

Interstellar Medium (ISM)

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

Interstellar Medium

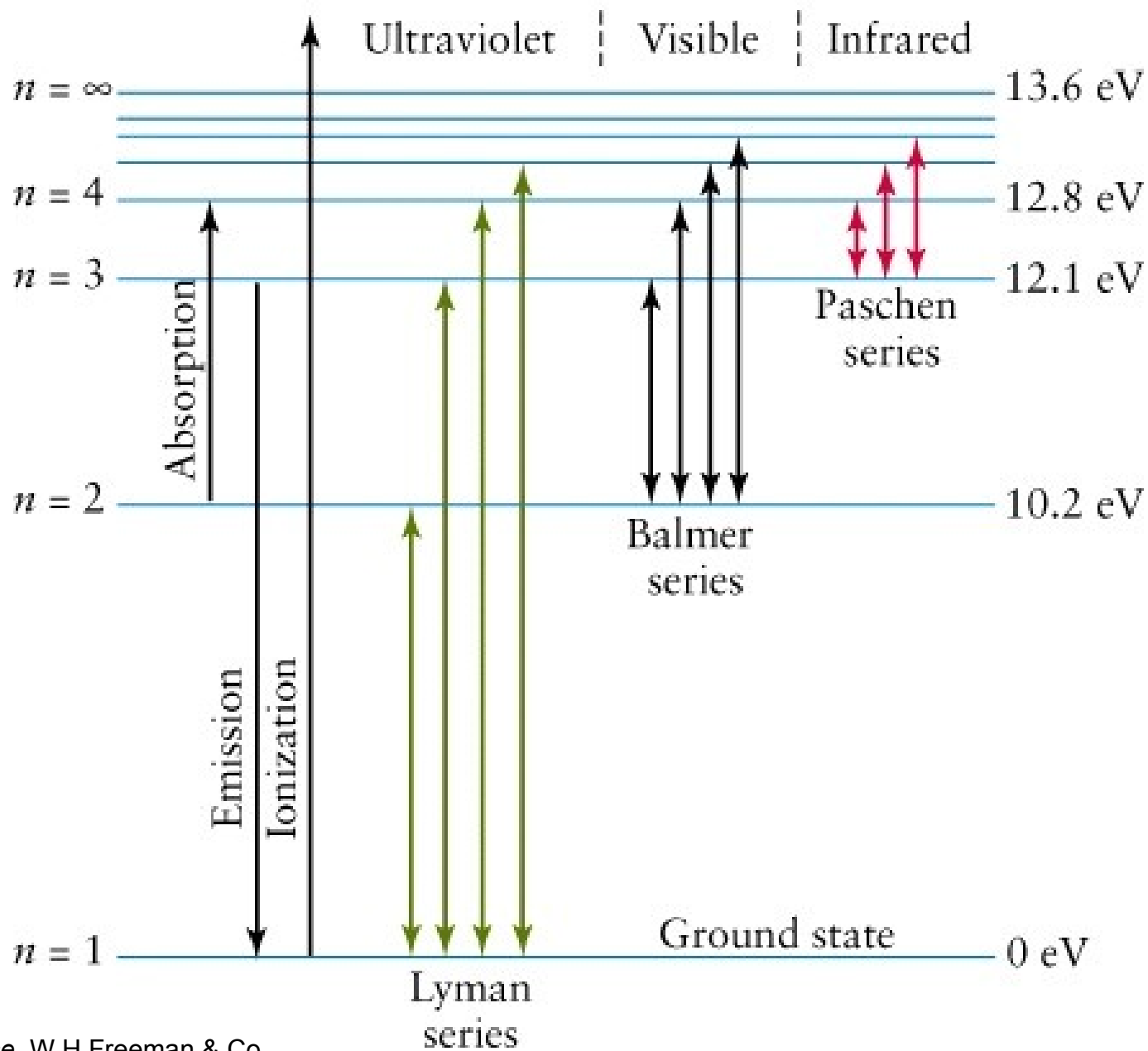
- The space between stars in spiral and irregular galaxies is not empty but contains gas and dust at very low density
- A typical average number density is about 10^6 m^{-3} or 1 particle per cubic centimetre !
- However, the interstellar gas exists in a vast range of temperatures and densities



Gemini Observatory

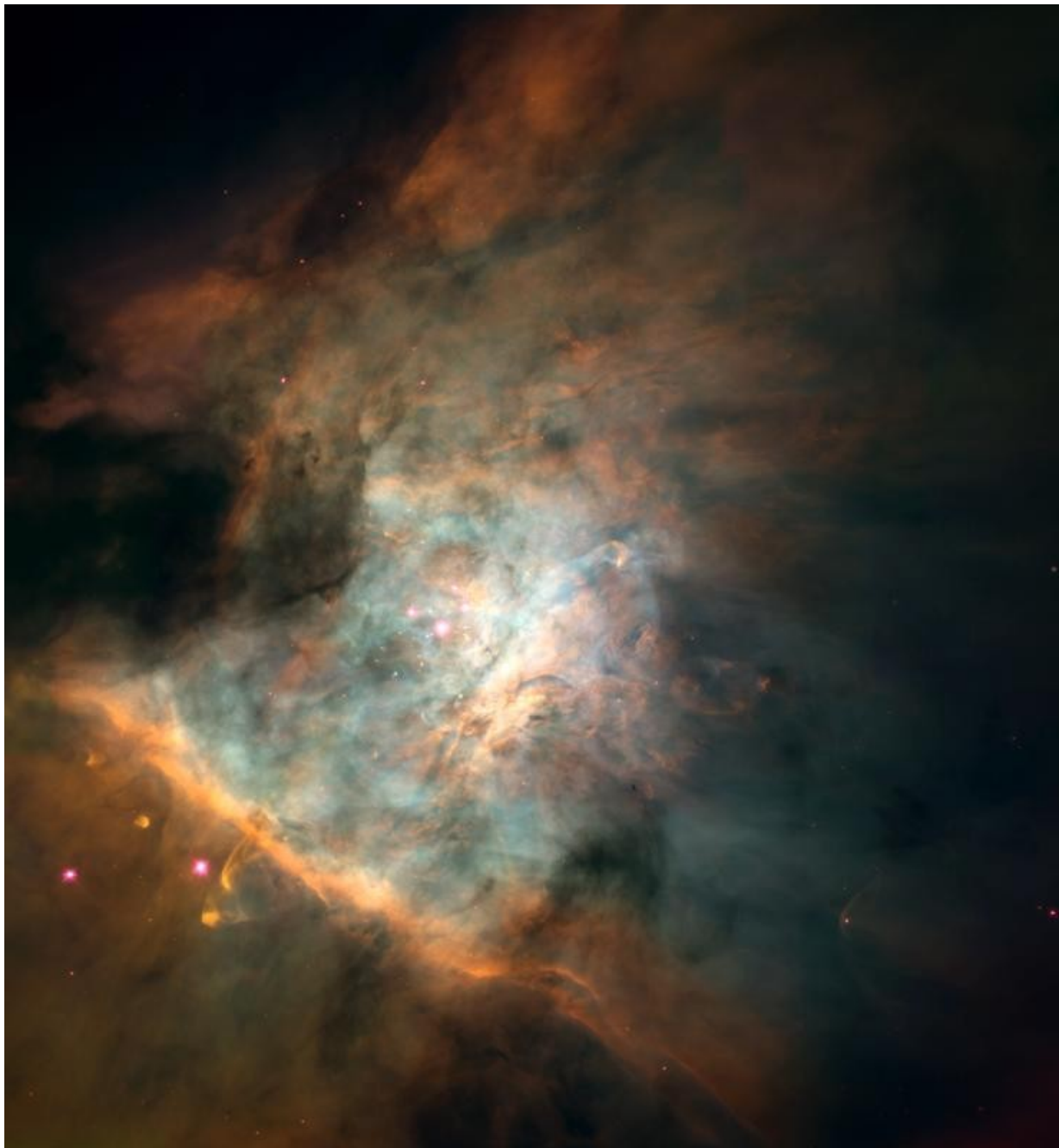
Ionized Gas

- 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)



H II Regions

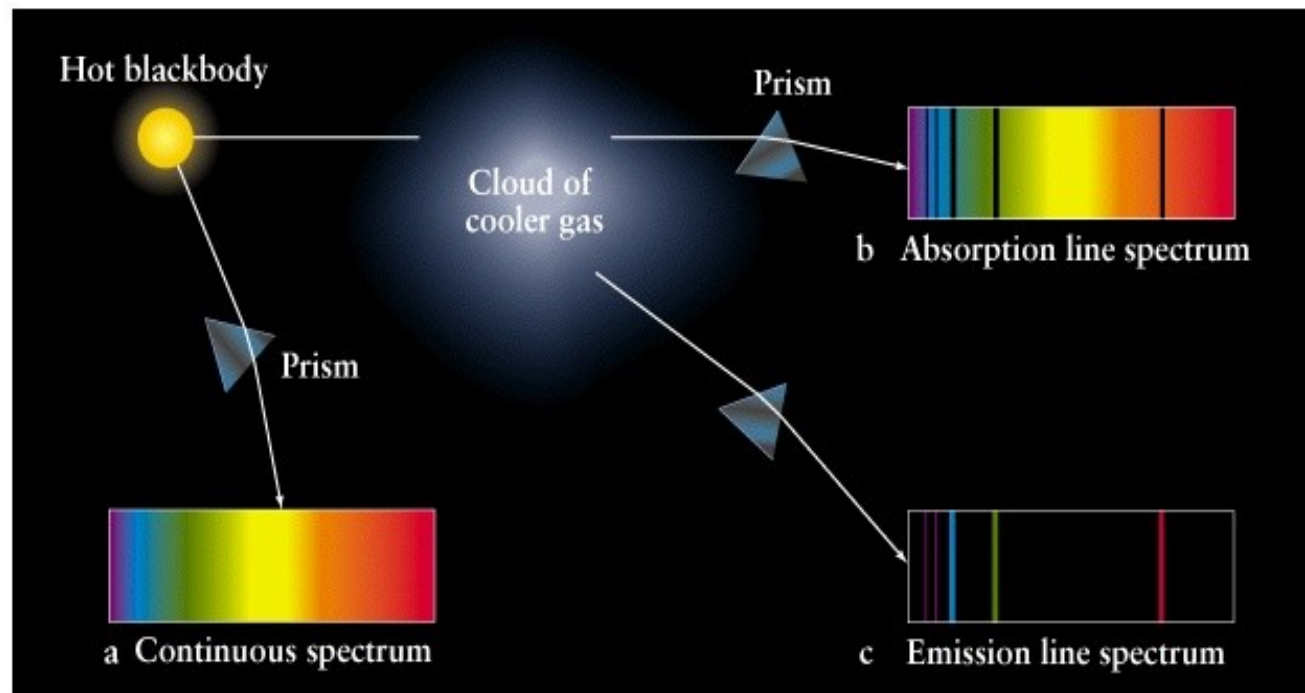
- Massive main sequence stars have $T > 30\,000\text{ K}$
- Young stars are also still surrounded by dense (10^{10} m^{-3}) gas
 - gives rise to ionized nebulae called H II regions
- The gas is hot $T \sim 10\,000\text{ K}$ and fluoresces



