DEVELOPMENT IN AFRICA WITH RADIO ASTRONOMY

DARA Basic Training

NAMIBIA-BOTSWANA 2019

UNIT 1: INTRODUCTION TO ASTROPHYSICS

Windhoek, 7 –18 January 2019

Interstellar Gas

- Interstellar Medium
- Ionized gas
- Atomic gas
- Molecular gas
- Supernova remnants

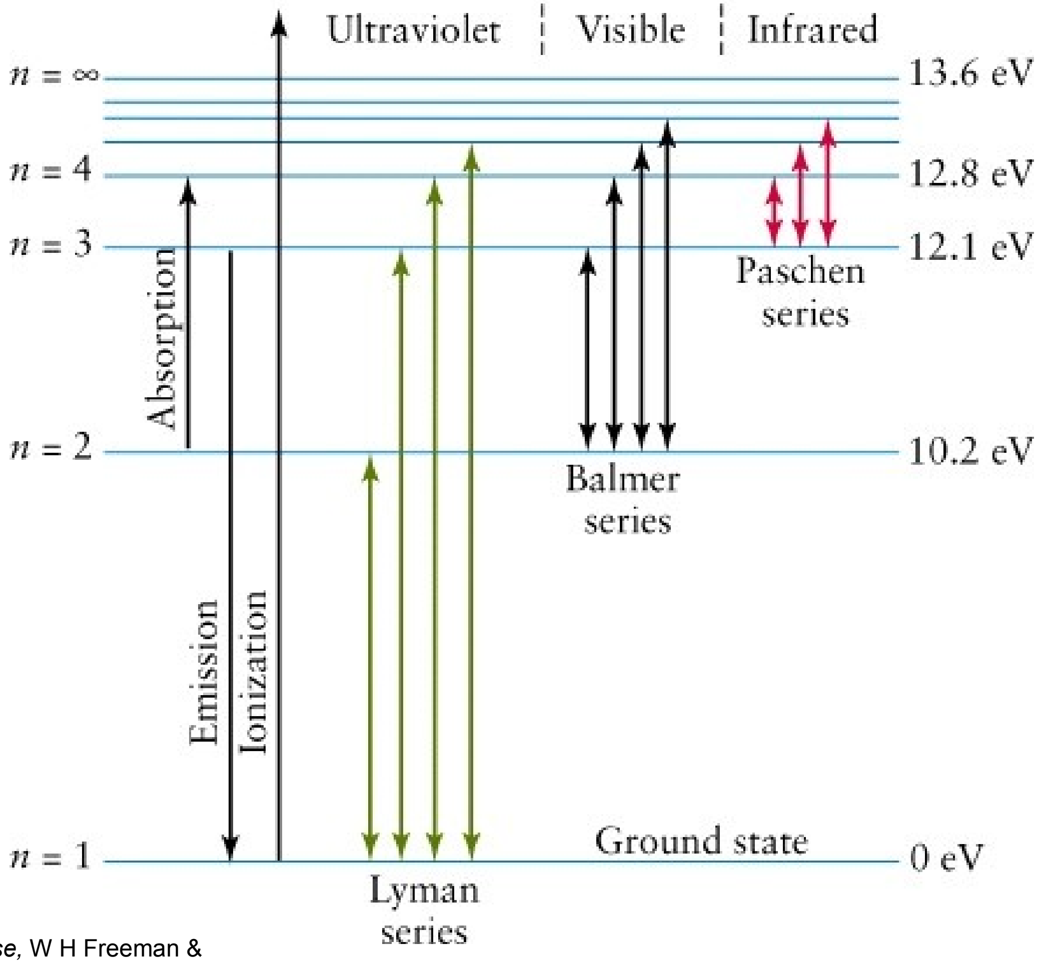
Interstellar Medium

- The space between stars in spiral and irregular galaxies is not empty but contains gas and dust at very low density
- A typical average number density is about 10^6 m^{-3} or 1 particle per cubic centimetre
- However, the interstellar gas exists in a vast range of temperatures and densities

Gemini Observatory

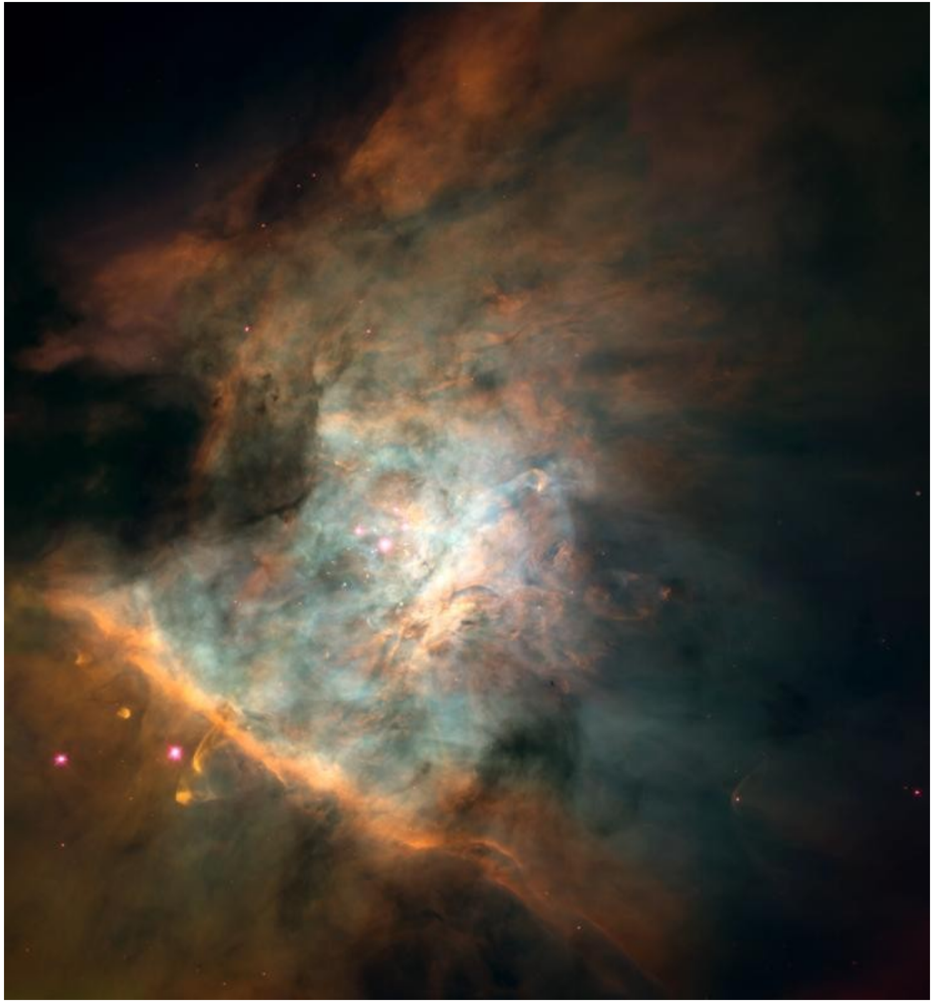
Ionized Gas

- When interstellar gas exists near hot stars it becomes ionized
- Hydrogen (by far the most abundant element) is ionized by photons with energy > 13.6 eV or with a wavelength shorter than 91.2 nm (far ultra-violet)


