from a quiet Sun and from a blackbody at 6000 K (figure after [1,2]).

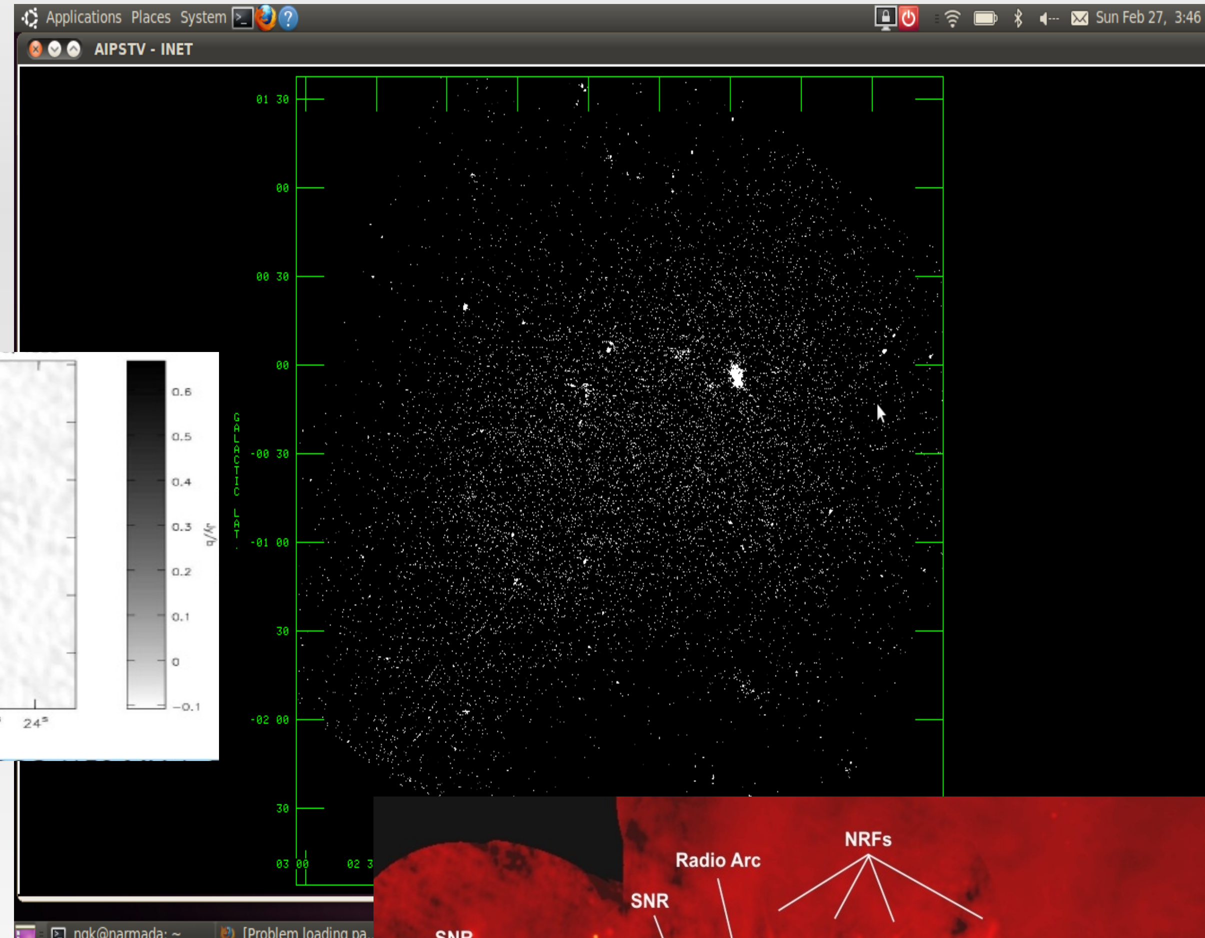
http://solar.nro.nao.ac.jp/norp/html/MicrowaveSunspot201306.pdf

