INTRODUCTION TO THE PHYSICS AND CHEMISTRY OF THE INTERSTELLAR MEDIUM

Hel.A.S. Summer School 2022

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Outline

Part A

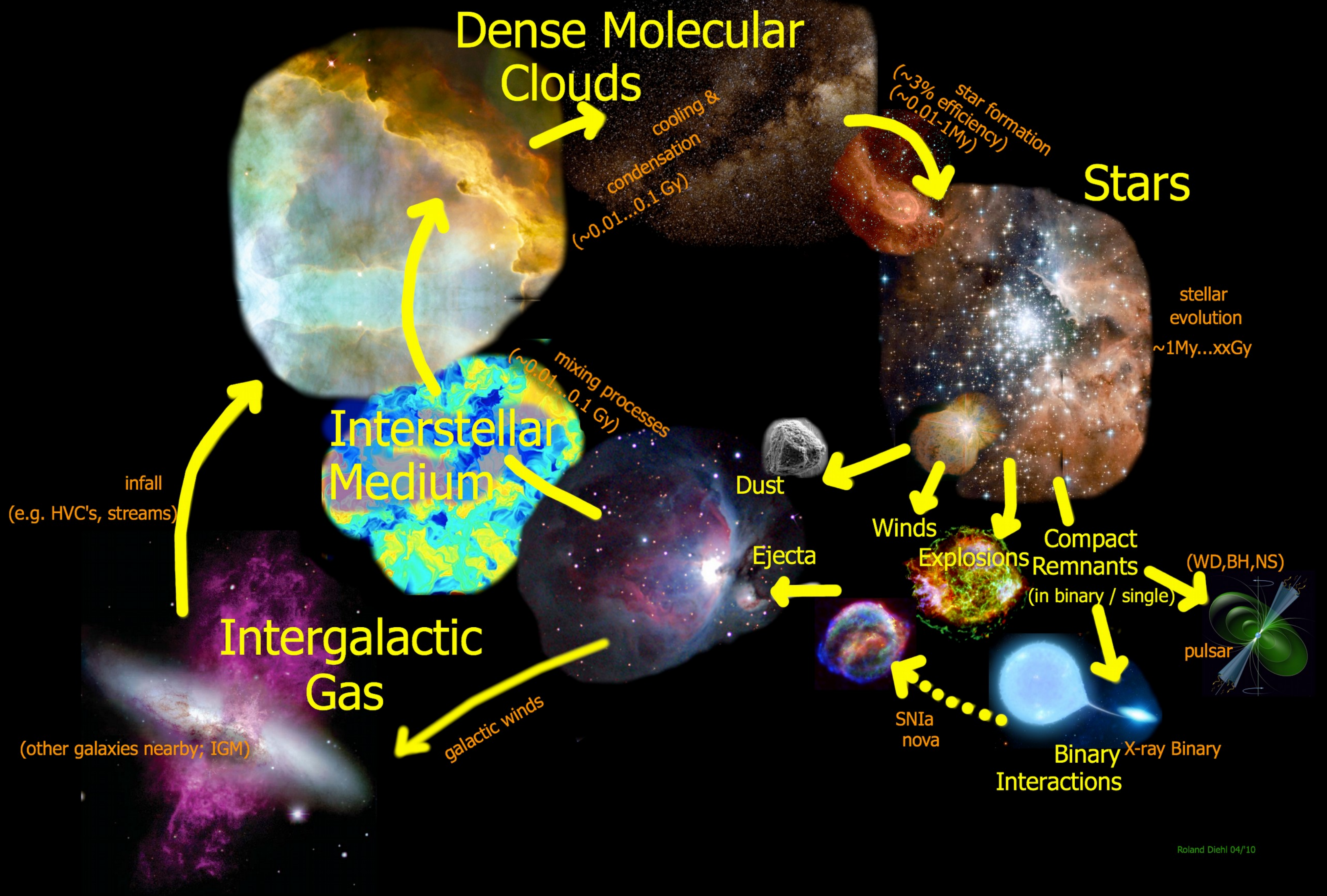
- Life cycle and phases of the ISM
- Introduction to the physics and chemistry of the ISM
- Dynamical evolution of HII regions
- Basics of star-formation

Part B

- Photodissociation Regions
- Examples from PDR simulations
- Numerical modeling and the 3D-PDR code

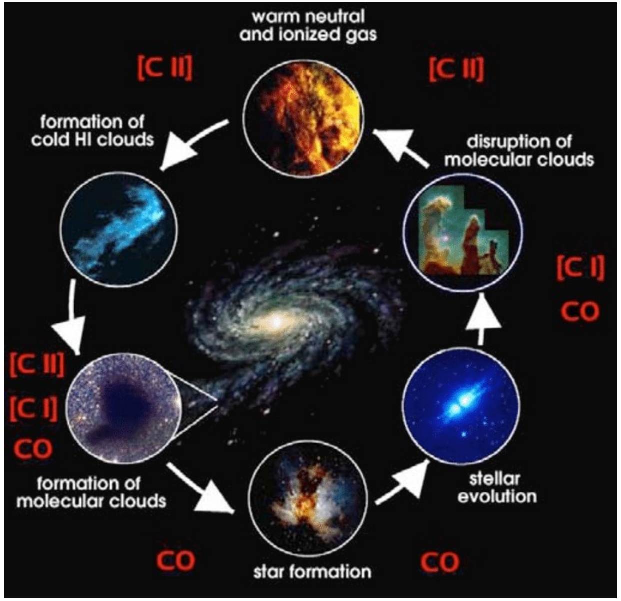
Hands-on

- PDR applications (3D-PDR and RADEX)



Dense Molecular Clouds
cooling & condensation (~0.01...0.1 Gy)
star formation (~3% efficiency) (~0.01-1My)
Stars
stellar evolution ~1My...xxGy
Dust
Winds
Explosions
Compact Remnants (in binary / single)
(WD,BH,NS)
pulsar
Ejecta
SNIa nova
Binary Interactions
X-ray Binary
mixing processes (~0.01...0.1 Gy)
Interstellar Medium
galactic winds
Intergalactic Gas
(other galaxies nearby; IGM)
infall
(e.g. HVC's, streams)
Roland Diehl 04/'10

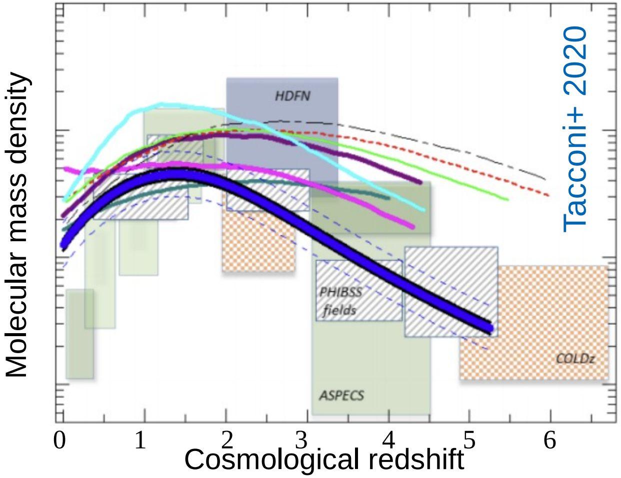
Life cycle of the interstellar medium



Describes the cycling of ISM material between its phases.

Star-formation takes place in relatively quiescent, dense and cold molecular gas.

Massive young stars ionize the surrounding ISM increasing its turbulence.



Tacconi+ 2020

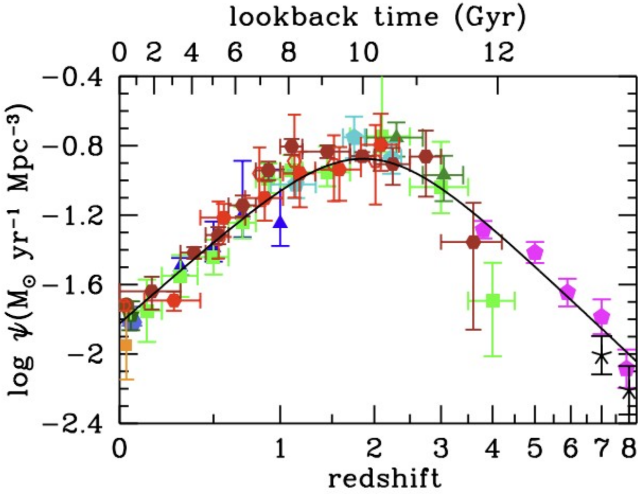
Evolution of molecular gas across epochs.

The maximum of the cosmic molecular gas density is at higher redshift (z~2).

Star Formation Rate across epochs.

At a redshift of z~2, the cosmic star-formation rate picked. This is a period of maximum star formation in the Universe.

The Universe was ~3 Gyrs old.



Madau & Dickinson 2014

SILCC: **SI**mulating the **L**ife**C**ycle of molecular **C**louds

The turbulent life of dust grains in the supernova-driven, multiphase interstellar medium

Thomas Peters
Svitlana Zhukovska
Thorsten Naab
Philipp Girichidis
Stefanie Walch
Simon C. O. Glover
Ralf S. Klessen
Paul C. Clark
Daniel Seifried

Peters et al., 2017, MNRAS 467, 4322

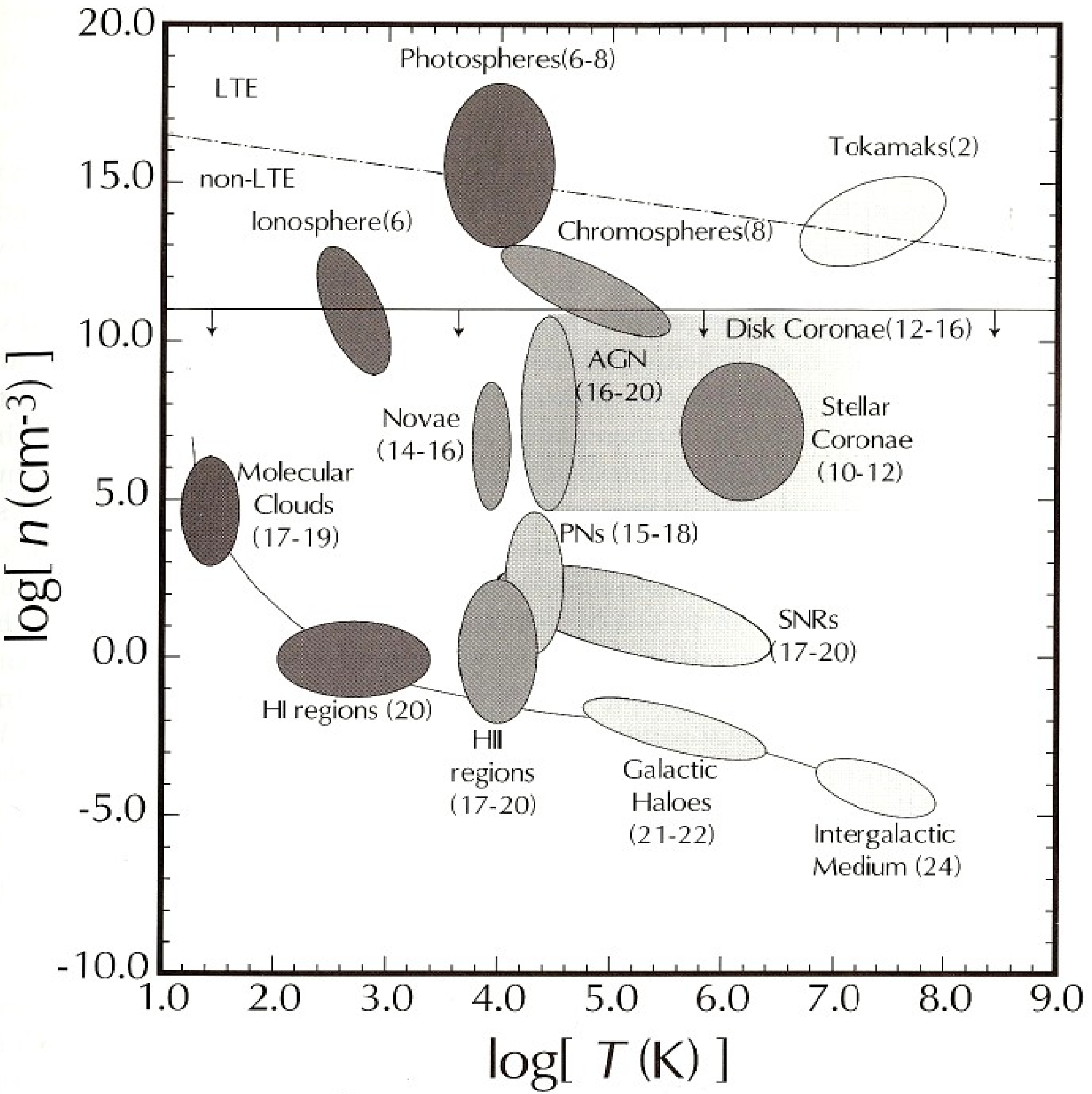
random driving

Components of the ISM

The ISM can be divided in different parts/phases according to its density and temperature. The ISM can be **ionized**, **neutral**, or **molecular**.

The diagram on the right shows the categories of each part according to its phase.

The numbers in the brackets correspond to the logarithm of the typical size (in cm).



Three phase model of the ISM

Three phases of the ISM

Field, Goldsmith & Habing (1969)
McKee & Ostriker (1977)

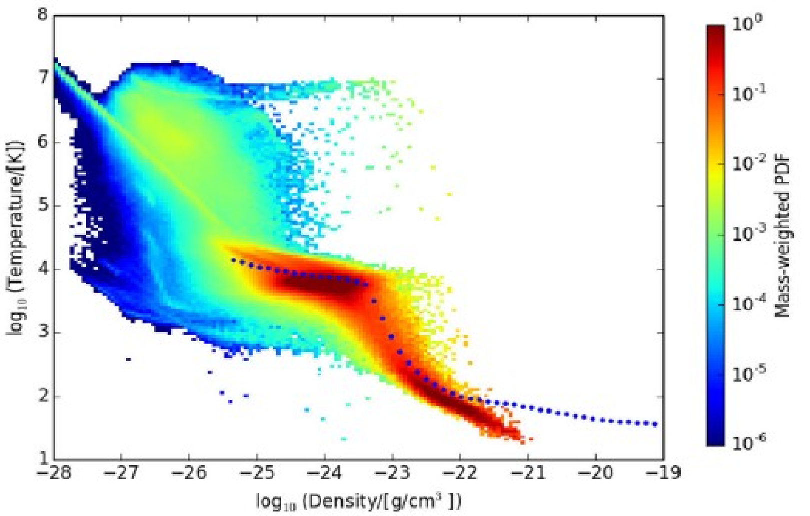
<u>Cold Neutral Medium</u>
n ~ 40 cm^{-3}
T ~ 80 K
~2-4%

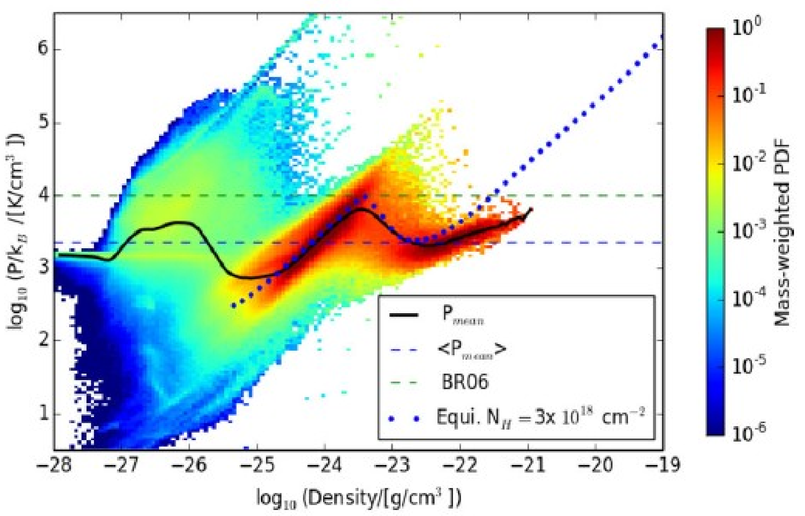
<u>Warm Interstellar Medium</u>
T ~ 8,000 K
~20%

<u>Hot Interstellar Medium</u>
n ~ $3.5x10^{-3}$ cm^{-3}
T ~ $4.5x10^{5}$ K
~70-80%

<u>Warm Neutral</u>

<u>Warm Ionized</u>





Walch et al. (2015)

Basic concepts

Column density $$N_{\rm H} = \int_0^R n_{\rm H} dr$$ [*cm*$^{-2}$]

Interstellar Medium: **Gas + Dust**

Radiation traveling in the ISM extinguishes (extinction) due to :

