A brief Introduction to the Physics of the Multi-Phase Interstellar Medium

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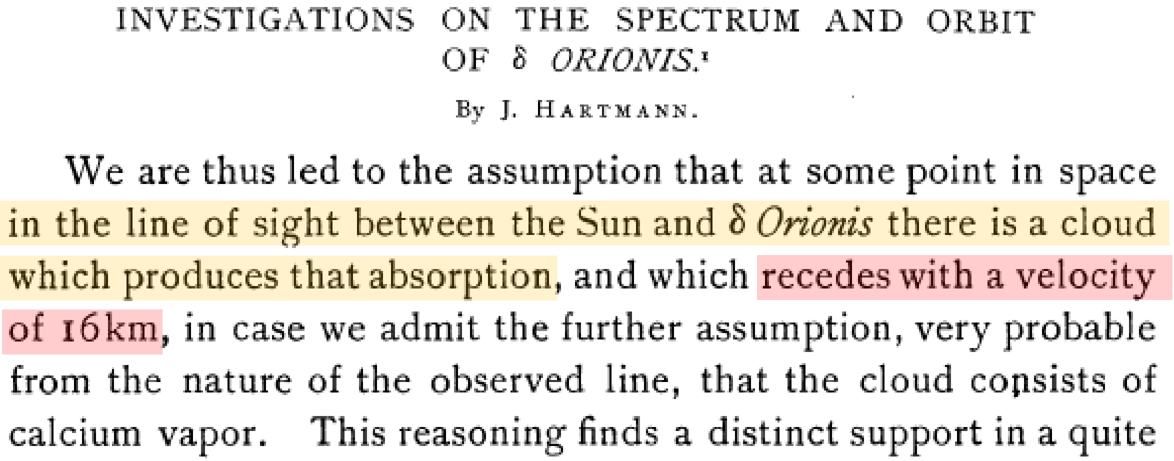
Recommended literature:
“The Physics & Chemistry of the Interstellar Medium”, Tielens
“Physical Processes in the Interstellar Medium”, Spitzer
“Radiative Processes in Astrophysics”, Rybicki & Lightman

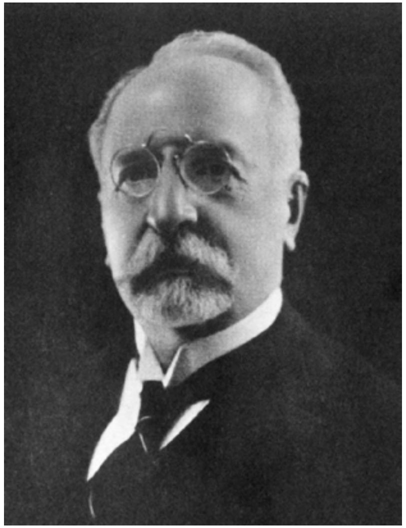
Introduction



INVESTIGATIONS ON THE SPECTRUM AND ORBIT OF δ *ORIONIS*.[1]

By J. HARTMANN.

We are thus led to the assumption that at some point in space in the line of sight between the Sun and δ *Orionis* there is a cloud which produces that absorption, and which recedes with a velocity of 16km, in case we admit the further assumption, very probable from the nature of the observed line, that the cloud consists of calcium vapor. This reasoning finds a distinct support in a quite



Dark clouds in the Taurus-Auriga region

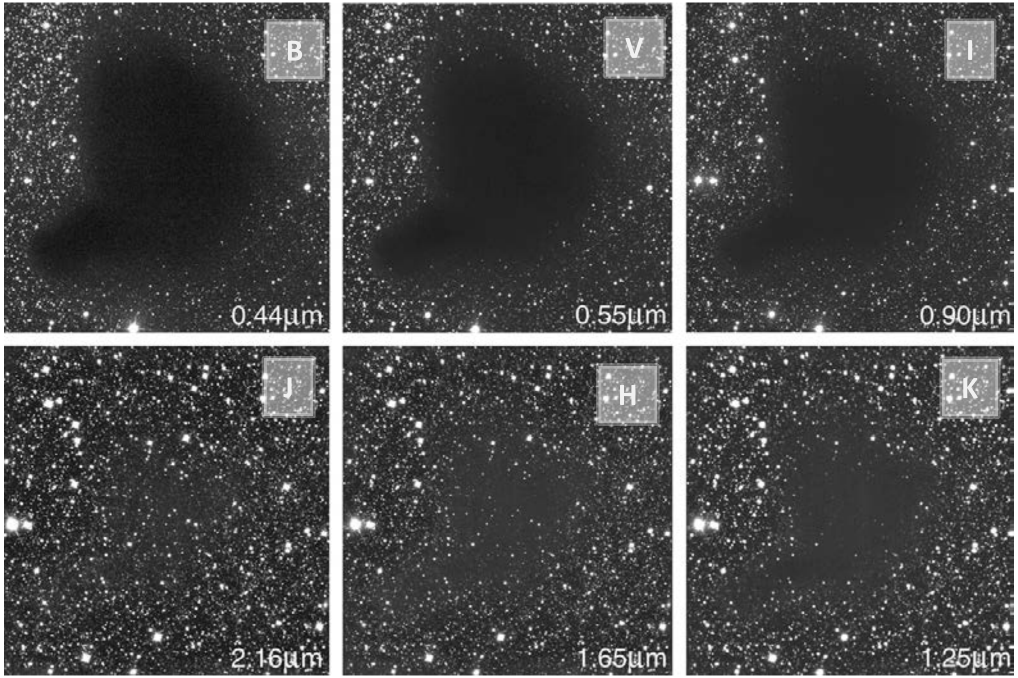
"Very few regions in the sky are so remarkable as the Taurus region. Indeed, the photograph is one of the most important of the collection, and bears the strongest proof of the existence of obscuring matter in interstellar space."

E.E. Barnard (1927)

$\sim$50 deg^2 - or 400 pc^2
(1 pc $\approx$ 2x10^5 AU $\approx$ 3x10^{16} m)