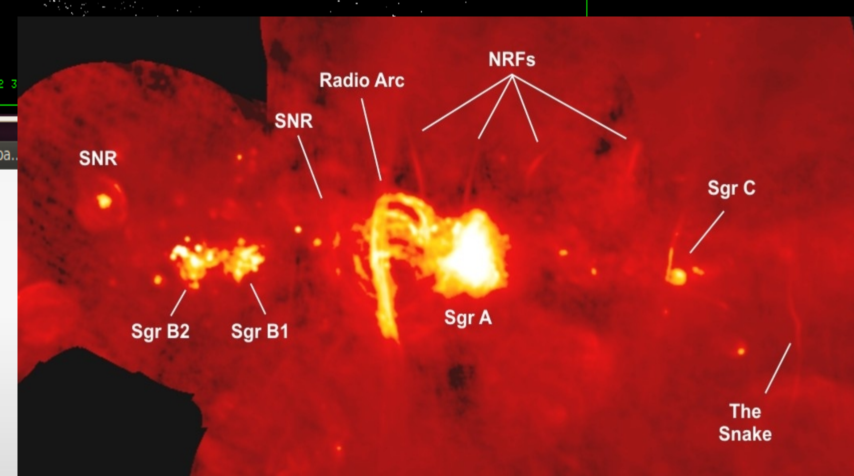
Galactic Radio Sky

Galactic centre - SgrA*

Sag A* - million solar mass black hole





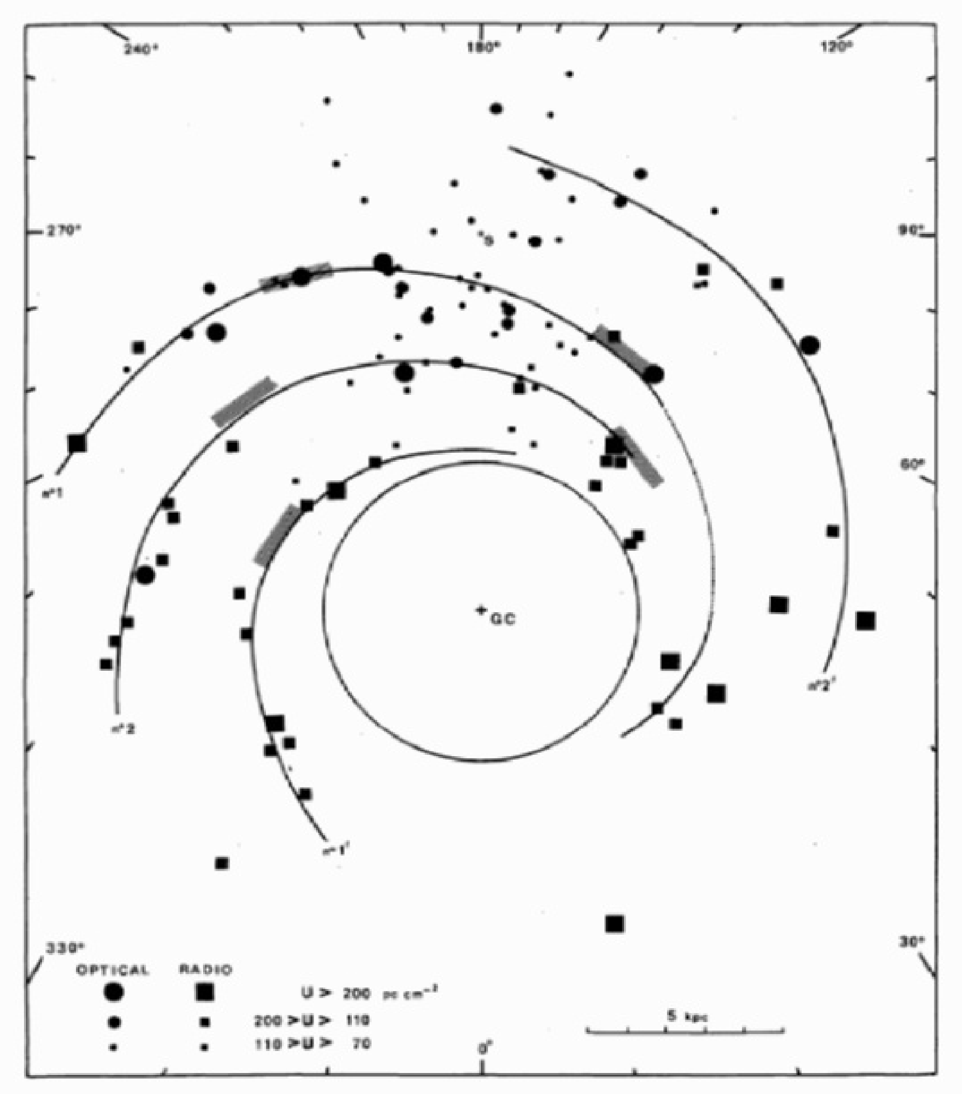


Sagittarius A – Sag A*,

Sag AEast(SNR)

Sag A West (HII region)

Galactic Radio Sky



- Observations of star forming regions revealed the spiral structure of the galaxy.
- Georgelin & Georgelin (1976)
- Diagnostics – radio recombination lines; stellar spectra.