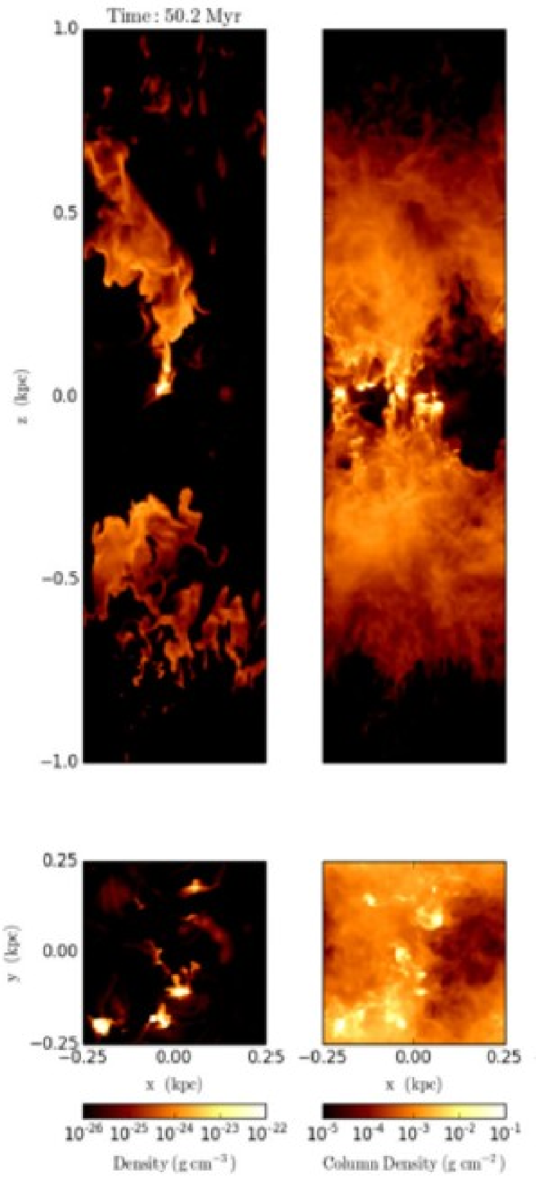
1) absorption
2) diffusion
3) geometrical dilution

Relation between extinction (due to dust) and column density:

$$\frac{A_{\rm V}}{N_{\rm H}} \sim 5.8 - 6.3 \times 10^{-22}\,[{\rm cm^2\,mag}]$$

(Bohlin+ 1978; Weingartner & Draine 2001; Roellig+ 2007; Rachford+ 2009)

***A*$_{\rm V}$ is the visual extinction**

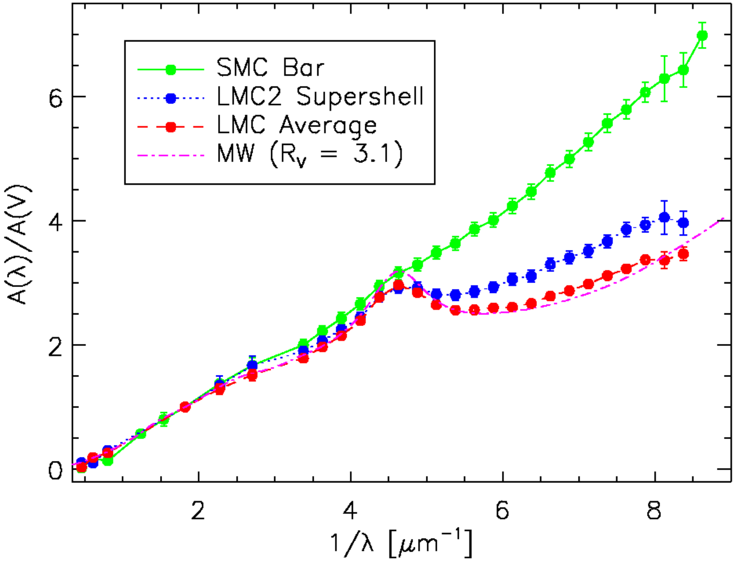


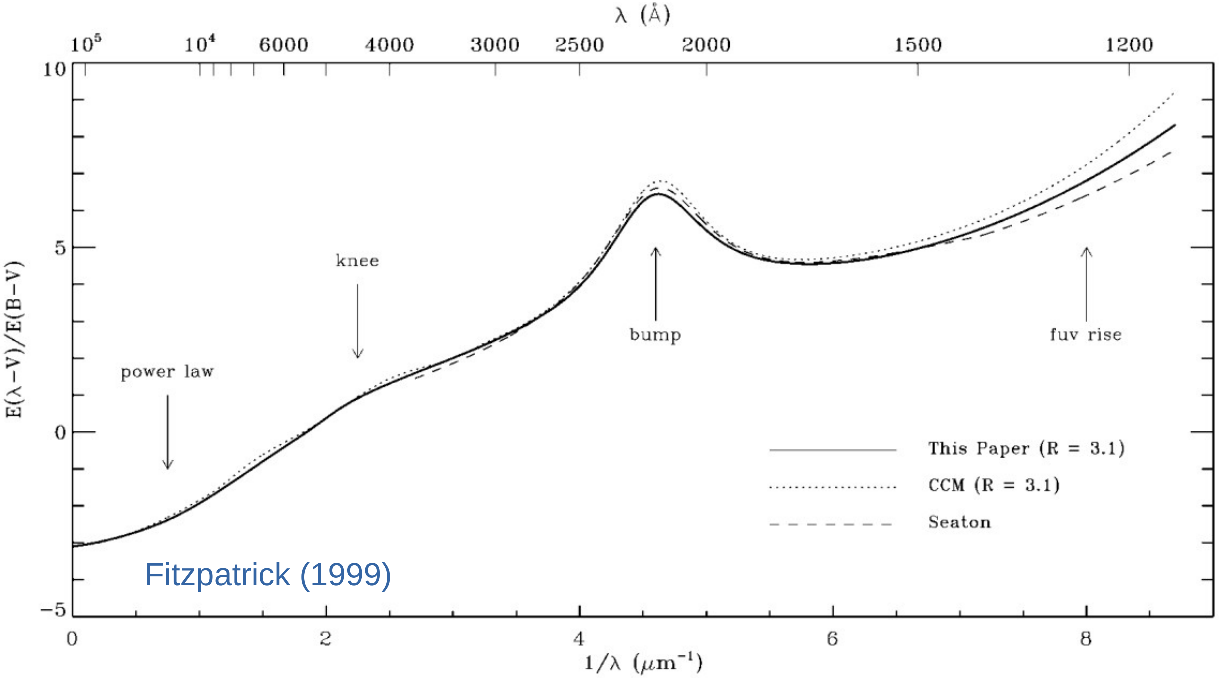
SILCC project

Interstellar absorption (reddening)

Diagram showing the average extinction curve. There are four interesting parts in this plot (from left to right): red, visible, local maximum at 2175A (UV) and far-UV

X-axis: optical depth
Y-axis: λ^{-1}





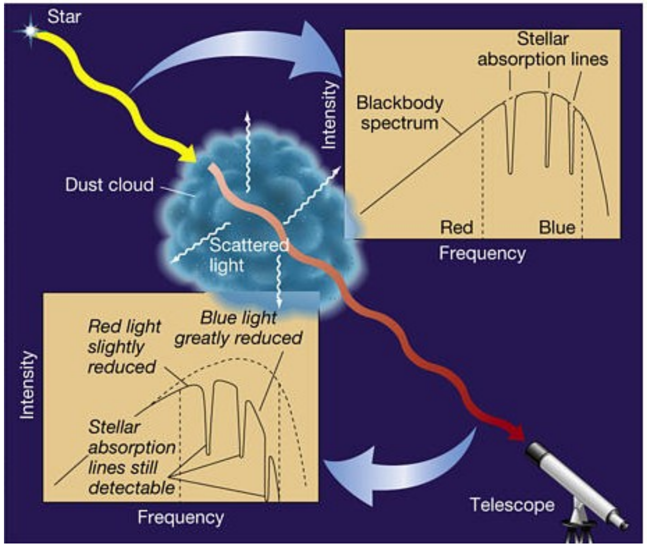
Observed curves of interstellar extinction for four different objects (Milky Way, Large Magellanic Clouds, Small Magellanic Cloud).

The shapes of the curves connect with the chemistry of the observed ISM.

Interstellar absorption (reddening)

Interstellar radiation is observed to become more red with distance (nothing to do with redshift!), because small wavelengths are scattered and absorbed easier from the interstellar dust particles.

In reality, objects are “de-blued”.



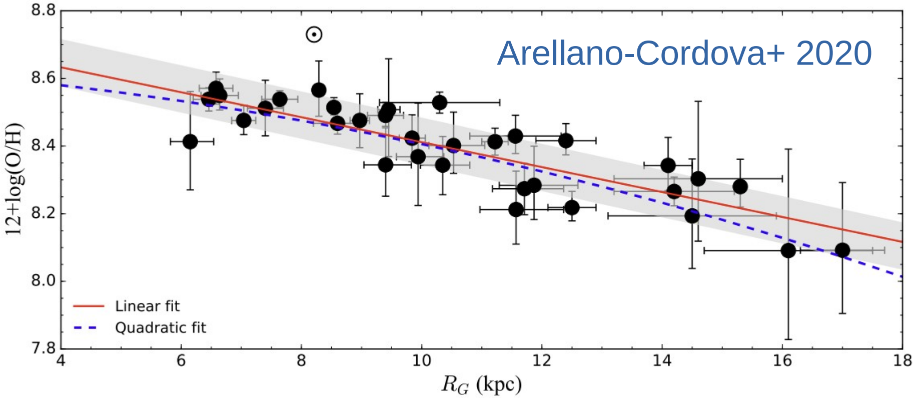
Metallicity

The *metallicity* (Z) of an object describes the fraction of all chemical elements that it consists of, except for hydrogen and helium. In Astrophysics/Astrochemistry, we call metals all elements *except* H and He.

$$Z = \sum_{i>\mathrm{He}} \frac{m_i}{M} = 1 - X - Y$$

Solar metallicity: the chemical composition of the Sun (Asplund+ 2009)
X = 0.73 (hydrogen)
Y = 0.25 (helium)
Z = 0.02 (metals)

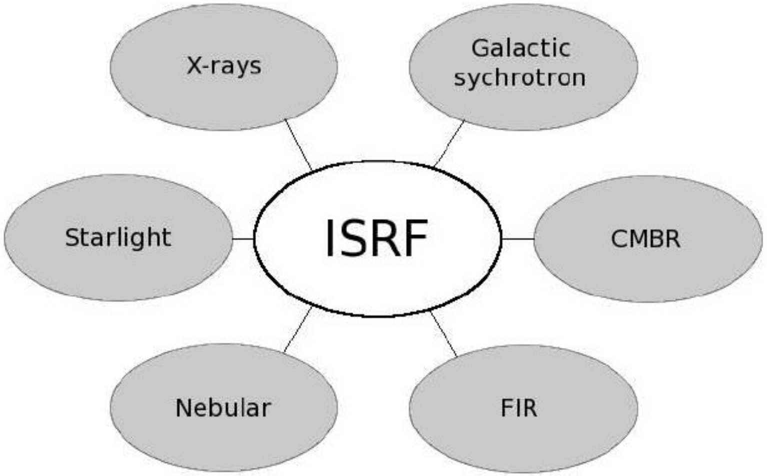
The chemical composition of the ISM depends on various parameters. For example, a supernova explosion enriches the ISM with metals. The ISM of the Early Universe had very small amount of metals, therefore its metallicity was much lower than the solar value.



Metallicity decreases as a function of the Galactocentric radius.

In the Galactic Center, metallicity is observed to be $Z=2Z_{\odot}$ (Giveon+ 2002)

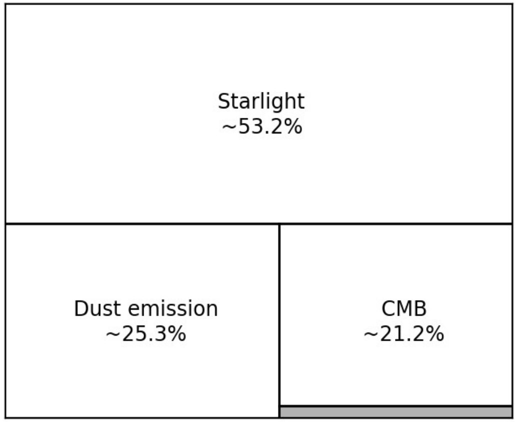
Interstellar Radiation Field (ISRF)

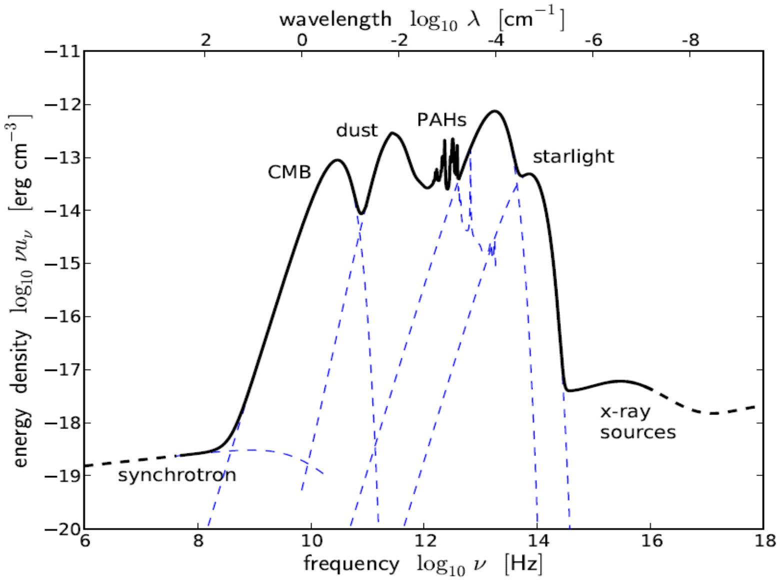


ISRF is divided typically in six components:

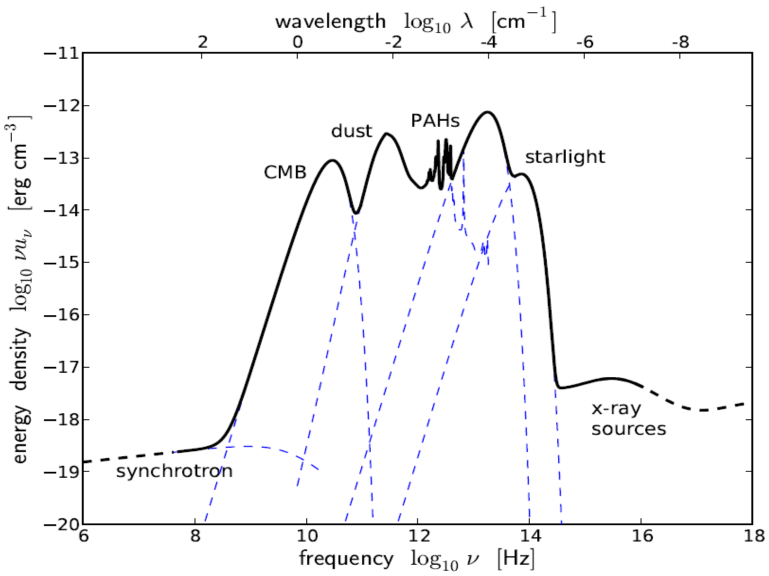
- Xrays: very high energy radiation able to penetrate high column densities (SNe, accretion in SMBH)
- Galactic sychrotron: produced when charged particle propagate in magnetic fields
- Nebular: energy/light emitted from nebulae
- Starlight, FIR, CMBR (see next slides)

Percentage of the most important components





Interstellar Radiation Field (ISRF)



CMB Radiation

$$T_{\rm CMB} \propto (1+z)$$
$$u_{\rm CMB} \propto (1+z)^4$$

Plays important role in the Early Universe

Dust emission in IR (FIR)

$$J_\nu \propto B_\nu(T_0)\left(\frac{\nu}{\nu_0}\right)^\beta$$
$$\langle T_{\rm d}\rangle \approx 20\ {\rm K} \quad \beta \approx 1.7$$

Average MW values

Starlight

$$\nu u_\nu = \sum_{i=1}^{3} \frac{8\pi h\nu^4}{c^3}\frac{W_i}{e^{h\nu/k_{\rm B}T_i}-1}\ {\rm erg\,cm^{-3}}$$
$$T_1 = 3000\,{\rm K},\ \ W_1 = 7.0\times10^{-13}\,,$$
$$T_2 = 4000\,{\rm K},\ \ W_2 = 1.65\times10^{-13}\,,$$
$$T_3 = 7500\,{\rm K},\ \ W_3 = 1.0\times10^{-14}\,.$$

Mathis+ (1983) summation of three BB

$$G_0 \equiv \frac{u(6-13.6\,{\rm eV})}{5.29\times10^{-14}\,{\rm erg\,cm^{-3}}}$$ Habing (1968)

$$\chi_0 = 1.69 G_0$$ Draine (1978)

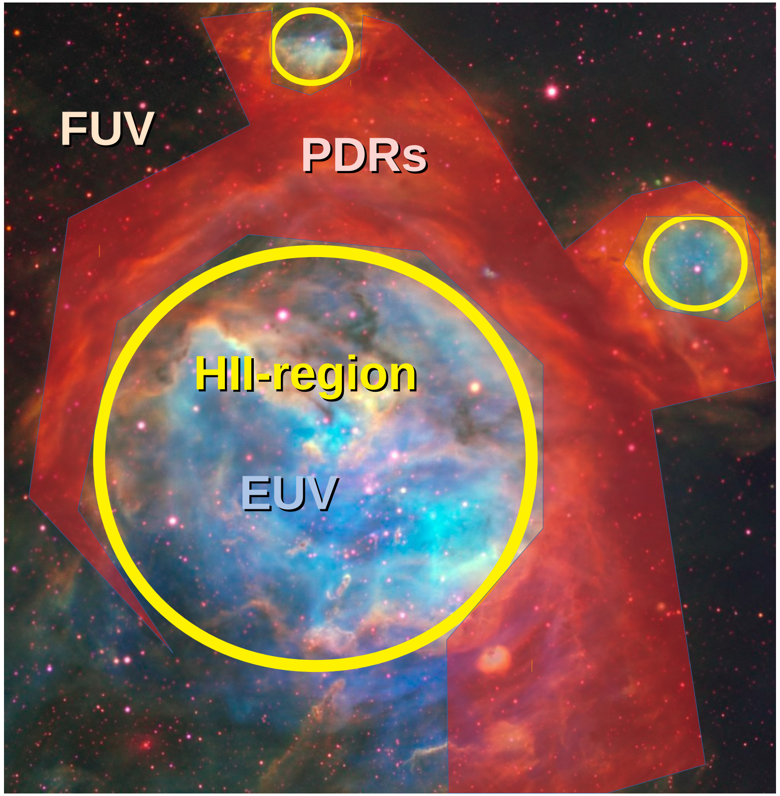
Interstellar Radiation Field (ISRF)

Extreme-ultraviolet (EUV): $h\nu \geq 13.6\,\mathrm{eV}$

Far-ultraviolet (FUV): $6 < h\nu < 13.6\,\mathrm{eV}$

The region around a bright source (e.g. a massive star) is rich in high energy radiation (EUV) which ionizes the surrounding medium, called an ‘**HII-region**’.