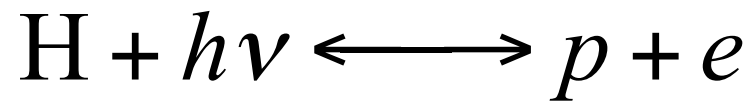
Credit: [NASA](#) and C.R. O'Dell (Vanderbilt University): HST (Optical)

Emission Line Spectrum

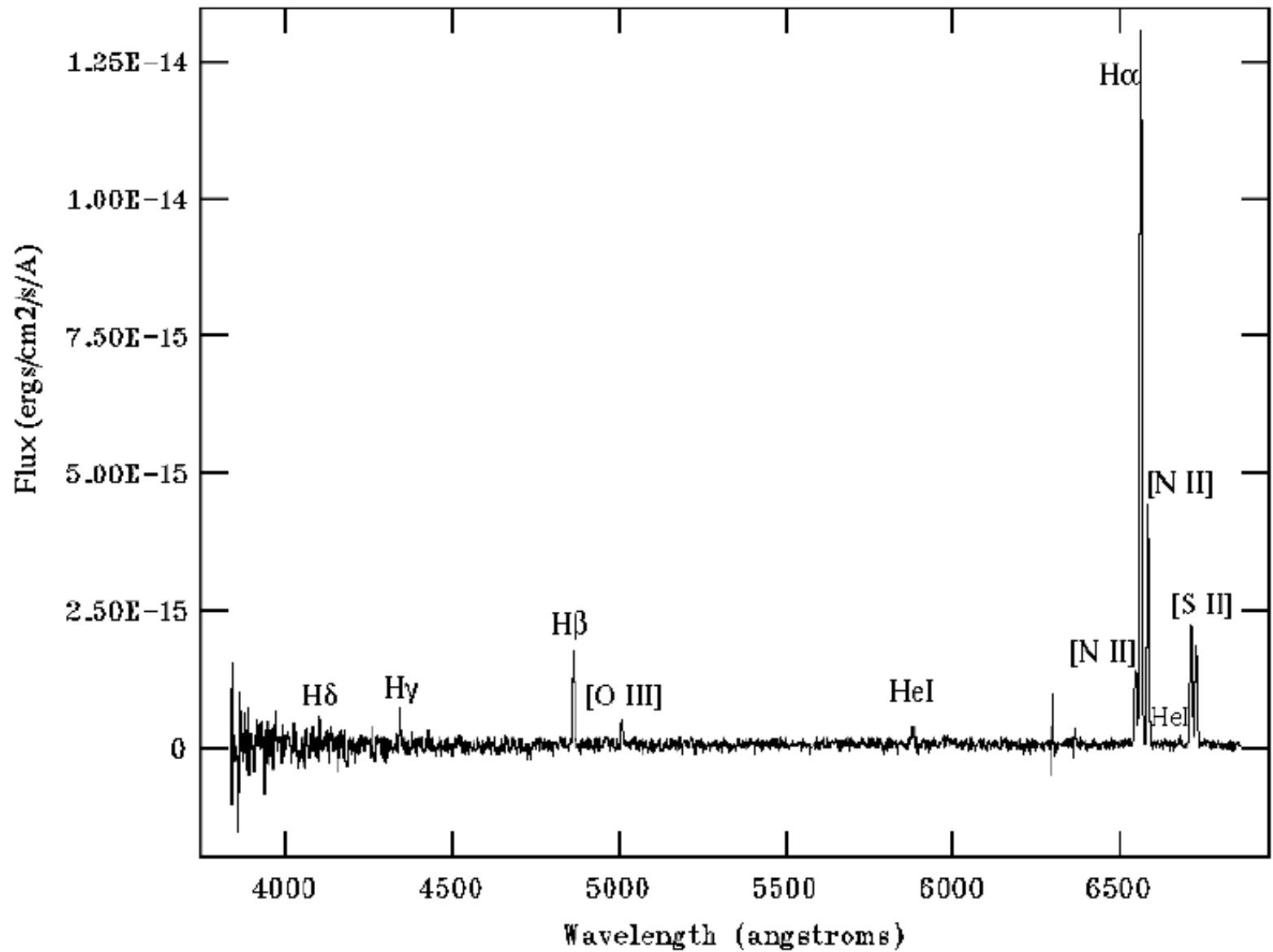
- Arises when hot gas is viewed against a colder background



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



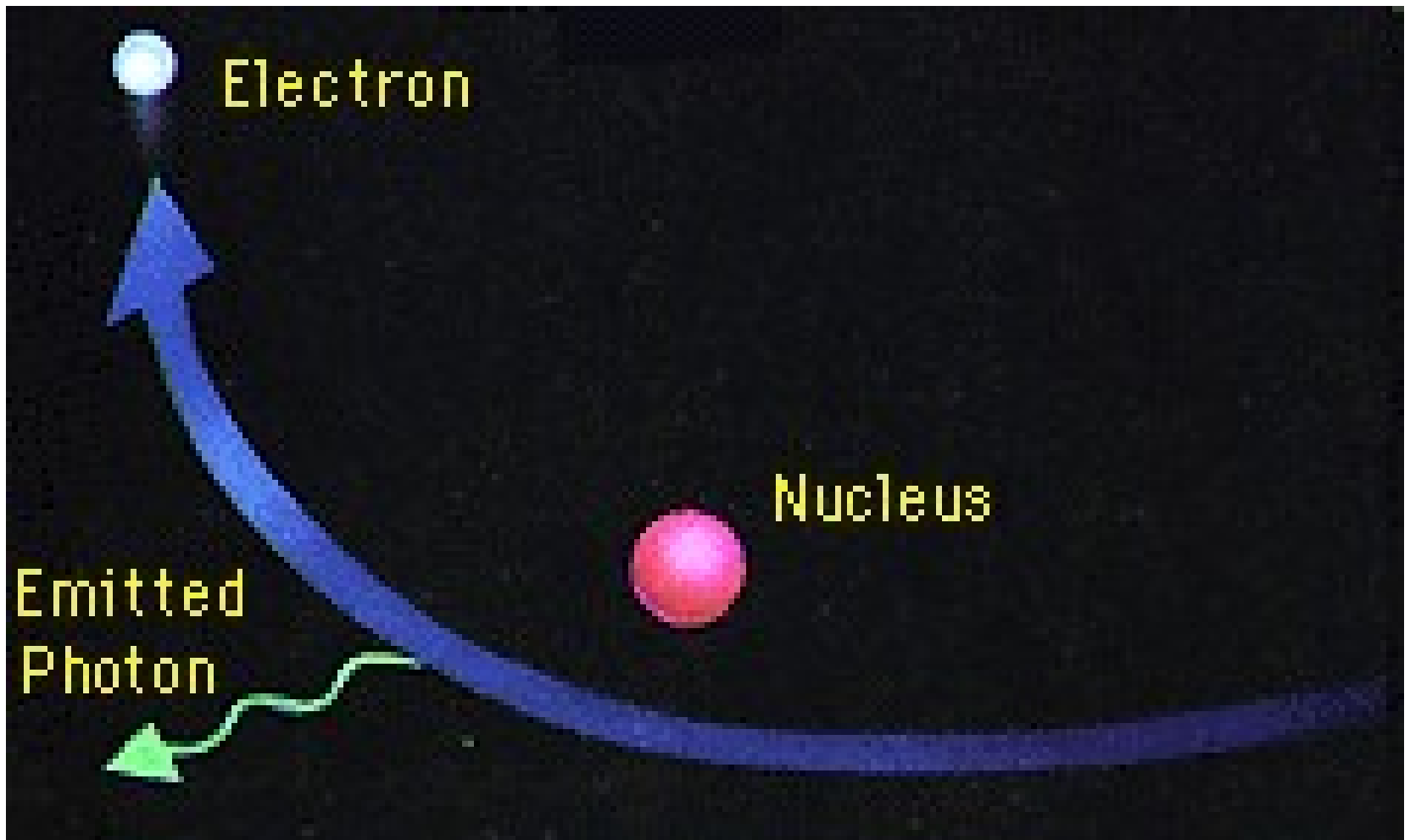
- The strongest is the H α line



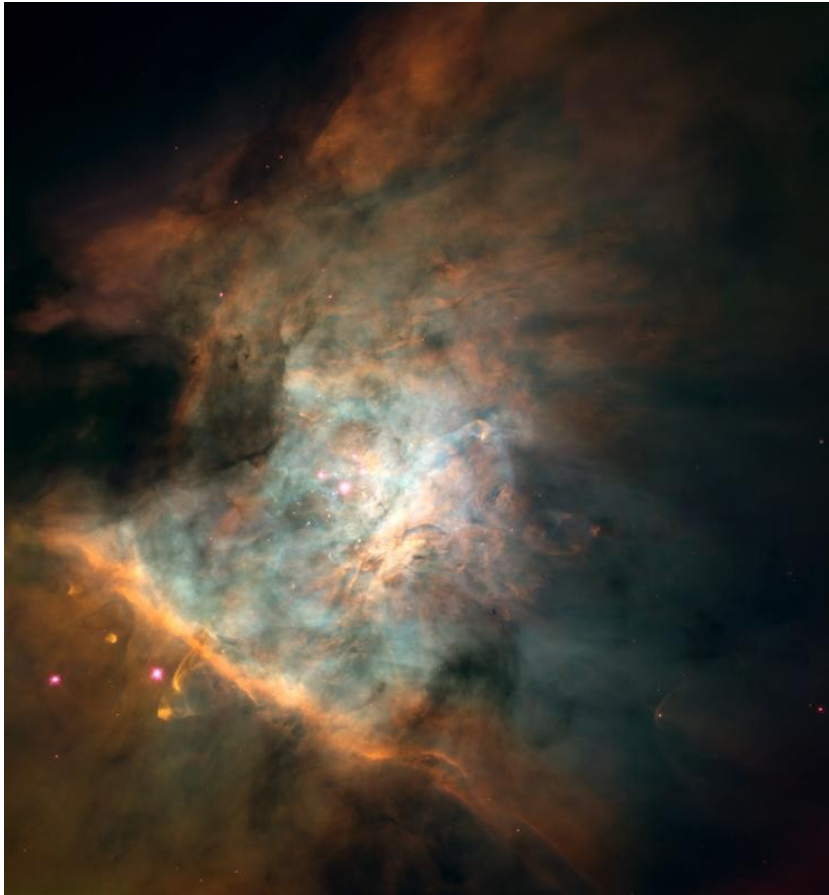
H II Region optical spectrum. S. Temporin & R. Weinberger, A&A 420, 225 (2004), Copyright ESO.

