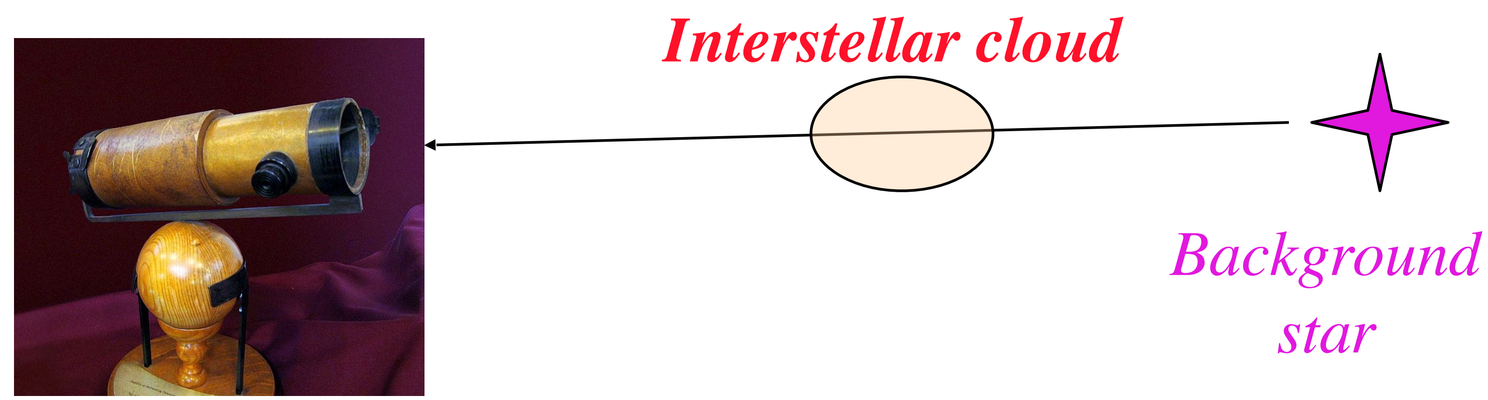
The interstellar medium

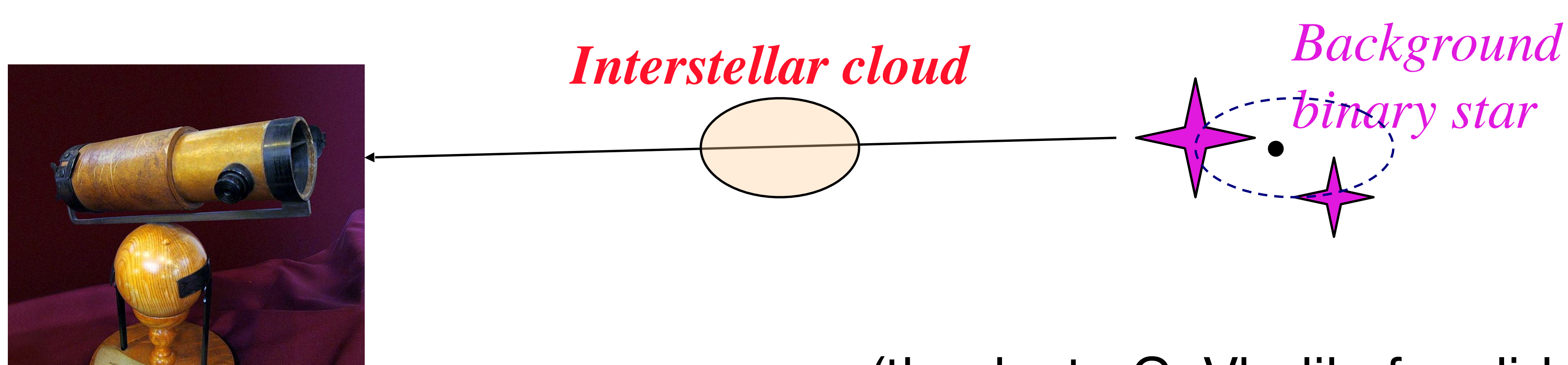
Pierluigi Monaco, Radiative Processes

2018/2019

Discovery of the diffuse interstellar medium



- Interstellar absorption spectroscopy
  - Discrimination of interstellar lines from stellar lines by means of radial velocity analysis
  - The star and the gas along the line of sight have, in general, a different radial velocity
  - If the star is a spectroscopic binary, the stellar lines will regularly shift in radial velocity according to the orbital period of the binary system; interstellar lines, on the other hand, will be "stationary"



(thanks to G. Vladilo for slides with this style)

Discovery of the diffuse interstellar medium

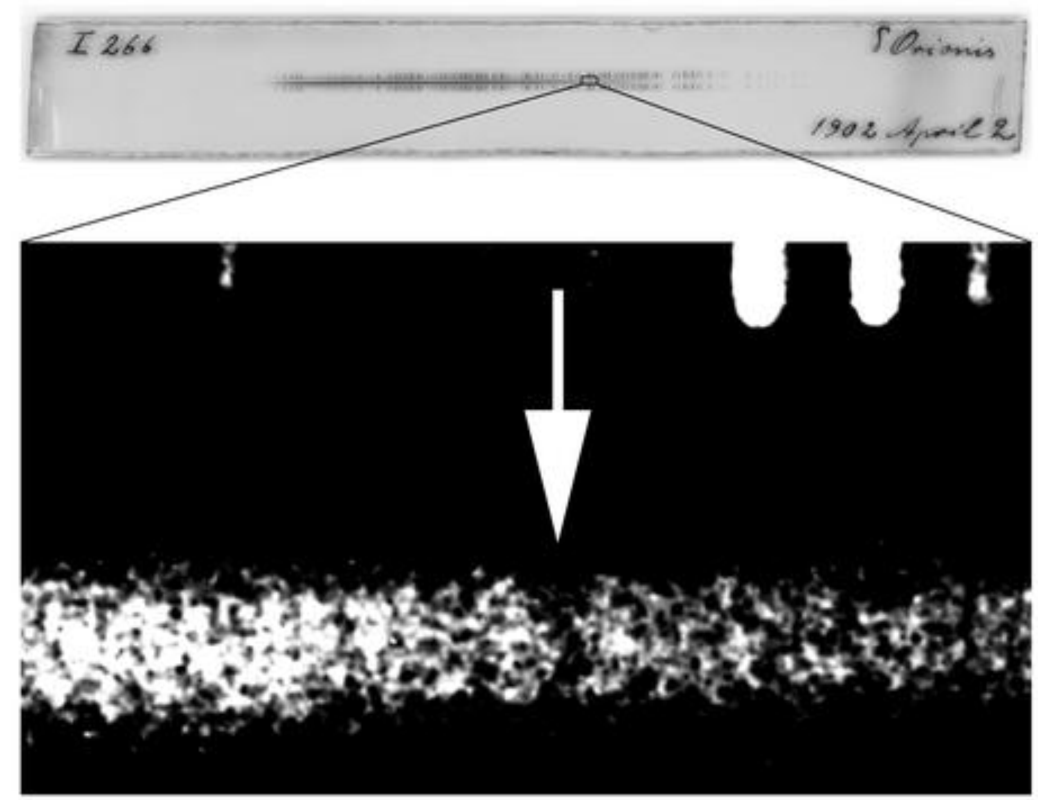
- Hartmann, 1904
  - "Stationary" CaII absorption lines in the spectrum of the spectroscopic binary δ Ori

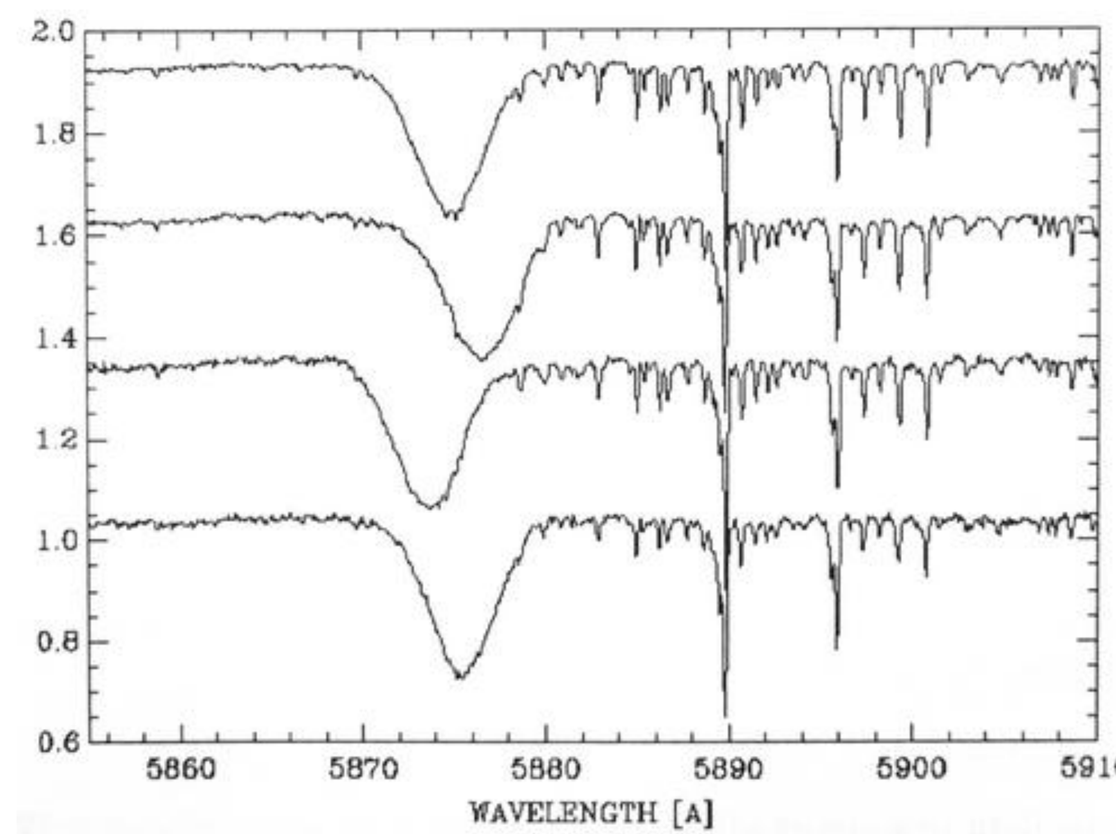
    Circumstellar or interstellar origin?
- Plaskett & Pearce, 1933
  - The CaII absorption becomes stronger with increasing distance of the background star

    Proven the interstellar origin

  Example:

  Stationary NaI lines in the spectrum of δ Ori





Historical evidence for dust: Trumpler, 1930

The apparent size of an open cluster decreases like the inverse of the diameter distance.