As radiation extinguishes and loses energy (due to absorption and diffusion), it loses the ability of ionizing the environment. However, it is still important as it controls the chemistry of the interstellar medium, in regions known as `**Photodissociation Regions**’ or **PDRs**.



Cosmic-rays

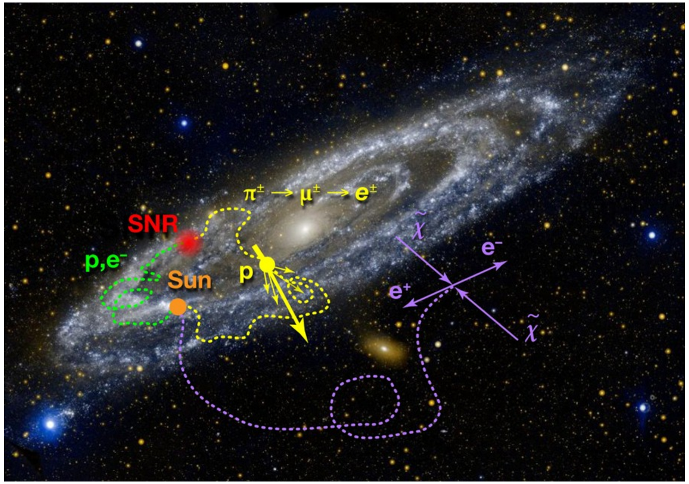
Cosmic-rays are NOT rays! They are not electromagnetic radiation but rather relativistic charged particles with energies of a few hundreds of MeV. The cosmic-ray energy density in the Milky Way is *on average* 1eV/cm^3. They were discovered by Viktor Hess in 1912.

Viktor Hess in the balloon (1911-1912). 24 years later he received the Nobel Prize for his discovery.

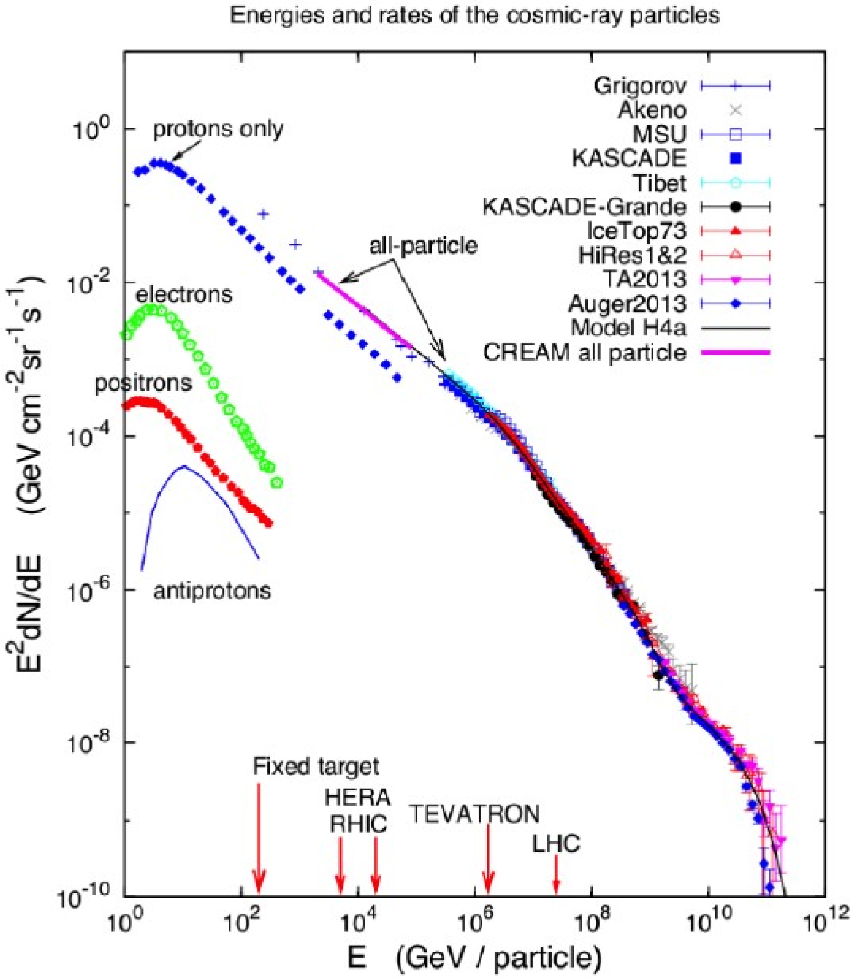
Cosmic-rays consist mainly of:

- ~90% protons
- ~9% Helium nuclei
- ~1% of nuclei heavier than Helium

Since they are charged particles, they follow the magnetic field lines of the Galaxy. In general, every particle of high energy is considered a cosmic-ray particle. It is almost impossible to accurately identify their origin.



Cosmic-rays



- With the exception of high energy particles, all the rest follow the magnetic field lines of our Galaxy
- The energy of cosmic-rays is *isotropic*.
- The most important component in ISM heating (see later slides) is CR particles of ~100MeV or less.
- The Heliosphere of our Solar System does not allow CR particles to penetrate further, so studying them observationally is almost impossible.
- It is expected that CR particles of lower energy are more important for igniting chemical reactions deep in the clouds.

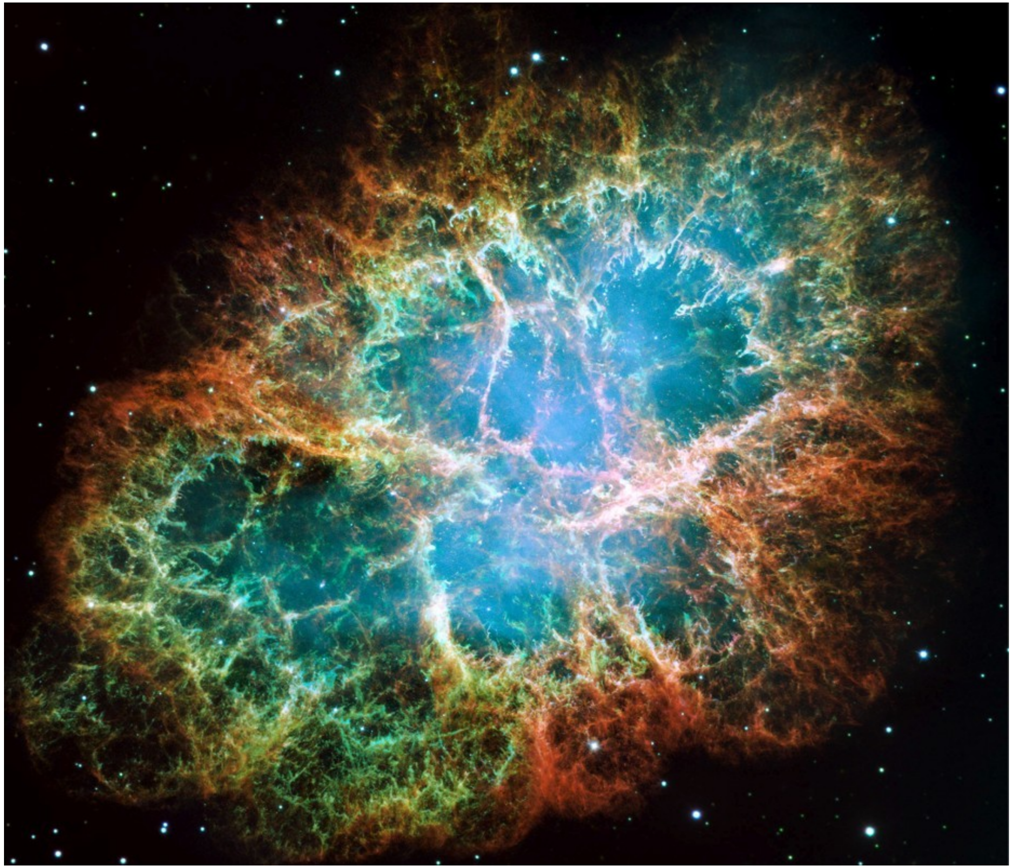
Cosmic-rays

The origin of CR particles in our Galaxy is not well understood. It is believed that supernova explosions play an important role in the acceleration of charged particles.

During a supernova explosion, gas moves at highly supersonic speeds (relative to the sound speed of the neutral medium). This forms a strong shock front (see later slides).

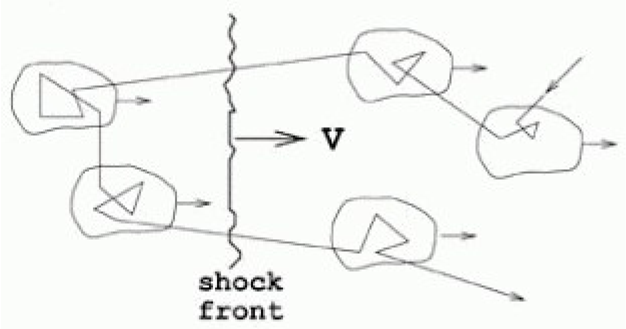
The shock front interacts with the charged particles and accelerates them. This is because during the expansion of the shock front, the particles suffer many head-on collisions.

The above mechanism is known as “Fermi mechanism” or “diffusive shock acceleration”.



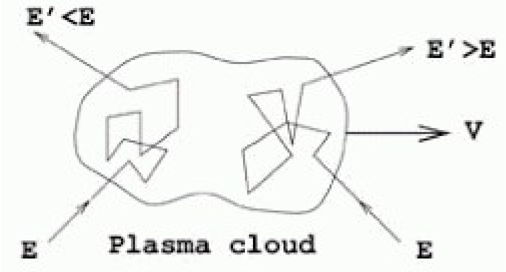
Crab nebula

Cosmic-rays acceleration mechanisms



1st order: supernova shock fronts

Fast mechanism, very efficient



2nd order: magnetic mirror (moving clouds)

Slow mechanism, not very efficient

Cosmic-ray particles are able to penetrate and even ionize the gas in an interstellar cloud, at a *statistically constant rate* known as **cosmic-ray ionization rate**, denoted as ζ_{CR}.

Measuring the cosmic-ray ionization rate

Chemistry and cosmic-rays

$$H_2 + CR \rightarrow H_2^+ + e^-,$$
$$H_2^+ + H_2 \rightarrow H_3^+ + H,$$
$$\boxed{H_3^+ + e^- \rightarrow \text{various products}}$$

This is a very important reaction! It ignites rich chemical networks and it is responsible for the chemistry of molecular clouds.

Measuring the ζ_{CR} value in our Galaxy

$$n_{H_3^+} = \frac{\zeta_{H_2}}{k_{dr}}\frac{n_{H_2}}{n_e} \rightarrow N_{H_3^+} = \frac{\zeta_{H_2}}{k_{dr}}\frac{N_{H_2}}{N_e} \rightarrow N_{H_3^+} = \frac{\zeta_{H_2}}{k_{dr}}\frac{N_{H_2}}{N_{C+}}$$

k_{dr}: dissociative rate coeff.

Assuming uniform-density

Assuming $N_e \sim N_{C+}$

$$\rightarrow \boxed{\zeta_{H_2} = \frac{N_{H_3^+} N_{C+} k_{dr}}{N_{H_2}}}$$

Typical value of our Galaxy $\boldsymbol{\zeta_{CR} \sim 10^{-16}}$ **[s^{-1}]** (Dalgarno 2006)

Typical value in the solar neighborhood $\boldsymbol{\zeta_{CR} \sim 10^{-17}}$ **[s^{-1}]** (Cummings+ 2015), from direct measurements of the Voyager-1 spacecraft.

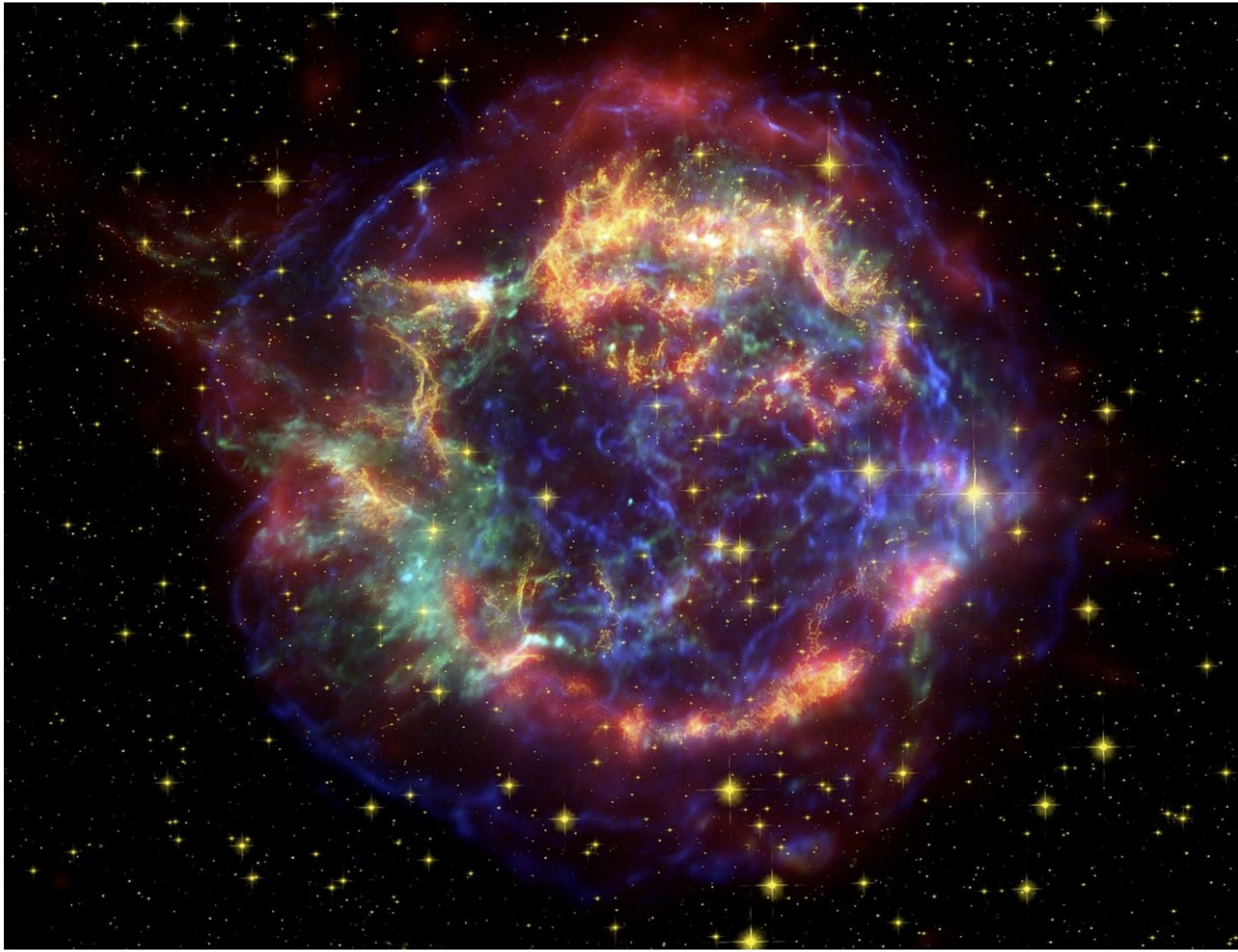
X-rays in the ISM

Cosmic protons and X-rays can ionize a hydrogen atom according to the reaction:

$$(p,X) + HI \rightarrow (p', X') + HII + e$$

X-rays have very high energy. Electrons that are produced through ionizations, can also produce ionizations themselved (secondary ionizations) deep inside molecular clouds.

X-rays and cosmic-rays are important factors for the chemistry and the heating at high column densities (implying high number densities).



Cas-A supernova remnant. Red: infrared (*Spitzer*). Gold: visible (*Hubble*). Blue & green: X-rays (*Chandra*). Small blue dot in the center: star’s core remnant

Interstellar dust particles

Interstellar dust particles form:

- In the environment of a dense and relatively cold medium
- In the envelopes (atmospheres) of red giants through i) radiation pressure, ii) stellar wind
- In dying stars and stellar explosions

Every dust particle stars as carbon / silicate.

They have sticky surface (sticking efficiency) which helps the formation of molecules.

They interact with FUV radiation and they emit back in IR.