Radio Emission

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

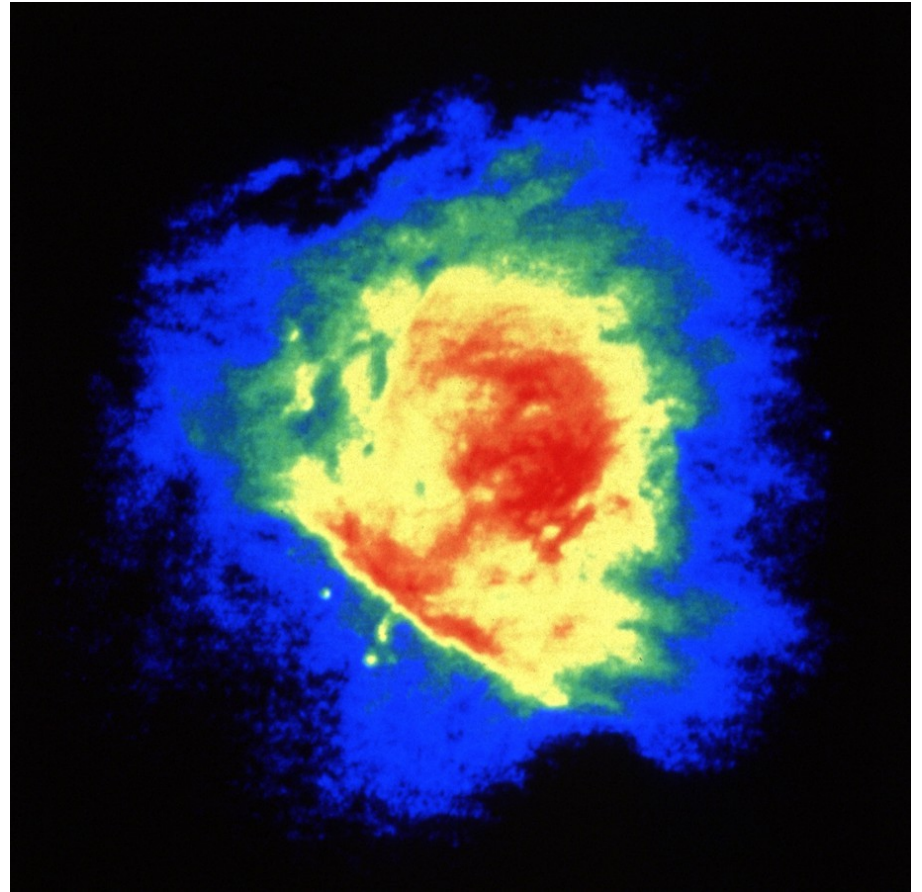


Bremsstrahlung mechanism. NASA [Goddard Space Flight Center](#).



HST (Optical)

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

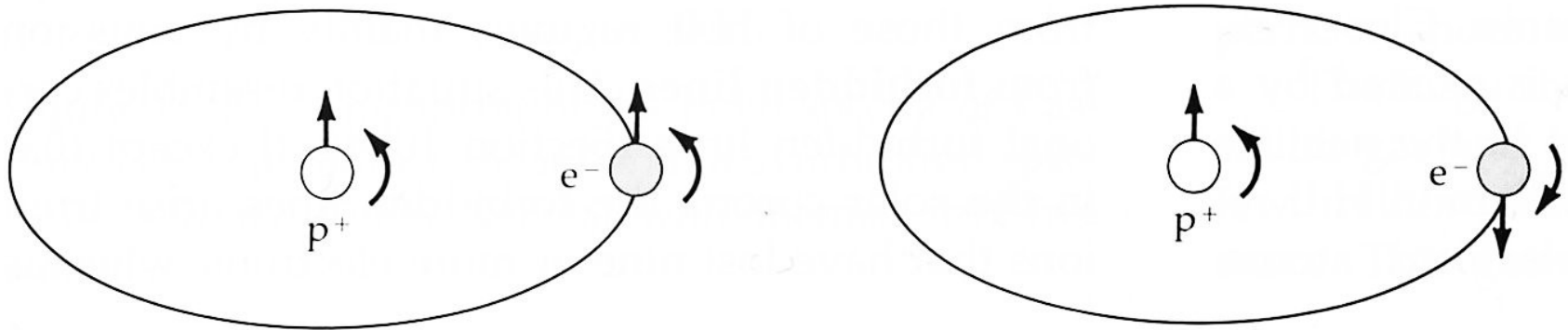


VLA Radio

Image courtesy
of NRAO/AUI

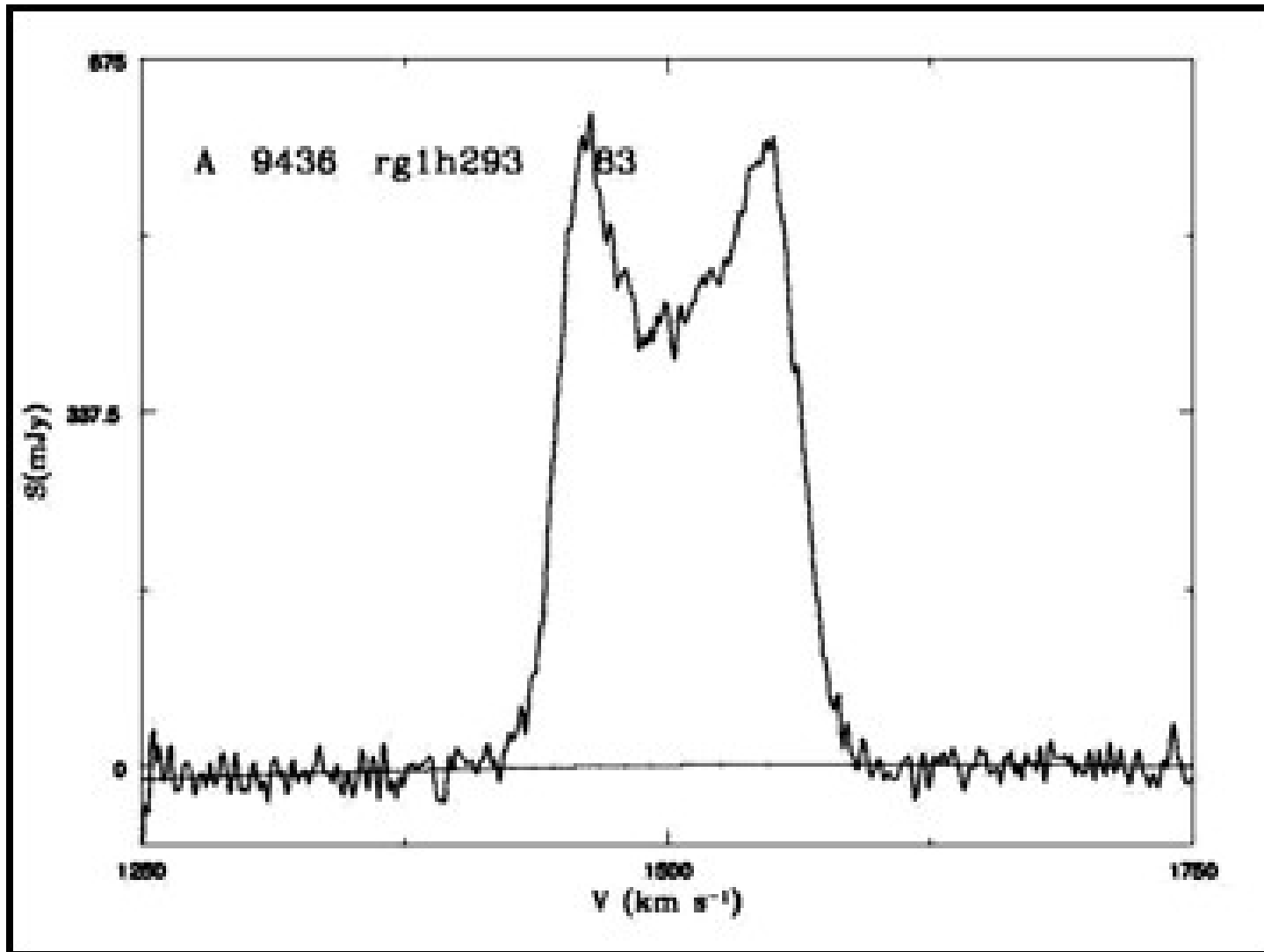
Atomic Gas

- Most of the mass of interstellar gas is in atomic form or H I
- Typical densities of 10^6 m^{-3}
- It is cool ($T \sim 100 \text{ K}$) 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

An excited atom takes ~10 million years to emit a radio photon !
(fortunately many atoms available)