Ultraviolet
Visible
Infrared
n = ∞
13.6 eV
n = 4
12.8 eV
n = 3
12.1 eV
n = 2
10.2 eV
n = 1
0 eV
Absorption
Emission
Ionization
Paschen series
Balmer series
Lyman series
Ground state

H II Regions

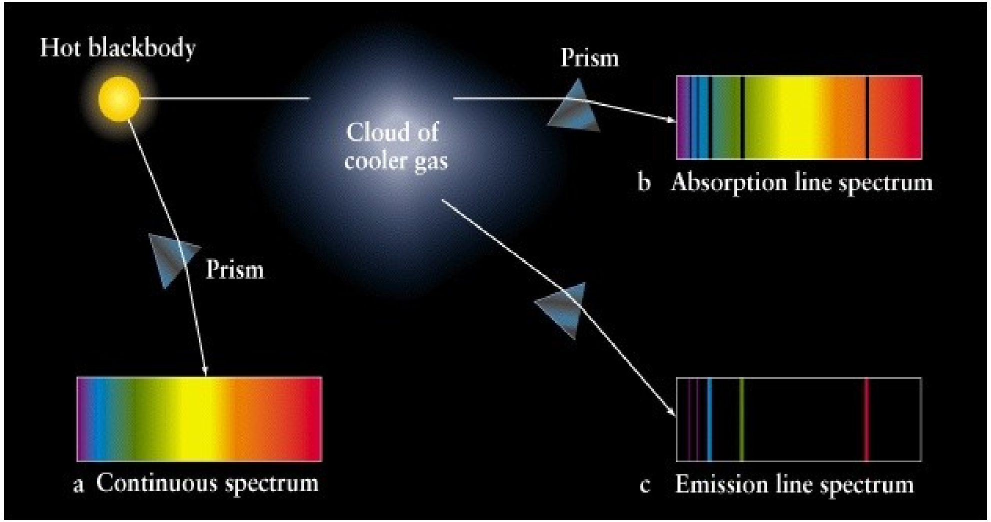
- Massive main sequence stars have T>30 000 K
- Young stars are also still surrounded by dense (10^{10} m^{-3}) gas
- gives rise to ionized nebulae called H II regions
- The gas is hot T~ 10 000 K and fluoresces



Credit: NASA and C.R. O'Dell (Vanderbilt University): HST (Optical)

Emission Line Spectrum

- Arise when hot gas is viewed against a colder background



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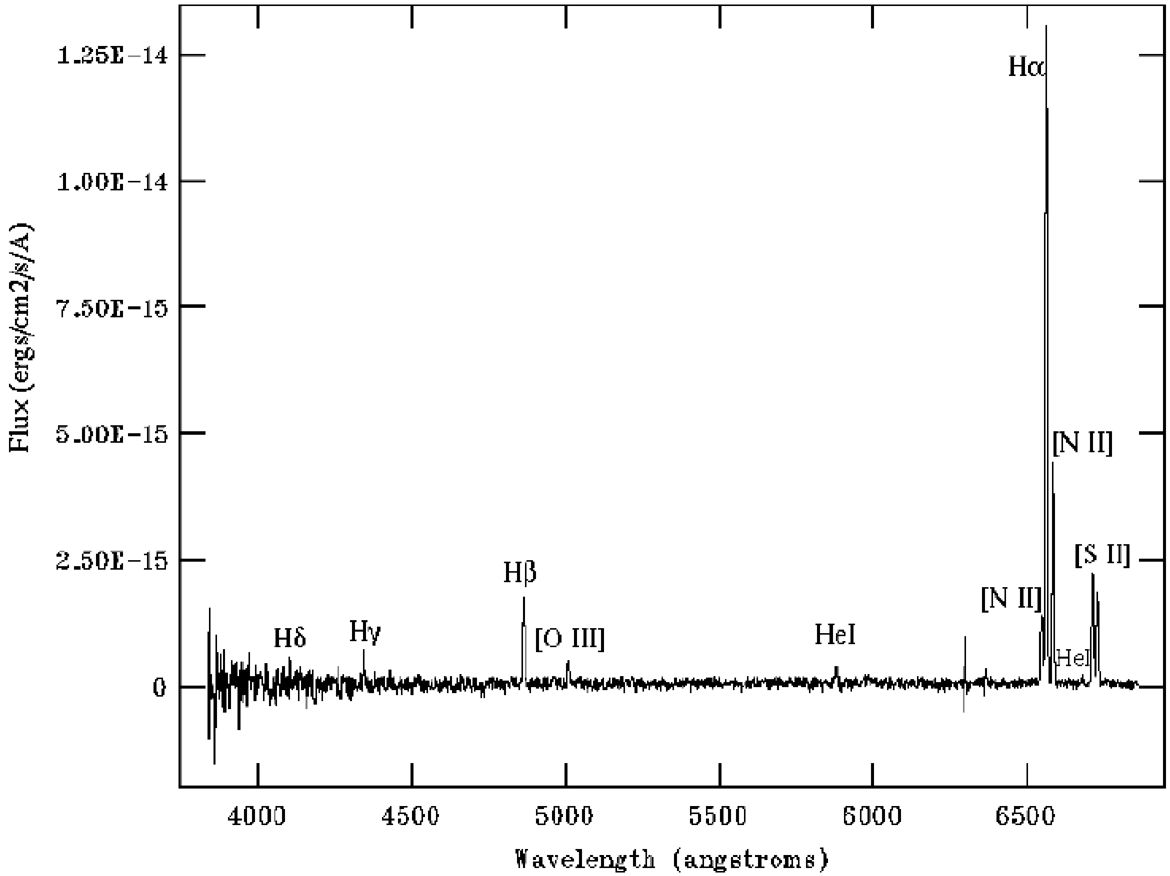
W H Freeman & Co.