<u>Properties</u>

Adsorption: atoms “stick” in the surface because during the collision they lose energy absorbed by the dust

Scanning/Mobility: atoms can move around the surface of the dust particle, creating reactions (Langmuir-Hinshelwood mechanism)

Desorption, liberation of molecules:
micro-continuous → liberation due to exothermic reactions
macro-continuous → rapid liberation (e.g. cosmic-rays)
violent-desorption → destruction of dust particles from shock waves

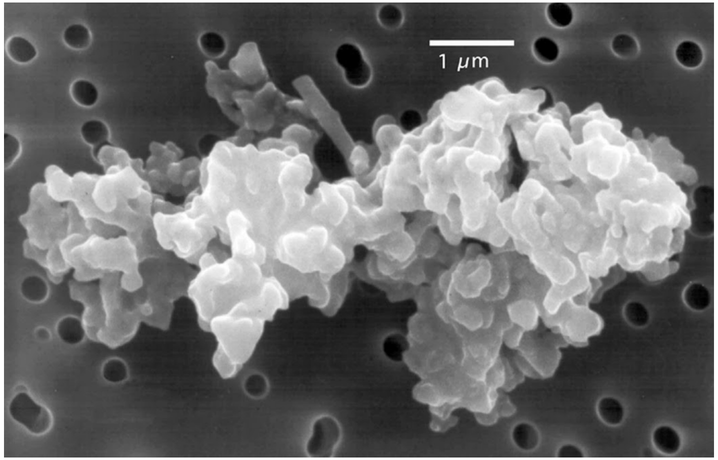
Interstellar dust particles

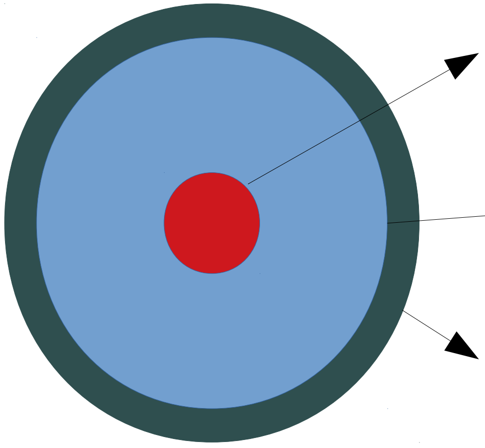
Nature of dust particles: they are solid bodies, macroscopic molecules from dielectric and strong material. It has similar properties to solid bodies.

Emission: thermal emission in infrared (mid-to-far IR)

An atom will stick in the surface of a dust particle if it collides with it and it does not have enough energy, through:

- Chemisorption (valence forces)
- Physisorption (van der Waals forces)

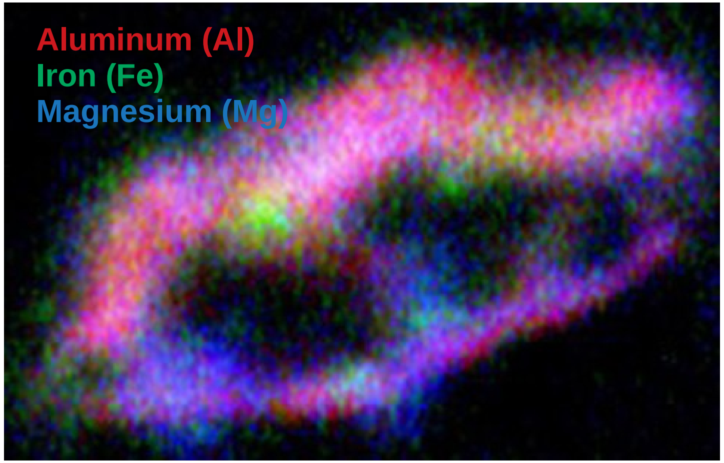




Nucleus
L~0.05μm
Si, Fe, C etc.

Mandle
L~0.5μm
CO_2, H_2O, CH_2, NH_3 etc.

Outer shell
Other molecules, organic material



The formation of water on interstellar dust particles

prof. Ewine F. van Dishoeck, PhD, A.L.M. “Thanja” Lamberts, MSc

Universiteit Leiden
The Netherlands

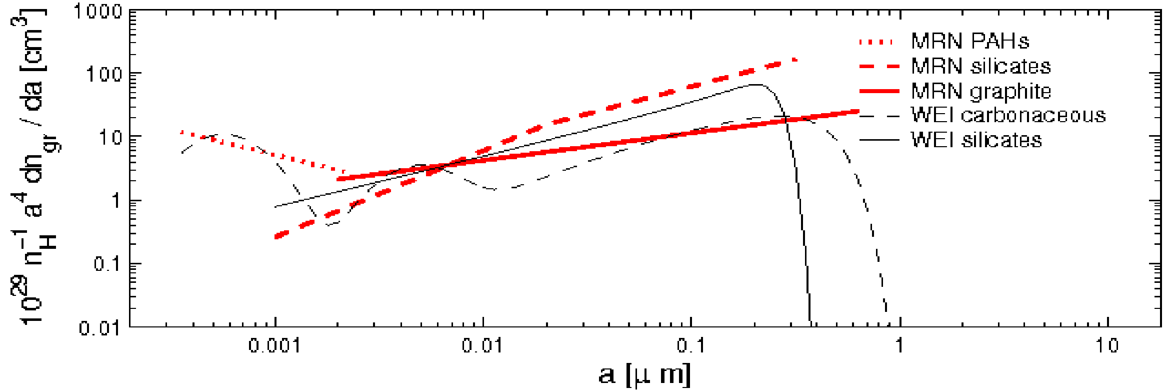
Interstellar dust particles

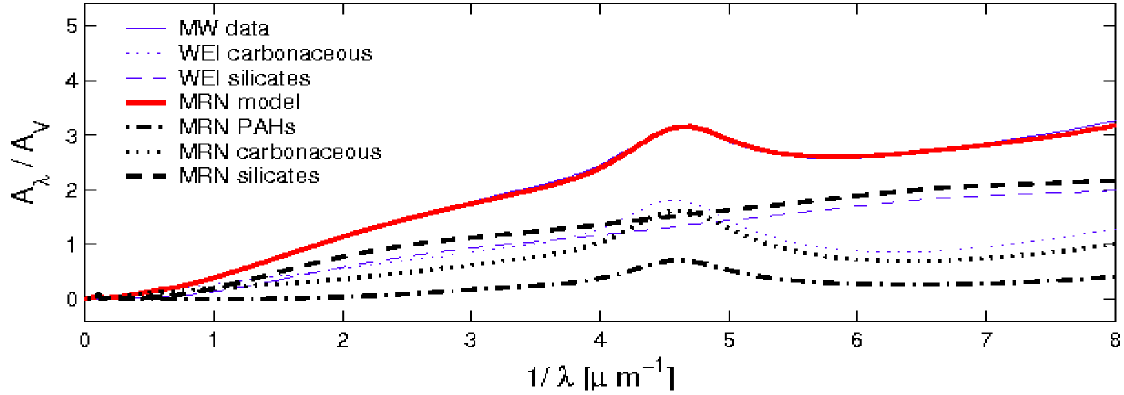
$N(a)da \propto a^{-3.5}da$, MRN distribution (Mathis, Rumpl & Nordsieck 1977)

The MRN distribution correlates the population of dust particles according to their size, α (from 50nm to 0.25μm)

It is the most widely used distribution and explains very the extinction curve of the Milky Way for 0.1 – 1μm.

Gas-to-dust ratio: 100





Dust in the Andromeda galxay

Spitzer Space Telescope

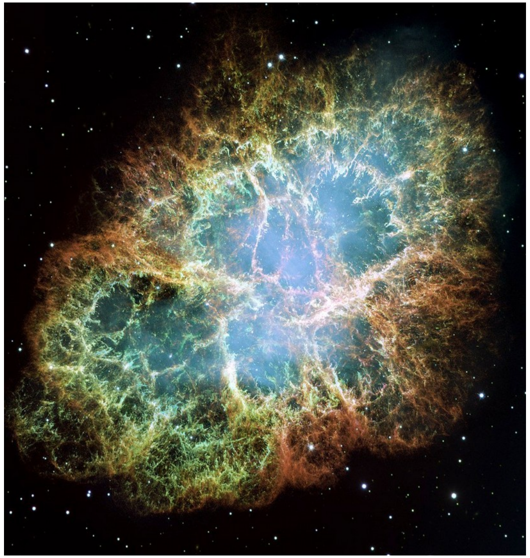
Dust in the solar system
(Gegenschein)

Physics of HII regions

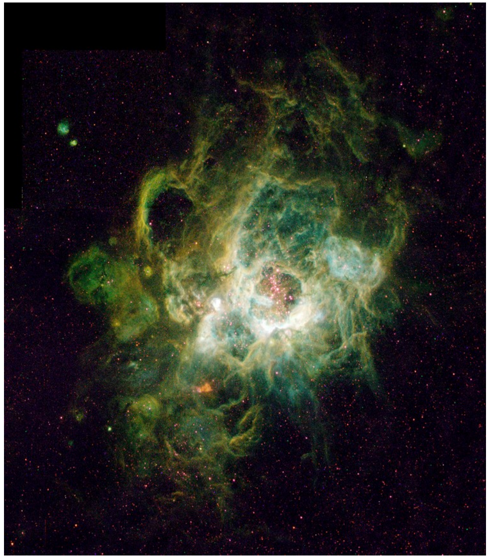
Nebulae

Reflection Nebula
The Witch Head (IC 2118)

Planetary Nebula
Southern Ring Nebula

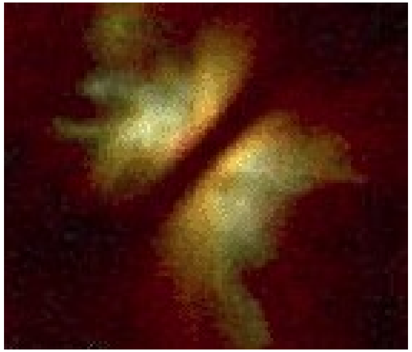


Supernova remnant
The Crab Nebula (M1)

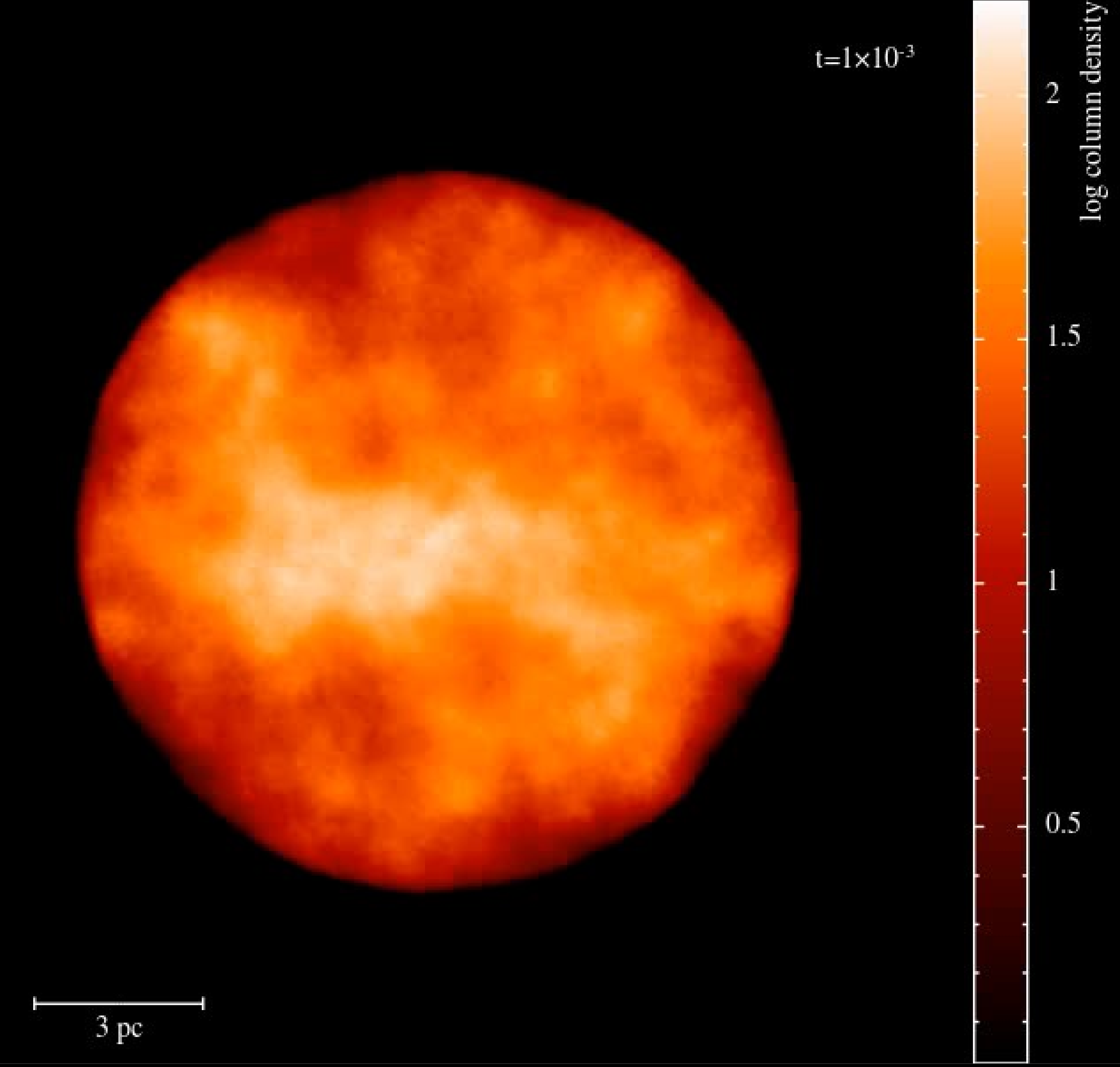


HII regions
NGC 604

Dark Nebula
Barnard 68

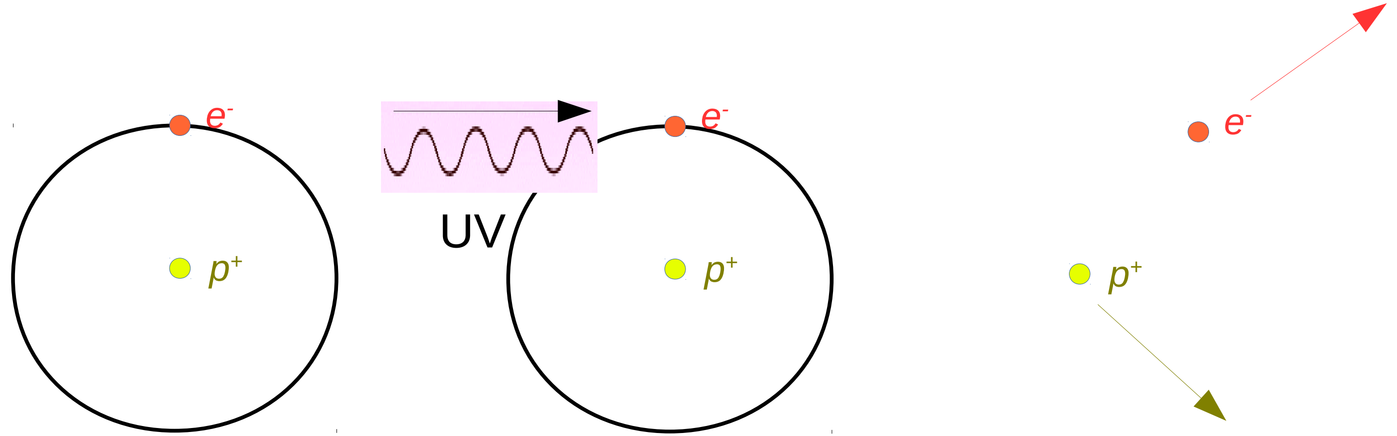


Young Stellar Object
(YSO)



t=1×10-3
log column density
2
1.5
1
0.5
3 pc

Photoionization and Recombination



$$H_2 \longrightarrow 2\,\mathrm{H\,I} - 4.5\,\mathrm{eV}$$

$$\mathrm{H\,I} \longrightarrow \mathrm{H\,II} + e^- - 13.6\,\mathrm{eV}$$

Photoionisation: the removal of electrons from gas atoms by photons.

For Hydrogen (most abundant atom) photons need to have an energy of *at least* **13.6 eV** (corresponding to λ < **912 Å**)

13.6 eV therefore = the "Ionisation Potential" of Hydrogen
= called **one Rydberg**

Only stars with T > 20 000 K (*spectral types O and B*) emit 'ionising' photons

ISM = low density
All Hydrogen is assumed to be in ground state (n = 1)
We only need to consider photoionisation from n = 1 state

Recombination: Attraction between protons and electrons leads to the recapture of the electron.

The on-the-spot approximation

When electrons and protons recombine to form hydrogen atom, the electron may either recombine directly to the ground state (n=1). This recombination creates a photon which has energy equal to the UV photon (91.2 nm). This photon may interact with a nearby hydrogen atom and it can therefore ionize it.

This process of recombination **directly** down to n=1 state (and *only* to that state!) produces UV radiation, called **diffuse radiation**.