The total flux of an open cluster decreases like the inverse square of the luminosity distance.

If open clusters have on average the same size and luminosity, one can get their luminosity ("photometric" in the plot) and diameter distances from observed flux and angular size.

As we are inside the galaxy, luminosity and diameter distances are the same.

Extinction of more distant objects is revealed by a flattening of the relation of luminosity vs diameter distance.

Because it is a continuum absorption, it must be due to dust.

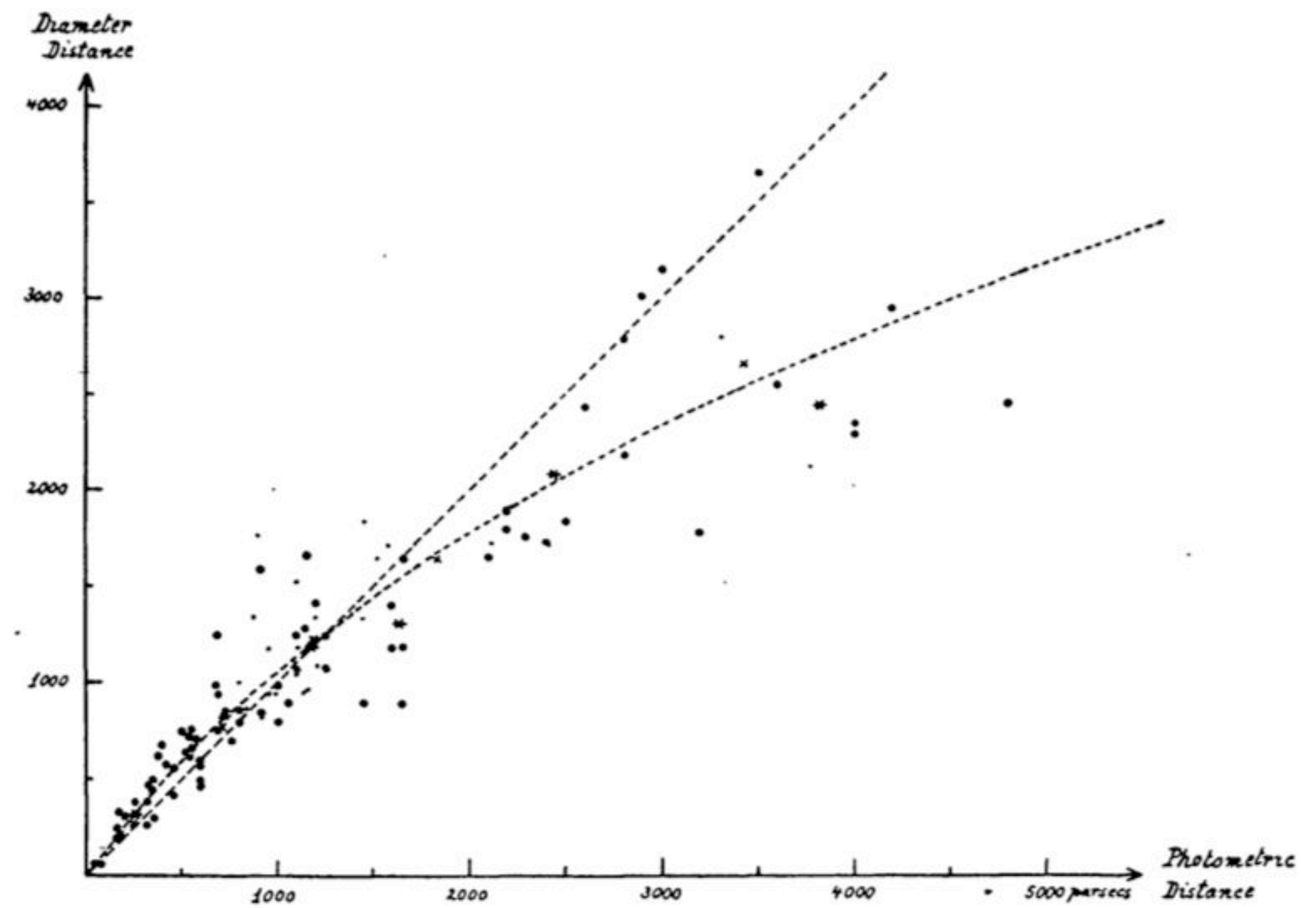
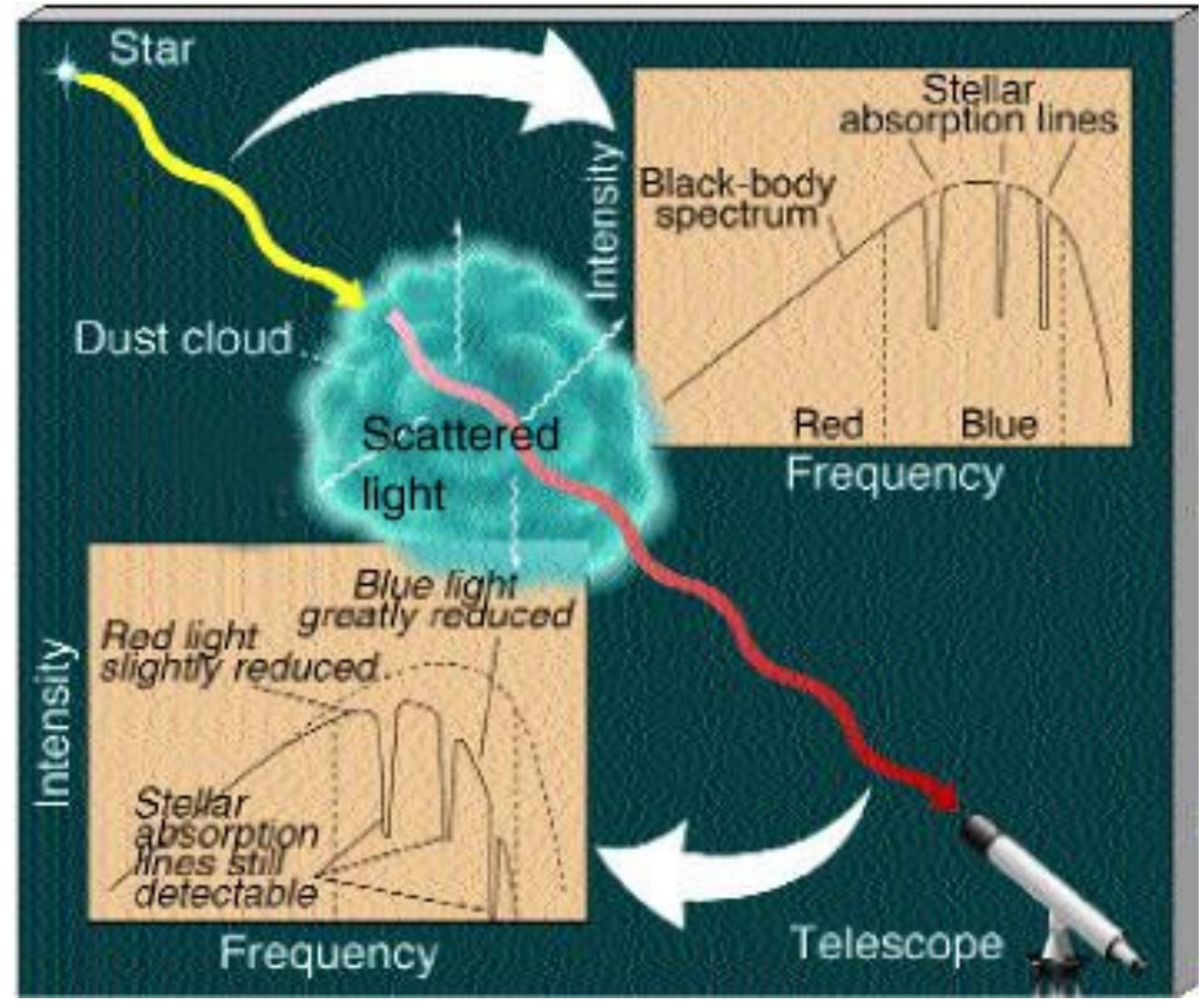


FIG. 1.—Comparison of the distances of 100 open star clusters determined from apparent magnitudes and spectral types (abscissae) with those determined from angular diameters (ordinates). The large dots refer to clusters with well-determined photometric distances, the small dots to clusters with less certain data (half weight). The asterisks and crosses represent group means. If no general space absorption were present, the clusters should fall along the dotted straight line; the dotted curve gives the relation between the two distance measures for a general absorption of $0^{\mathrm{m}}.7$ per 1000 parsecs.

The effect of dust



reddening:

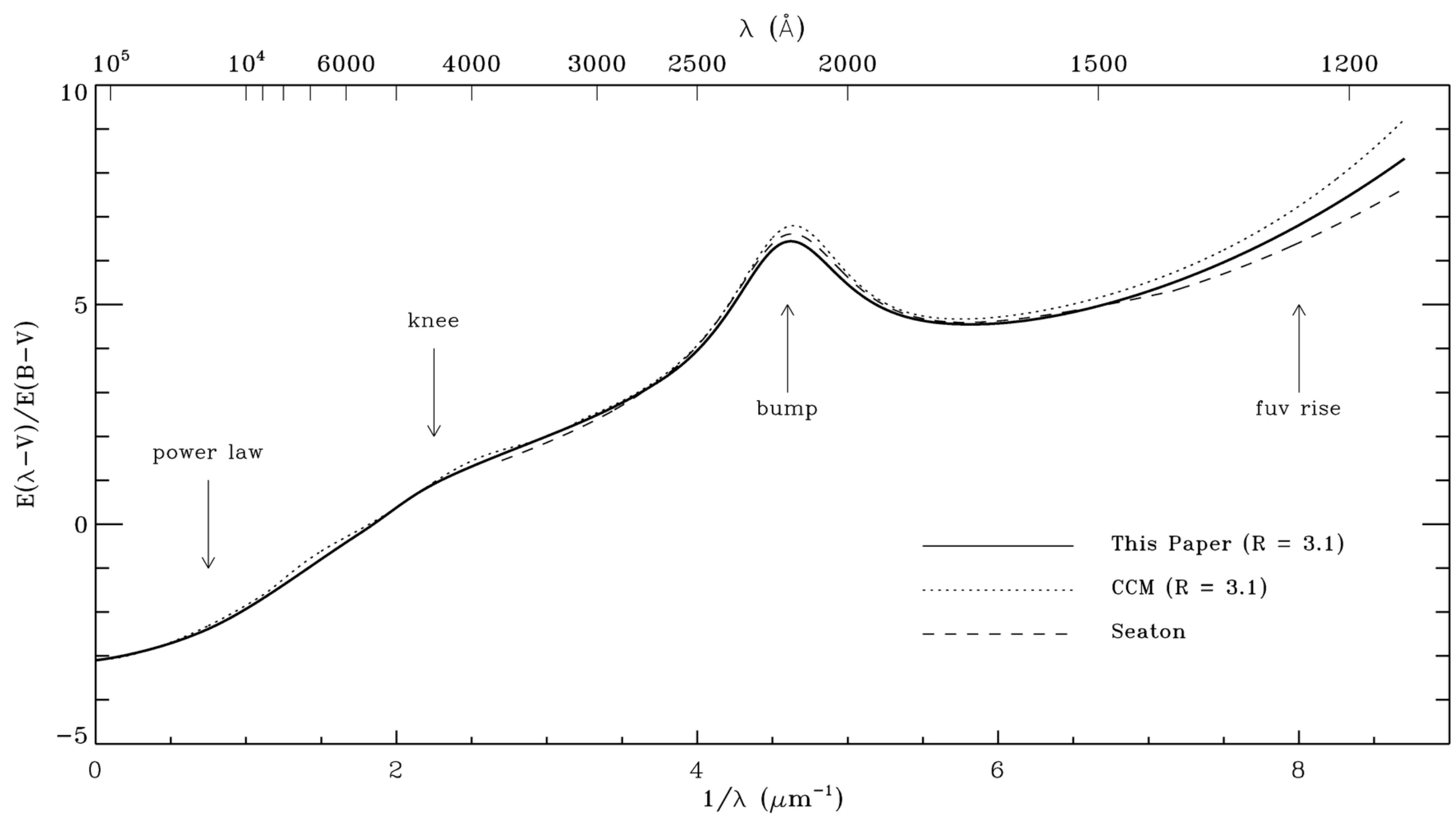
$$E(B-V) := (B-V)_{\rm obs} - (B-V)_{\rm true}$$