Slide courtesy of Jes Jørgensen

Reddening of starlight and dust extinction



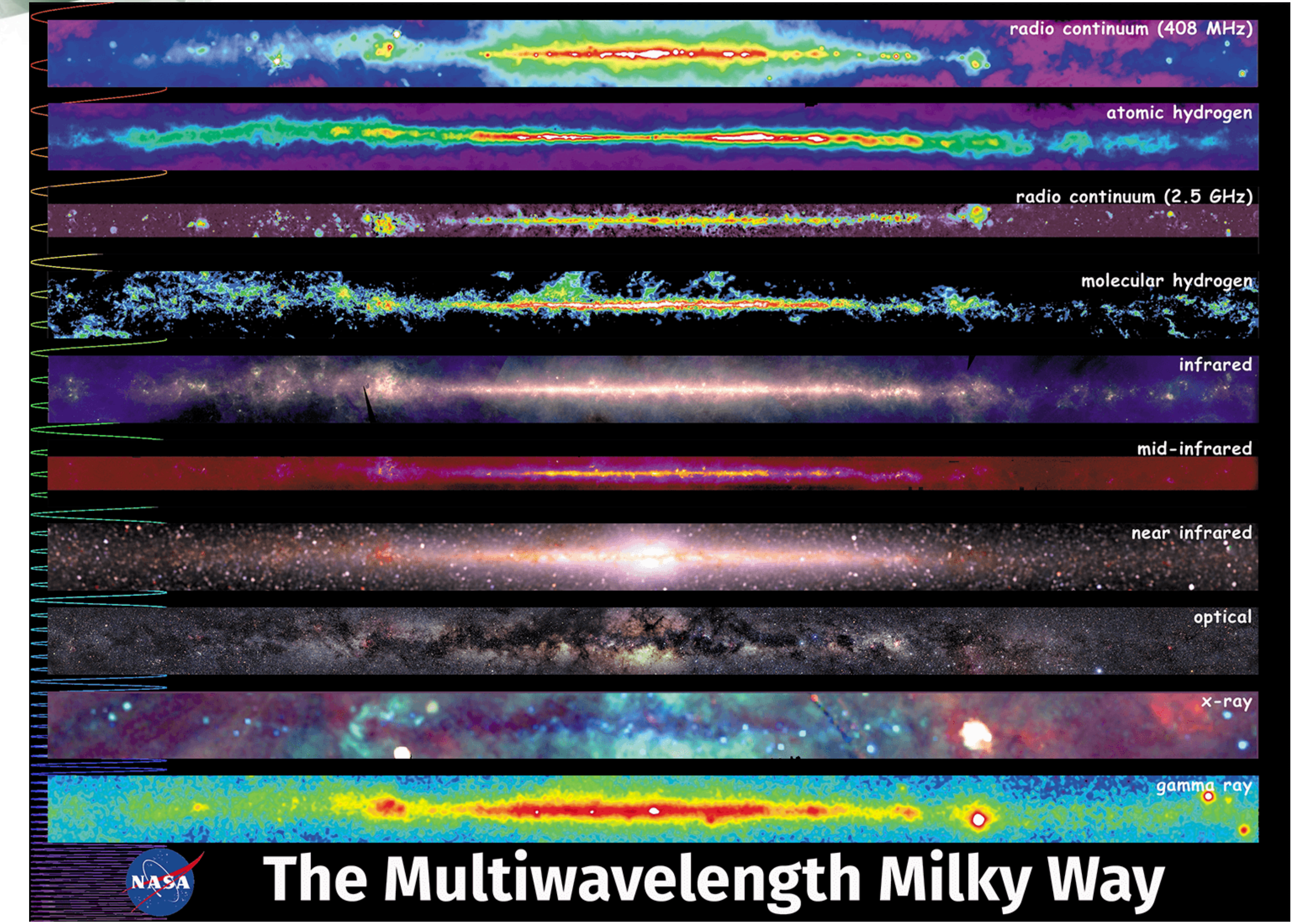
- Dust to gas ratio of approx. 1:100 by mass
- Reddening of starlight from further-away stars (depending on the grainsize distribution)
- Dust collisionally coupled to the gas (can both heat and cool the gas)
- Dust acts as a catalyst for chemical reactions (e.g., formation of molecular hydrogen)

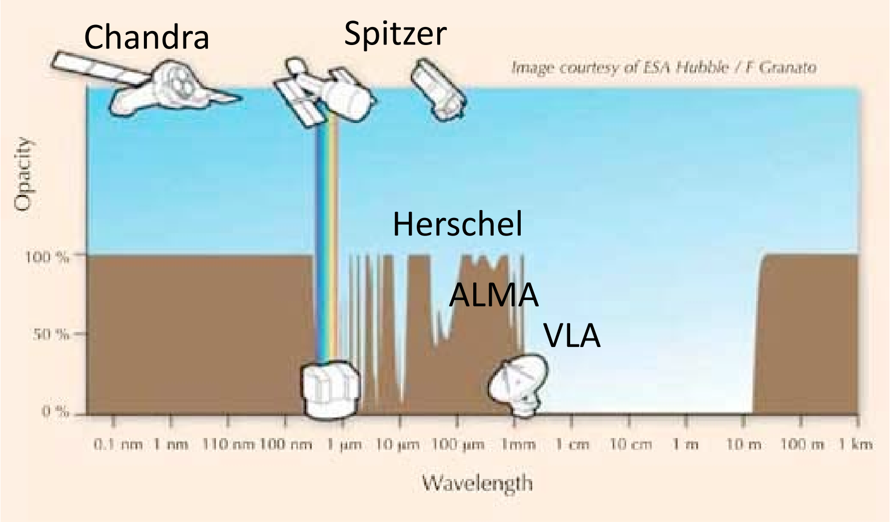
Slide courtesy of Troels Haugbølle

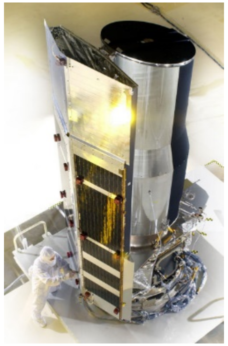
Whirlpool Galaxy - M51

Milky Way

Slide courtesy of Troels Haugbølle


radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
NASA
The Multiwavelength Milky Way





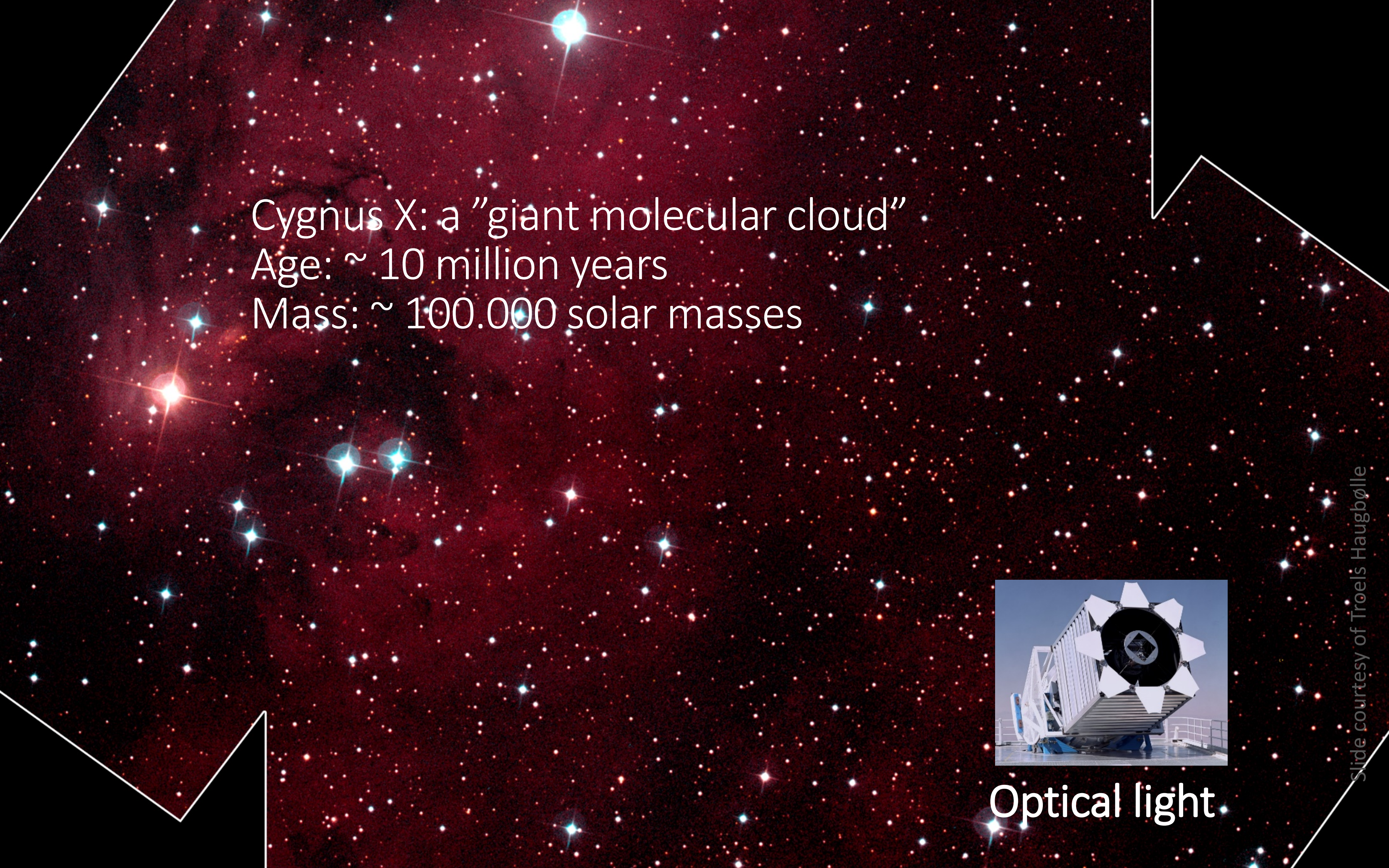
Spitzer

VLA

ALMA

Herschel

Slide courtesy of Troels Haugbølle



Cygnus X: a ”giant molecular cloud”