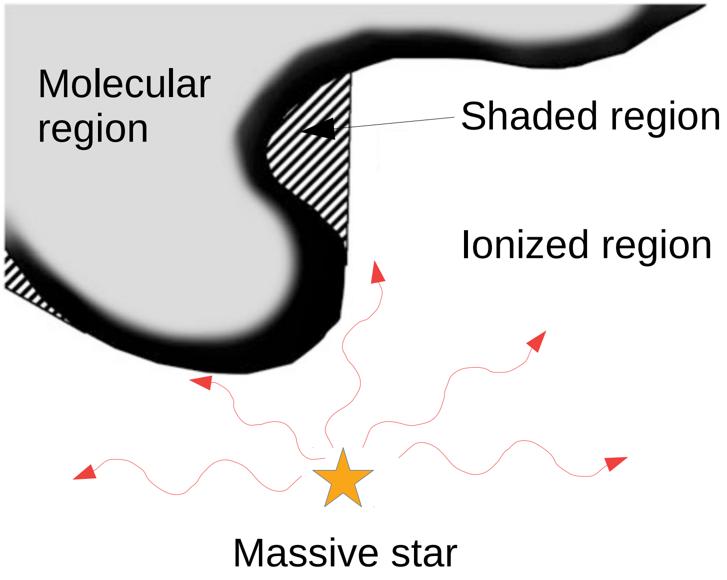
When examining equilibrium in ionized regions, it is convenient to *neglect* recombinations down to n=1 state. By neglecting them we then take into account all other possible recombination cases (i.e. to n=10 and then down to n=3 or n=1 etc.) until the electron finally falls back to the ground state. This approximation of recombinations to excited states only is called **on-the-spot approximation**.

$$\alpha_{\mathrm{A}} = \sum_{N=1}^{\infty} \alpha_N(\mathrm{HI}, T)$$

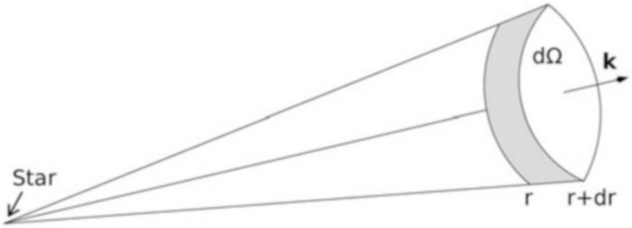
$$\alpha_{\mathrm{B}} = \alpha_{\mathrm{A}} - \alpha_1(\mathrm{HI}, T) = \sum_{\mathrm{N}=2}^{\infty} \alpha_N(\mathrm{HI}, T)$$

$$\alpha_{\mathrm{B}} \simeq 2.7 \times 10^{10} \left(\frac{T}{[\mathrm{K}]}\right)^{-3/4} \mathrm{cm}^3\,\mathrm{s}^{-1}$$

Assuming $T=10^4$ K $\boxed{\alpha_{\mathrm{B}} = 2.7 \times 10^{-13}\,\mathrm{cm}^{-3}\,\mathrm{s}^{-1}}$



Photoionization equilibrium



Consider the element of volume defined by the infinitesimal solid angle $d^2\Omega$ about the unit vector **k** (as seen from the ionizing source) and the infinitesimal range of radii (r, $r+dr$), as measured from the star. If the number flux of ionizing photons in the direction **k** is $\dot{N}(r)$, then the equation of ionization balance gives:

$$\dot{N}(r)r^2d^2\Omega = \underbrace{\alpha_B n^2(r)r^2d^2\Omega dr}_{\text{Photons have fully ionized this material}} + \underbrace{\dot{N}(r+dr)\cdot(r+dr)^2d^2\Omega}_{\text{Remaining photons propagate}}$$

$$\dot{N}(r+dr)(r+dr)^2 - \dot{N}(r)r^2 = -\alpha_B n^2(r)r^2dr$$

$$\dot{N}(r+dr)(r+dr)^2 - \dot{N}(r)r^2 = \frac{d}{dr}\left(\dot{N}(r)r^2\right)dr$$

$$d(\dot{N}(r)r^2) = -\alpha_B n^2(r)r^2dr$$

$$\boxed{\dot{N}(r)r^2 = \frac{\dot{N}_\star}{4\pi} - \alpha_B\int_0^r n^2(r)r^2dr}$$

<u>Photoionization balance condition</u>

Ionizations = Recombinations

Strömgren sphere

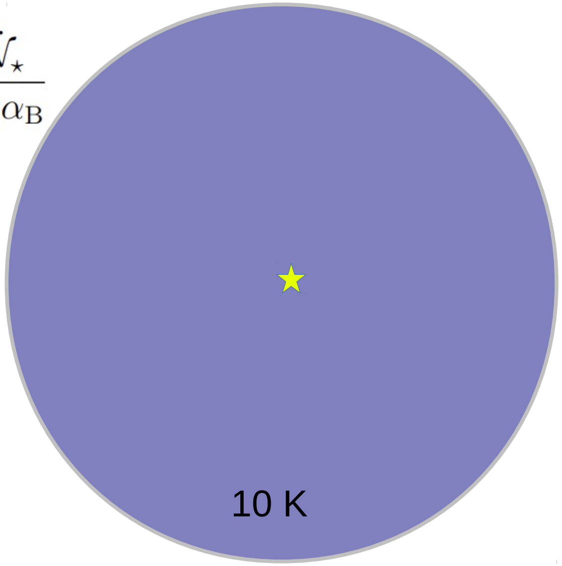
Suppose that you have a uniform density medium and that you switch on an ionizing source in its centre (which, say, defines the centre of a co-ordinate system). Then the ultraviolet photons emitted by the star will ionize a spherical region around it.

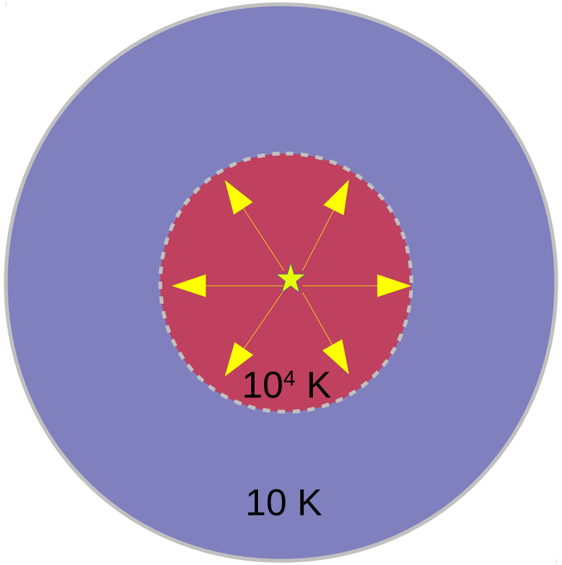
Inside this sphere the material is ionized and the rate of ionizations matches the rate of recombinations. In other words, there is a photoionization balance.

The HII region is maintained by the continual reionization of recombined HI atoms due to the flux of ultraviolet photons from the central star. This spherical HII region, is called **Strőmgren sphere**.

$$0 = \frac{\dot{\mathcal{N}}_\star}{4\pi} - \alpha_\mathrm{B} \int_0^{R_\mathrm{IF}} n^2(r) r^2 dr \Rightarrow \int_0^{R_\mathrm{IF}} n^2(r) r^2 dr = \frac{\dot{\mathcal{N}}_\star}{4\pi\alpha_\mathrm{B}}$$

$$R_\mathrm{Str} \equiv R_\mathrm{IF} = \left(\frac{3\dot{\mathcal{N}}_\star}{4\pi\alpha_\mathrm{B} n_0^2}\right)^{1/3}$$





Example

An OB star emits ionizing photons at a rate of $\dot{\mathcal{N}}_\star = 10^{49}\,\mathrm{s}^{-1}$. *Around the star there is a uniform cloud of neutral hydrogen and density* $n_0 = 10\,\mathrm{cm}^{-3}$. *The case-B recombination coefficient is* $\alpha_\mathrm{B} = 2.7\times10^{-13}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$ *Find the Strömgren radius.*

$$R_\mathrm{Str} \equiv R_\mathrm{IF} = \left(\frac{3\dot{\mathcal{N}}_\star}{4\pi\alpha_\mathrm{B} n_0^2}\right)^{1/3}$$

$$\boxed{R_\mathrm{Str} = \left(\frac{3\cdot10^{49}}{4\pi\cdot2.7\times10^{-13}\cdot10^2}\right)^{1/3} \Rightarrow R_\mathrm{Str}\sim14.4\,\mathrm{pc}}$$

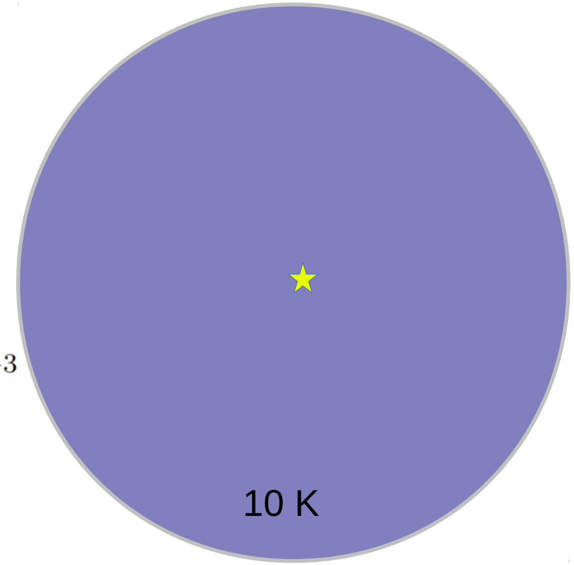
It is interesting to investigate how sharp the initial HII region is. The mean free path of photons in the area where ionization is 50% is

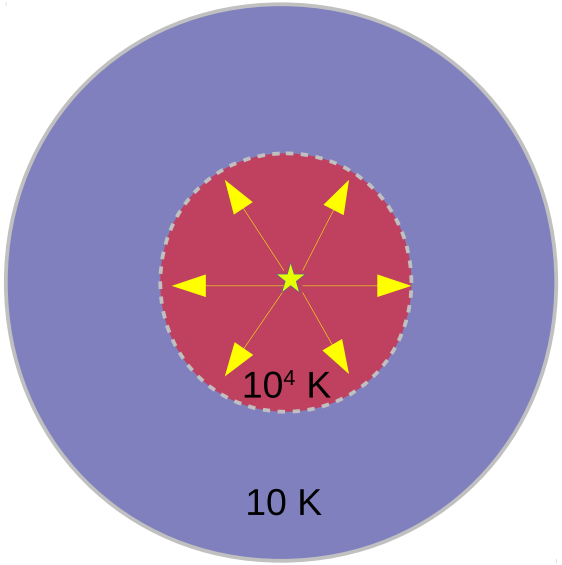
$$\ell = \frac{1}{\bar{\sigma} n_\mathrm{HI}}$$

where $\bar{\sigma} = 6.3\times10^{-18}\,\mathrm{cm}^2$ is the photoionization cross section and n_{HI} is the number density of neutral hydrogen. In the area with 50% ionization degree, we obtain $n_\mathrm{HI} = 0.5\cdot n_0 = 5\,\mathrm{cm}^{-3}$

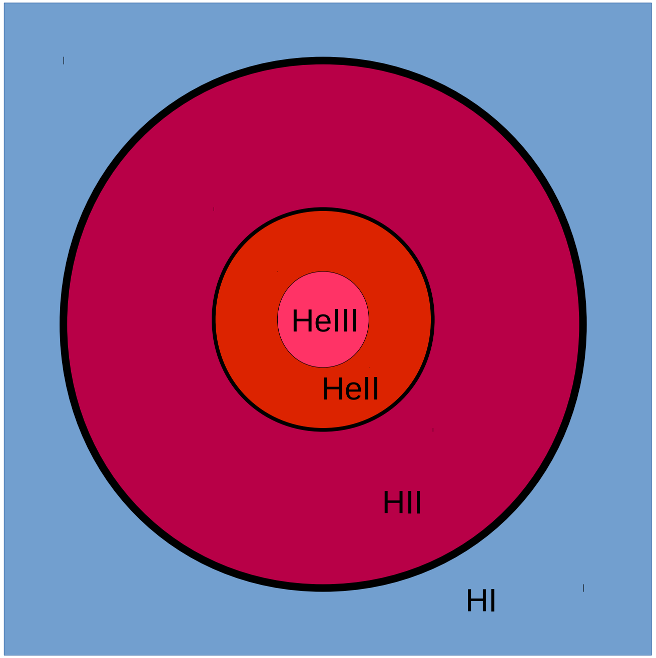
Thus $\boxed{\ell\sim0.01\,\mathrm{pc}}$

The edge of an HII is very sharp!





What about helium?



If the ionizing star produces sufficient energy, then it can also ionize Helium. Helium can be found in either singly ionized form (HeII) or doubly ionized form (HeIII).

Since the double ionization of Helium requires much more energy than the single ionization, HeIII is found only in the vicinity of the star.

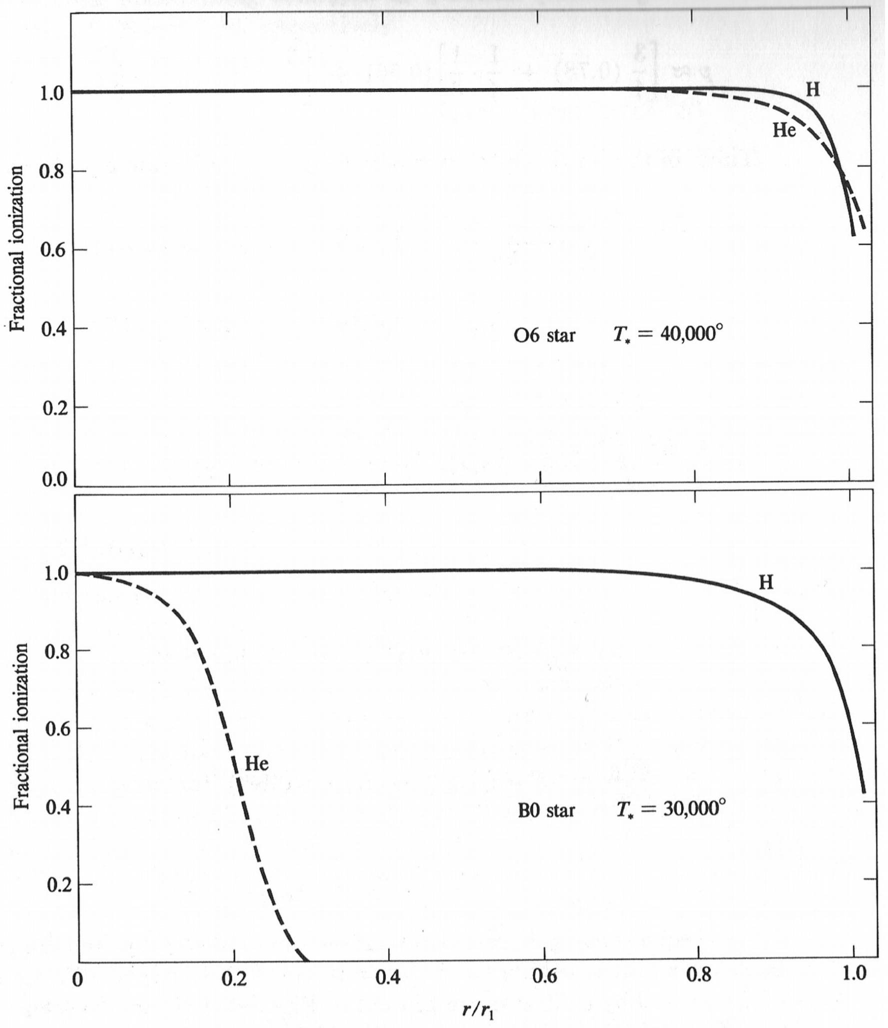
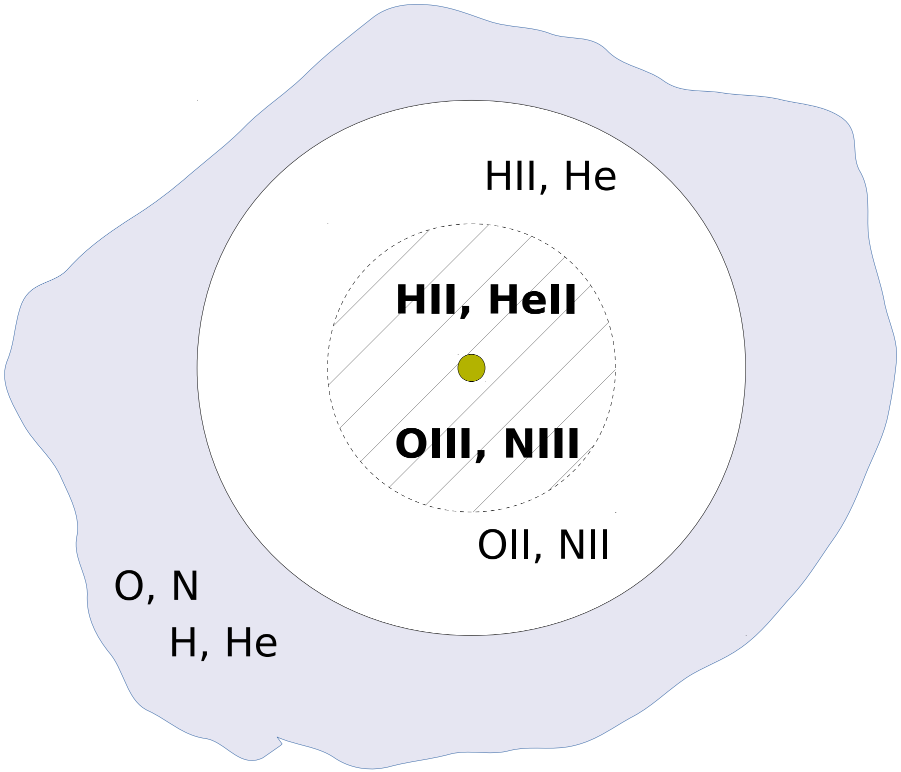
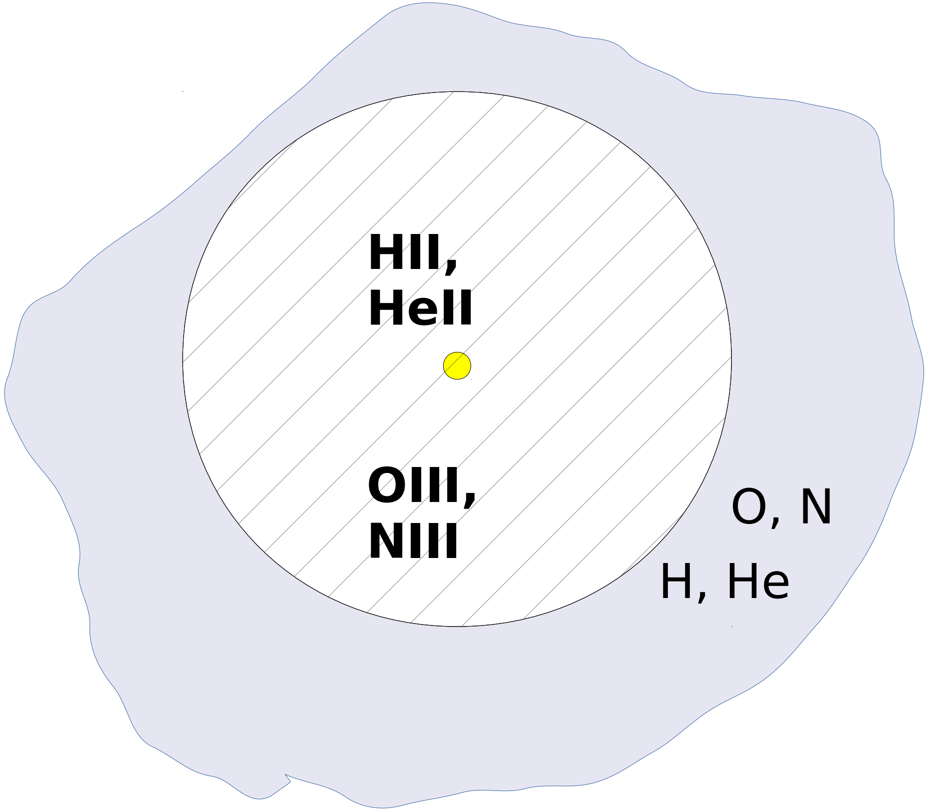


FIGURE 2.4
Ionization structure of two homogeneous H + He model H II regions.