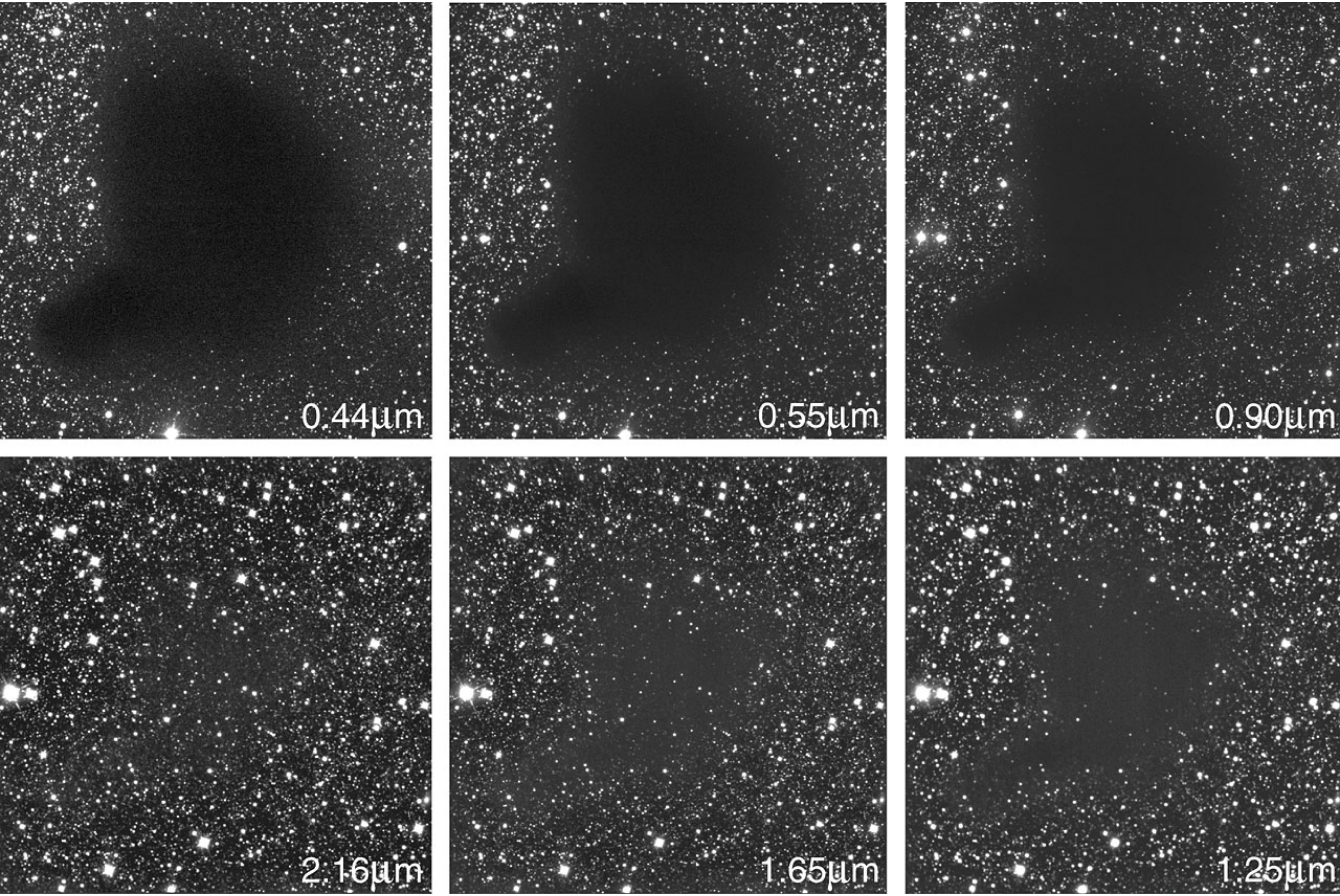
extinction in the V band:

$$A_V = R_V\, E(B-V)$$

extinction at wavelength λ :

$$A_\lambda = R(\lambda)\, E(B-V)$$




0.44µm
0.55µm
0.90µm
2.16µm
1.65µm
1.25µm

Optical:
dust absorbs background Hα light
from hydrogen recombination

MIR: dust thermal emission + PAH

21-cm emission of interstellar HI

- Van de Hulst, 1945
  - Prediction of the existence of the 21 cm line

    Transition between two possible states of the proton-electron spin coupling

    parallel spins (higher energy)

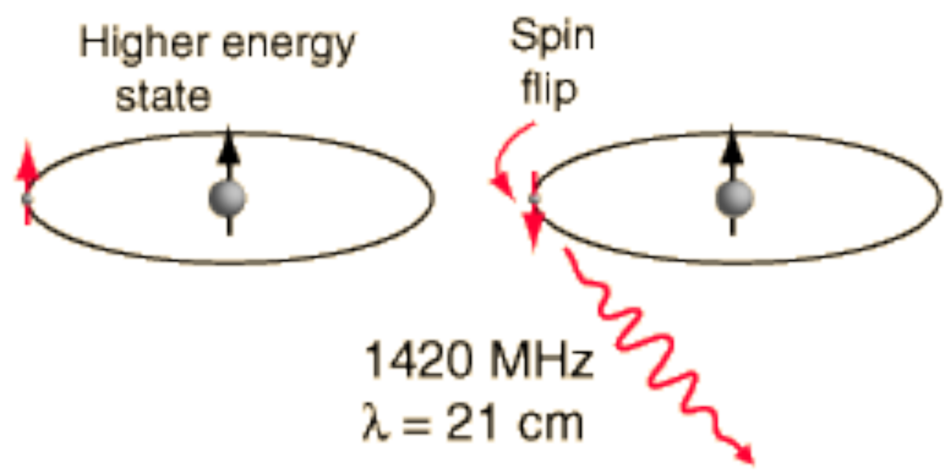
    antiparallel spins (lower energy)
  - "Forbidden" transition

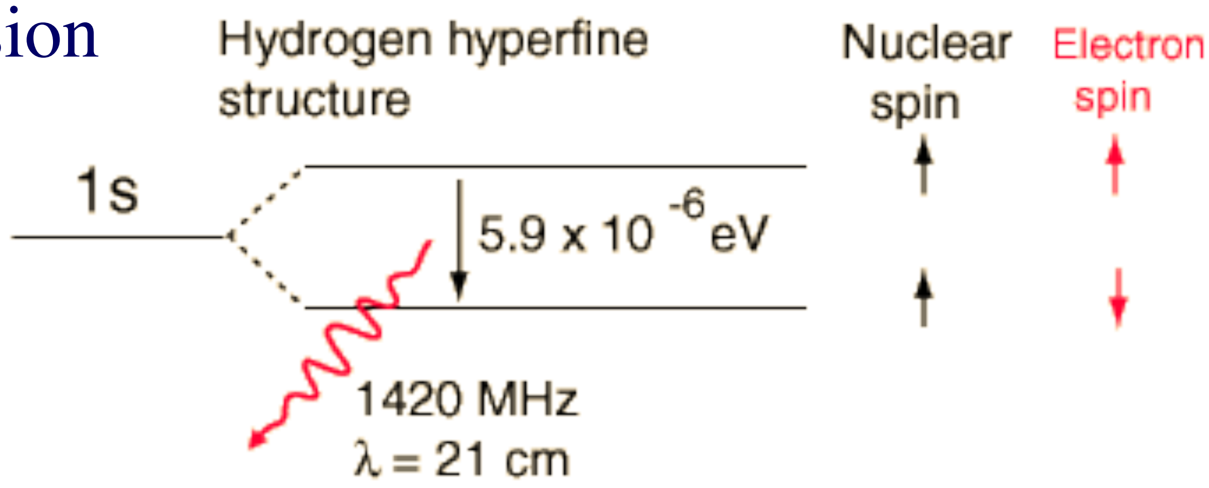
    Einstein coefficient of spontaneous emission