- Optical spectrum is made up of emission lines
- The strongest being the Hα line
- These result from the recombination of an electron and a proton following photo-ionization

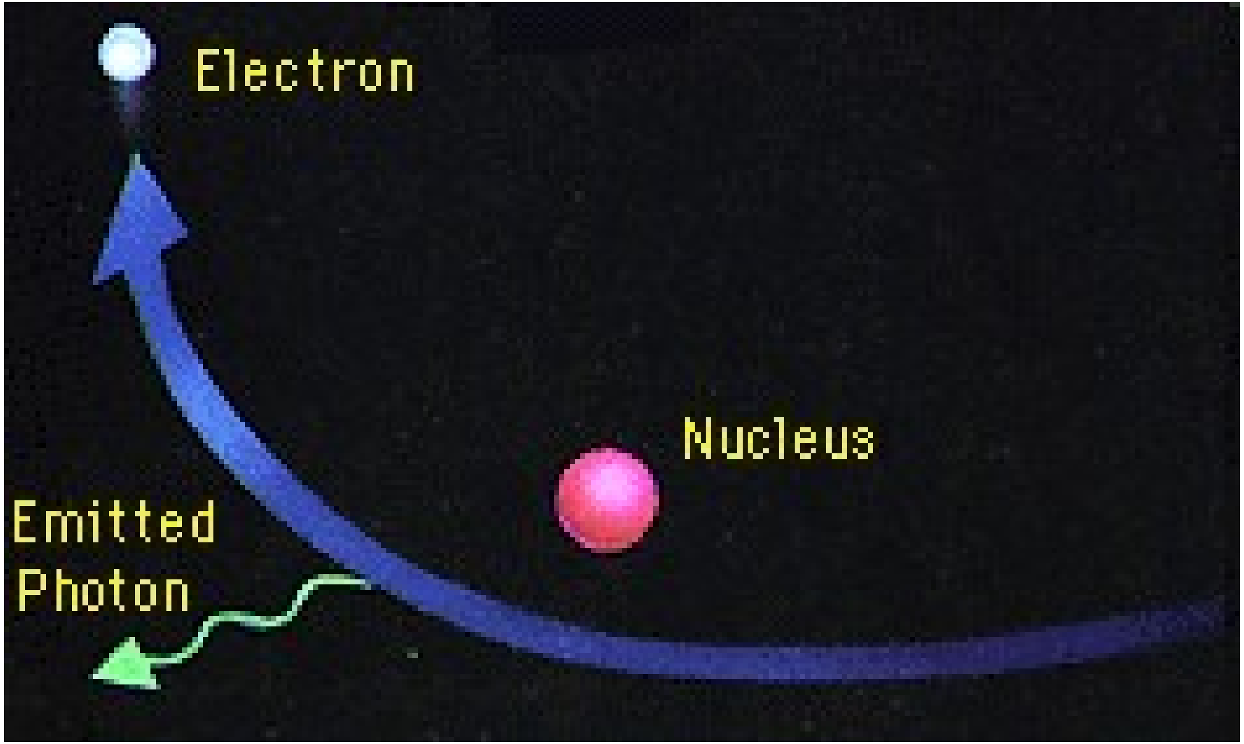
$$\mathrm{H} + h\nu \longleftrightarrow p + e$$



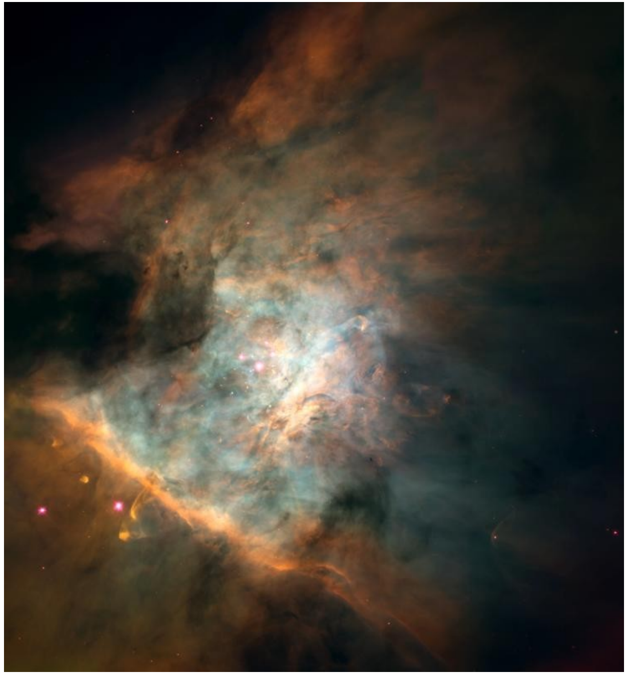
H II Region optical spectrum. S. Temporin & R. Weinberger, A&A 420, 225 (2004), Copyright ESO.

Radio Emission

- H II regions also emit strong radio continuum emission
- Occurs when free electrons are accelerated by ions
- This is called thermal bremsstrahlung
- Strong at cm wavelengths

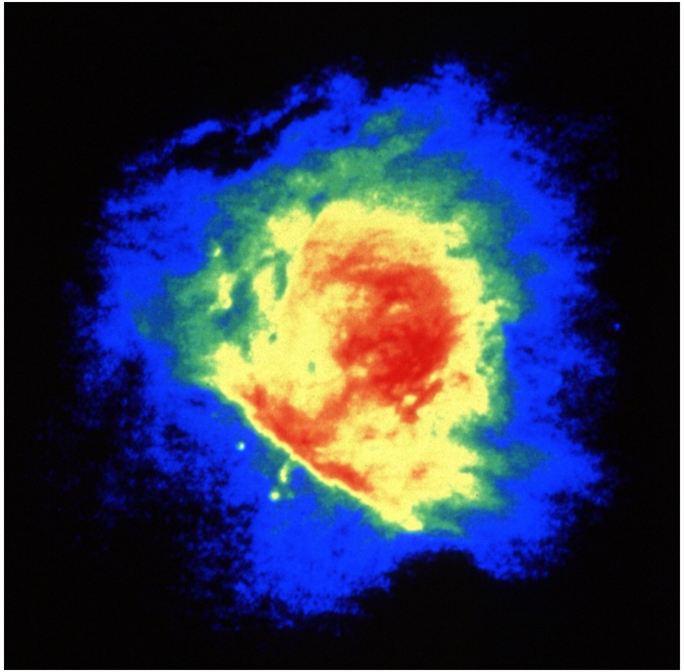


Bremsstrahlung mechansim. NASA [Goddard Space Flight Center](#).