Galactic Radio Sky

Important radio discoveries....

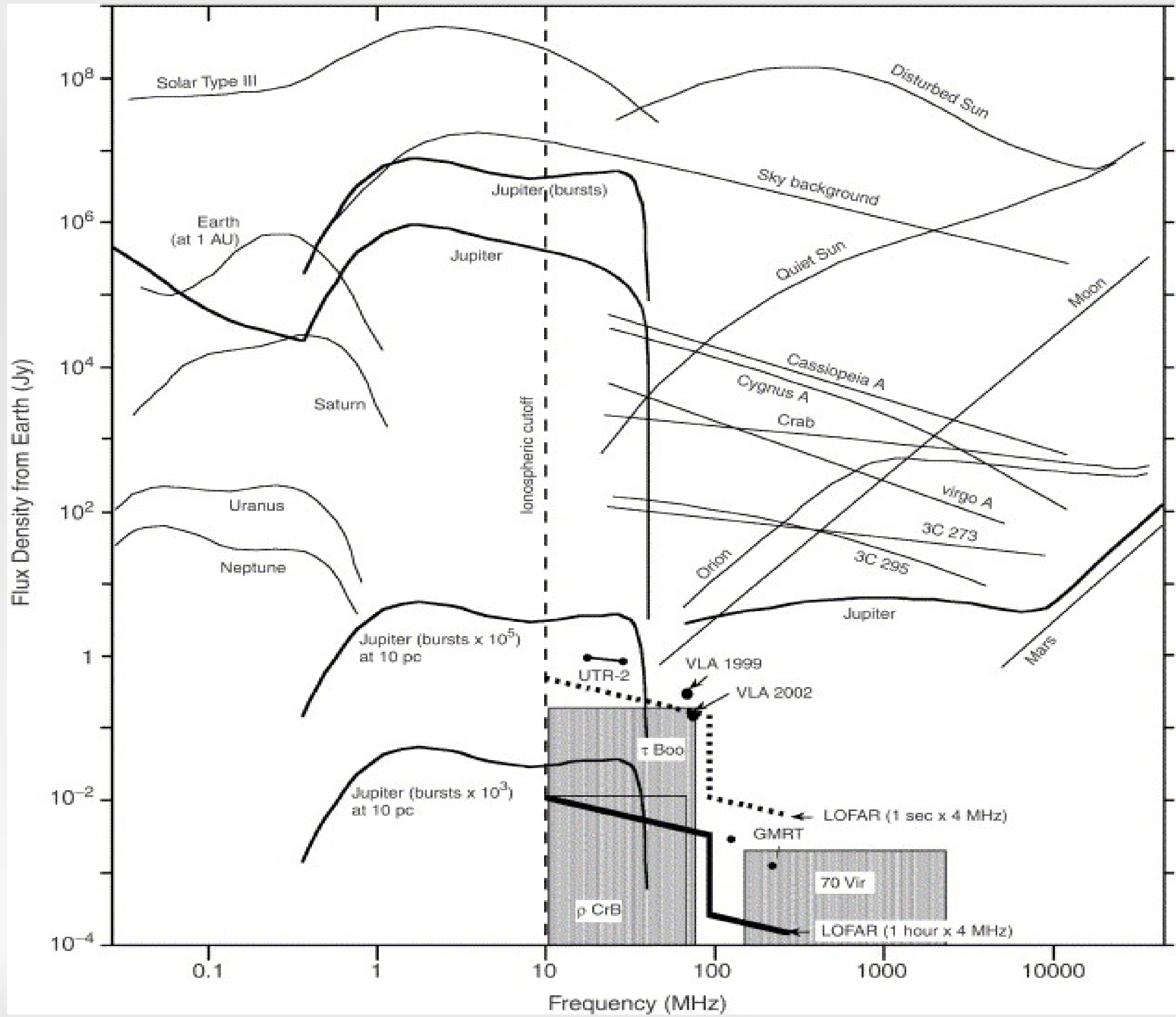
- Discovery of extrasolar radio signals – 1933
- HI 21cm signal – 1951
- Transitions in large Rydberg atoms – 1964
- Radio line from a molecule – 1963
- Differential rotation in the galaxy – 1960s – dark matter inferred from nature of the kinematics in the outer galaxy.
- A carbon atom with electron in n~631 discovered – size of atom would be 50 micron against Bohr radius of 0.5 x 10^(-4) micron ! - 1980
- Multiphase ISM – 1969, 1977