    $A_{ul} = 2.87 \times 10^{-15}\ s^{-1}$

    Life time of the higher level

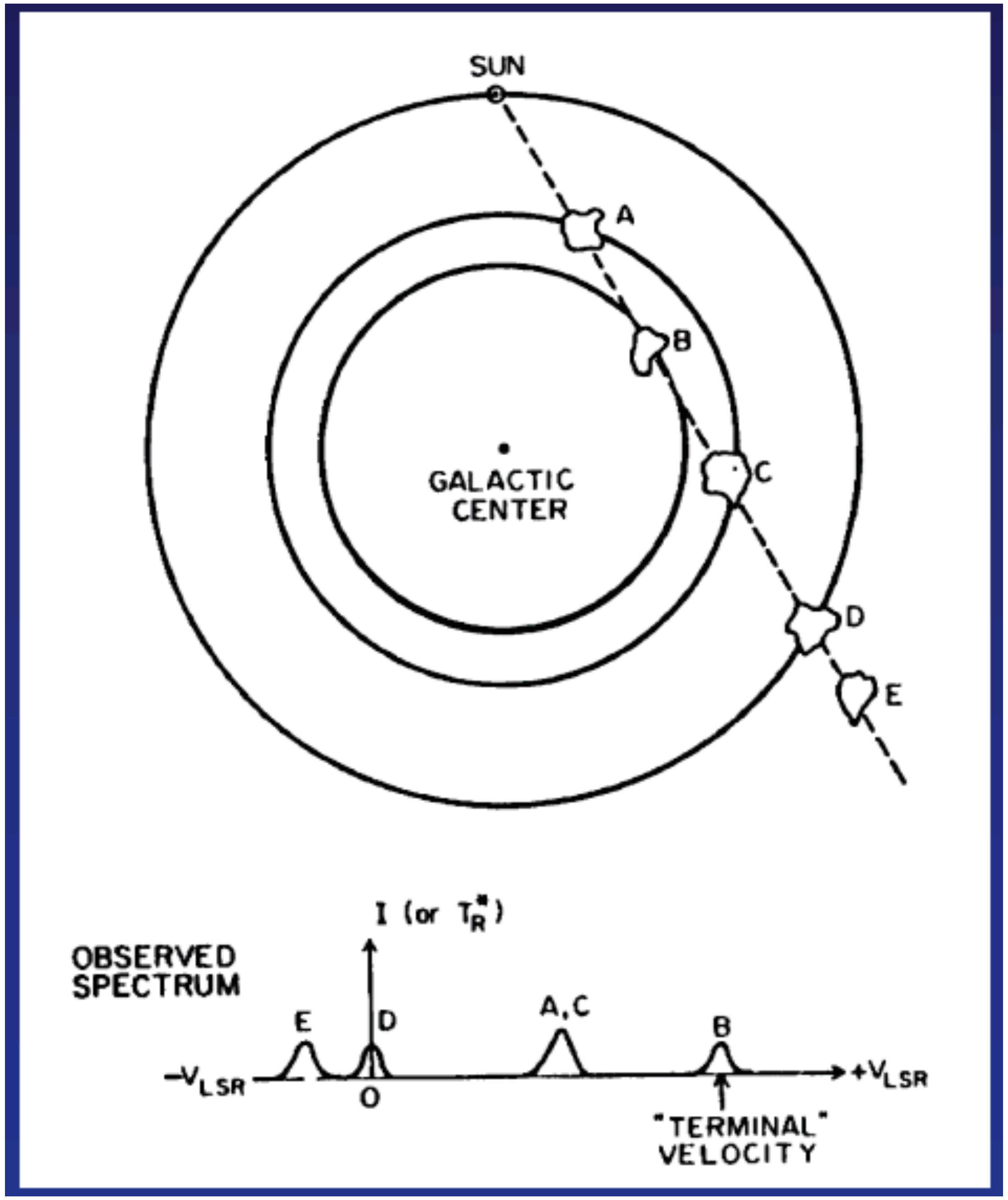
    $t = 1/A_{ul} = 1.1 \times 10^{7}$ yr
- Ewen & Purcell, Oort & Muller, 1951
  - Discovery of the 21 cm emission

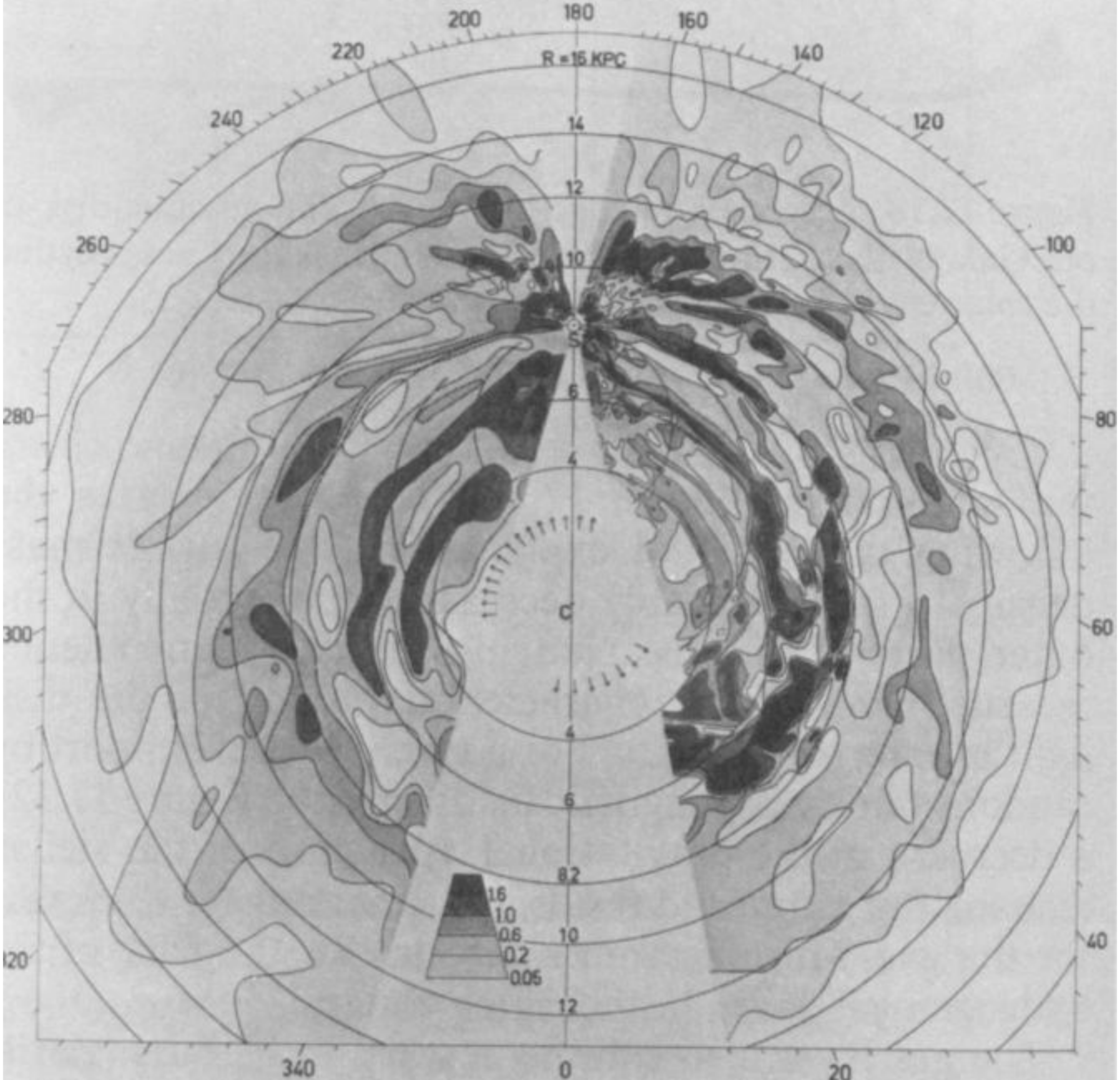




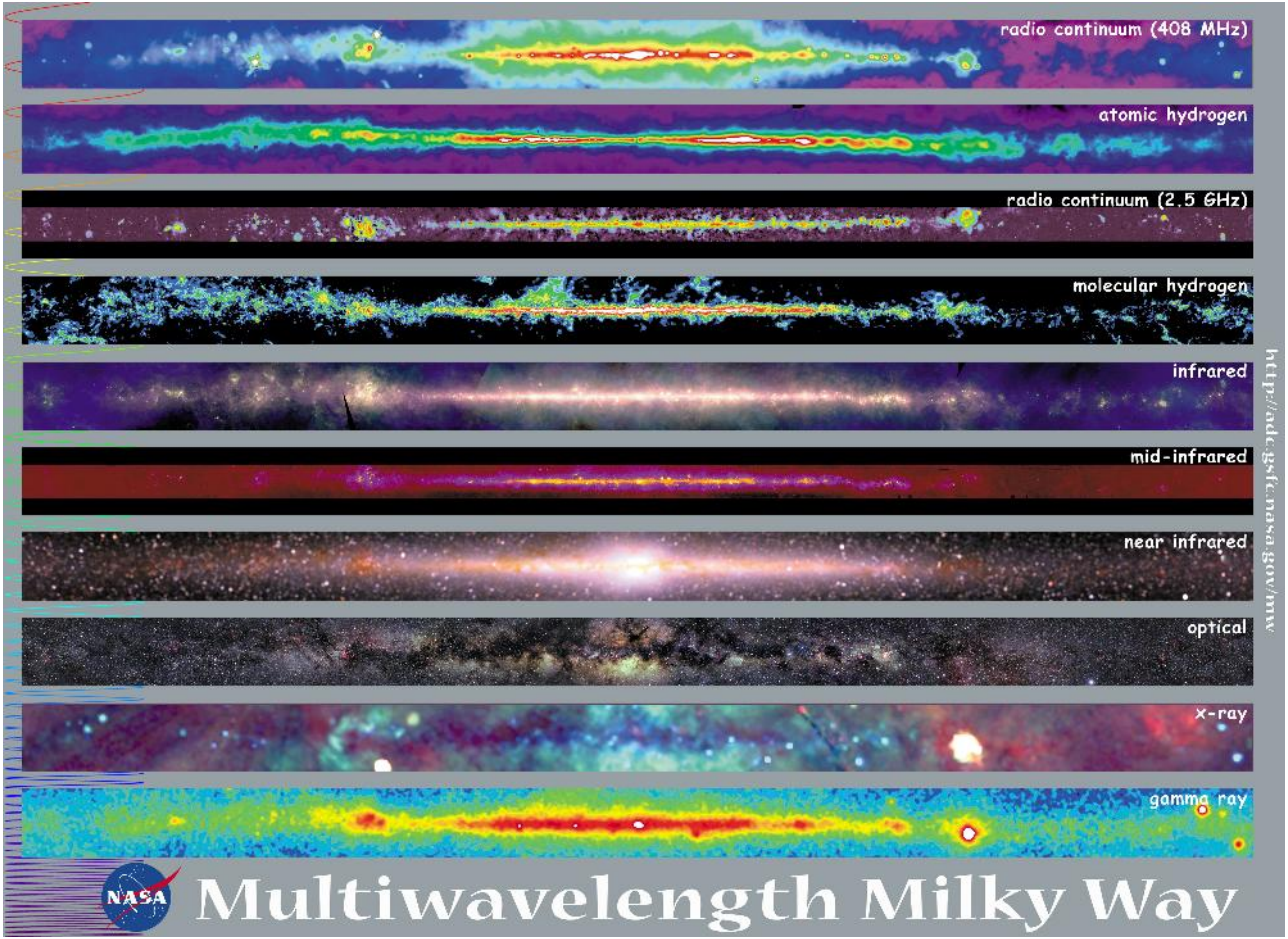
Distribution of the neutral gas in the Galactic plane