HST (Optical)

Credit: NASA and C.R. O'Dell
(Vanderbilt University):

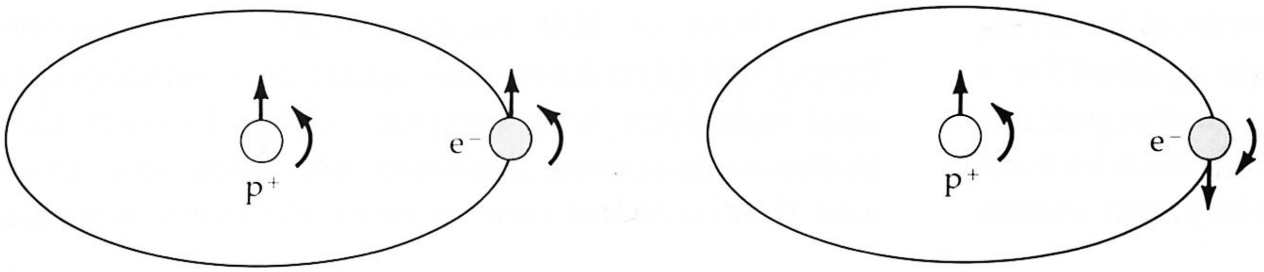


VLA Radio

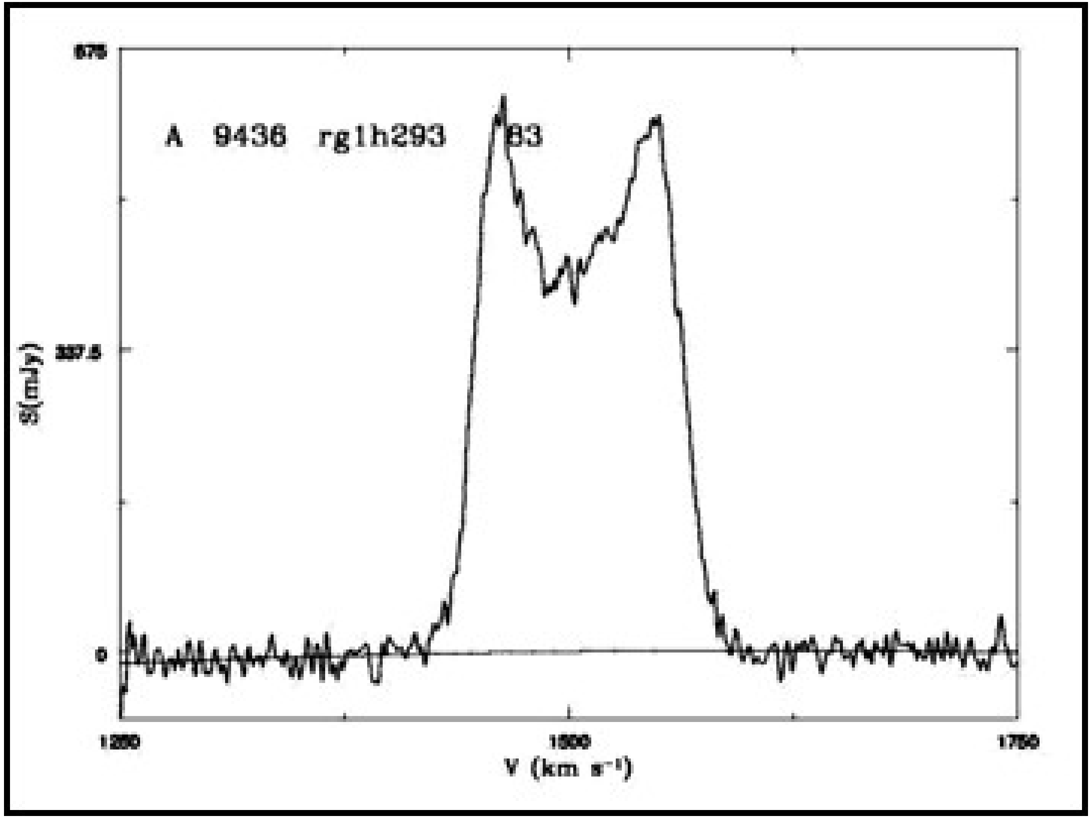
Image courtesy
of NRAO/AUI

Atomic Gas

- Most of the mass of interstellar gas is in atomic form or H I
- Typical densities of 10^6 m^{-3}
- It is cool (T~100 K) and in the ground state
- Can only emit via a hyperfine transition that occurs at a wavelength of 21 cm in the radio part of the spectrum



21 cm Hyperfine transition in atomic hydrogen. Zeilik Fig 15-12



Example H I line profile for a galaxy

alfalfasurvey.wordpress.com/2009/01/

Shell of H I emission in our Galaxy

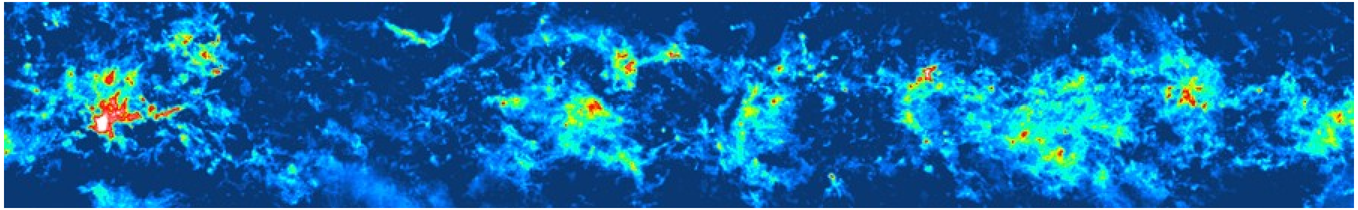
Image courtesy of NRAO/AUI and Jayanne English (U. Manitoba) & Jeroen Stil, supported by Russ Taylor (U. Calgary)

Molecular Gas

- In dense (10^{10} m^{-3}), cold ($T<30$ K) regions molecules form from the atomic phase
- Molecular hydrogen (H_2) does not normally emit
- Other trace molecules have to be observed instead, principally carbon monoxide (CO)