Example H I line profile for a galaxy

– width is from the Doppler shift due to the rotation of the galaxy

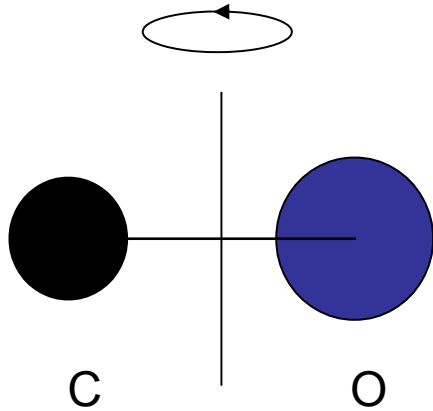


Shell of H I emission in our Galaxy

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

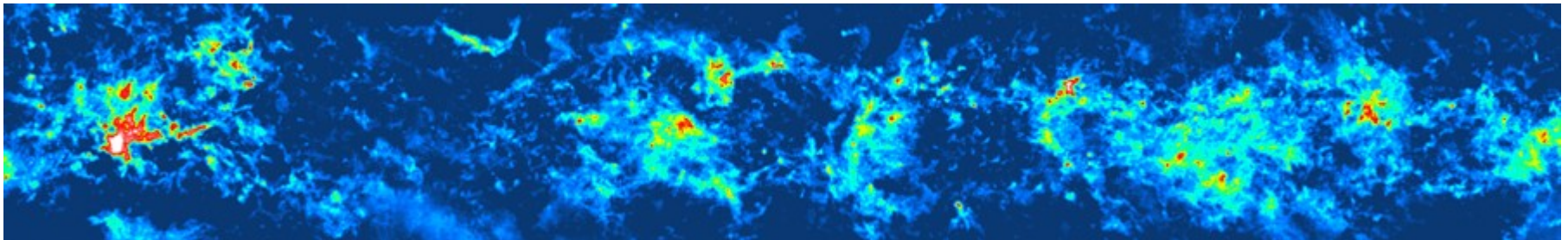
Molecular Gas

- In dense (10^{10} m^{-3}), cold ($T < 30 \text{ K}$) 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)



- The CO molecule emits due to rotational transitions excited by collisions

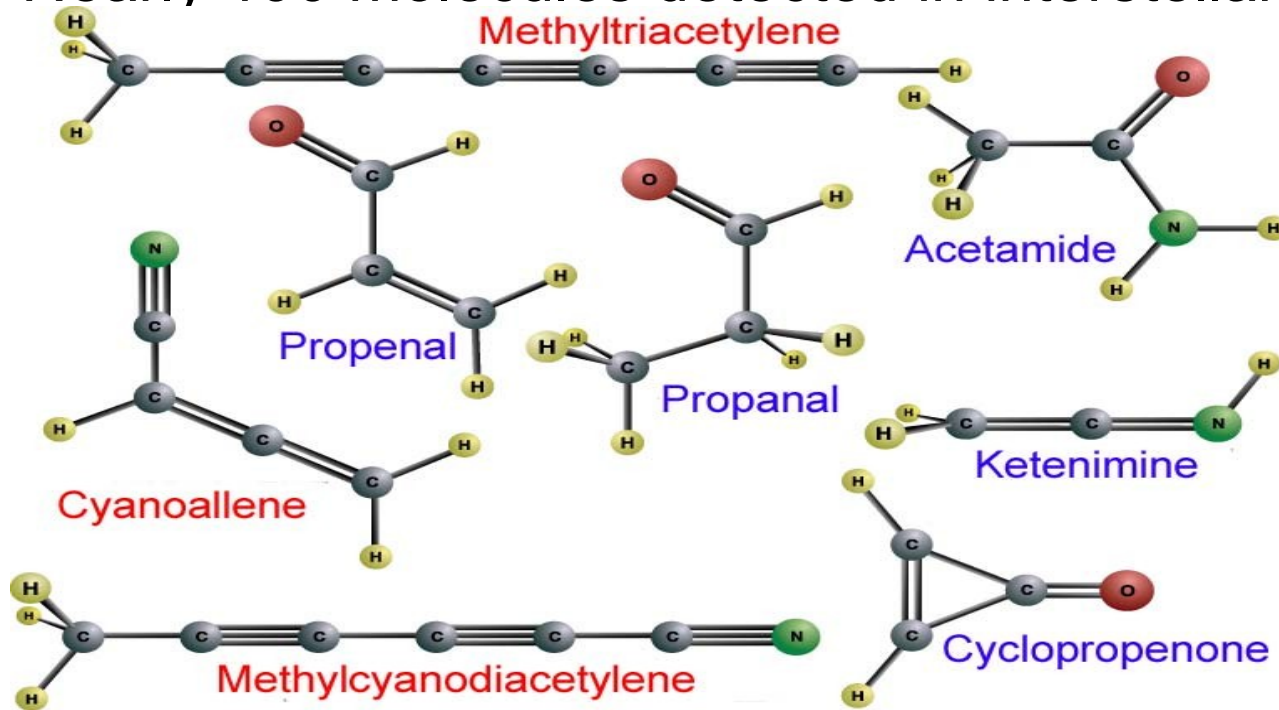
- The ground state transition is at $\lambda \sim 3$ mm
- Many other molecules are observed



^{13}CO survey of the Milky Way

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

Nearly 190 molecules detected in interstellar space.



http://www.space.com/scienceastronomy/060808_st_life_molecules.html

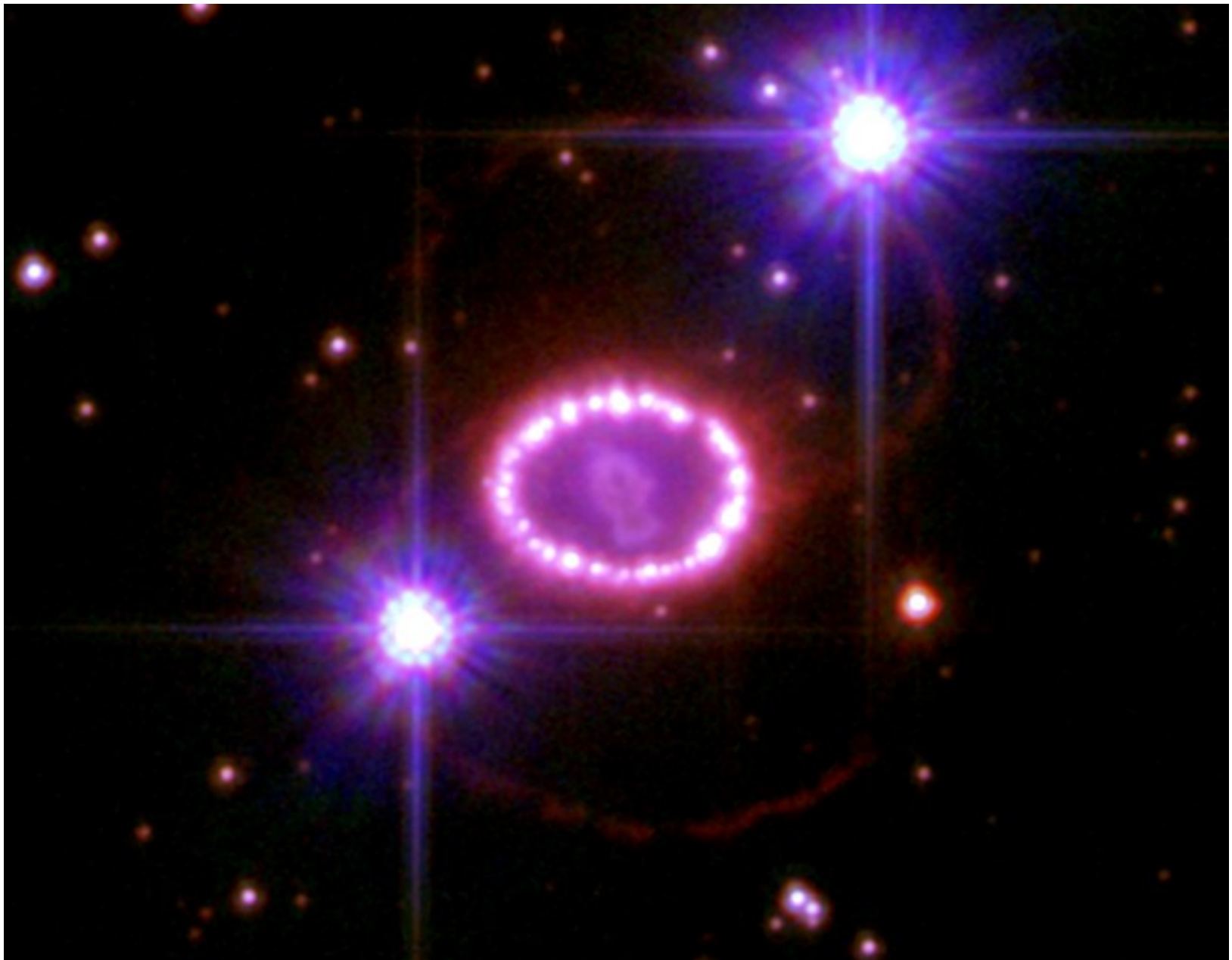
- Many of these are “organic.”
 - Illustrates importance of carbon in chemistry of life.
 - Are there biological molecules not yet detected? (Amino acids?)

Supernova Remnants

- The exploding material is initially ejected at mildly relativistic speeds
- Shocks to very high temperatures $\sim 10^6$ K which emits at X-ray wavelengths
- They continue to expand for \sim 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