- The HI distribution can be reconstructed from a kinematical analysis of the 21-cm emission profiles observed at different Galactic longitudes
- The reconstruction is based on a kinematical model of Galactic rotation, w(R)
  - It is assumed that interstellar clouds at Galactocentric distance *R* move in orbits with angular velocity ω(*R*)
  - From the observed radial velocity at a given longitude one can estimate the cloud distance
- The existence of spiral arms was first proven with this technique





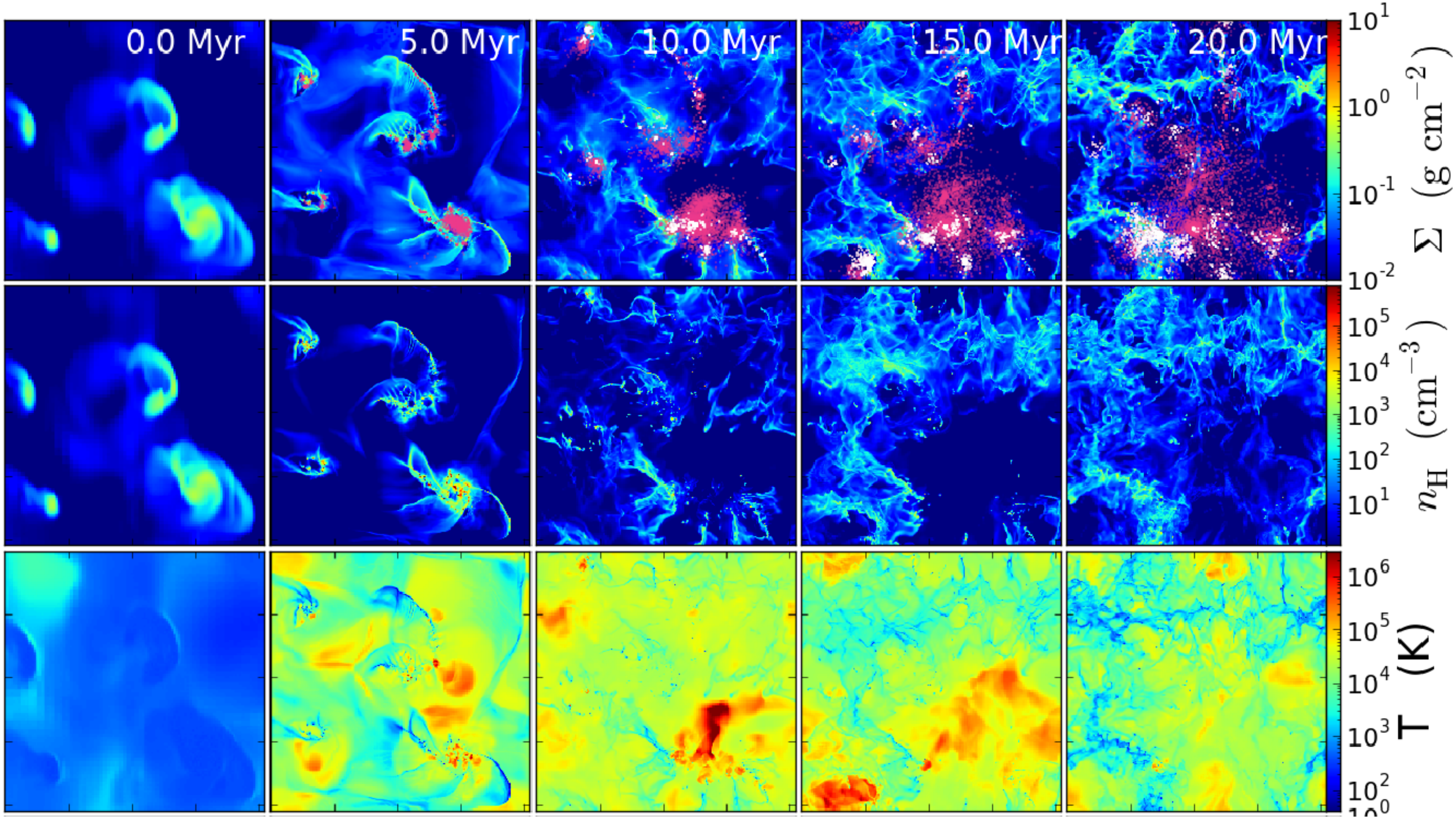
180
200
160
220
140
R = 16 KPC
240
120
14
12
260
100
10
S
6
280
80
4
C
300
60
4
6
8.2
1.6
1.0
0.6
0.2
0.05
10
320
40
12
340
0
20


radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
http://adc.gsfc.nasa.gov/mw
NASA
Multiwavelength Milky Way

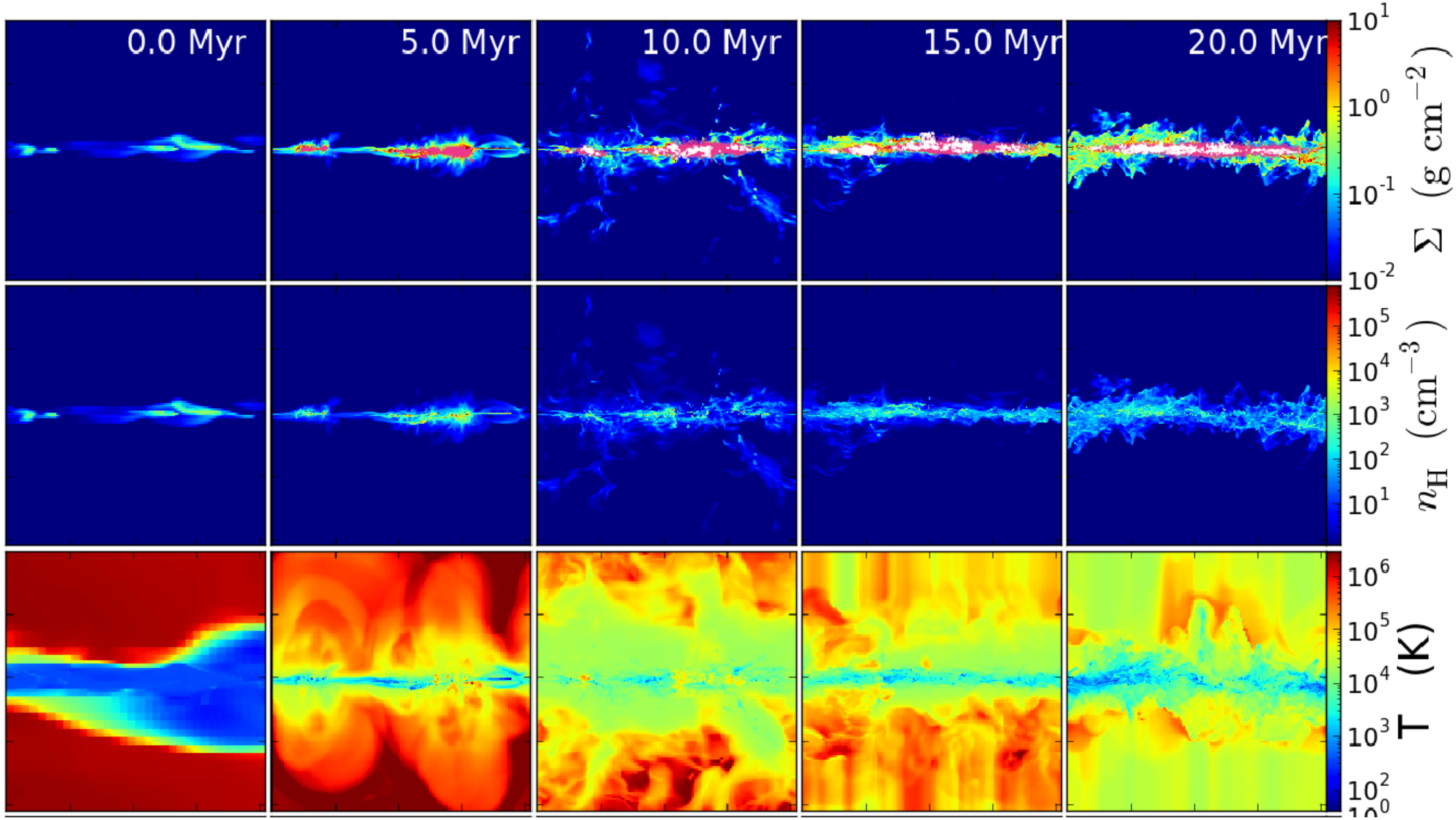
The insterstellar medium is characterized by:

- very low density (prohibited lines),
- a large range of temperatures, from ~10 to 10^6 K,
- possibly different temperatures for electrons and ions,
- a large range of ionization states,
- complex geometry, complex kinematics,
- significant presence of dust,
- very long mean free paths for particles, thermodynamic equilibrium is hard to achieve,
- several coexistent phases in rough pressure equilibrium,
- rough vertical equilibrium with different, temperature-dependent scale heights for various phases,
- weak magnetic fields,
- significant presence of cosmic rays.

ISM simulation, face-on



ISM simulation, edge-on



A note on turbulence

The interstellar medium is characterized by turbulence, that is supersonic in the coldest phases.

Dominant contributions to pressure:

- ram pressure from turbulent motions,
- magnetic fields,
- cosmic rays accelerated at shock fronts.

Thermal pressure is negligible in the warm and cold phases.

Turbulence is driven by:

- disc rotation,
- magneto-rotational instability,
- supernova explosions.

Molecular clouds: the cradles of star formation

density: ~100-1000 cm-3

temperature: ~10 K

internal velocities: 10 km/s

supported by supersonic turbulence

cloud properties:

$$M \sim 10^6 \, M_\odot, \quad R \sim 50 \text{ pc},$$

$$\Sigma_{\rm gas} \sim 100 \, M_\odot \, \text{pc}^{-2}$$

gas tracers: CO, C^+, HCN...