Age: ~ 10 million years

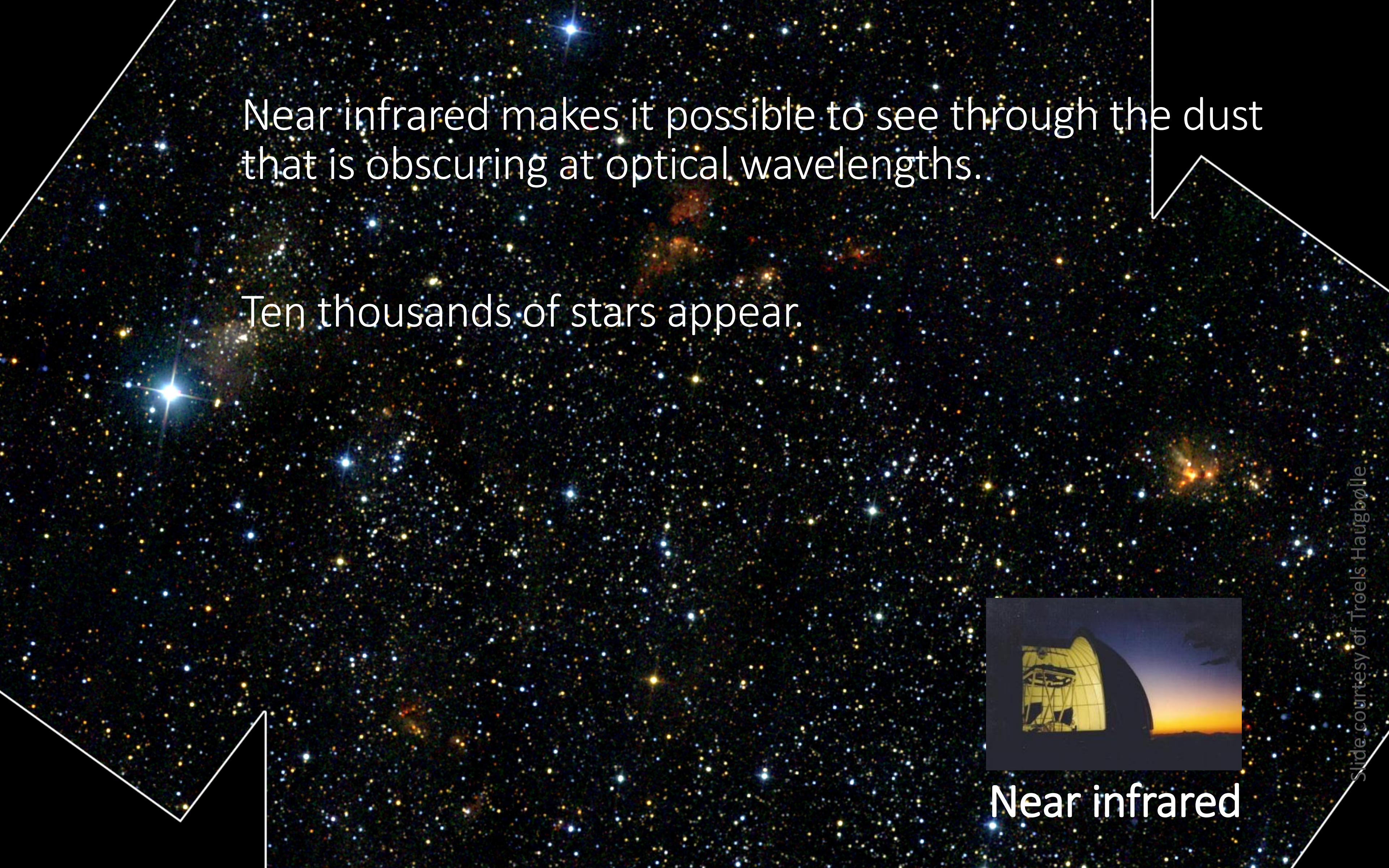
Mass: ~ 100.000 solar masses

Optical light

Slide courtesy of Troels Haugbølle

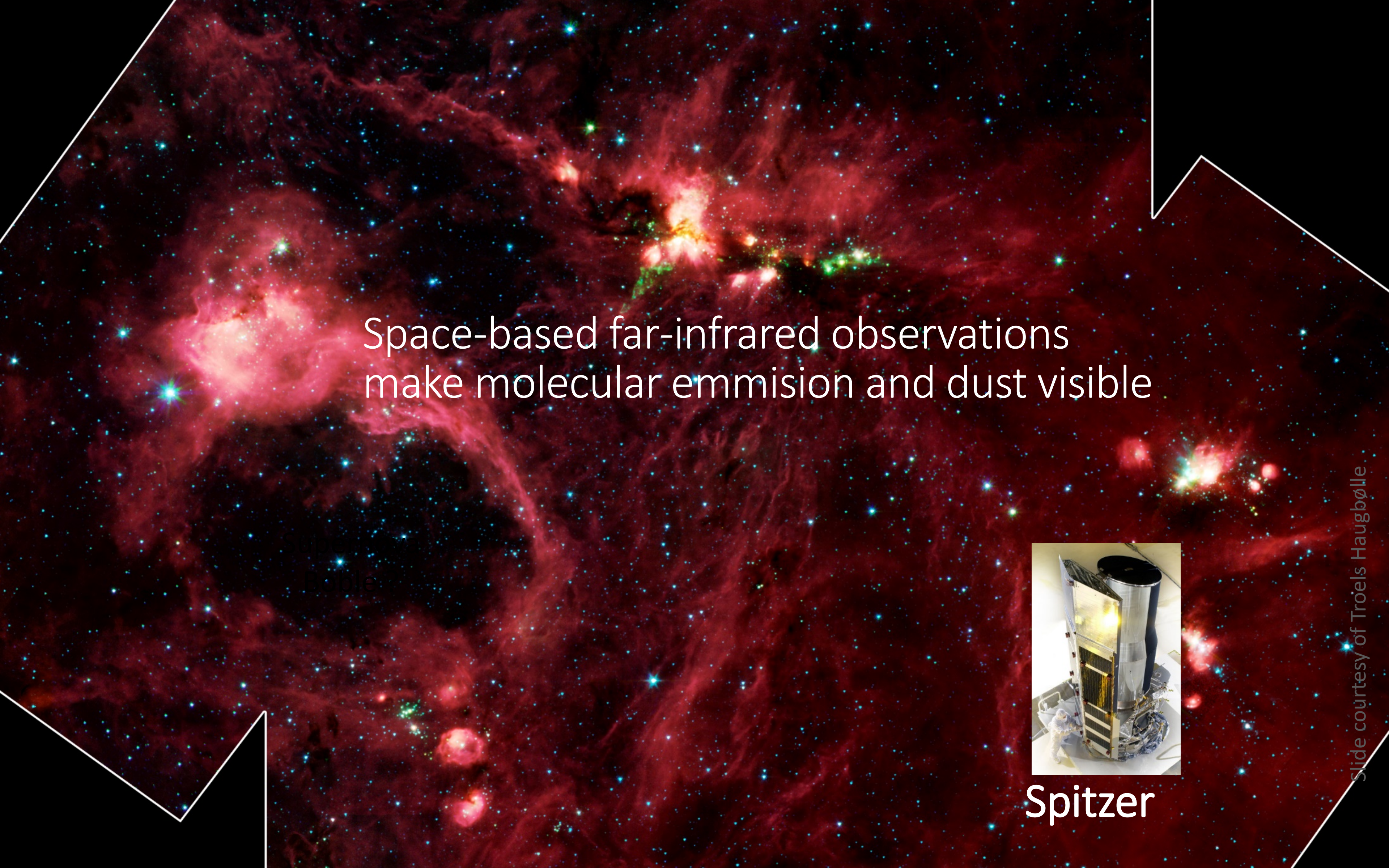
Near infrared makes it possible to see through the dust that is obscuring at optical wavelengths.