Galactic Radio Sky

NGK 19August2013 RAS

Galactic Radio Sky

Flux density of different Galactic radio sources



From Zarka 2007

Galactic Radio Sky

Emission Mechanisms

- *Non-thermal synchrotron from relativistic plasma in B*
- *Free-free thermal from ionized media; recombination lines*
- *21cm spectral line from atomic hydrogen*
- *Spectral lines from molecules*
- *Radio recombination lines from ionised media*
- *Curvature radiation*

Galactic Radio Sky

- Interstellar medium

Atomic clouds

Synchrotron Radiation field

Molecular clouds

Supernova remnants

HII regions

Planetary nebulae

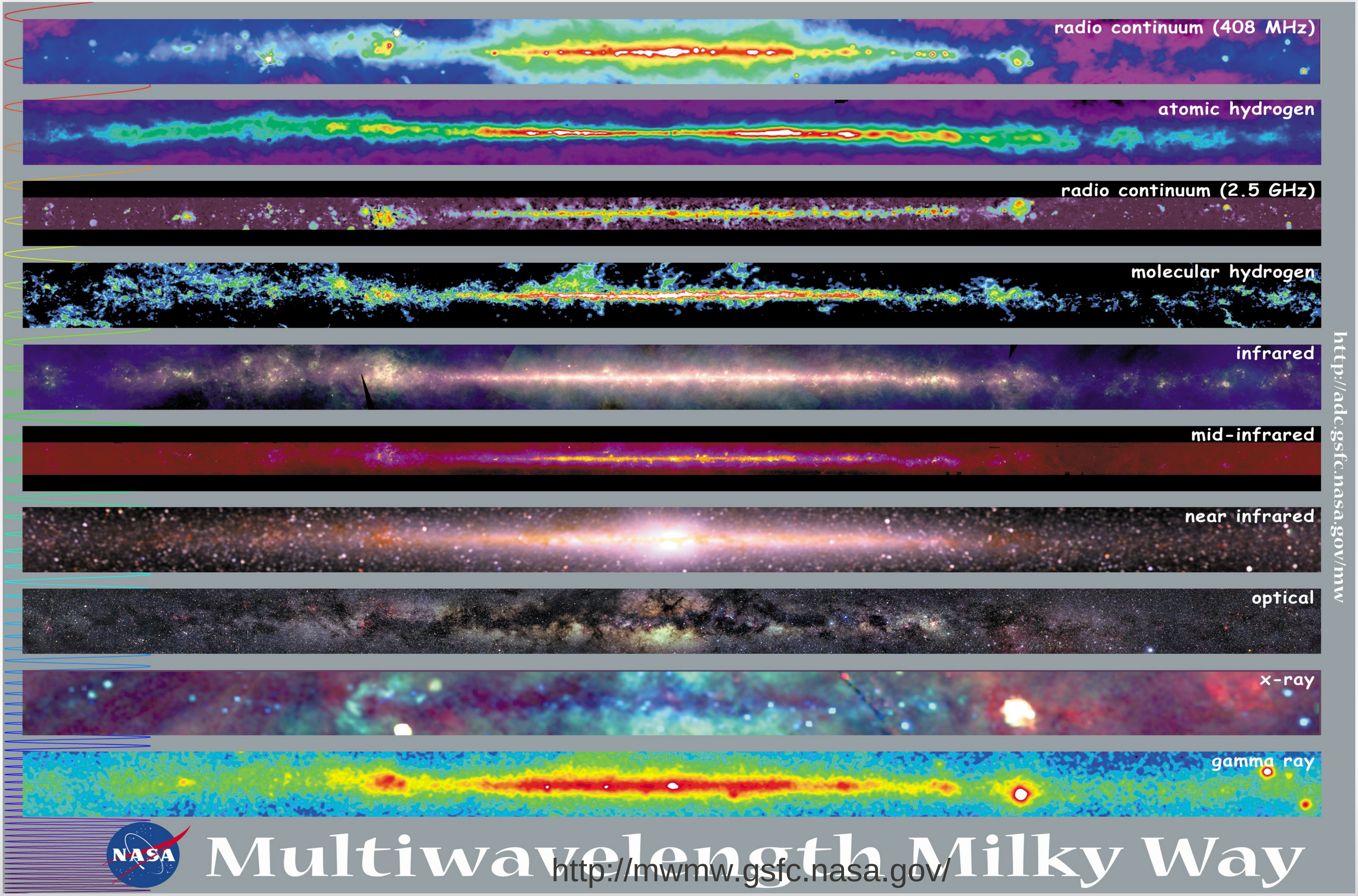
- Galactic centre - SgrA*
- Stars including sun,pulsars.
- Planets – e.g. Jupiter
- Dark matter