HI regions, Cold Neutral Medium (CNM)

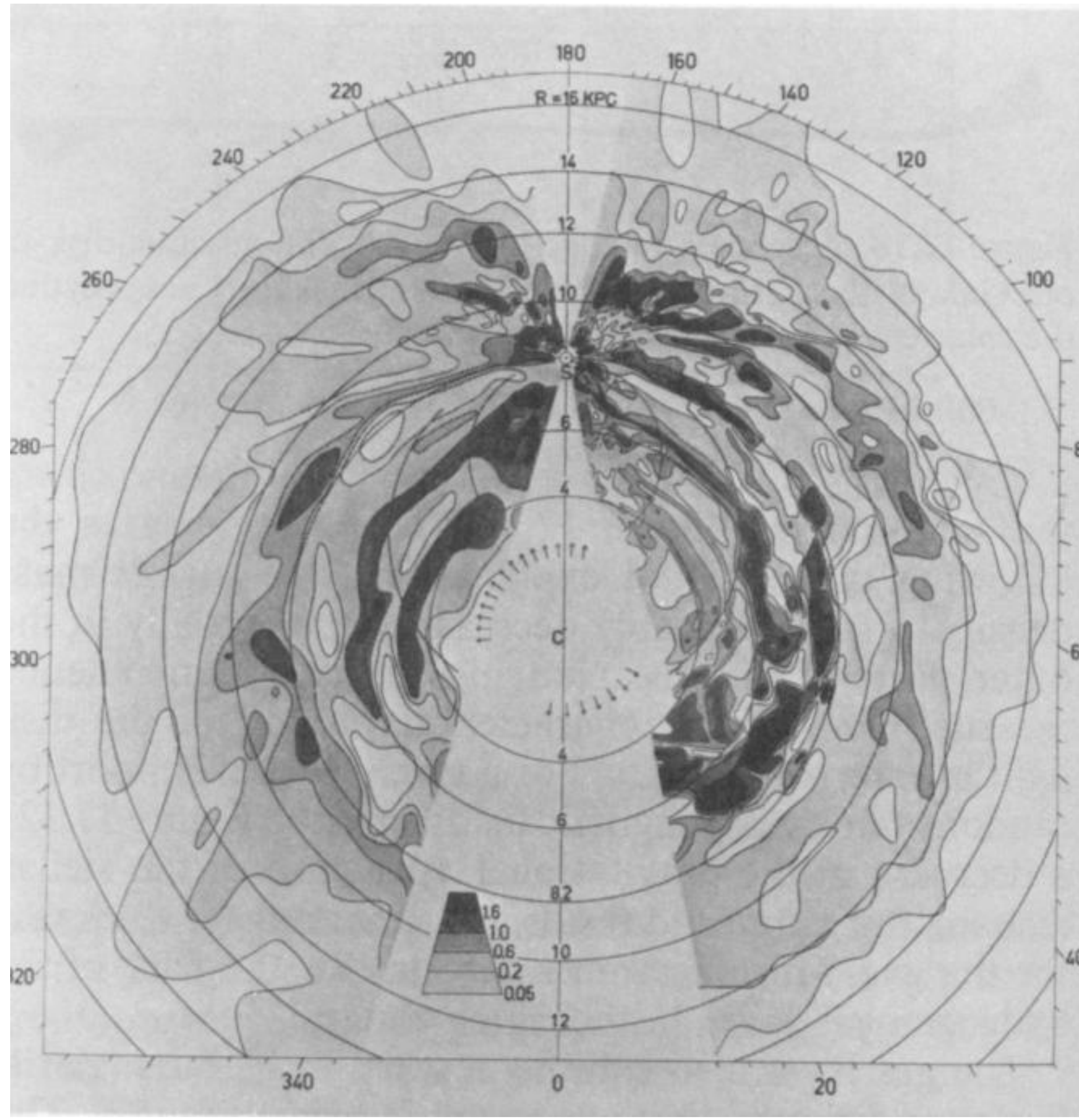
density: ~10 cm-3

temperature: ~100 K

internal velocities: 10 km/s

supersonic turbulence

gas tracer: 21 cm



Warm Neutral Medium (WNM), Warm Ionized Medium (WIM)

density: ~10^{-1} cm-3

temperature: ~10^4 K

thermal velocities: 10 km/s

mildly supersonic turbulence

gas tracer: 21 cm (neutral), various nebular emission lines including Halpha, absorption lines

Hot ionized medium

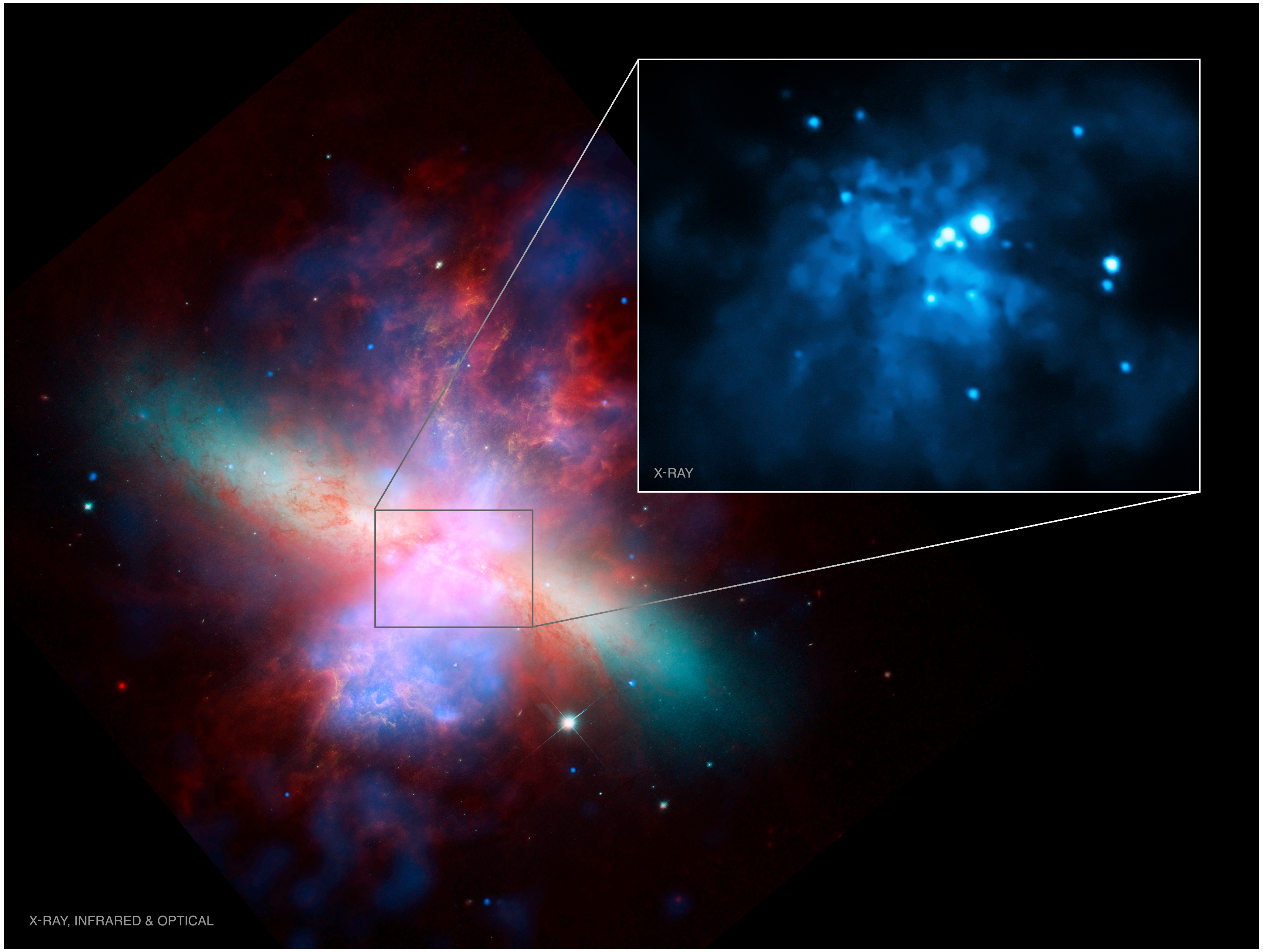
density: ~10^{-3} cm-3

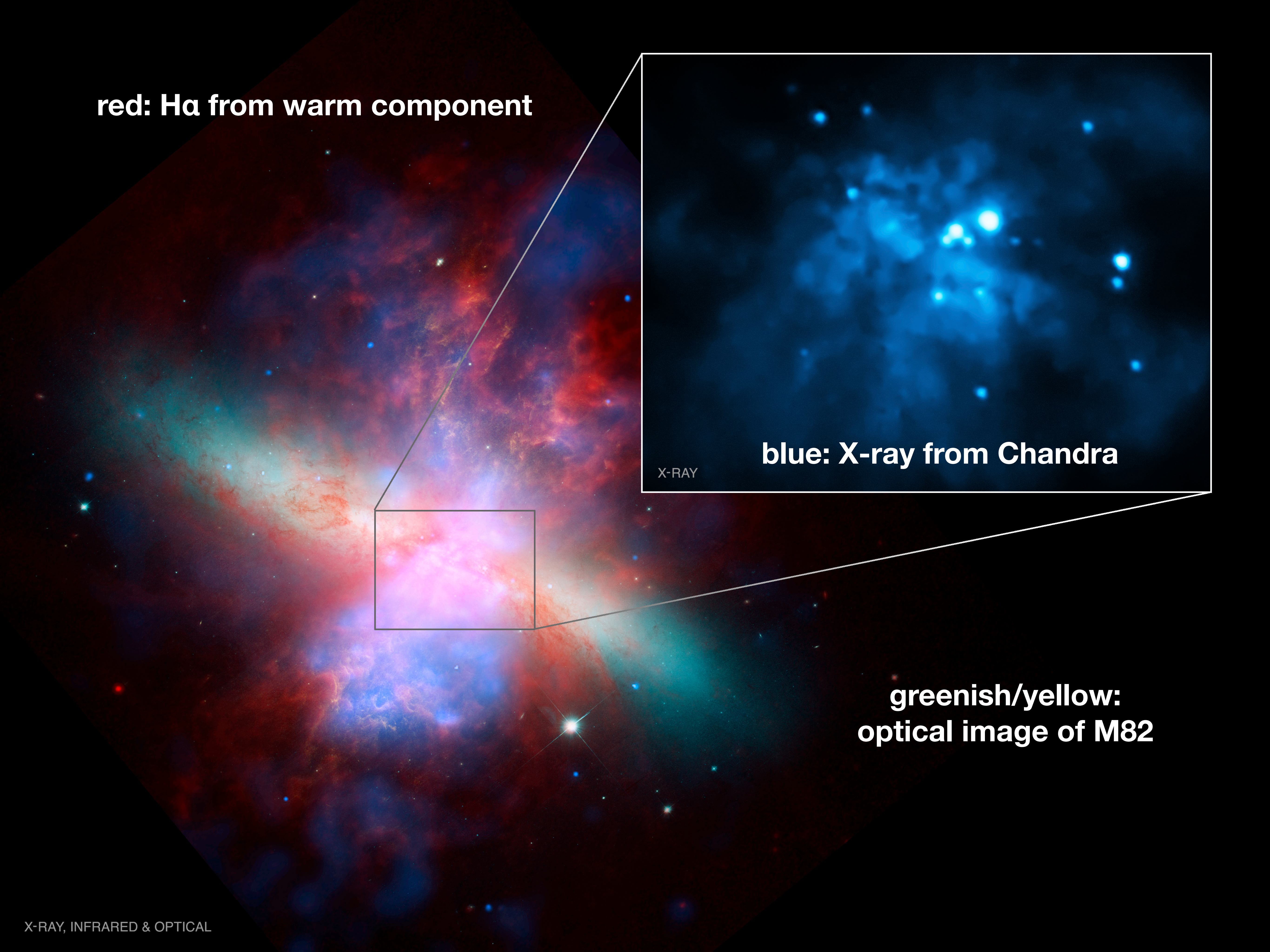
temperature: ~10^6 K

thermal velocities: 100 km/s

complex kinematics

gas tracer: X-rays, high-ionization absorption lines: OVI, CIV, NV etc.




red: Hα from warm component
blue: X-ray from Chandra
X-RAY
greenish/yellow:
optical image of M82
X-RAY, INFRARED & OPTICAL

Collisional ionization equilibrium

A species X is ionised from X^{+i} to X^{+i+1}. by a source of luminosity L_ν at distance r.