Distribution of ions of heavy elements

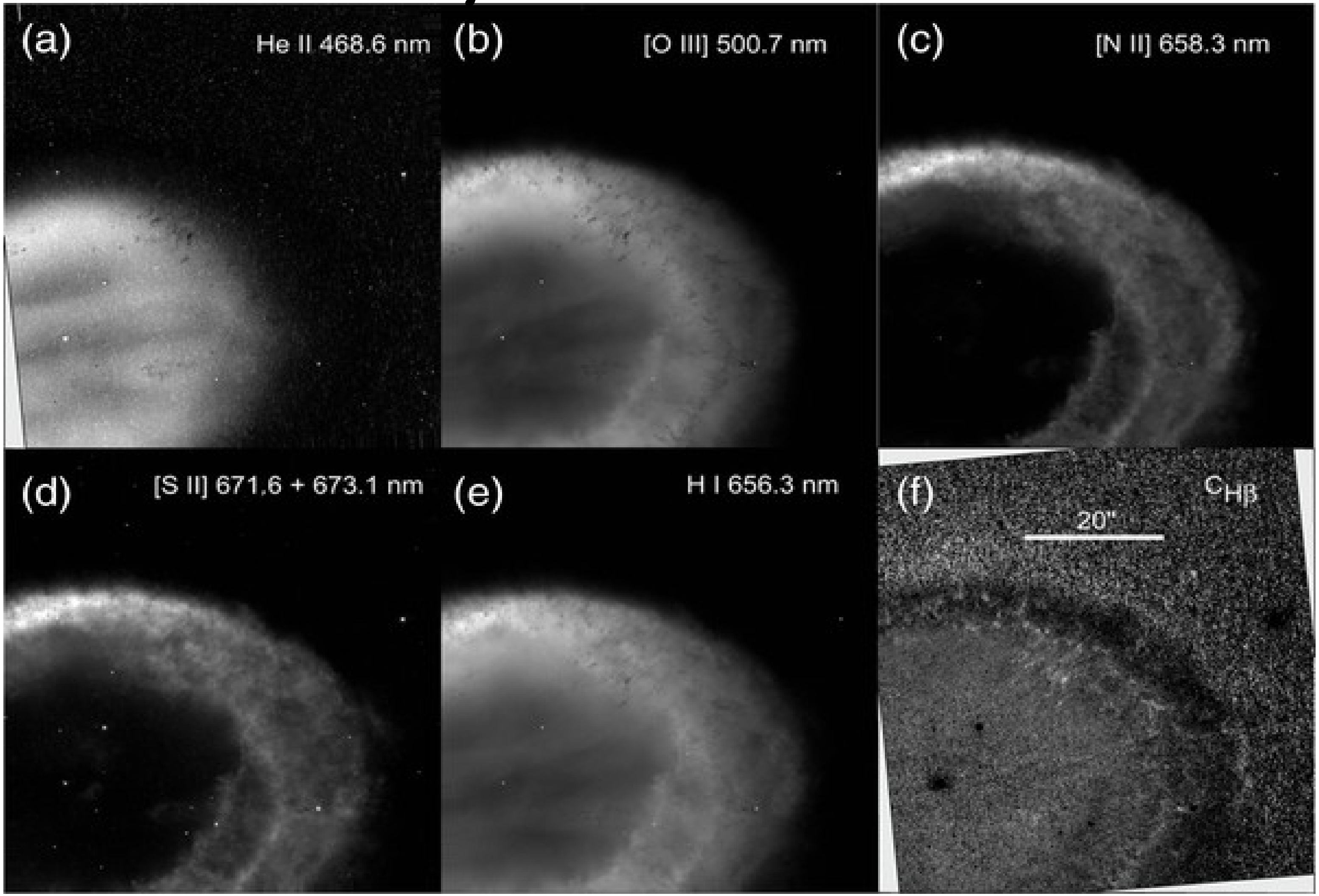


$T_* < 40{,}000$ K



$T_* > 40{,}000$ K

Distribution of ions of heavy elements



R-type expansion: how fast does a Strömgren sphere form?

The speed at which the Stromgren sphere forms is so fast that the gas cannot respond hydrodynamically

R-phase: R → Rarefied

The gas is **not** in photoionization balance. Therefore: $\dot{N}_{\rm surplus} = \dot{N}_\star - \frac{4\pi}{3} r_{\rm IF}^3 \alpha_{\rm B} n^2$

This equation tells us that the remaining photons are equal to those that the star emits minus the absorbed ones. The remaining photons cause ionizations in an expanding sphere with volume: $4\pi r_{\rm IF}^2 dr_{\rm IF}/dt$ **No hydro expansion!**

We can therefore write: $\dot{N}_{\rm surplus} = 4\pi n r_{\rm IF}^2 \frac{dr_{\rm IF}}{dt}$

Combining the the first and the above equations we get: $4\pi n r_{\rm IF}^2 \frac{dr_{\rm IF}}{dt} = \dot{N}_\star - \frac{4\pi}{3} r_{\rm IF}^3 \alpha_{\rm B} n^2$

If we solve the equation $R_{\rm Str} \equiv R_{\rm IF} = \left(\frac{3\dot{N}_\star}{4\pi\alpha_{\rm B} n_0^2}\right)^{1/3}$ for $\dot{N}_\star$ and we replace it to the above, we end up with:

$$\boxed{r_{\rm IF}(t) = R_{\rm Str}\left(1 - e^{-n\alpha_{\rm B} t}\right)^{1/3}}$$

$t_{\rm rec} = (n\alpha_{\rm B})^{-1}$

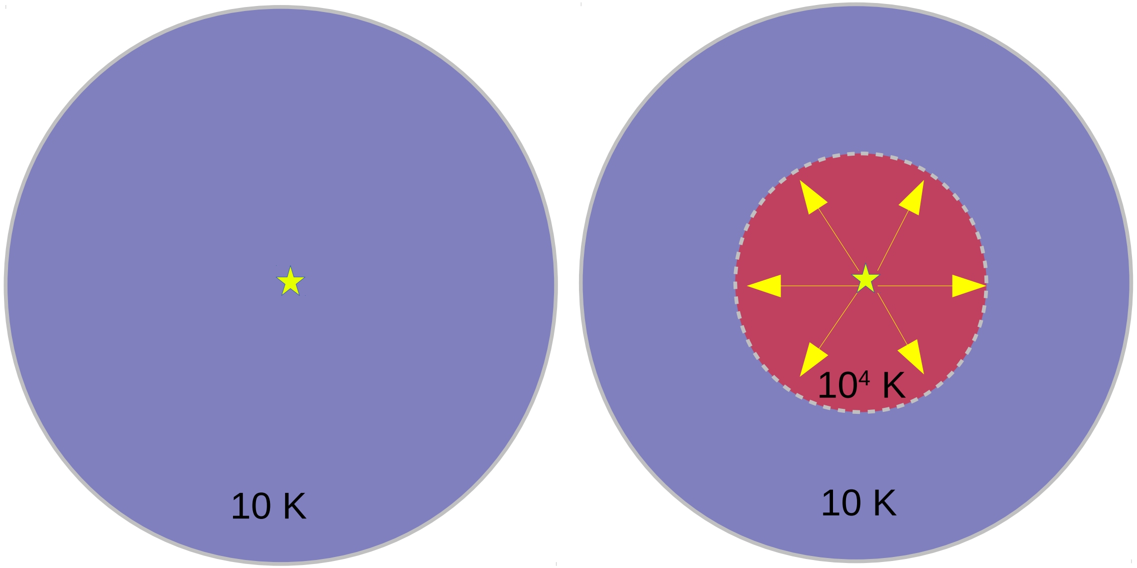
Recombination time

The R-type will end when $e^{-n\alpha_{\rm B} t} \sim 0$ which in practice happens when $t \sim 3/n\alpha_{\rm B}$. So it terminates within $3t_{\rm rec}$

Example (cont.)

In the previous example, the cold medium had density of $n_0 = 10\,\mathrm{cm}^{-3}$

The recombination time is 11.7 kyrs, therefore the R-type will terminate in $t \sim 3t_{\rm rec} = 3(n\alpha_{\rm B})^{-1} \sim 35\,\mathrm{kyr}.$



D-type expansion

As long as the R-type terminates, a sphere with density *n* and with temperature of 10^4 K will form. This sphere will be embedded in interstellar gas of a much lower temperature (we assume here the ISM has the same density, *n*). Since the two densities are equal, there will be an enormous difference in thermal pressures, causing the ionized sphere to expand. This expansion is *hydrodynamical* and it defines the start of the D-type phase (D: Dense).

In a hypothetical cloud consisting of pure hydrogen (μ=1, mean molecular mass) and with temperature 10 K, the sound speed is $\boldsymbol{c_o \sim 0.2}$ **km/s**. In the ionized medium (μ=0.5) and with temperature 10^4 K, the sound speed is $\boldsymbol{c_i \sim 12.8}$ **km/s**. The expanding velocity of the ionization front (IF) is supersonic compared to c_o. This results in the formation of a shock front (SF) ahead of the IF.

From photoionization balance equation, $\dot{N}(r)r^2 = \frac{\dot{\mathcal{N}}_\star}{4\pi} - \alpha_{\rm B}\int_0^r n^2(r)r^2 dr$, we obtain $\dot{\mathcal{N}}_\star = \frac{4\pi}{3}a_{\rm B}n_o R_{\rm Str}^3 = \frac{4\pi}{3}a_{\rm B}n_i(t)R_{\rm IF}^3(t)$

Solving for n_i, we obtain: $n_i(t) = n_o\left(\frac{R_{\rm Str}}{R_{\rm IF}(t)}\right)^{3/2}$

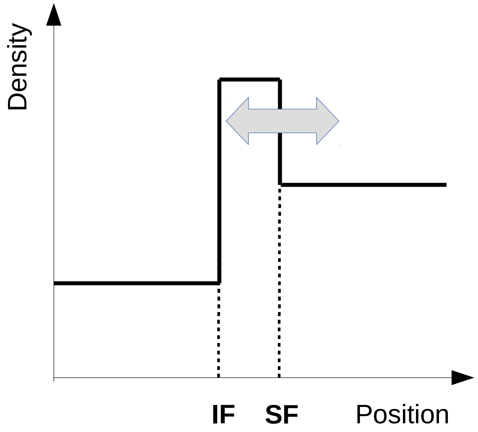
The ionized mass is: $M_i(t) = \frac{4\pi}{3}n_o R_{\rm Str}^{3/2}R_{\rm IF}^{3/2}(t)$

There are two approaches for finding the equation of motion of the ionization front, giving two different results (see Bisbas et al. 2015 for a review of these). Hydrodynamical simulations have shown that HII-regions expand in a different way, mimicking a dumping oscillator until they reach a stagnation radius $R_{\rm STAG}$ at which D-type terminates.

Approach I and the "Spitzer equation"

By assuming the thin shell approximation and by equating the pressure of the neutral gas in the shell between the ionization front and the shock front with the ram pressure of the undisturbed gas as it is swept up by the shock front, we obtain (see Raga et al., 2012b):

"Raga-I equation"
$$\boxed{\frac{1}{c_i}\frac{dR}{dt} = \left(\frac{R_{\rm Str}}{R}\right)^{3/4} - \left(\frac{c_o}{c_i}\right)^2 \left(\frac{R_{\rm Str}}{R}\right)^{-3/4}}$$



When the HII-region starts expanding, R ~ R_{St} and because $\left(\frac{c_o}{c_i}\right)^2 \sim 200^{-1}$ the term $\left(\frac{c_o}{c_i}\right)^2 \left(\frac{R_{\rm Str}}{R}\right)^{-3/4} \sim 0$. The above equation can then be easily integrated:

$$\frac{1}{c_i}\frac{dR}{dt} = \left(\frac{R_{\rm Str}}{R}\right)^{3/4} \Rightarrow \quad \int_0^t dt = \int_{R_{\rm Str}}^{R_{\rm IF}} \left(\frac{R}{R_{\rm Str}}\right)^{3/4} c_i dR$$

leading to $\boxed{R_{\rm IF}(t) = R_{\rm Str}\left(1 + \frac{7}{4}\frac{c_i t}{R_{\rm Str}}\right)^{4/7}}$ This is the so-called "**Spitzer equation**" (Spitzer 1978; Dyson & Williams 1980)

The Spitzer equation is the most commonly used equation for expanding HII regions.

Approach I and the "Spitzer equation" (cont.)

At later times when $R_{\rm IF} \gg R_{\rm Str}$ we need to include all terms in the "Raga-I" equation:

$$\boxed{\frac{1}{c_i}\frac{dR}{dt} = \left(\frac{R_{\rm Str}}{R}\right)^{3/4} - \left(\frac{c_o}{c_i}\right)^2 \left(\frac{R_{\rm Str}}{R}\right)^{-3/4}}$$

The HII-region will expand until it reaches a maximum size. When this happens, $dR/dt = 0$ which leads to:

$$\left(\frac{R_{\rm Str}}{R}\right)^{3/4} = \left(\frac{c_o}{c_i}\right)^2 \left(\frac{R_{\rm Str}}{R}\right)^{-3/4}$$

From this one we find:

$$\begin{aligned} R_{\rm STAG} &= \left(\frac{c_i}{c_o}\right)^{4/3} R_{\rm Str} \\ \rho_{i,\rm STAG} &= \rho_o \left(\frac{c_o}{c_i}\right)^2 \\ M_{i,\rm STAG} &= \frac{4\pi}{3} R_{\rm Str}^3 \rho_o \left(\frac{c_i}{c_o}\right)^2 \end{aligned}$$

Approach II and the “Hosokawa-Inutsuka equation”

In the previous approach, inertia was not taken into account. To include the term for the inertia, we construct the following equation (Raga et al., 2012a):

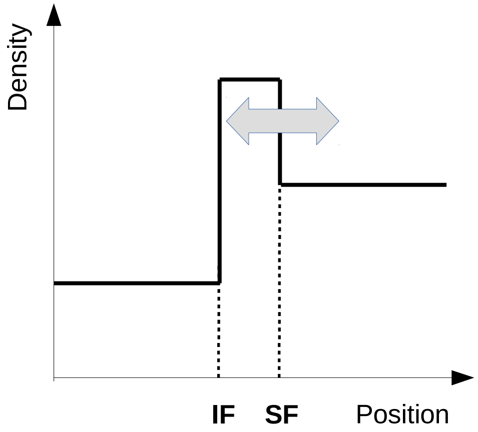
$$\frac{d}{dt}\left(M\dot{R}\right) = 4\pi R^2 \left(P_i - P_o\right)$$

Considering the relation $n_i(t) = n_o \left(\frac{R_{\rm Str}}{R_{\rm IF}(t)}\right)^{3/2}$ we construct the following second-order differential equation:

“Raga-II equation” $$\boxed{\ddot{R} + \left(\frac{3}{R}\right)\dot{R}^2 = \frac{3R_{\rm Str}^{3/2}c_i^2}{R^{5/2}} - \frac{3c_o^2}{R}}$$

The above equation is solvable and we can obtain the expanding velocity:

$$\dot{R} = c_i\sqrt{\frac{4}{3}\left(\frac{R_{\rm Str}}{R}\right)^{3/2} - \frac{1}{2}\left(\frac{c_o}{c_i}\right)^2}$$



Approach II and the "Hosokawa-Inutsuka equation" (cont.)