- Interstellar medium
- Stars

- Radio emission allows study of physical conditions – temperature, magnetic fields, composition, densities, sizes, morphology, distances, kinematics, Galactic structure.......

Radio Sky

Galactic Radio Sky



http://mwmw.gsfc.nasa.gov/

Galactic Radio Sky

- *408 Mhz – synchrotron emission - wideband*
- *HI – hyperfine bound-bound transition in hydrogen ~ 21cm wavelength – narrow band*
- *2.5 Ghz – synchrotron + thermal emission – wideband*
- *H2 – rotational transition in CO molecule used as tracer – narrow band emission*
- *FIR, MIR – cold dust, warm dust – thermal emission wideband*
- *NIR – low mass stars – thermal emission wideband*
- *Optical – starlight upto ~ 3 kpc; rest dust obscured; wideband photometry*
- *X-ray – hot thermal gas ~ million degrees K*
- *Gamma rays - collision of cosmic rays with IS nuclei.*

Galactic Radio Sky

- Riegel-Crutcher cloud - edge of the local bubble ~ 125 pc away
- Sheet-like cold HI region (thickness ~ 1 to 5 pc and sky extent > 17pc)which shows filamentary structure!
- Self-absorbing cloud

68 *McClure-Griffiths et al.*

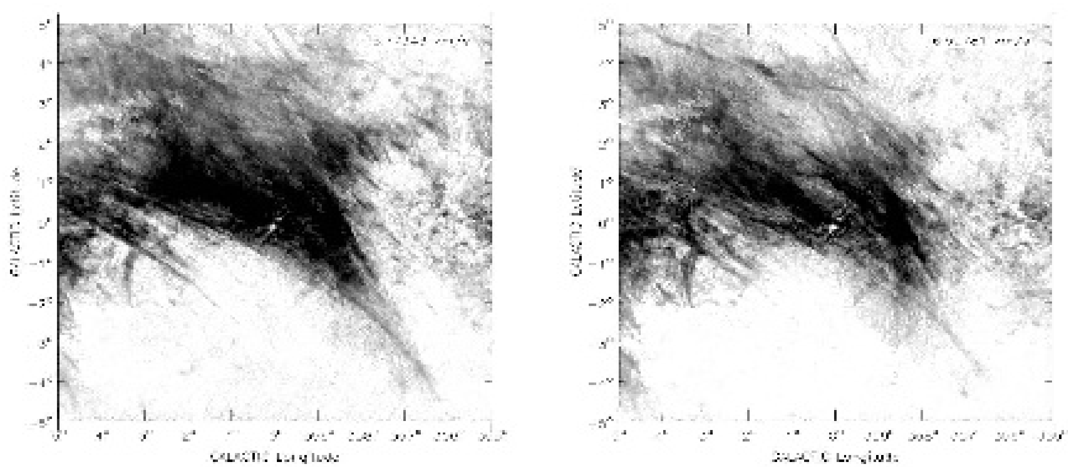
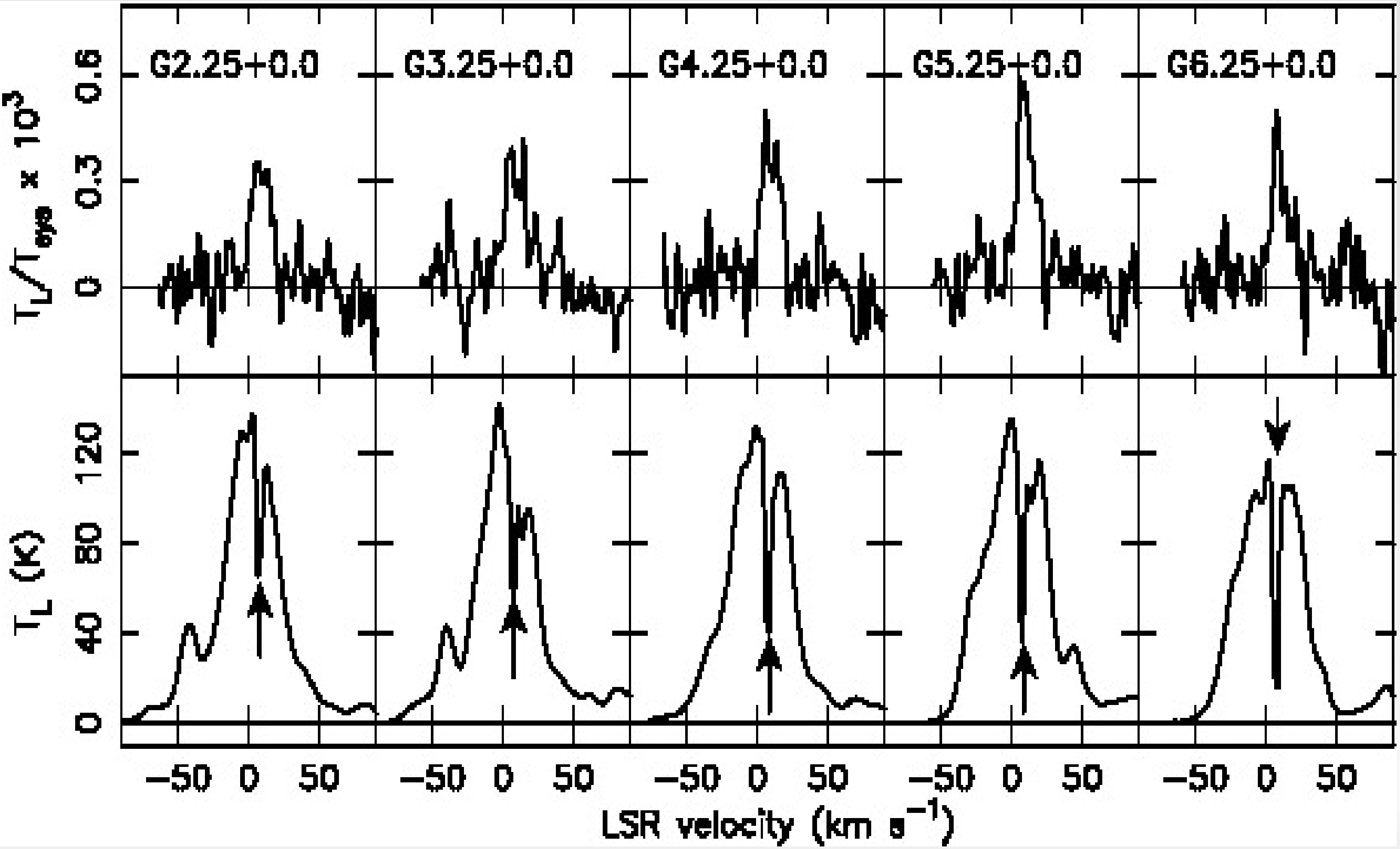


Figure 2. H I channel images of the Riegel-Crutcher cloud after subtraction of the background emission. The grey scale is linear and runs between 0 K (*white*) and -90 K (*black*).

Galactic Radio Sky

- Riegel-Crutcher cloud – carbon RRL at 327 Mhz with Ooty Radio Telesocpe and HI spectrum.



- HI Self-absorbing features – kinematics match C RRL
- Interpretation: common origin
- Physical properties- use both diagnostics