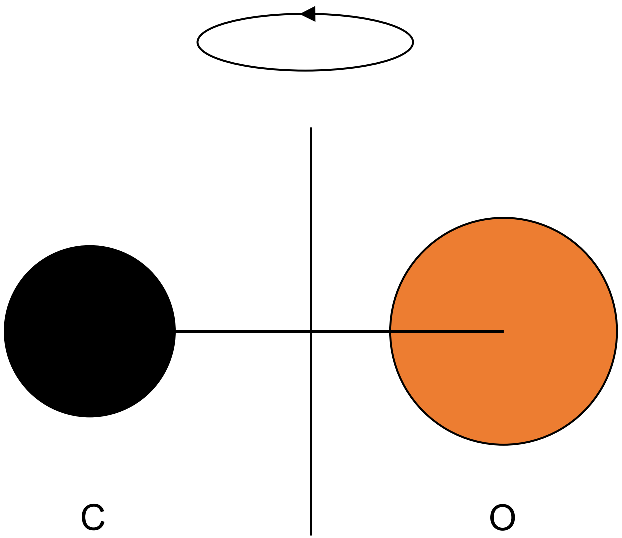
CO Observations

- The CO molecule emits due to rotational transitions excited by collisions
- The ground state transition is at λ ~ 3 mm
- Many other molecules are observed
- These and H_2 are destroyed (dissociated) by ultra-violet radiation (λ~120 nm)



^{13}CO survey of the Milky Way

Boston University-FCRAO Galactic Ring Survey (GRS) /www.bu.edu/galacticring



Rotational transition of the CO molecule.

Supernova Remnants

- The exploding material is initially ejected at mildly relativistic speeds
- Shocks to very high temperatures ~10^6 K which emits at X-ray wavelengths
- They continue to expand for ~ million years before reaching equilibrium and hence fill a large volume of the galaxy with a tenuous hot phase of the ISM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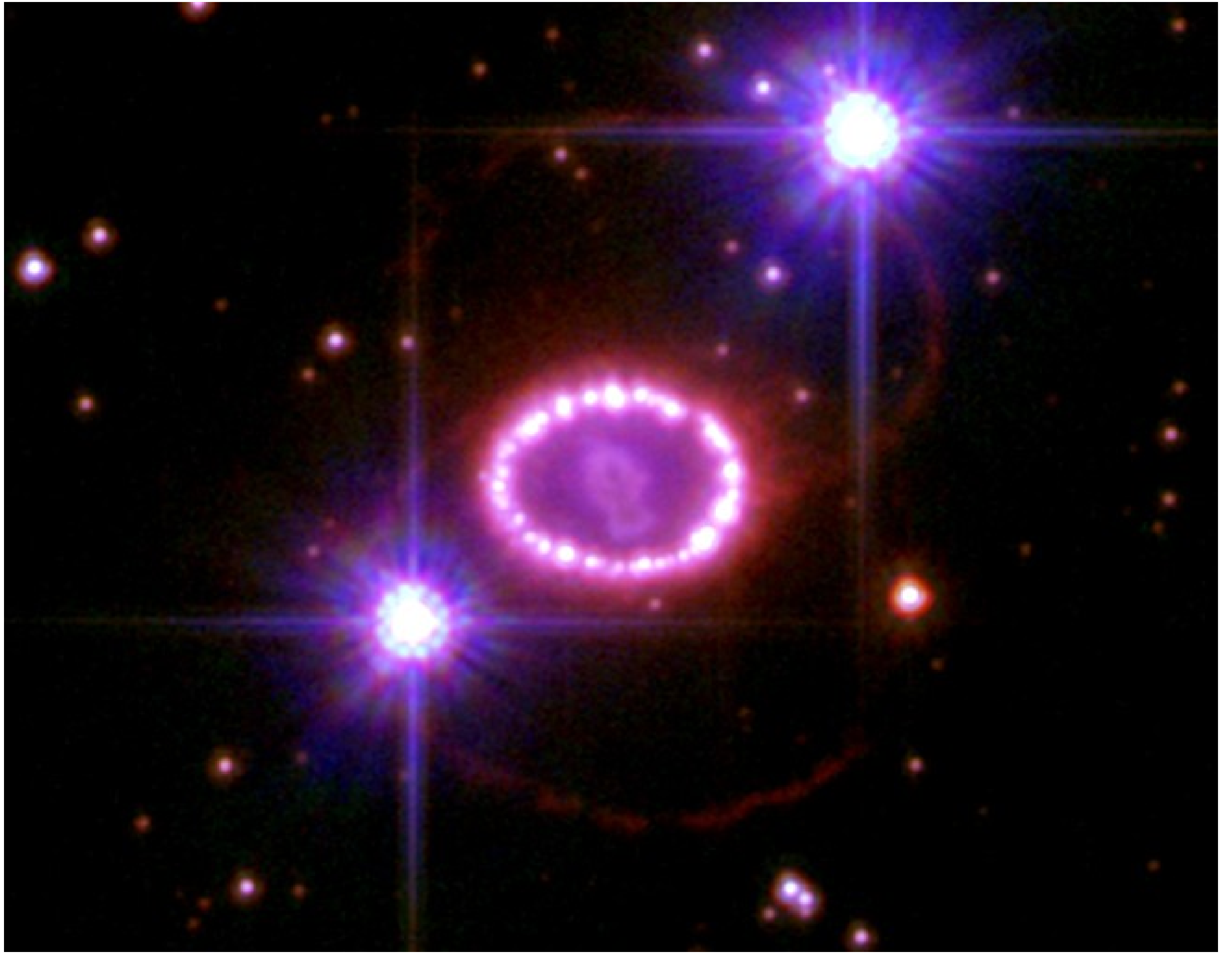
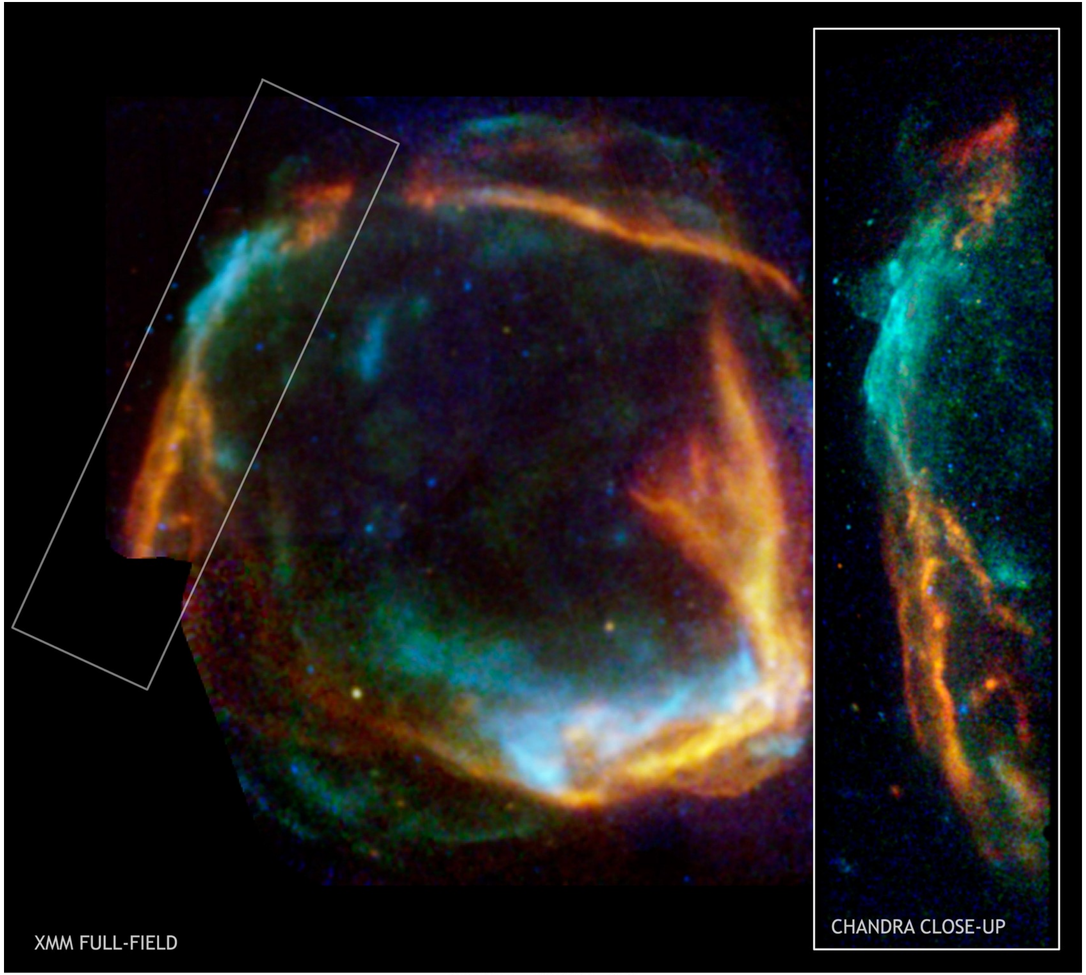