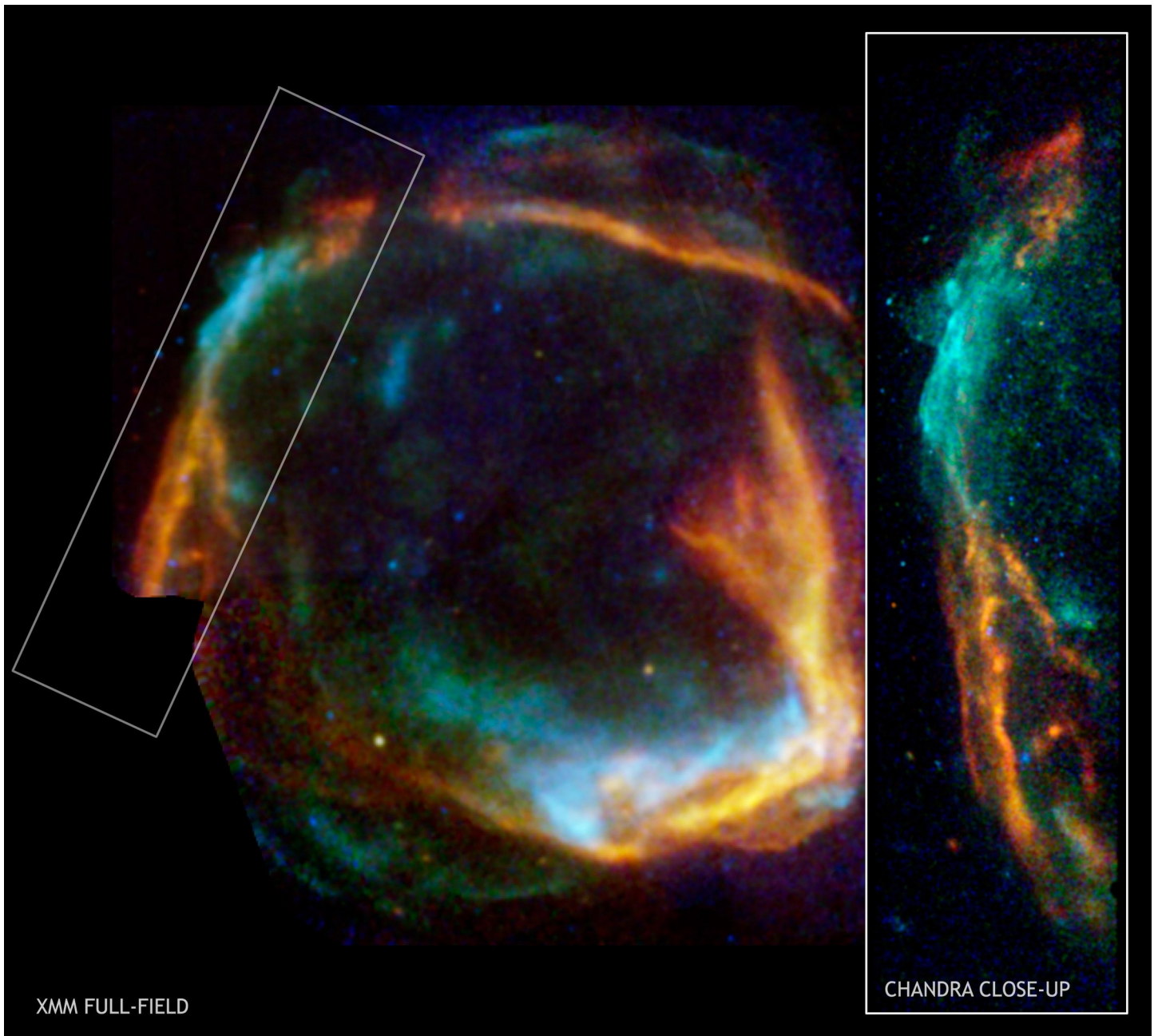
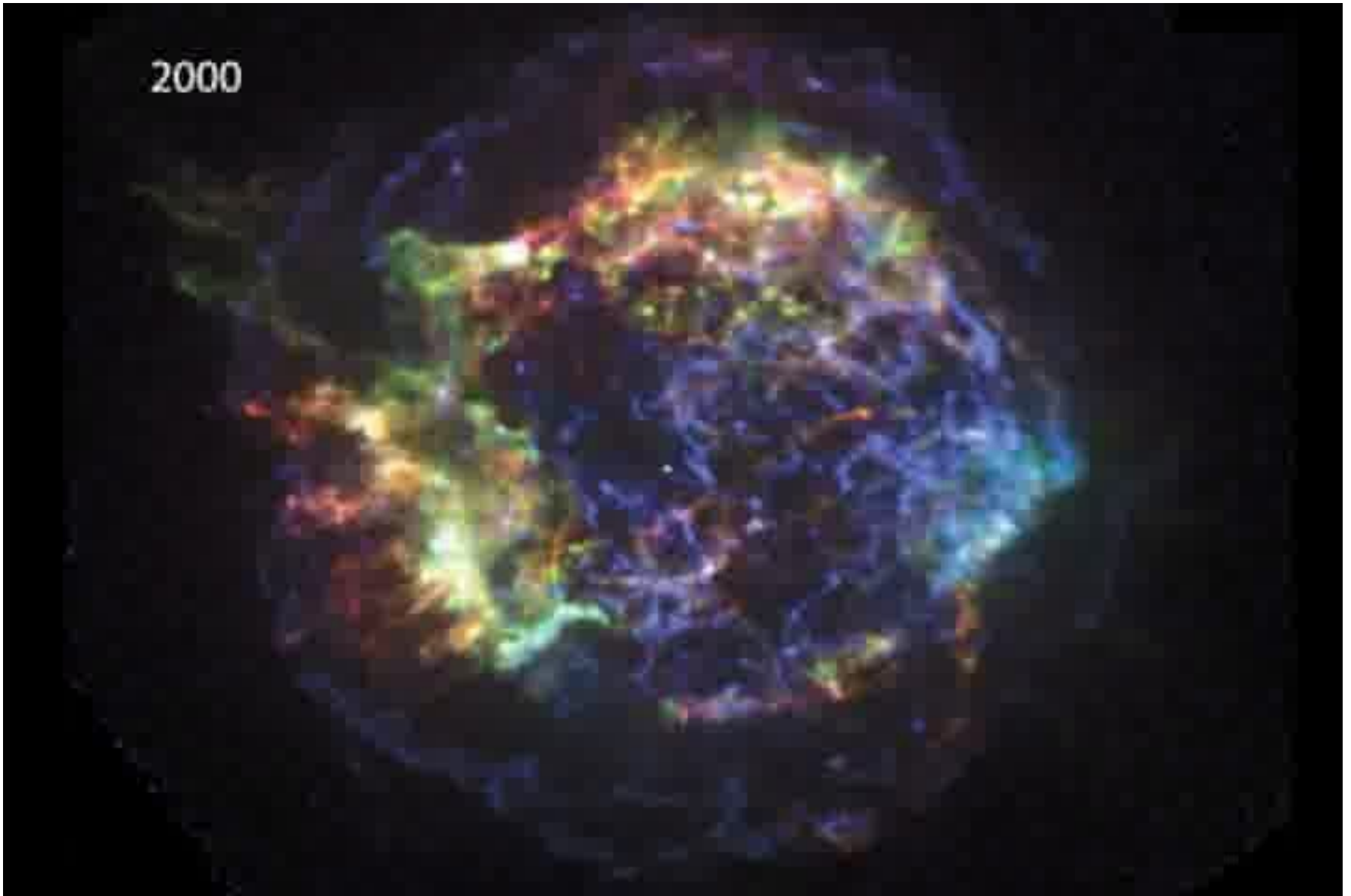


Image courtesy of Jacco Vink (SRON Utrecht)