In this case the electron transits form a bound to a free state. Ionization is due to photon absorption, recombination is a kind of collision.

$$\text{Ionization rate}: \quad N(X^{+i}) \int_{\nu_i}^{\infty} \frac{L_\nu}{4\pi r^2 h\nu} b_\nu d\nu$$

in cm^{-3} s^{-1}, where ν_i corresponds to the ionization energy and the coefficient b_ν (cm^2) gives the probability of ionization by that photon, taking into accout all the excitation states of the species.

$$\text{Recombination rate}: \quad N_e N(X^{+i+1})\, \alpha(X^{+i}, T_e)$$

where the recombination coefficient $\alpha(X^{+i}, T_e)$ (cm^3 s^{-1}) depends on electron temperature.

The production rate of photons that ionize X^{+i} or the Hydrogen atom is (units of s^{-1}):

$$Q(X^{+i}) = \int_{\nu_i}^{\infty} \frac{L_\nu}{h\nu} d\nu, \quad Q(H) = \int_{\nu_H}^{\infty} \frac{L_\nu}{h\nu} d\nu$$

We define an average ionization coefficient:

$$\bar{b}(X^{+i}) = \frac{1}{Q(X^{+i})} \int_{\nu_i}^{\infty} b_\nu \frac{L_\nu}{h\nu} d\nu$$

The ratio of the two ionized species can then be written with some math as:

$$\frac{N(X^{+i+1})}{N(X^{+i})} = c\eta\, U \frac{\bar{b}(X^{+i})}{\alpha(X^{+i}, T_e)}$$

where we defined two adimensional parameters:

$$\eta = \frac{Q(X^{+i})}{Q(H)} \qquad U = \frac{Q(H)}{4\pi r^2 N_e c}$$

U is the **ionization parameter**, roughly giving the number of ionizing photons per electron, i.e. per Hydrogen atom. Even for $U \sim 10^{-3}$ hydrogen is highly ionized.

HII regions: Stromgren sphere around massive stars

Take a young massive star embedded in a uniform ISM. The hydrogen ionization rate is:

$$N_H \int_{\nu_H}^{\infty} \frac{L_\nu}{4\pi r^2\, h\nu} b_\nu d\nu = N_H \frac{\bar{b}_\nu}{4\pi r^2} Q(H)$$

At small *r* the ionization rate is very large, and the hydrogen gets completely ionised, so N_H becomes very small. At large *r* the ionization rate becomes small, the gas gets "screened" (ionizing photons have been absorbed before) and the hydrogen remains neutral.

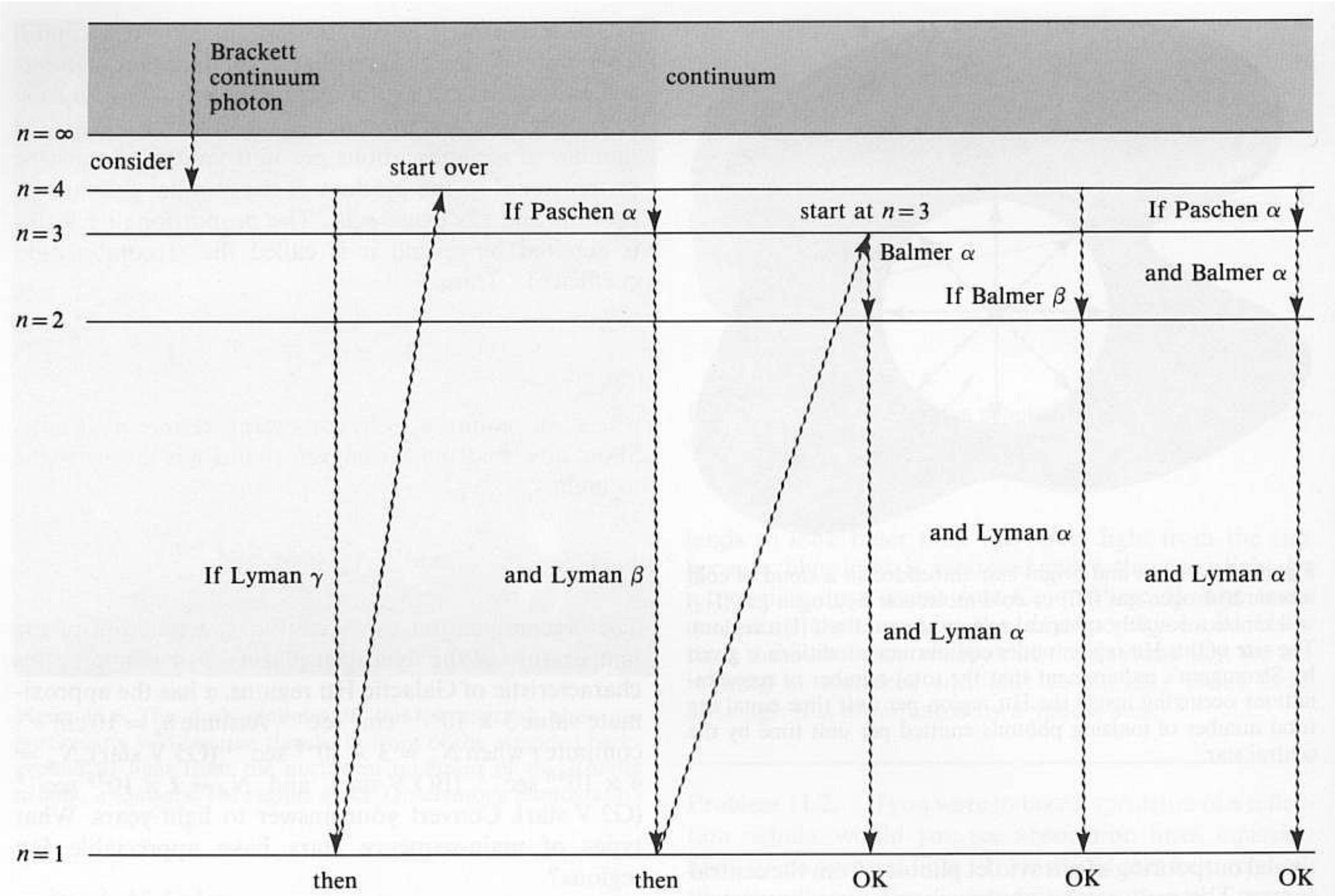
The radius of the sphere that is kept ionized by the star can be computed in equilibrium by assuming that each recombination is balanced by an ionization.

$$\frac{4}{3}\pi r_{\rm str}^3\, \alpha\, N_e N_{H^+} = Q(H)$$

Assuming that $N_e \simeq N_{H^+}$:

$$r_{\rm str} = \left(\frac{3Q(H)}{4\pi\alpha N_e^2}\right)^{1/3}$$

Resonant scattering of Lyman alpha, fluorescence



Circumstellar regions

Emission nebulae in the Galaxy

Reflection Nebulae
HII regions
Planetary nebulae
Supernova remnants

Reflection nebulae

– Non ionized circumstellar gas that scatters photons of a late-type star
The the central star is not sufficiently hot to produce photons with $h\nu > 13.6$ eV
Hydrogen is not ionized by stellar radiation