In the equation $\dot{R} = c_i\sqrt{\frac{4}{3}\left(\frac{R_{\rm Str}}{R}\right)^{3/2} - \frac{1}{2}\left(\frac{c_o}{c_i}\right)^2}$ the term $\left(\frac{c_o}{c_i}\right)^2 \sim 200^{-1}$ appears again.

As with the previous approach, considering also R ~ R_{St}, we can assume P_O ~ 0. Therefore, from

$$\frac{d}{dt}\left(M\dot{R}\right) = 4\pi R^2\left(P_i - P_o\right)$$

we end up (at early times) to the relation:

$$\boxed{R_{\rm HI}(t) = R_{\rm Str}\left(1 + \frac{7}{4}\sqrt{\frac{4}{3}}\frac{c_i t}{R_{\rm Str}}\right)^{4/7}}$$

Spitzer equation

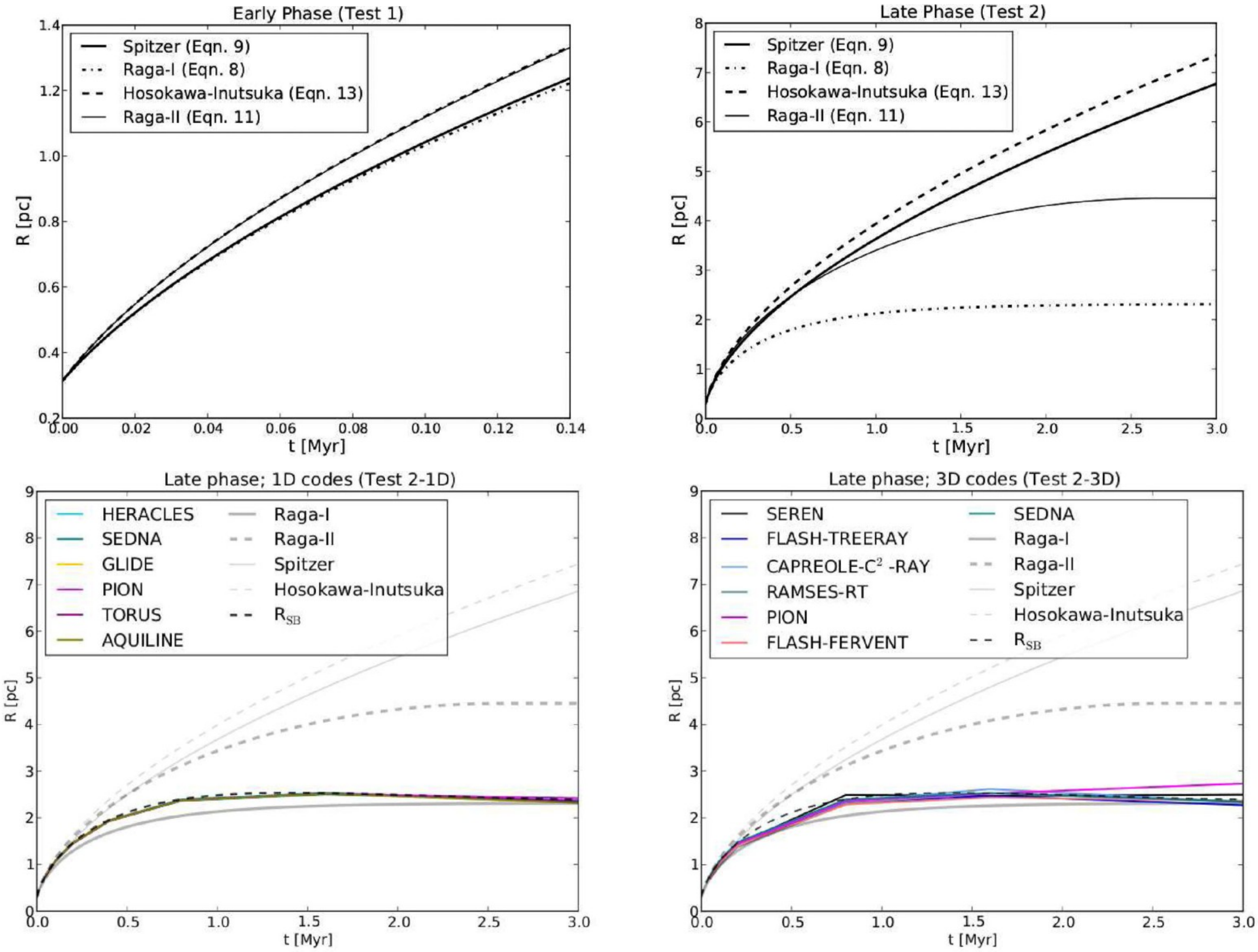
$$\boxed{R_{\rm IF}(t) = R_{\rm Str}\left(1 + \frac{7}{4}\frac{c_i t}{R_{\rm Str}}\right)^{4/7}}$$

This is the "Hosokawa-Inutsuka equation" (Hosokawa & Inutsuka, 2006) and it differs from the Spitzer equation by the factor $\sqrt{4/3}$ which results from the inclusion of inertia. For $dR_{\rm IF}/dt = 0$ we obtain the maximum (stagnation) radius where the D-type terminates.

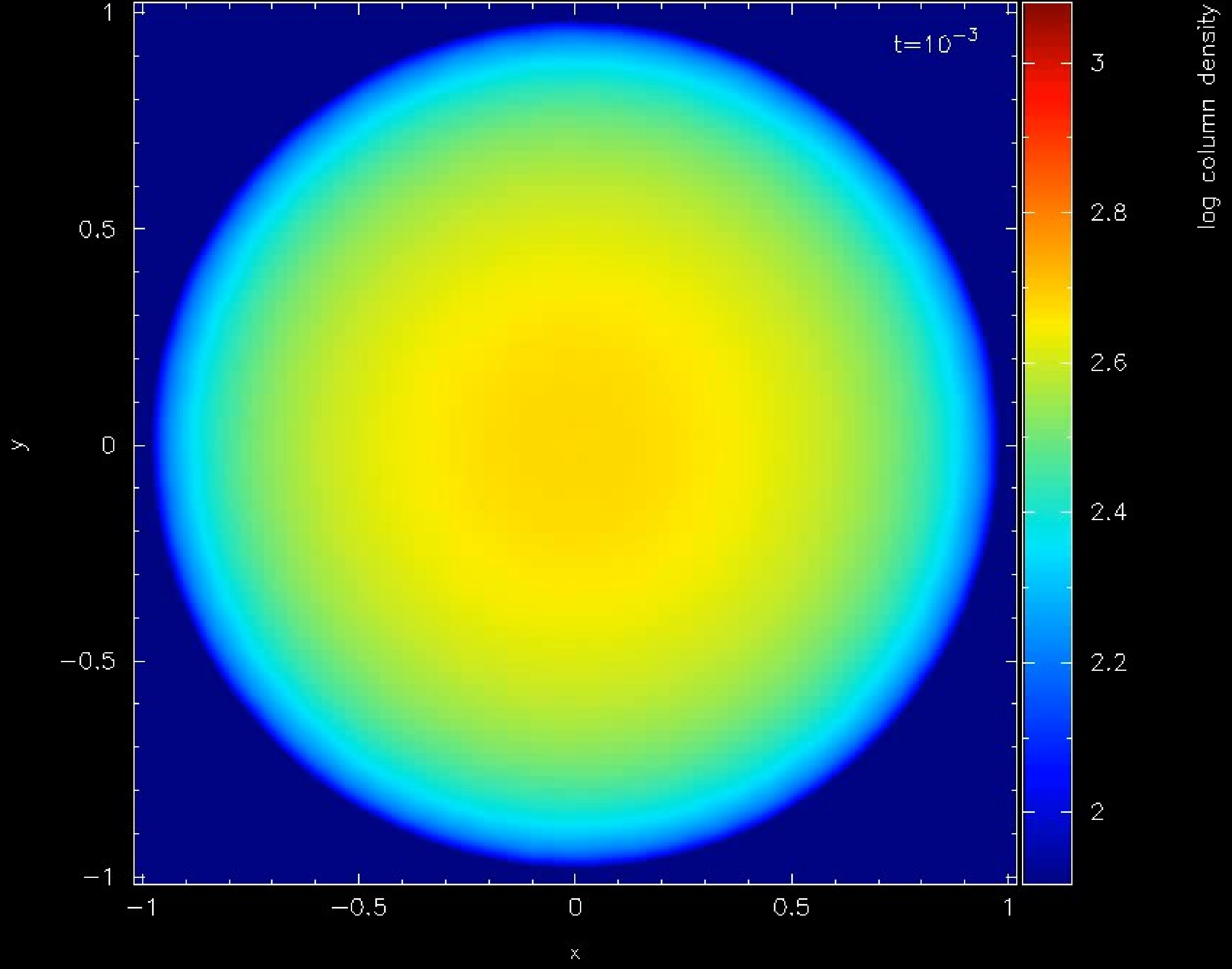
$$R_{\rm STAG} = R_{\rm Str}\left(\frac{8}{3}\right)^{2/3}\left(\frac{c_i}{c_o}\right)^{4/3} \qquad \rho_{i,\rm STAG} = \rho_o\left(\frac{8}{3}\right)^{2/3}\left(\frac{c_o}{c_i}\right)^{4/3} \qquad M_{i,\rm STAG} = \frac{4\pi}{3}R_{\rm Str}^3\rho_o\left(\frac{8}{3}\right)^{8/3}\left(\frac{c_i}{c_o}\right)^{8/3}$$

STARBENCH

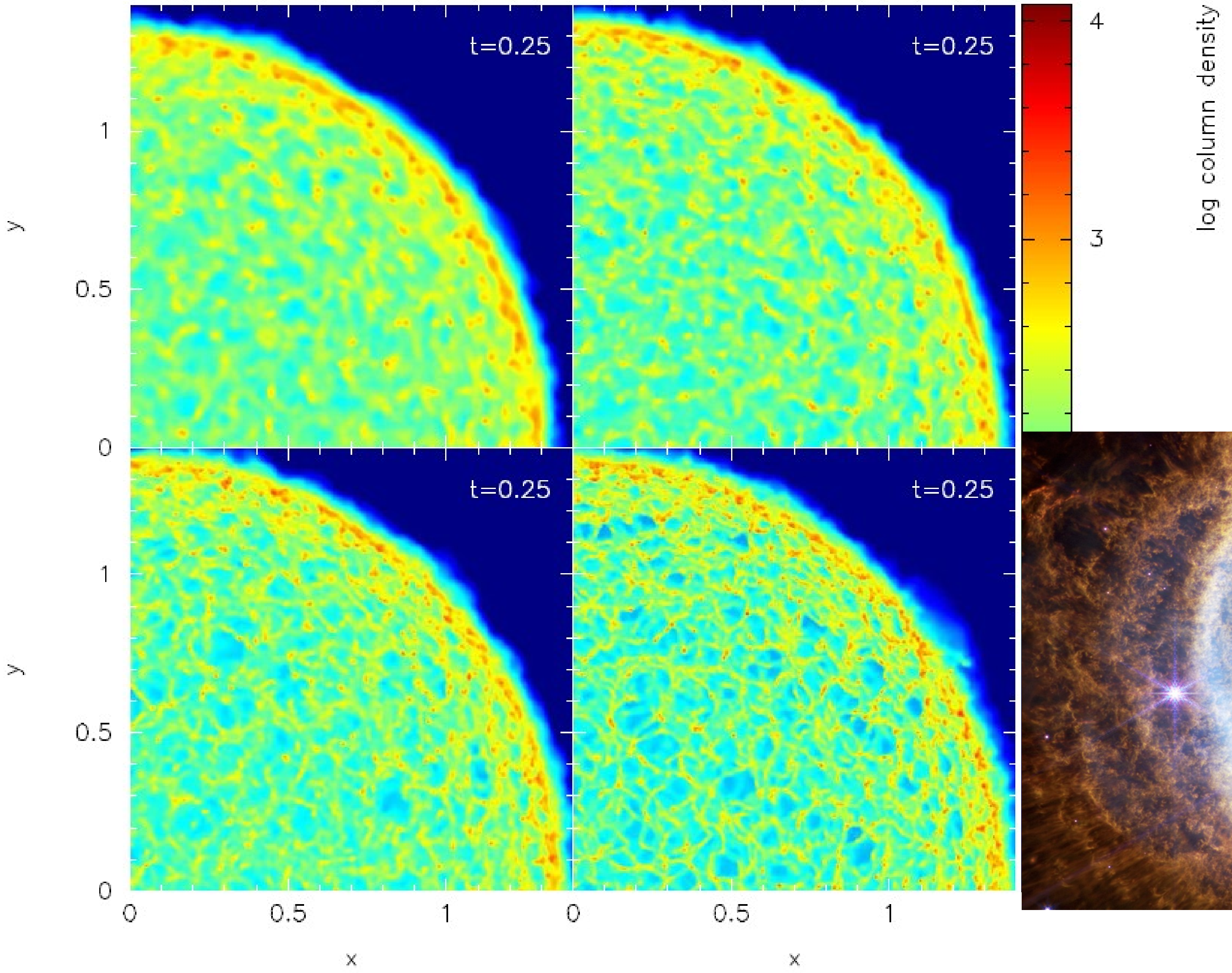
Bisbas et al. 2015
Williams et al. 2018



Simulations of HII regions



t=10^-3
log column density
3
2.8
2.6
2.4
2.2
2
y
1
0.5
0
−0.5
−1
x
−1
−0.5
0
0.5
1