Ten thousands of stars appear.



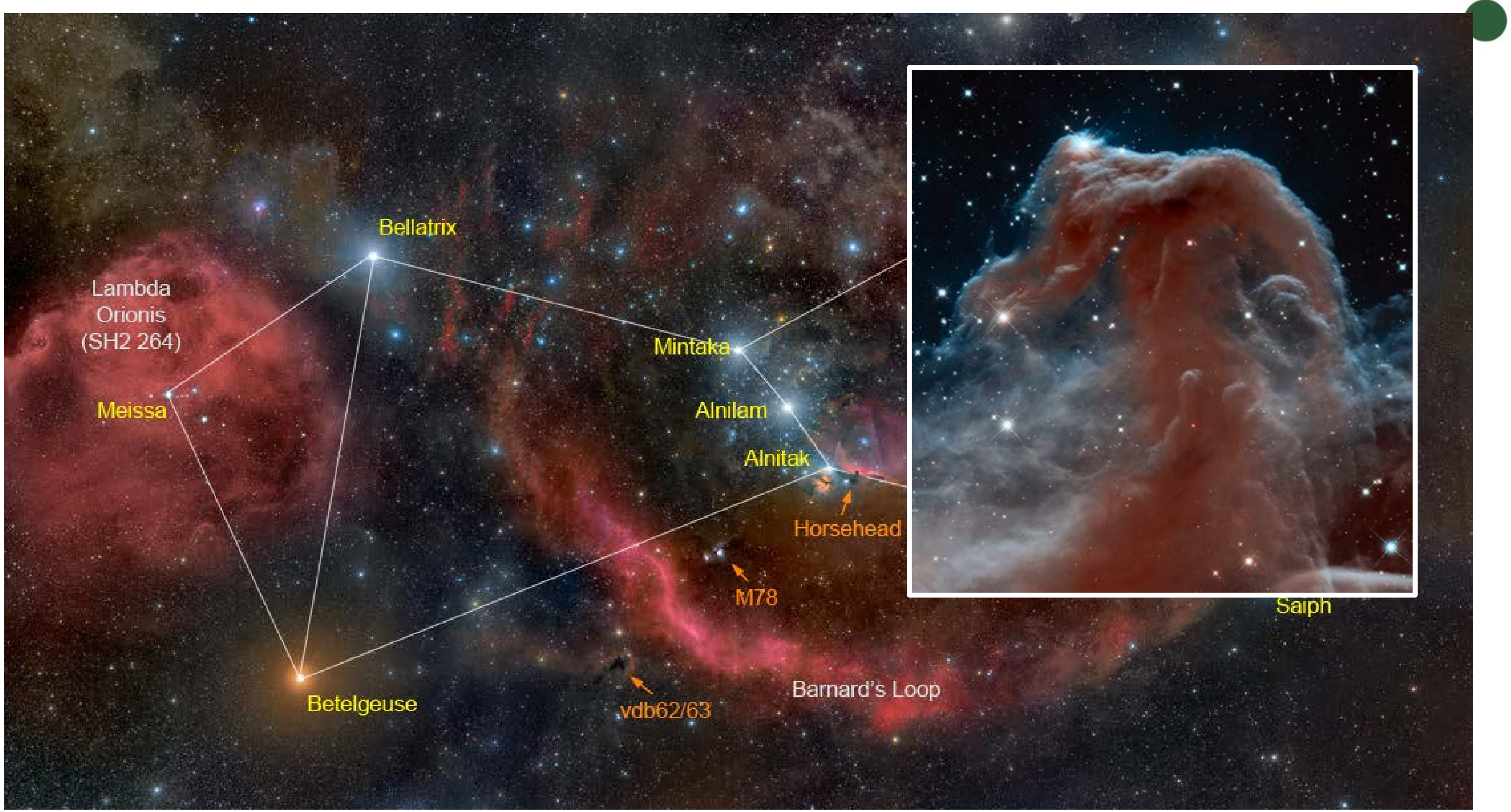
Slide courtesy of Troels Haugbølle

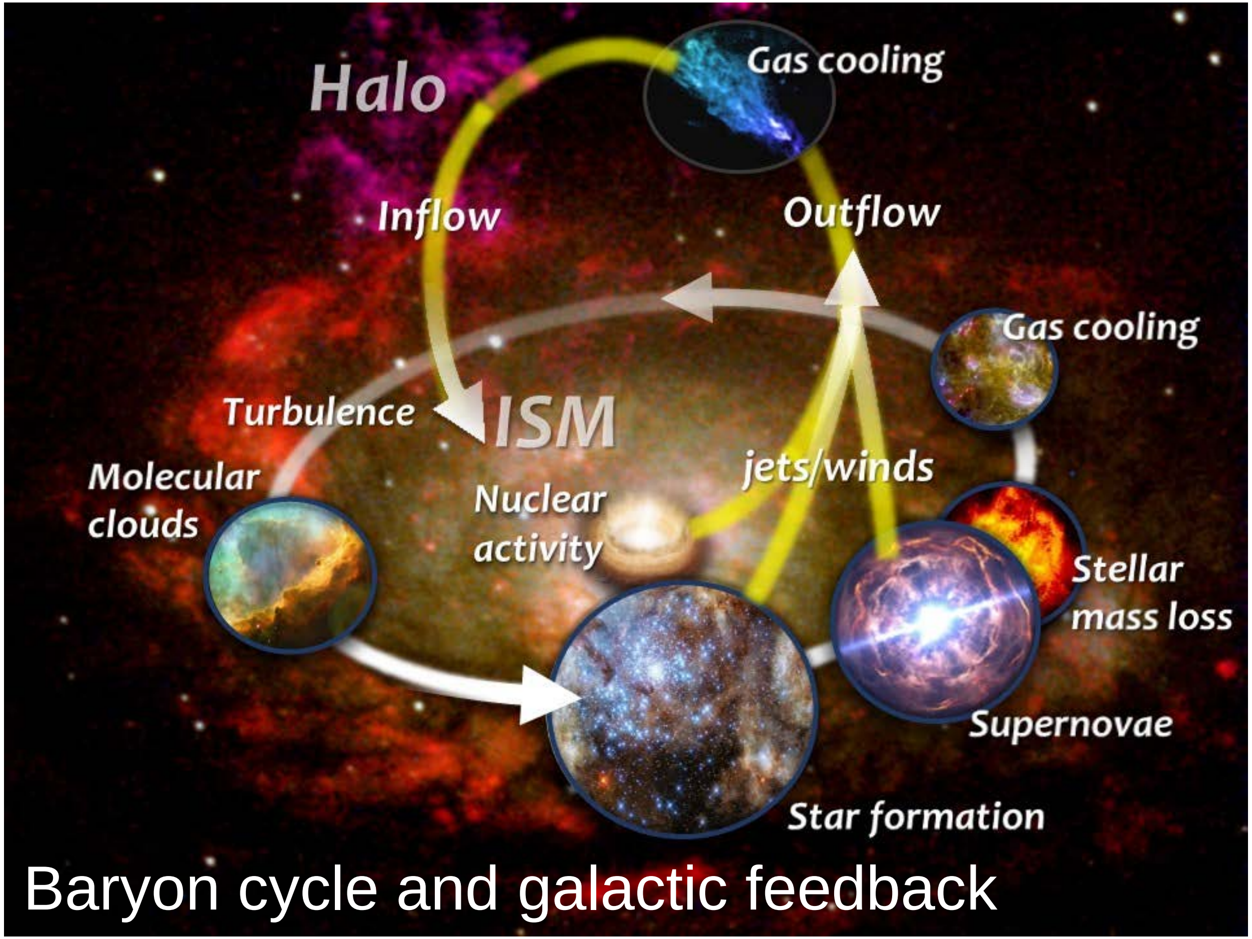
Space-based far-infrared observations make molecular emmision and dust visible