NASA HST image of SN 1987A

NASA HST movie of SN 1987A

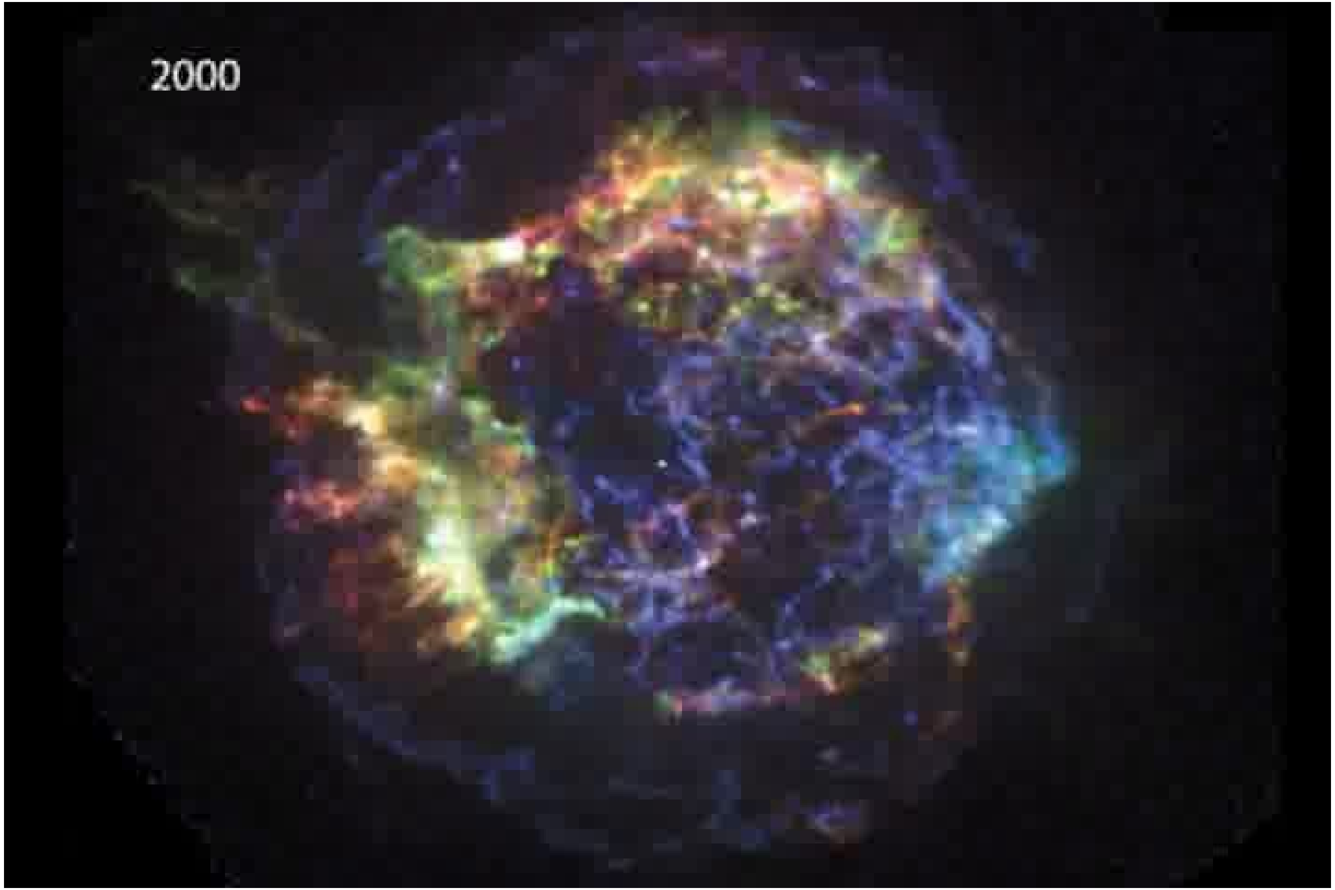


Oldest-recorded supernova unveiled by XMM-Newton and Chandra

Image courtesy of Jacco Vink (SRON Utrecht)