– The scattering of stellar photons is due to dust grains embedded in the gas

Example: Reflection Nebula V838

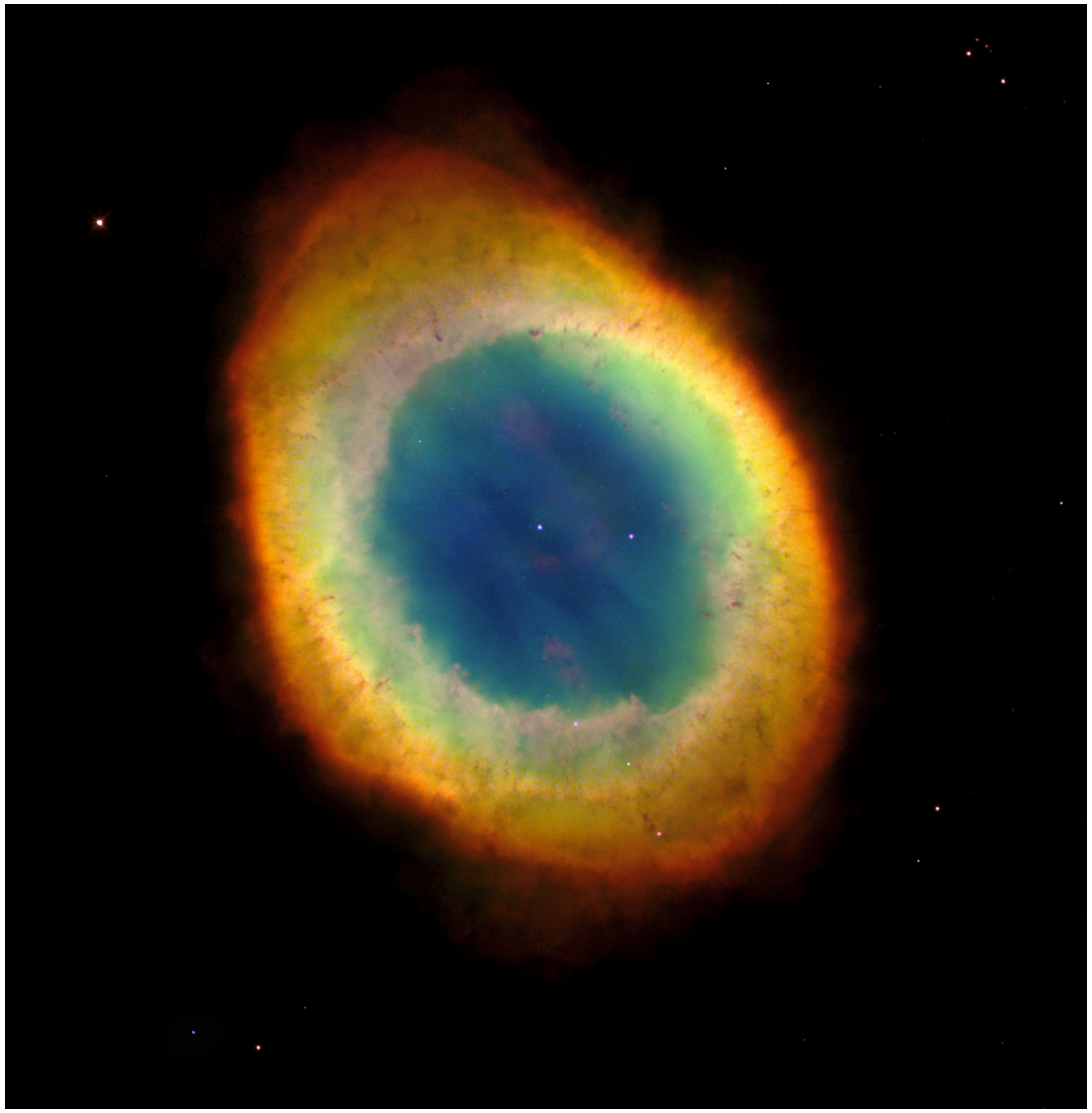
HII regions

- Low-density clouds of partially ionized gas surrounding short-lived, early-type stars
  Mechanisms of ionization:
    - radiation of early-type stars (UV stellar photons with $h\nu > 13.6$ eV)
    - collisional ionization, in presence of shocks due by stellar ejecta
- HII regions are typically associated with regions of recent star formation and with giant molecular clouds; they can be quite extended, sometimes a few hundred pc
- The main observational diagnostics of HII regions in the optical band is the Hα emission line
  transition from n=3 to n=2 of the Balmer series

Orion Nebula
Hubble mosaic

Planetary nebulae

- Expanding shell of ionized gas ejected from old red giant stars late in their lives
- During the red giant phase, the outer layers of the star are expelled by strong stellar winds
- After most of the red giant's atmosphere is dissipated, the remaining hot luminous core emits ultraviolet radiation that ionizes the ejected outer layers
- Absorbed ultraviolet light energises the shell of nebulous gas, causing it to appear as a brightly coloured planetary nebula

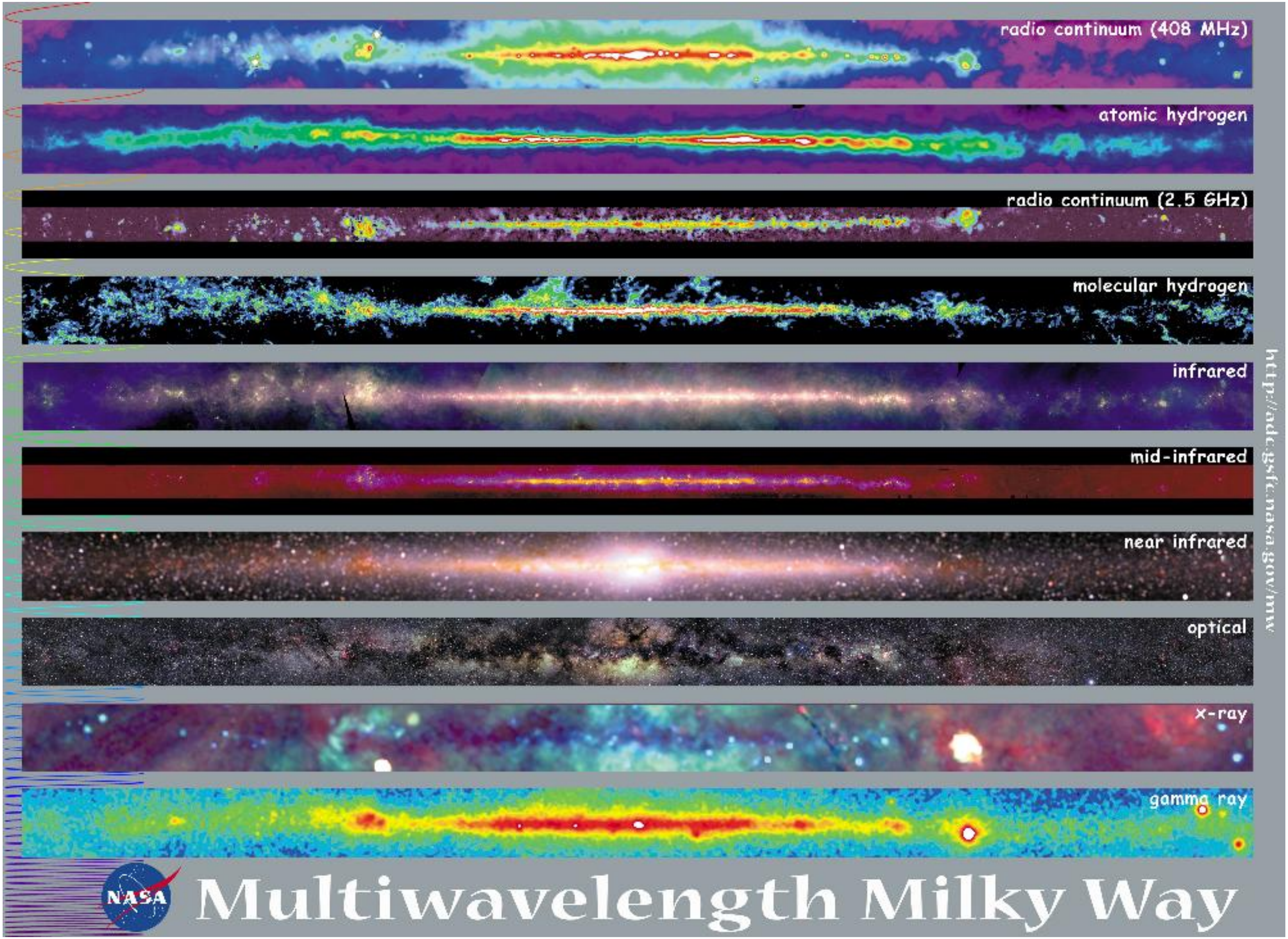


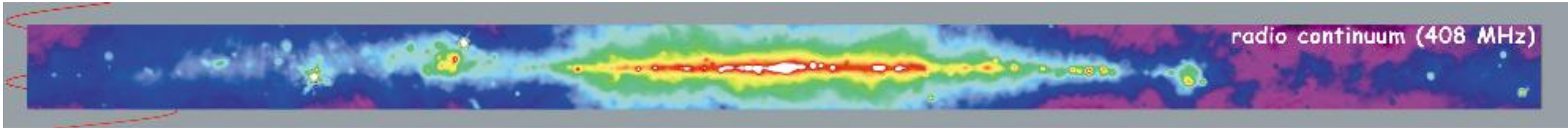
NGC 6720, The Ring Nebula
STScI/AURA

Supernova remnants (SNRs)

- A supernova remnant is the structure resulting from the explosion of a star in a supernova
- The supernova remnant is bounded by an expanding shock wave, and consists of ejected material expanding from the explosion, and the interstellar material it sweeps up and shocks along the way
- The supernova explosion expels much or all of the stellar material with supersonic velocities (up to 10^4 km/s)
- A strong shock wave forms ahead of the ejecta, that heats the upstream plasma up to temperatures well above millions of K
- The shock continuously slows down over time as it sweeps up the ambient medium
- It can expand over tens of parsecs before its speed falls below the local sound speed.

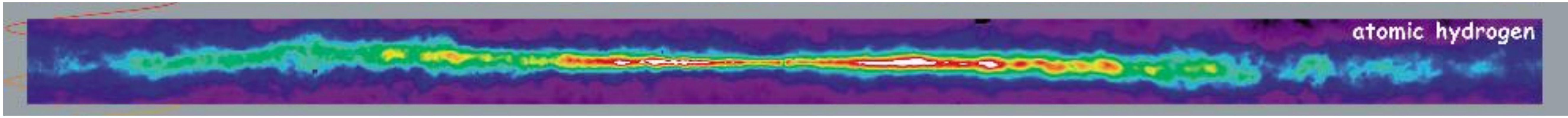
SN 1054 remnant (Crab Nebula)


radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
http://adc.gsfc.nasa.gov/mw
NASA
Multiwavelength Milky Way

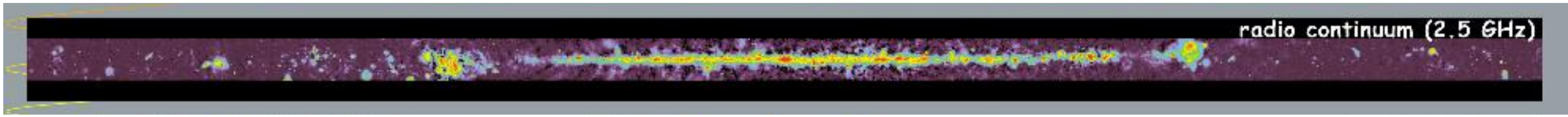


Synchroton radiation

Generated by relativistic electrons accelerated by SN shocks and pulsars, traveling in the $\sim \mu G$ magnetic field of the galaxy.



21 cm radiation from neutral (atomic) hydrogen

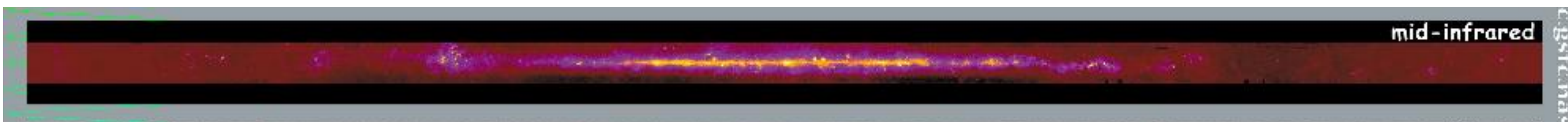


Synchroton radiation from electrons,
bremsstrahlung radiation from supernova remnants
and from hot gas in general

Far IR

Thermal emission from dust,
heated by old stars (diffuse dust or cirrus)
or by young massive stars in molecular clouds

Line emission from polycyclic aromatic hydrocarbons (PAH)
in the diffuse dust component



Emission from old stars (main sequence and giants) with little dust absorption

Emission from stars, with dust absorption

X-ray binaries and some emission from hot gas,
some absorption from diffuse hydrogen

Compact sources, gamma-ray photons from collisions of cosmic rays with diffuse gas