Spitzer

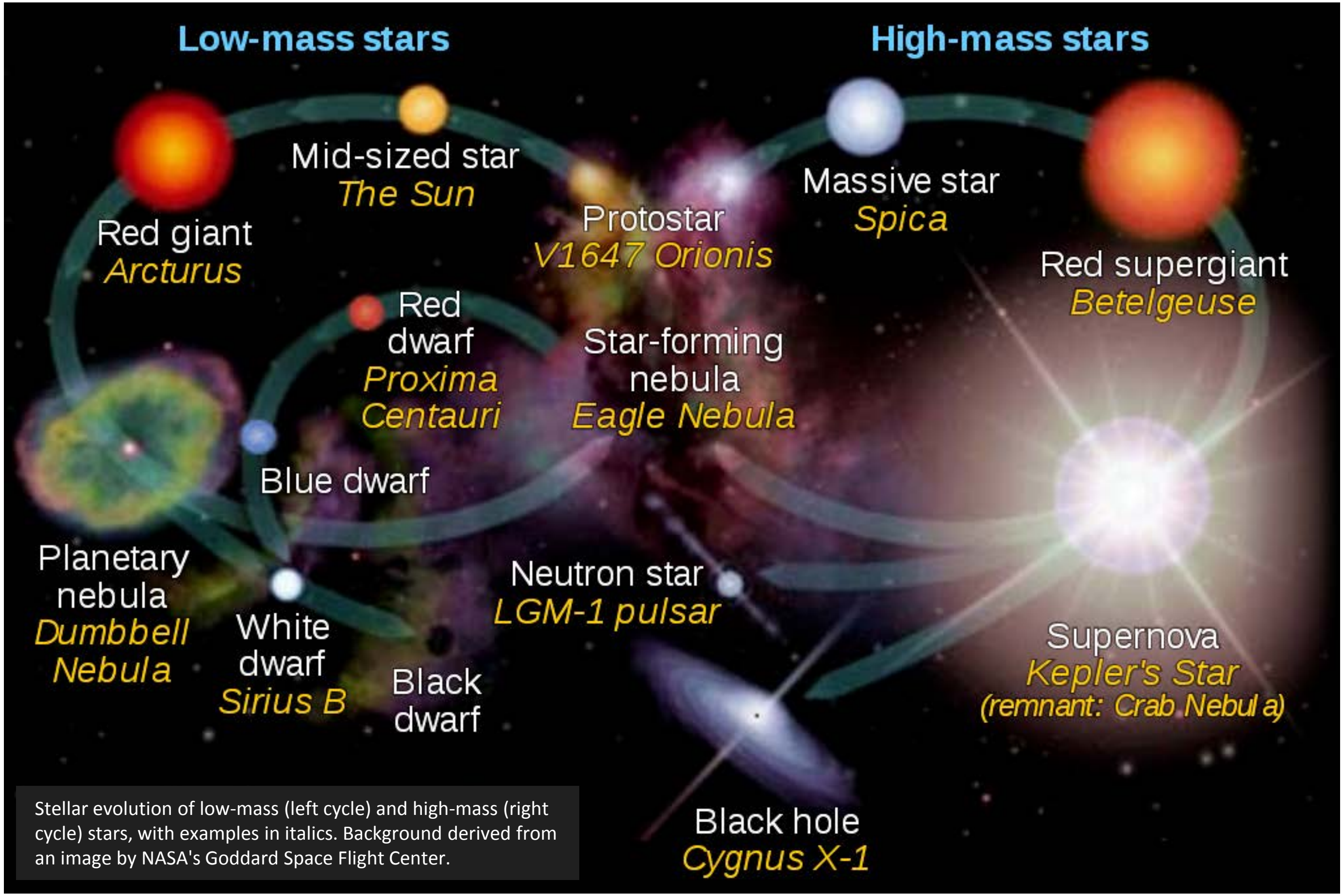
Slide courtesy of Troels Haugbølle


Bellatrix
Lambda
Orionis
(SH2 264)
Meissa
Mintaka
Alnilam
Alnitak
Horsehead
M78
Saiph
Betelgeuse
vdb62/63
Barnard's Loop