European Space Agency

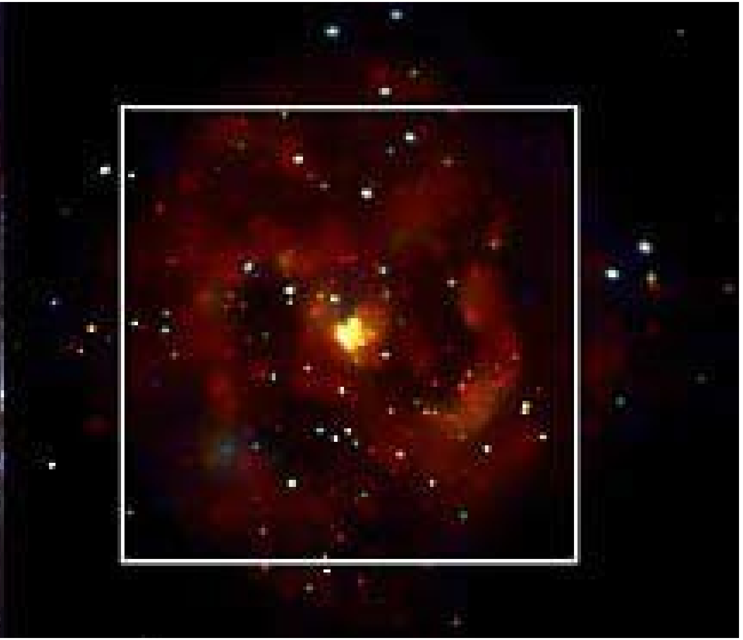
Credit: Chandra: NASA/CXC/Univ. of Utrecht/J.Vink et al. XMM-Newton: ESA/Univ. of Utrecht/J.Vink et al.



Cas A SNR Movie

Credit: NASA/CXC/SAO/D.Patnaude et al.

Optical from ESO

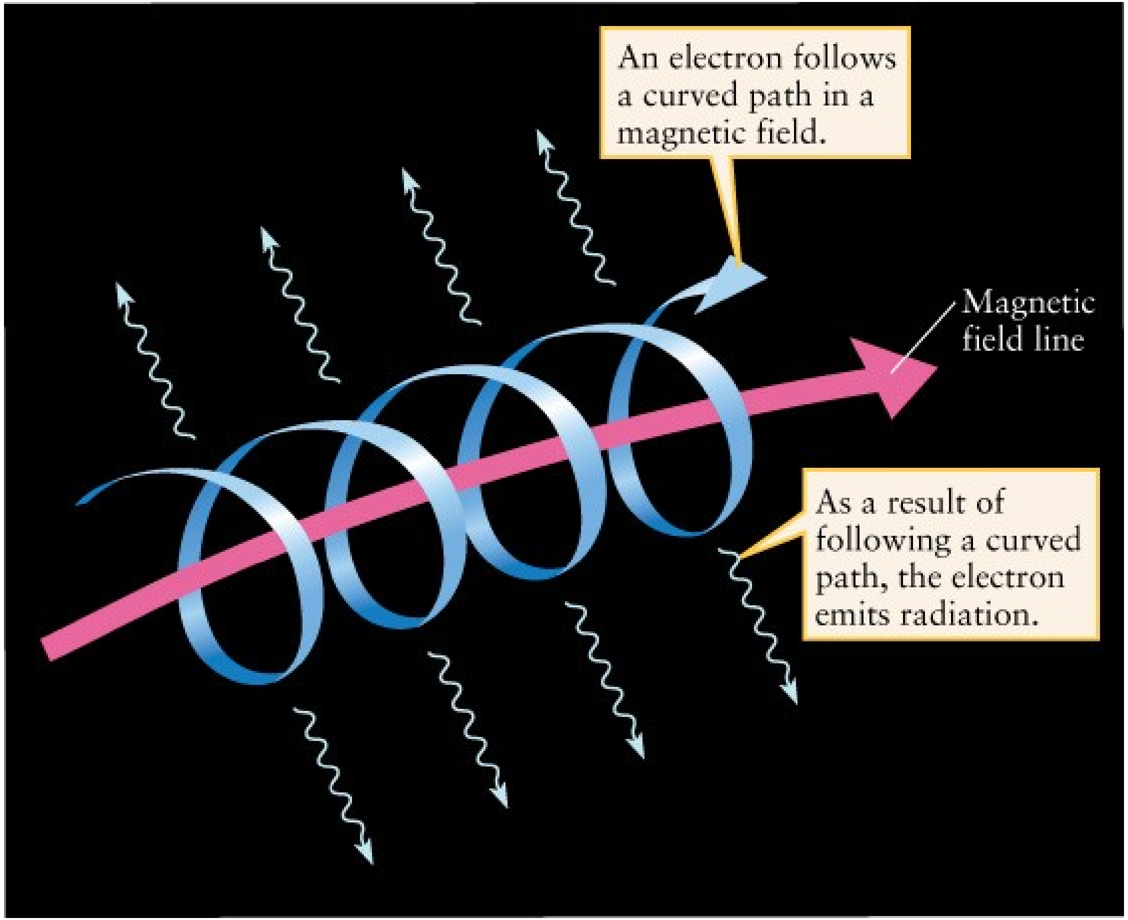


X-rays from NASA Chandra Satellite

Spiral galaxy M83 showing diffuse X-ray emission along the spiral arms from hot phase of the ISM

Radio Emission

- Supernovae also emit strongly at radio wavelengths
- The combination of fast moving electrons and magnetic fields gives rise to synchrotron radiation
- The electrons spiral around the magnetic field


An electron follows a curved path in a magnetic field.
Magnetic field line
As a result of following a curved path, the electron emits radiation.