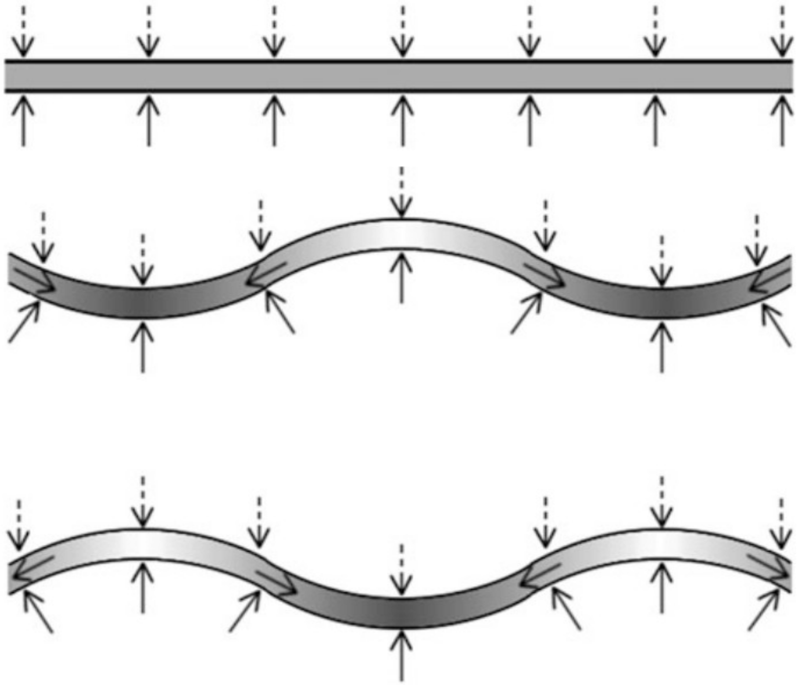


Resolution increases

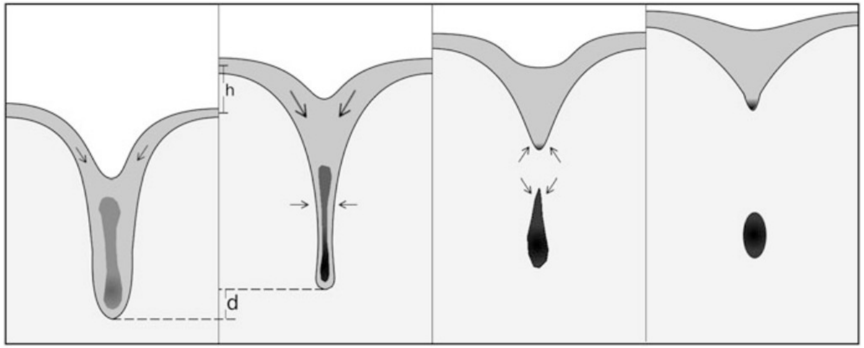
Development of instability

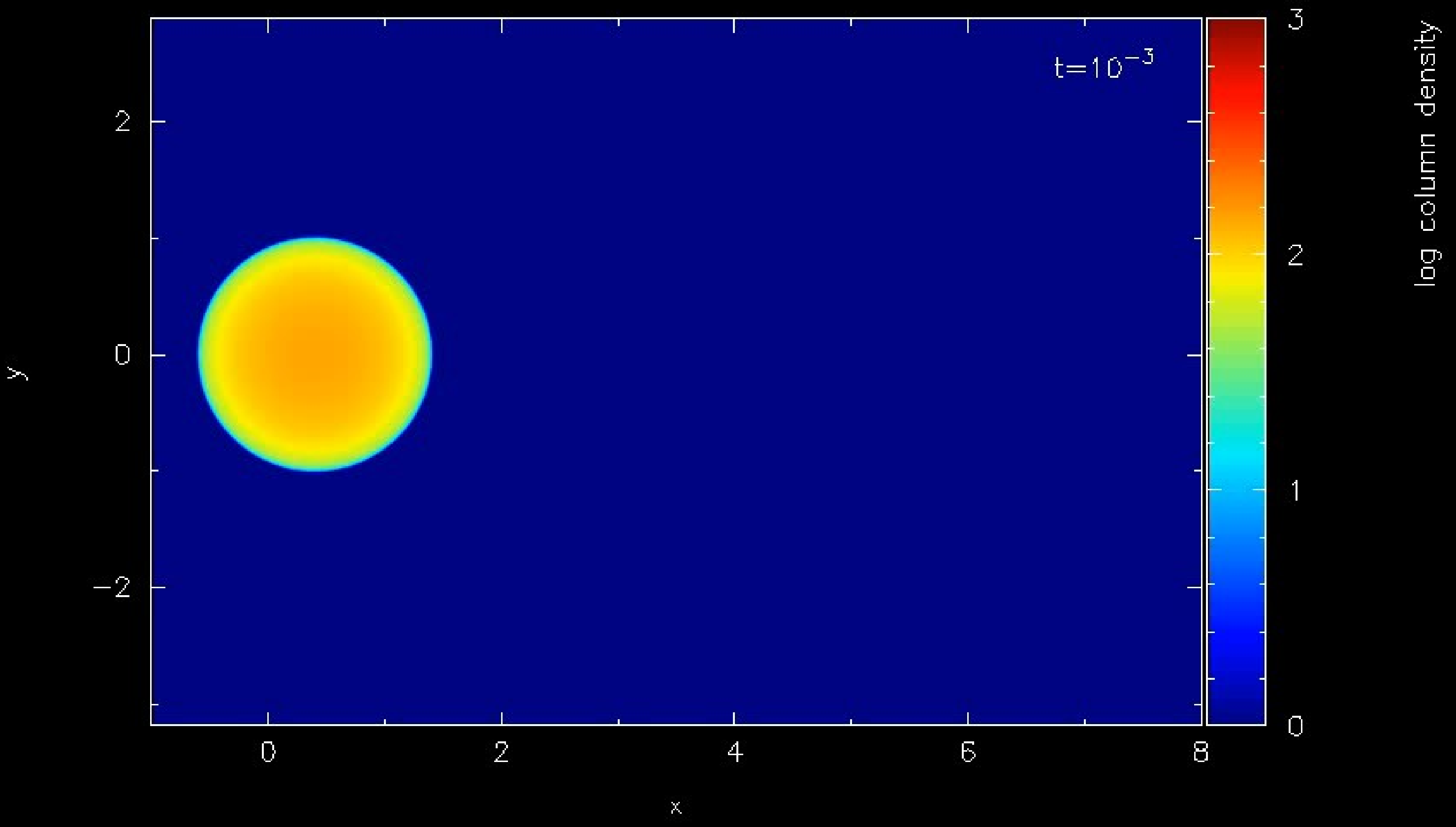
Vishniac instability

Vishniac (1983)

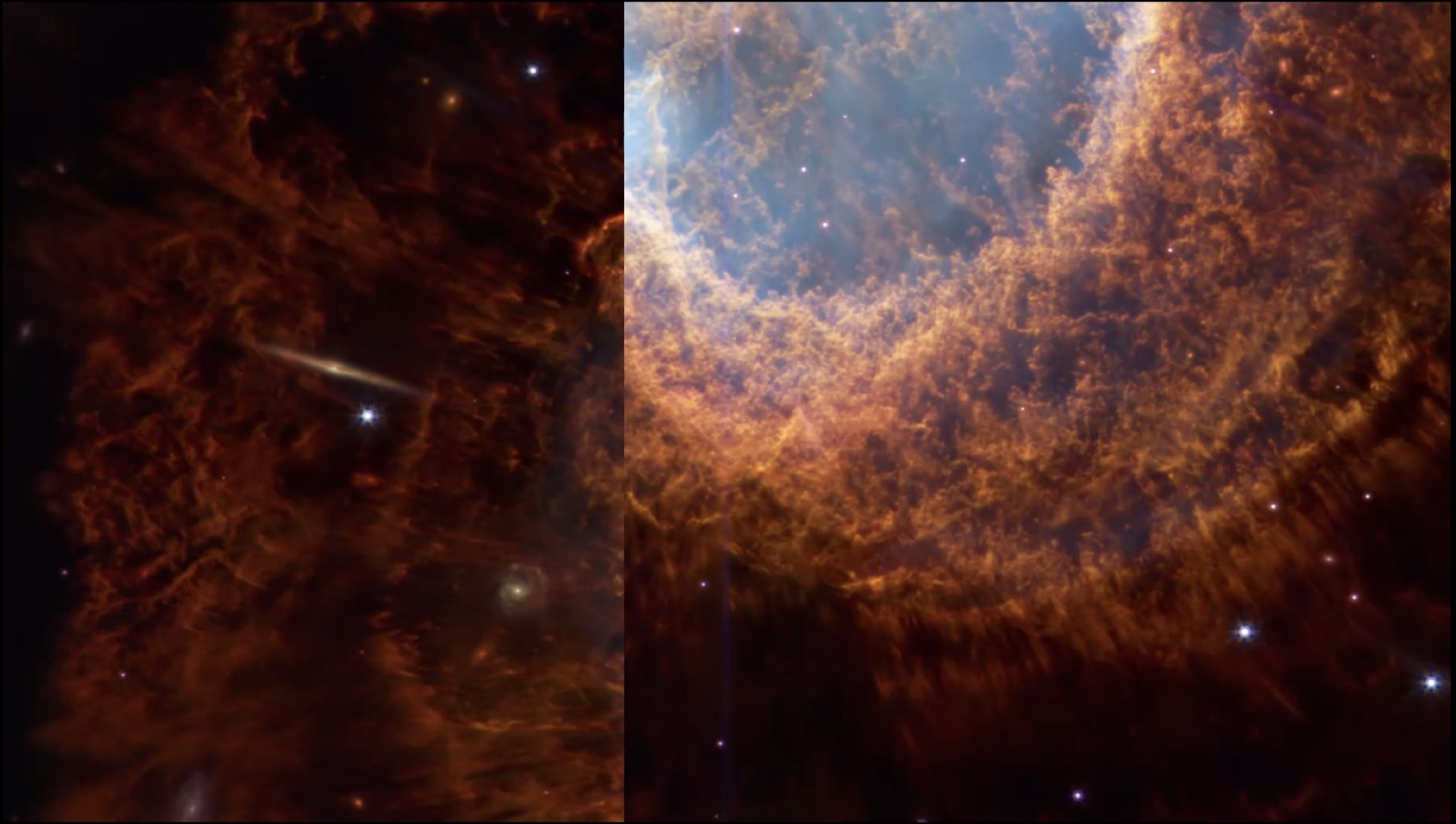


Rayleigh-Taylor instability

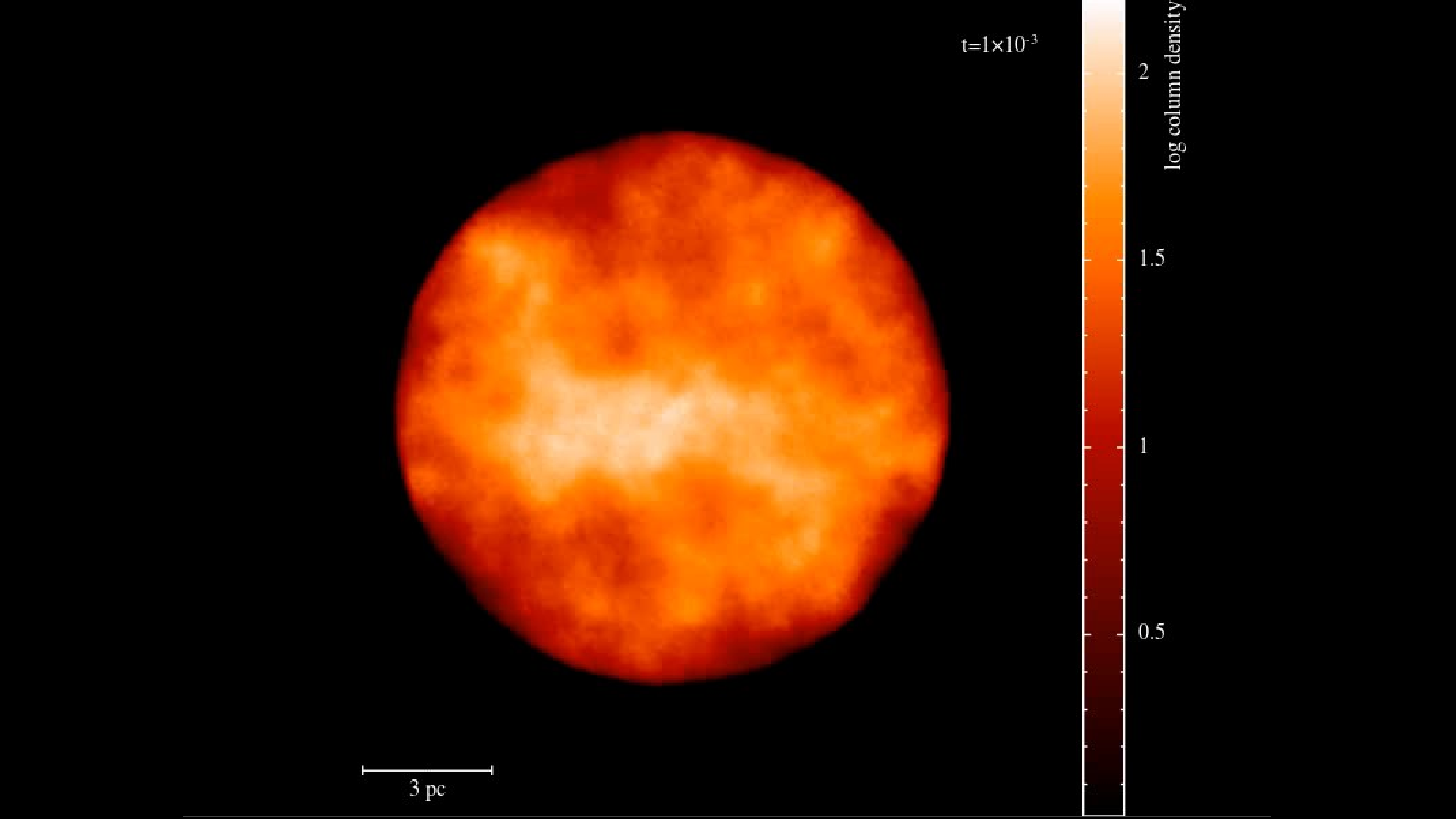




t=10^{-3}
2
0
−2
0
2
4
6
8
x
y
3
2
1
0
log column density

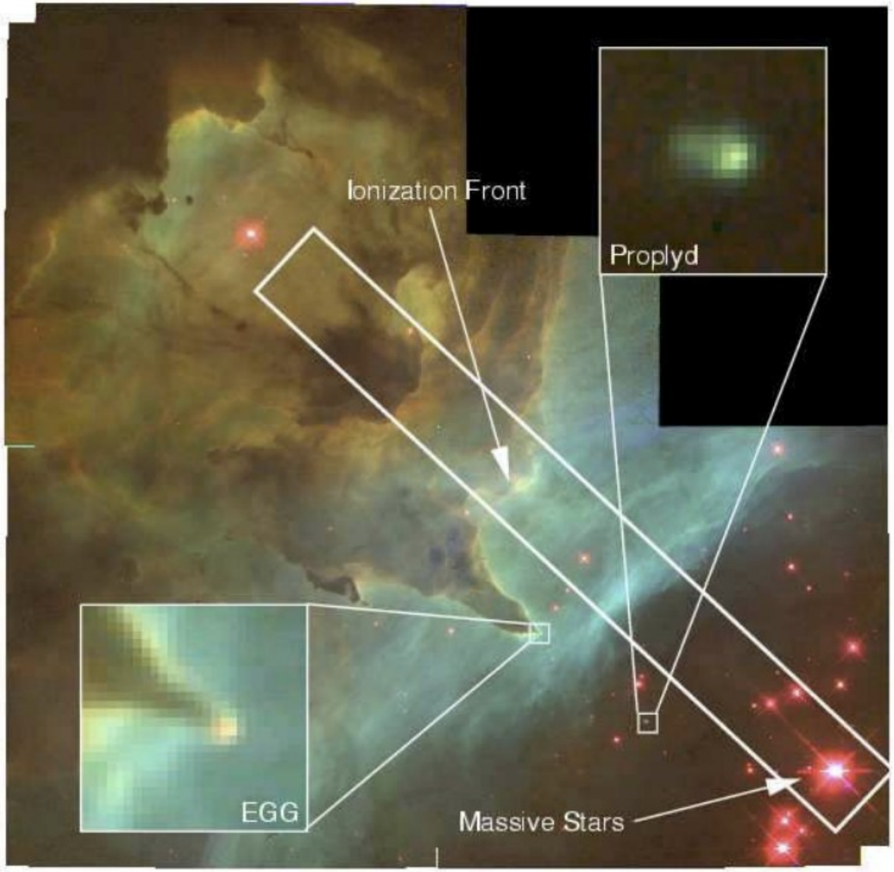



t=0



t=1×10-3
log column density
2
1.5
1
0.5
3 pc

Triggered star-formation in expanding HII regions



Hester & Desch (2005)

(1) Radiation from a massive star drives an ionization front into surrounding molecular gas.

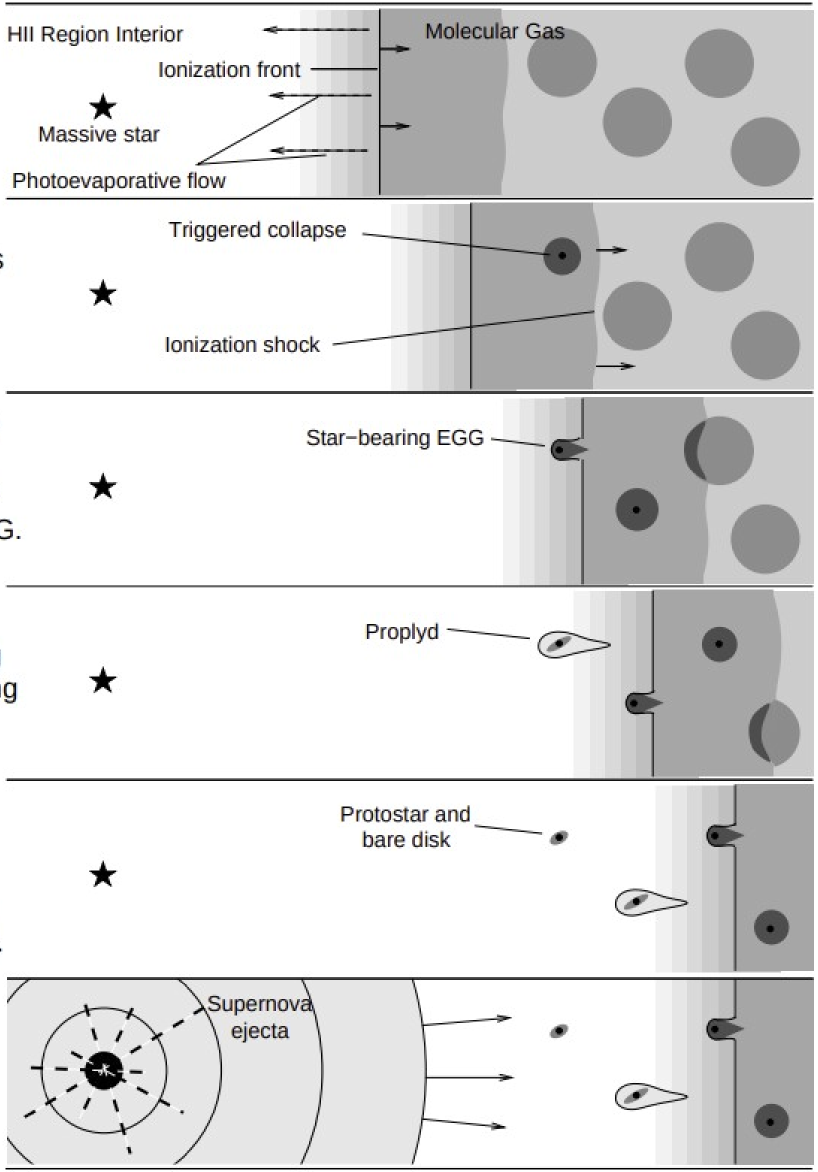
(2) The ionization front (plus winds and previous SNe) drive a shock, triggering collapse of molecular cores.

(3) ~100,000 years after triggered collapse, the ionization front overruns the core, forming an EGG.

(4) EGGs evaporate in ~10,000 years, exposing the disk. The evaporating disk is a proplyd.

(5) In ~10,000 years, disks erode to ~50 AU. Disk evaporation ends, leaving a protostar and bare protoplanetary disk.

(6) The massive star goes supernova, injecting newly synthesized elements into surrounding disks.



Take home messages

1. The chemical state of the interstellar medium is characterized by the environmental parameters defining the:

    a) the intensity of the FUV radiation field
    b) the value of the cosmic-ray ionization rate
    c) the value of metallicity
    d) other values such as X-rays, turbulence (not explored here but also important)

2. Molecular hydrogen forms on dust grains, where other molecules also form. Dust plays a major role in the study of Molecular Astrophysics.

3. HII regions expand due to thermal pressure of the ionized medium. They stagnate at a maximum radius. During their expansion they may trigger the formation of new stars.