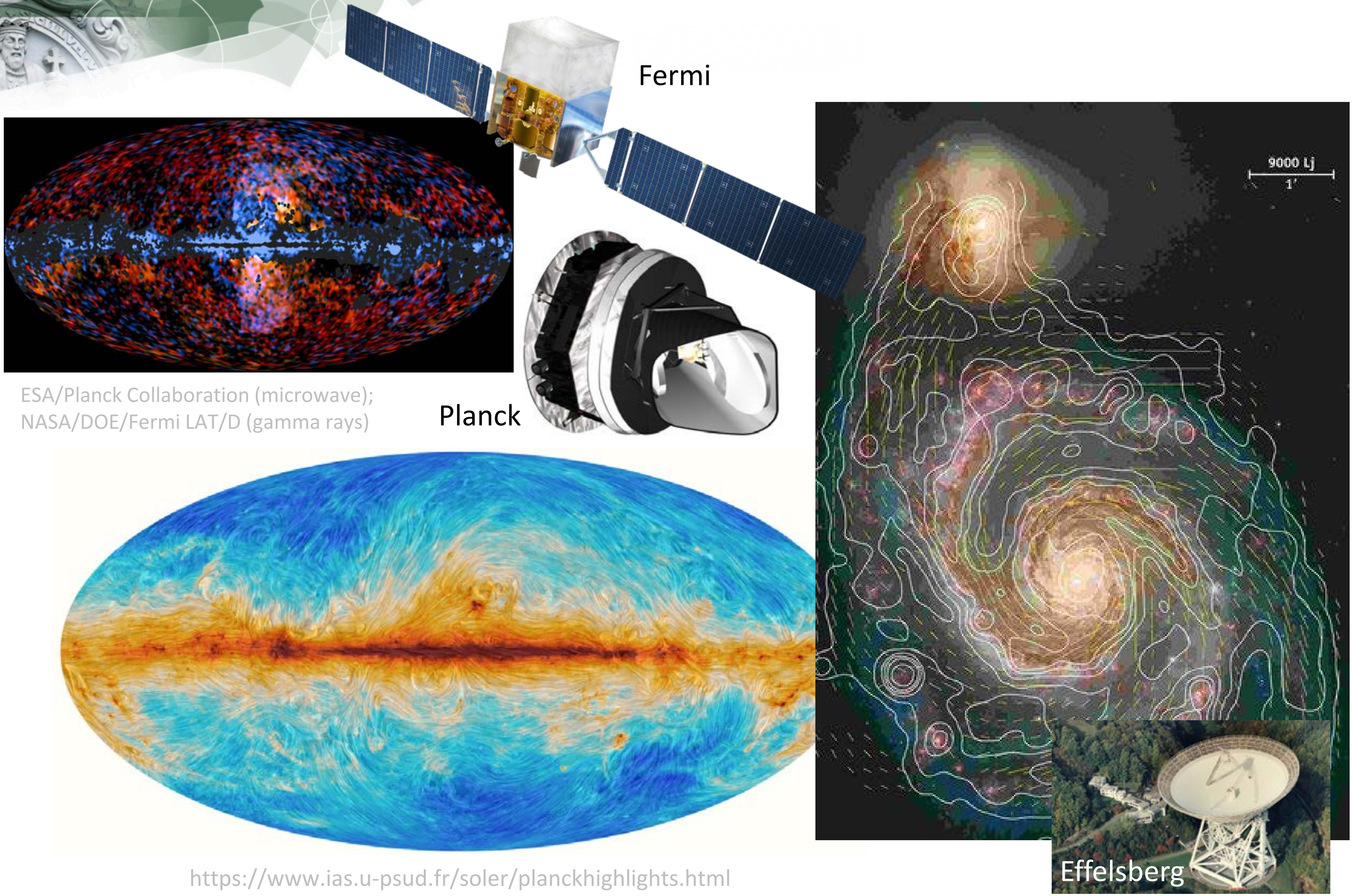
Baryon cycle and galactic feedback

www.spica-mission.org



Stellar evolution of low-mass (left cycle) and high-mass (right cycle) stars, with examples in italics. Background derived from an image by NASA's Goddard Space Flight Center.

https://www.wikimedia.org



Fermi

ESA/Planck Collaboration (microwave);
NASA/DOE/Fermi LAT/D (gamma rays)

Planck

https://www.ias.u-psud.fr/soler/planckhighlights.html

Effelsberg

Spiral galaxy M 51 with magnetic field data. Credit: MPIfR Bonn

The multi-phase ISM

The interstellar medium

	Fraction (volume)	Temperature [K]	Density [atoms / cm^3]
"Hot" ionised medium	30-70%	1-10 mio.	0.0001-0.01
"Warm" medium (ionised/neutral)	30-70% (hereof 10-20% neutral)	6000-10000	0.2-0.5
Cold neutral medium	1-5%	20-50	20-50
Molecular clouds	< 1%	10-20	100 - 1 mio

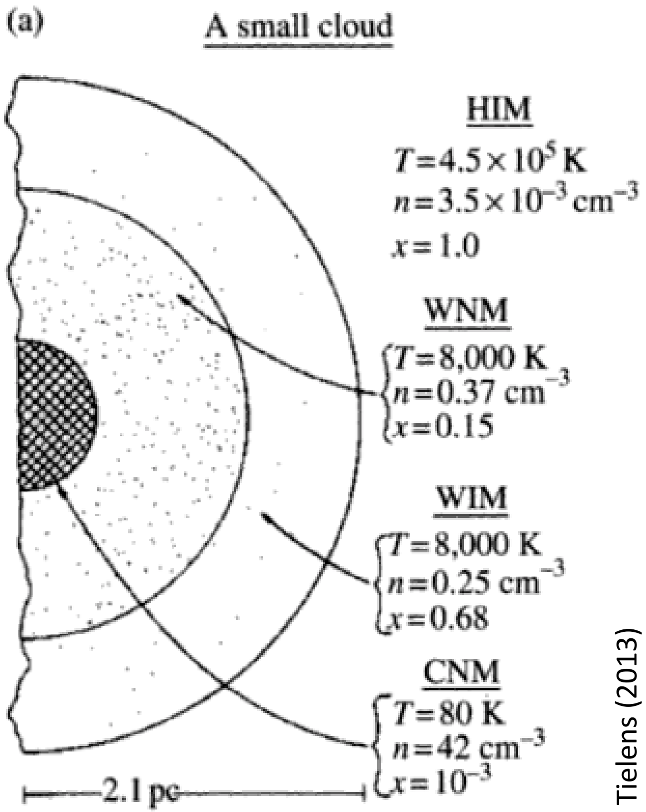
Slide courtesy of Jes Jørgensen

Heating Mechanisms

- UV photoelectric heating via ejecting e^- from grains
- photoionization heating
- X-ray photoelectric heating via e^- from atoms
- cosmic ray heating (where UV field is shielded)
- heating released in shocks
- chemical heating (e.g. H_2 formation)

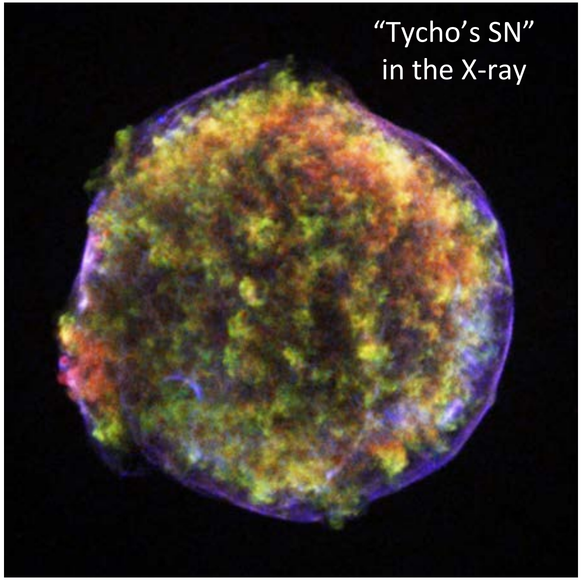
Cooling Mechanisms

- Collisionally-excited line emission
- Collisional ionization/ excitation of H
- Recombination cooling of H
  Thermal Bremsstrahlung
- Molecular cooling at low temperature
- (non-)thermal emission from dust grains
- Since these processes involve collisions, their cooling rates go with n^2.

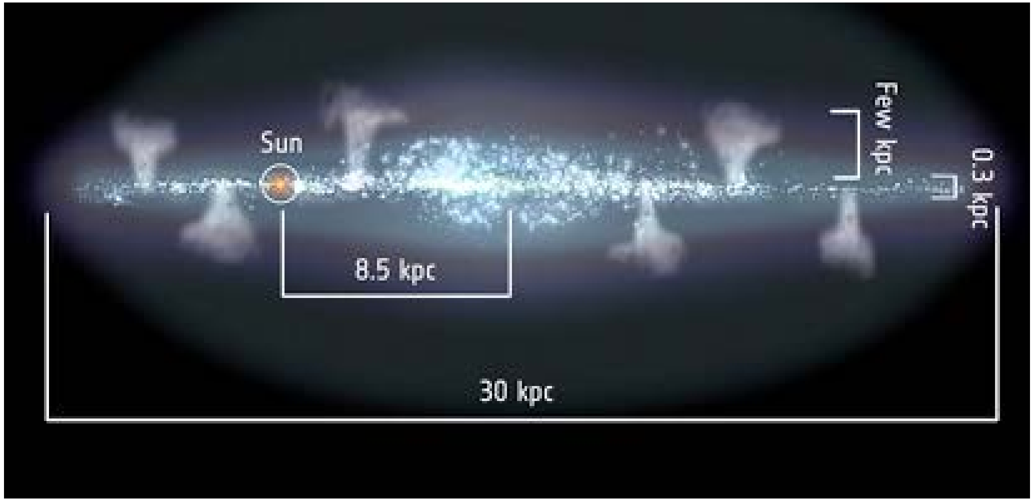


Tielens (2013)

Hot Ionised Medium T ~ 10^6 K


“Tycho’s SN” in the X-ray

- Supernovae warm the ISM to million of degrees
- Associations of massive stars create “super bubbles”
- Plasma creates chimneys and the Galactic fountain
- Compressed clumps cool and rain down onto the disk