SN1006

X-ray: (blue)

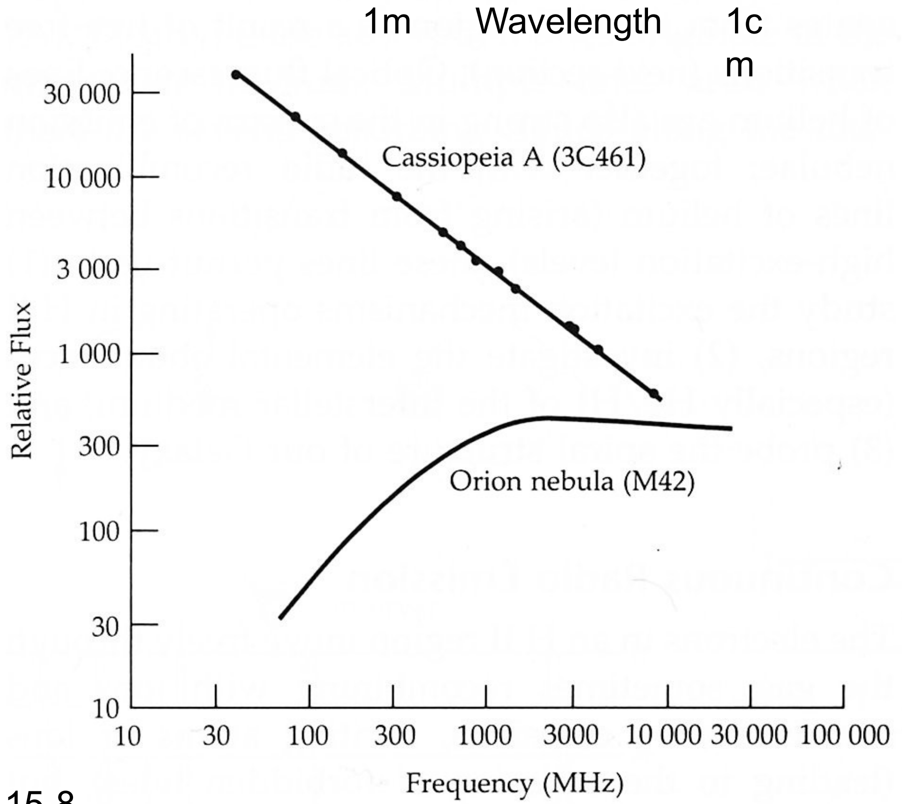
Radio: (red);

Optical:(yellow)

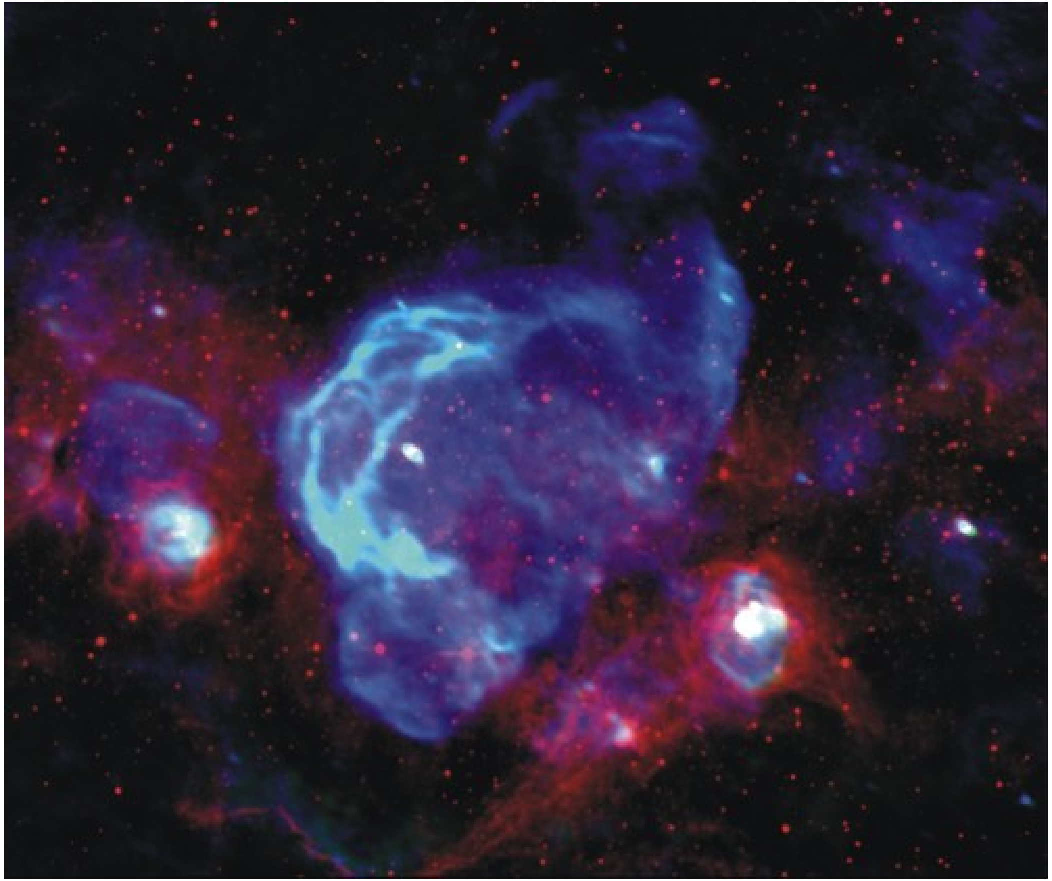
Credit: X-ray: (blue) NASA/CXC/Rutgers/G.Cassam-Chenaï, J.Hughes et al.; Radio: (red) NRAO/AUI/NSF/GBT/VLA/Dyer, Maddalena & Cornwell; Optical: (yellow) Middlebury College/F.Winkler, NOAO/AURA/NSF/CTIO Schmidt & DSS

- The synchrotron radiation is strongest at long radio wavelengths ($\lambda \sim$ 1 m)
- Also referred to as non-thermal radio emission to distinguish it from thermal bremsstrahlung

- Note the different slopes of the radio spectra for thermal sources like the H II region M42 and non-thermal sources like the SNR Cas A



Zeilik Fig 15-8



W28 region with SNRs and H II regions

Blue: radio 90 cm; Red mid-infrared 8 microns

Image courtesy of NRAO/AUI and Brogan et al.

Summary

- H II regions arise where massive stars form and are observed mainly in Hα and cm-wave radio continuum
- H I is observed using the 21 cm line and makes up most of the mass of the ISM
- H_2 is traced using mm lines from molecules such as CO and is the material from which stars form

- Supernova remnants are one of the main sources of energy input into the interstellar medium
- They can be observed at X-ray and long wavelength (m) radio wavebands
- They are responsible for the hot phase of the interstellar medium