Oldest-recorded supernova unveiled by XMM-Newton and Chandra

European Space Agency

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

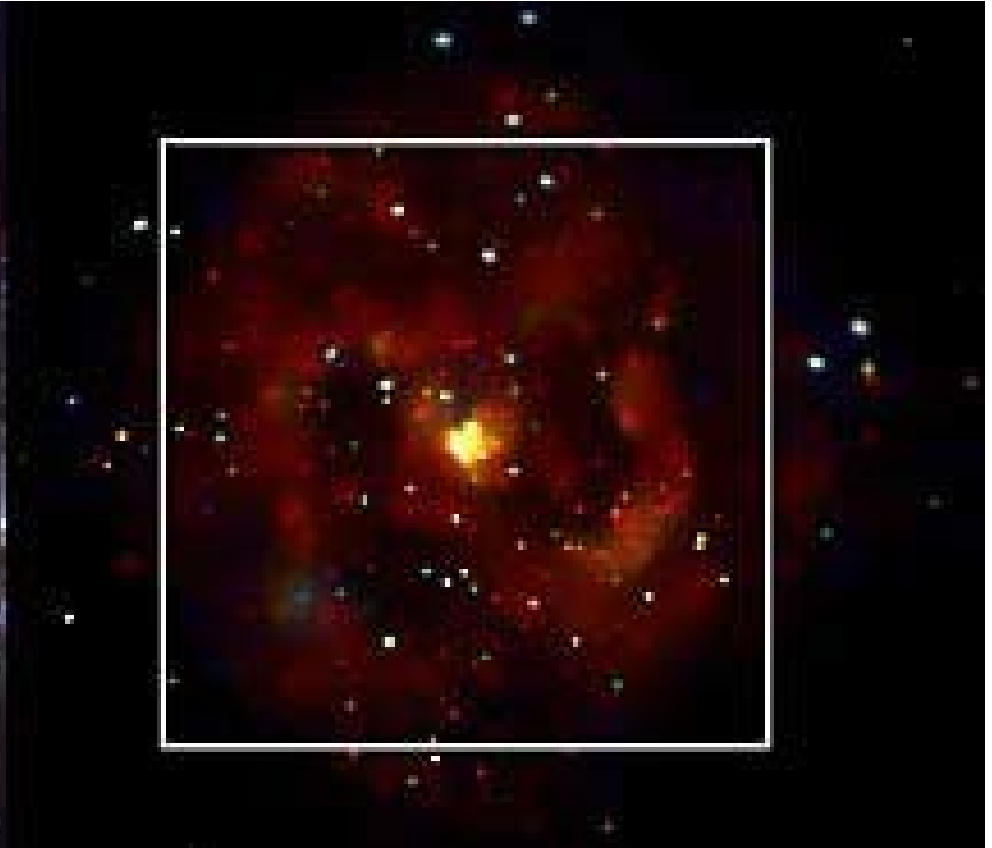


Cas A SNR Movie

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



Optical from ESO

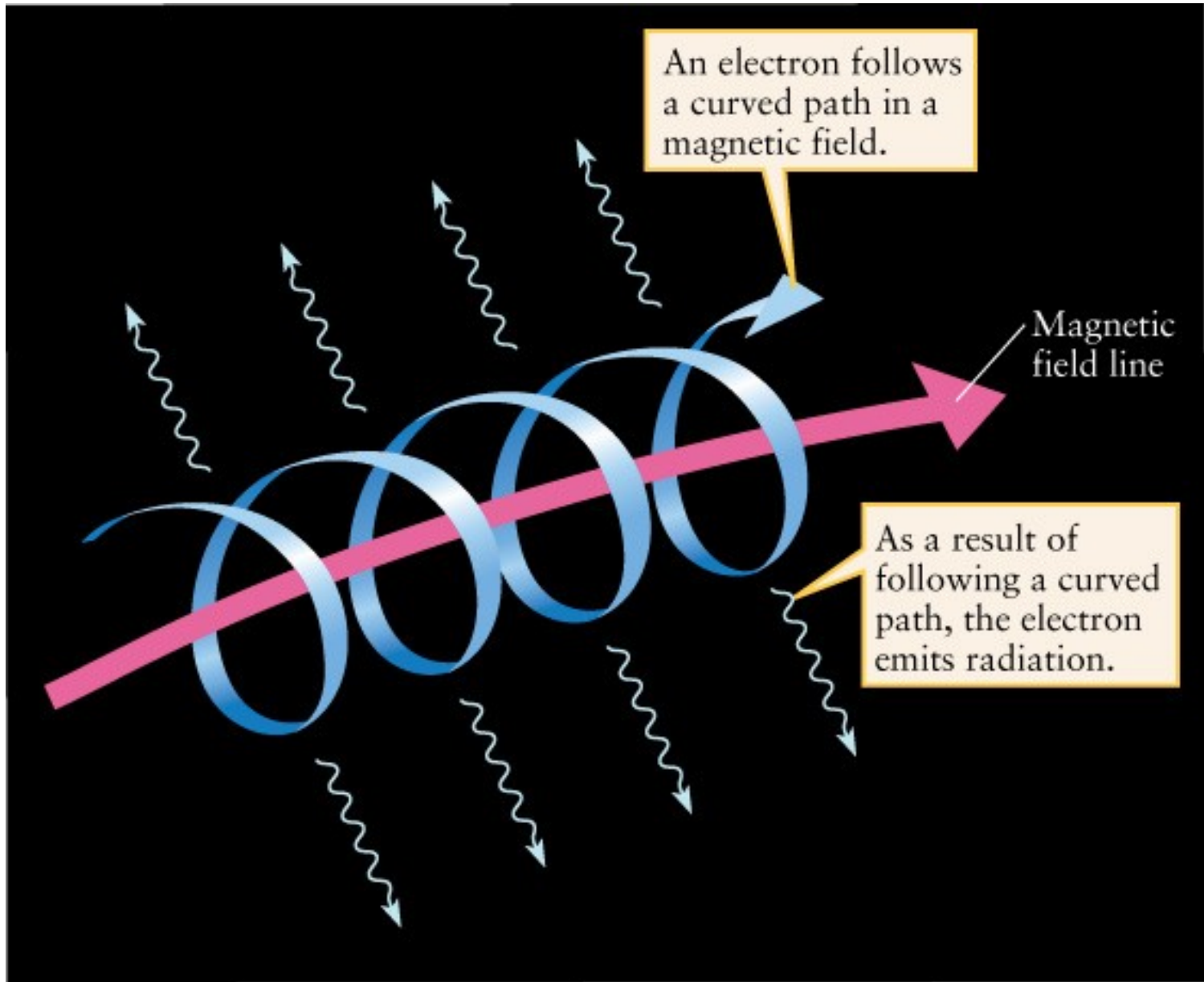


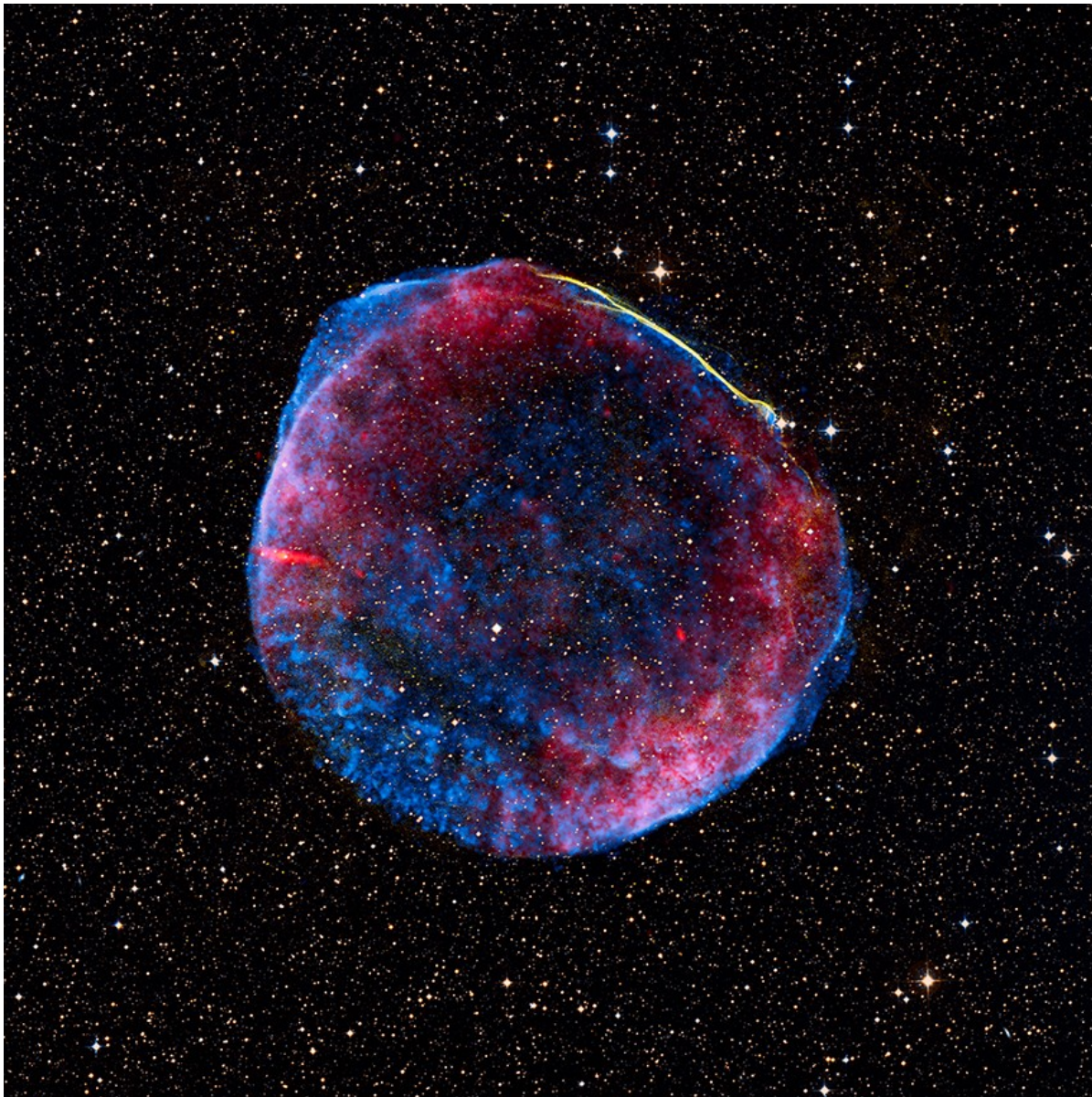
X-rays from NASA Chandra Satellite

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 – and hence are continuously *accelerated*





SN1006

X-ray: (blue)

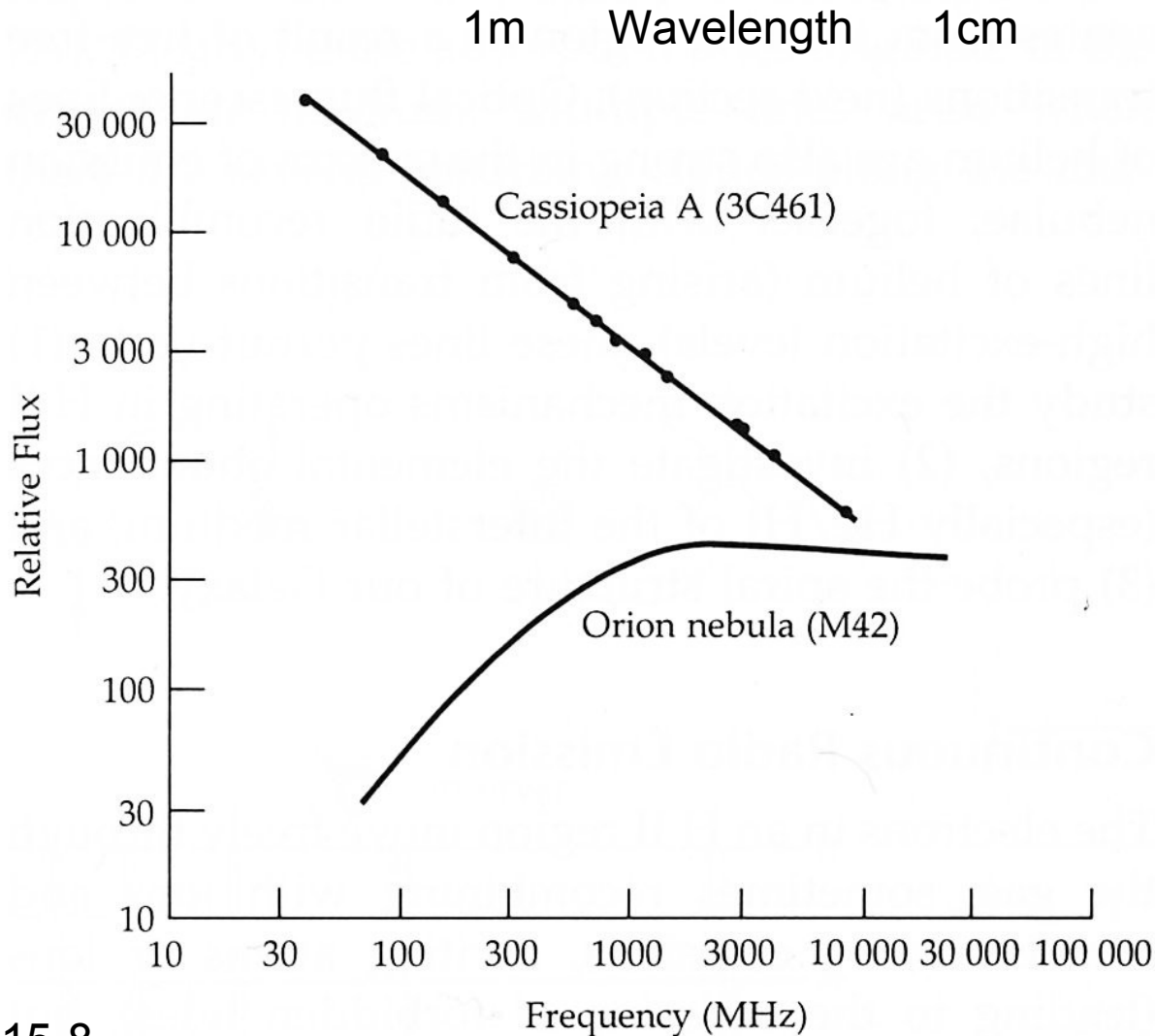
Radio: (red);