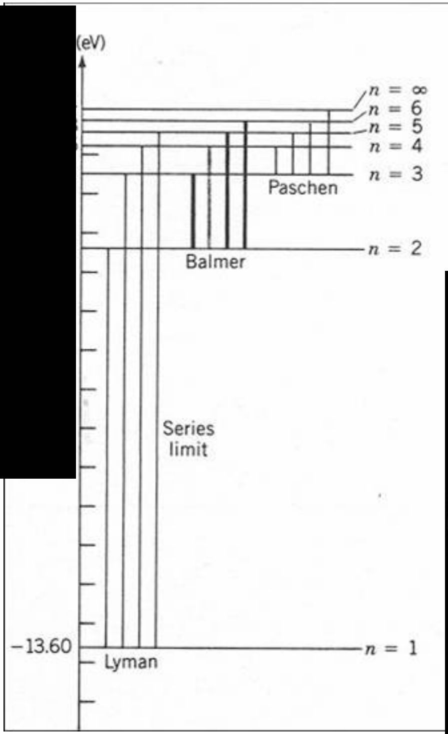


Milky Way: Filling factor: 20-70% Density: 10^{-4} – 10^{-2} cm^{-3} Temperature: 10^5-10^7 K

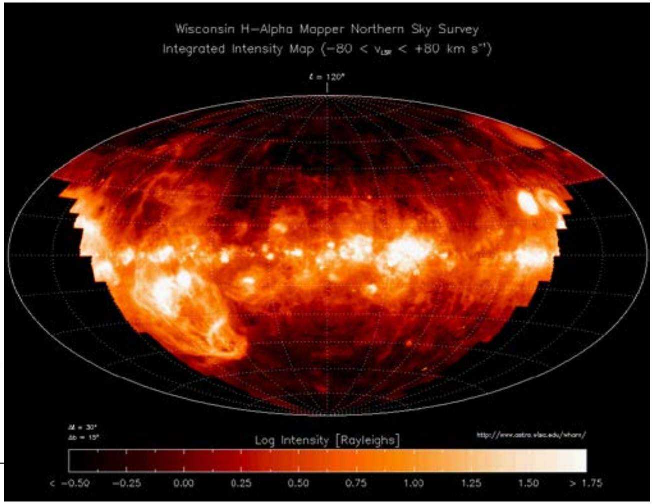
Slide courtesy of Troels Haugbølle

Warm Ionised Medium T ~ 8,000 K

HII – ionised gas



- Heavy O/B stars produce ultraviolet radiation
- UV creates *Strömgren* spheres around stars and regions of ionized hydrogen
- Hydrogen *recombines* to excited states and emits H-α radiation

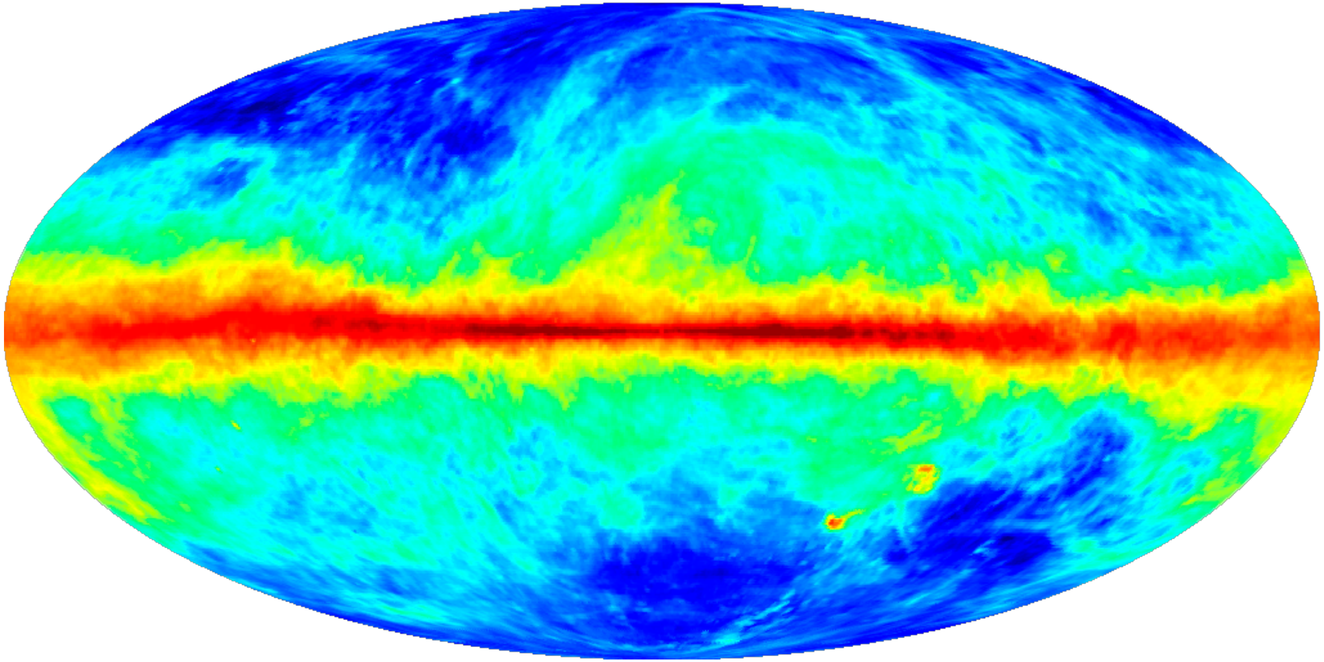


Milky Way: Filling factor: 20-50% (?) Masse: > 1.6 10^9 $M_\odot$ Density: 0.2 – 0.5 cm^{-3} Temperatur: 8,000 K

Slide courtesy of Troels Haugbølle

Neutral Medium T ~ 80-8,000 K

HI – neutral gas

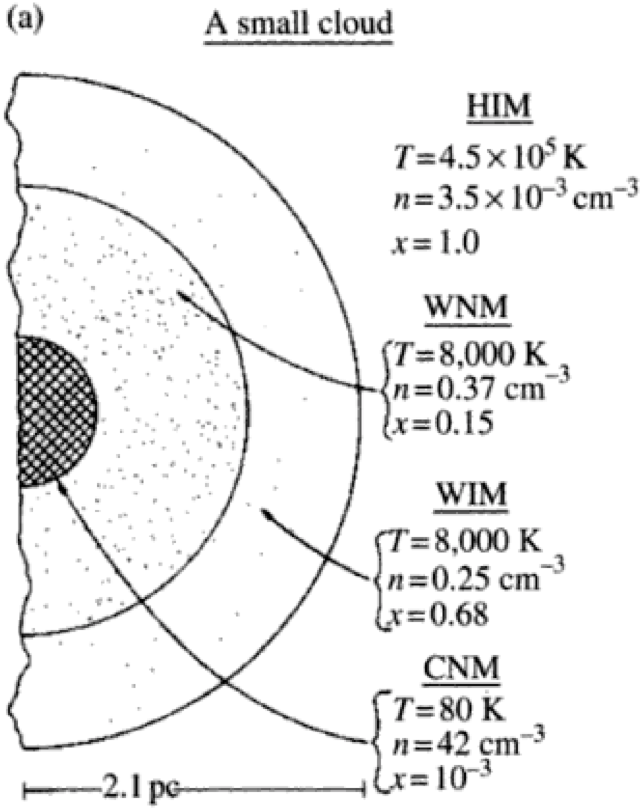


Milky Way: Filling factor: 10-20% Masse: $> 6\ 10^9\ M_\odot$ Density: 0.2 – 100 cm^{-3} Temperatur: 50-8,000 K