Optical:(yellow)

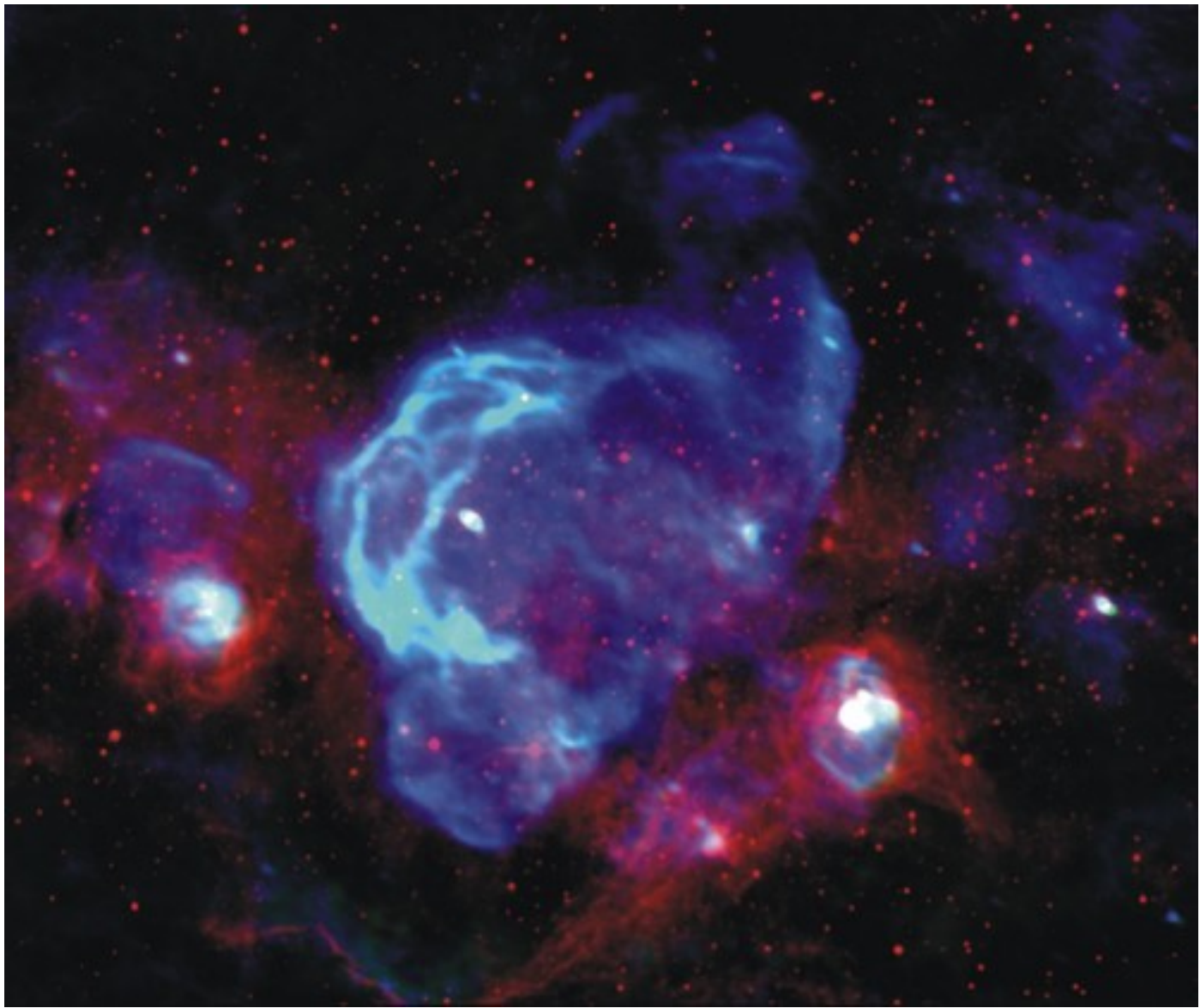
Credit: X-ray: (blue) NASA/CXC/Rutgers/G.Cassam-Chenaï, J.Hughes et al.; Radio: (red) NRAO/AUI/NSF/GBT/VLA/Dyer, Maddalena & Cornwell; Optical: (yellow) Middlebury College/F.Winkler, NOAO/AURA/NSF/CTIO Schmidt & DSS

- 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 (i.e. free-free emission)

- 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.

Interstellar Dust

- Interstellar extinction
- Interstellar reddening
- Dust emission

Interstellar Extinction

- The presence of interstellar dust is inferred from the dark extinction lanes seen in our Galaxy and other galaxies
- Background starlight or nebular light is blocked out
- The dust is made of small grains mixed with the interstellar gas
- Grain size ~ 5 to 500 nm, i.e. $\sim \lambda$ of light



M64: Credit: NASA and The Hubble Heritage Team (AURA/STScI)



M104: Credit: NASA and The Hubble Heritage Team (AURA/STScI)



NGC5866: Credit: NASA and The Hubble Heritage Team (AURA/STScI)



Interstellar dust clouds

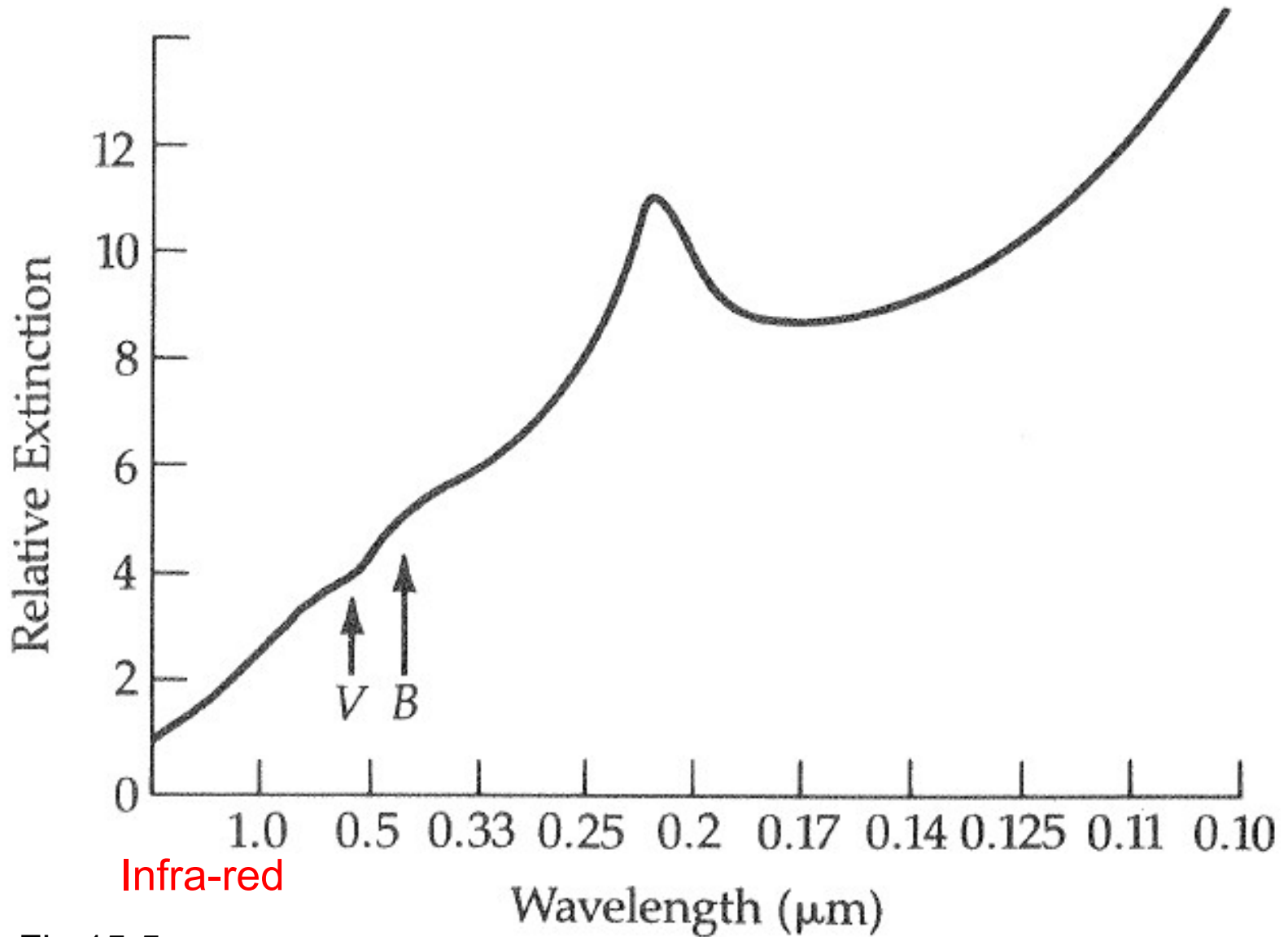
Interstellar Reddening

- The amount of extinction varies with wavelength
- Extinction is larger at blue wavelengths than red wavelengths, i.e. $A_B > A_V$
- Therefore interstellar dust causes background objects to appear redder as well as dimmer



Credit: NASA, NOAO, ESA and The Hubble Heritage Team (STScI/AURA)

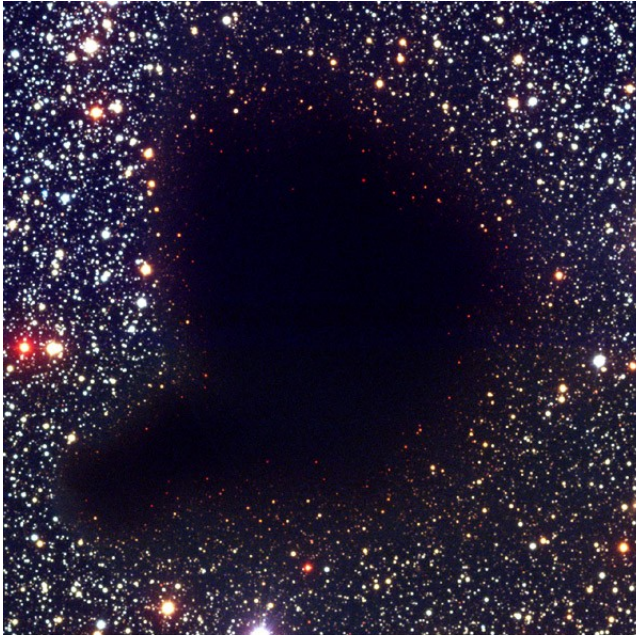
Interstellar extinction varies with wavelength



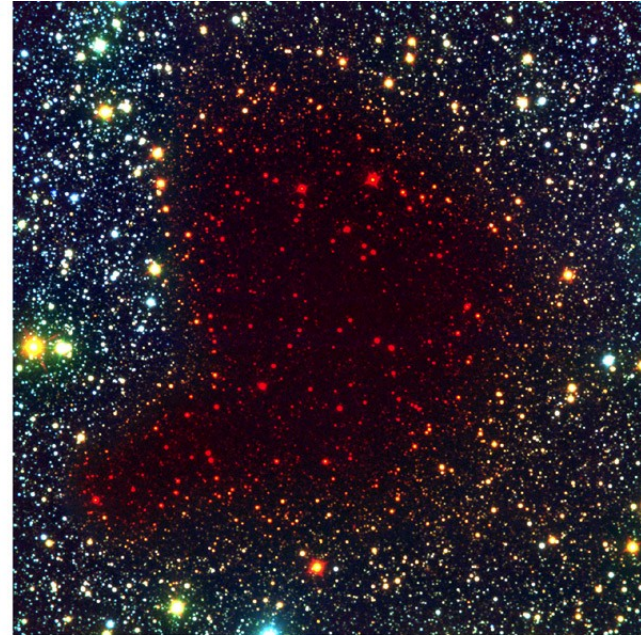
Zeilik Fig 15-5

Near-infrared Observations

- Observations at near-infrared wavelengths are good for seeing through dust obscuration



B, V, I



B, I, K

Pre-Collapse Black Cloud B68 (comparison)
(VLT ANTU + FORS 1 - NTT + SOFI)

Dust Emission

- Dust grains in interstellar space are usually at a temperature of about 30 K
- Hence, they emit at around $100\ \mu\text{m}$ which is at far-infrared wavelengths
- If dust grains are near a hot star then they can get heated up to around 300 K
- Then they emit at mid-infrared wavelengths, i.e. $\sim 10\ \mu\text{m}$

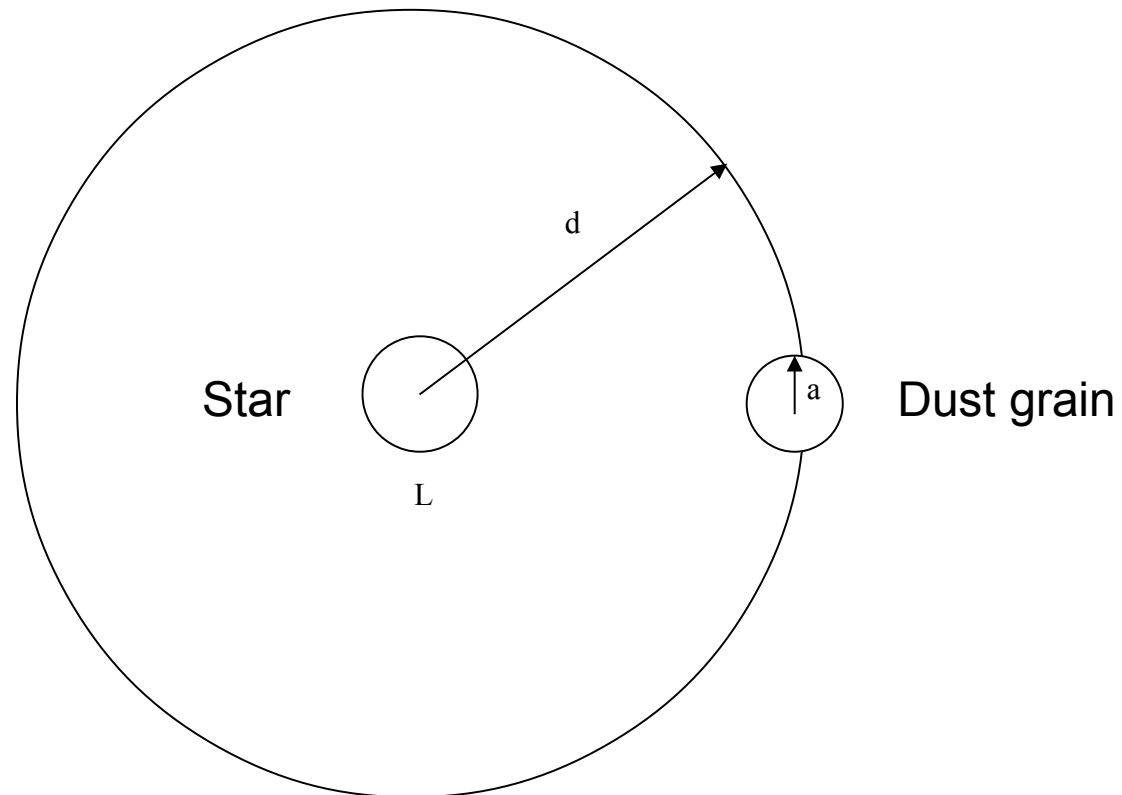


M8 nebula
in the mid-
infrared at
8-20
microns

Courtesy NASA/JPL-
Caltech

Temperature of a dust grain

- Consider a grain with radius, a , at distance, d , from a star of luminosity, L .



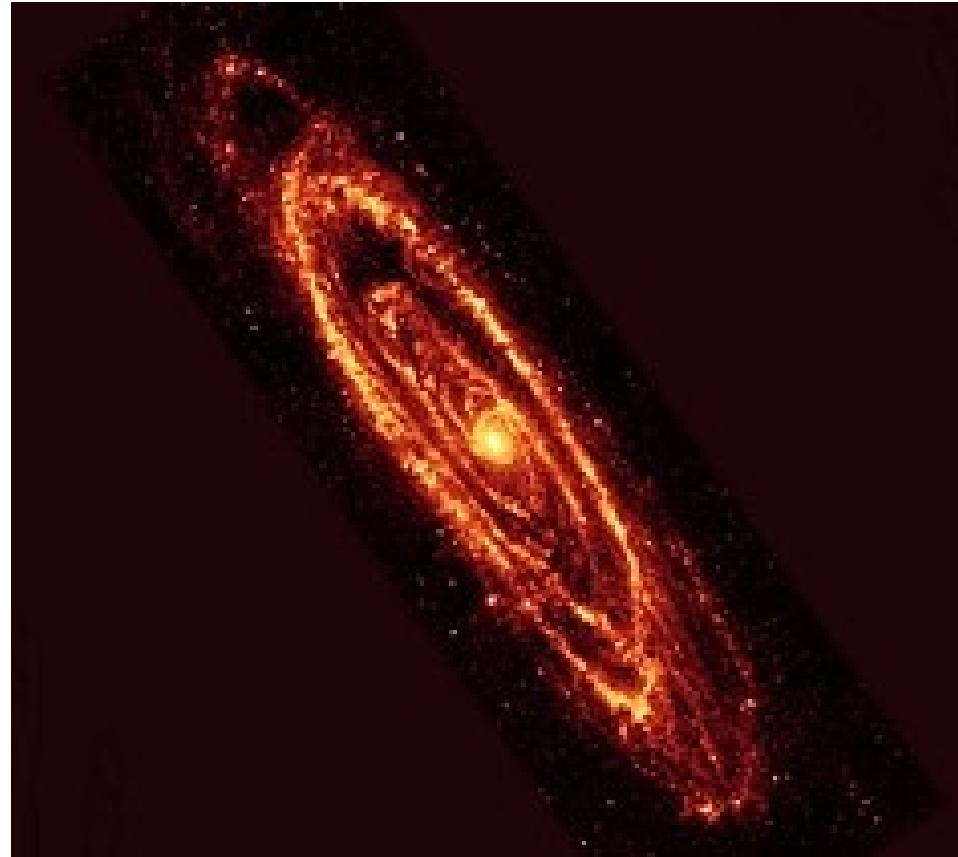
- Equate fraction of star's luminosity absorbed by grain with blackbody emission from the grain

$$\frac{\pi a^2}{4\pi d^2} L \approx 4\pi a^2 \sigma T^4$$

$$T \approx \left(\frac{L}{16\pi\sigma d^2} \right)^{\frac{1}{4}}$$

Star Forming Regions

- When stars form the dust in the molecular clouds gets heated up by the new stars
- Hence, star forming regions are bright infrared sources, in particular where massive, hot stars are being born



NASA Spitzer 24 microns



M31 NASA Spitzer 24, 70, 160 microns

Summary - 1

- H II regions arise where massive stars form and are observed mainly in H α and cm-wave radio continuum
- H I is observed using the 21 cm line and makes up most of the mass of the ISM
- H₂ is traced using mm lines from molecules such as CO and is the material from which stars form

Summary - 2

- 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

Summary - 3

- Interstellar dust is responsible for extinction and reddening of starlight at optical and ultraviolet wavelengths
- Near-infrared is used to see through the dust
- Mid-infrared and far-infrared is used to see emission from warm and cool dust

END

Additional slides

Visual Extinction

- The dust along the line of sight causes objects to appear dimmer
- This amount of dimming is measured in magnitudes and is called total extinction
- In the V-band this is called A_V

$$A_V = m_V (\text{observed}) - m_V (\text{intrinsic})$$

- In terms of absolute magnitude

$$m_V - M_V = 5 \log d - 5 + A_V$$

The magnitude system is defined by

- A. A difference of 1 magnitude is a factor of 10 in brightness
- B. A difference of 5 magnitudes is a factor of 10^5 in brightness
- C. A difference of 5 magnitudes is a factor of 100 in brightness
- D. A difference of 5 magnitudes is a factor of 5 in brightness



Colour Excess

- The amount of reddening is also measured in magnitudes and is the difference between the observed and intrinsic colour

$$E(B - V) = (B - V)_{\text{observed}} - (B - V)_{\text{intrinsic}}$$

- This is called the colour excess

Extinction Law

- How the extinction varies with wavelength is called the extinction law
- The slope of the law allows the visual extinction to be related to the colour excess

$$A_V \approx 3E(B - V)$$

- If the intrinsic colour of a source is known, then the extinction can be measured



B, V, I