Slide courtesy of Troels Haugbølle

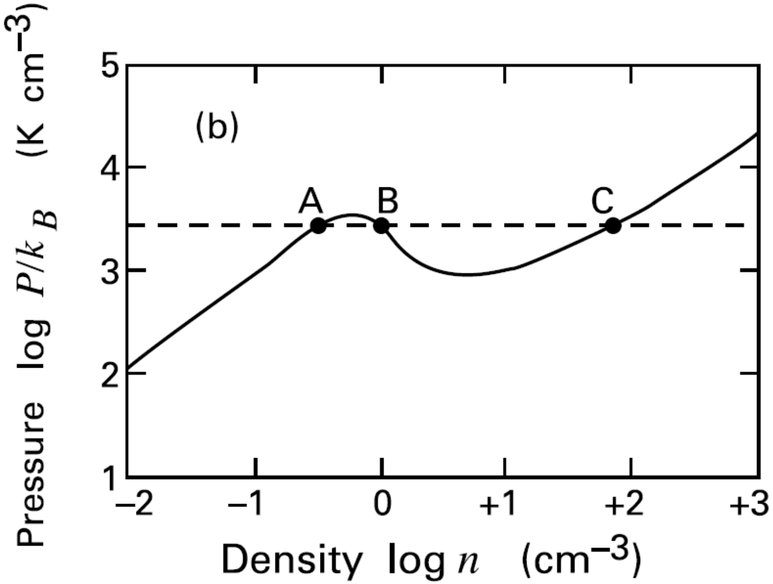
Molecular clouds

Thermodynamics of the ISM



Tielens (2013)

- Heating from absorption and dissipation in shocks
- Emission via collisionally excited mol. transitions
- Recombination of hydrogen acts as a thermostat
- Approximate pressure equilibrium between phases



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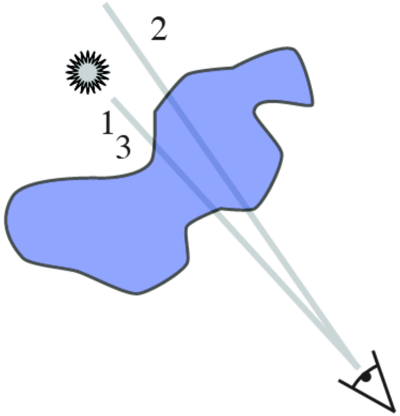
Measurement of excitation temperature

- Consider three lines of sights toward an H I cloud.



$$T_B(1) = T_B(\mathrm{BS})\exp(-\tau) + T_{\mathrm{ex}}(1 - \exp(-\tau))$$

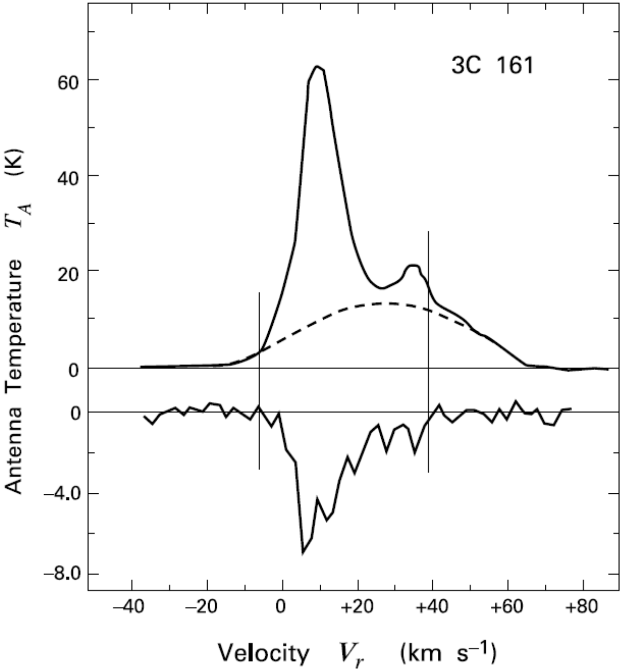
$$T_B(2) = T_{\mathrm{ex}}(1 - \exp(-\tau))$$

$$T_B(3) = T_B(\mathrm{BS})$$

Slide courtesy of Jes Jørgensen

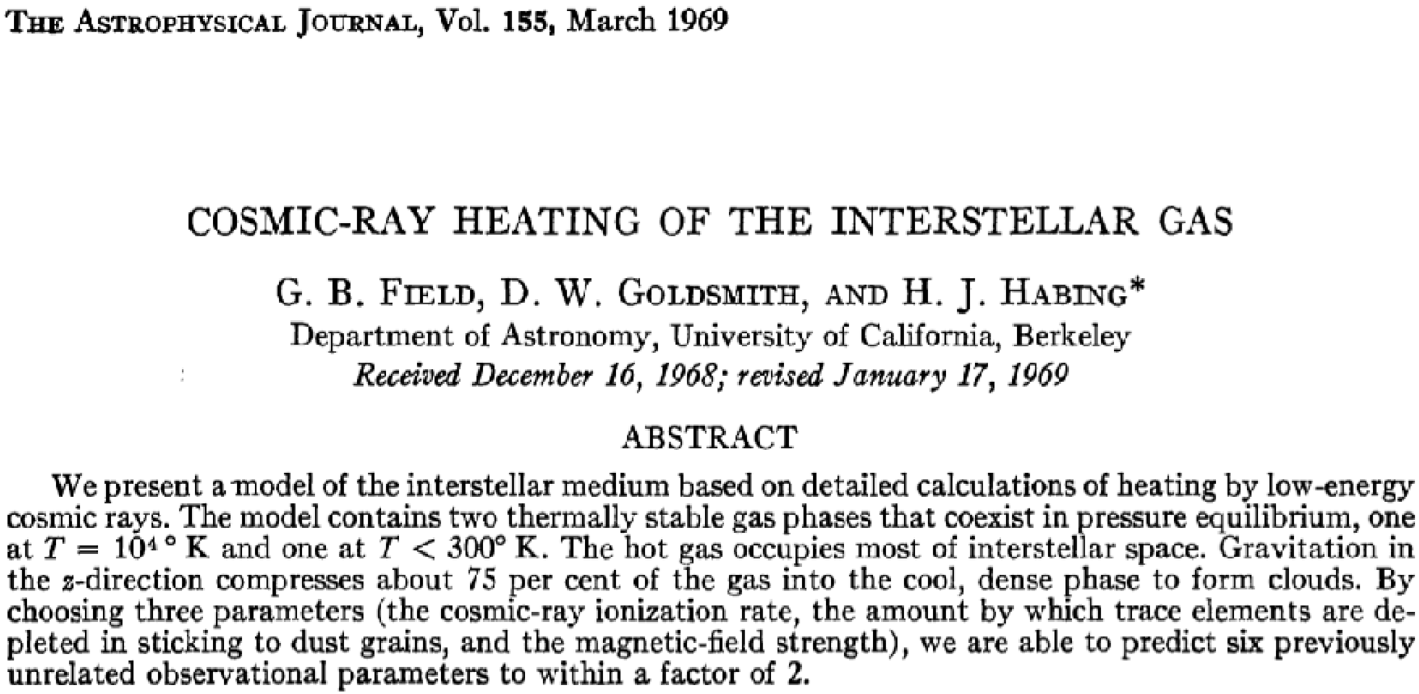
H I clouds

- Temperature: ~80 K
- Density: 10 to 100 cm^{-3}
- Clumps with sizes from 1 to 100 pc
- Extended warm component with density of 0.5 cm^{-3} and temperature of 8000 K.
- Almost pressure equilibrium between the two components.



Stahler & Palla's book

Slide courtesy of Jes Jørgensen



THE ASTROPHYSICAL JOURNAL, Vol. 155, March 1969

COSMIC-RAY HEATING OF THE INTERSTELLAR GAS

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Department of Astronomy, University of California, Berkeley

Received December 16, 1968; revised January 17, 1969

ABSTRACT

We present a model of the interstellar medium based on detailed calculations of heating by low-energy cosmic rays. The model contains two thermally stable gas phases that coexist in pressure equilibrium, one at $T = 10^4$ ° K and one at $T < 300°$ K. The hot gas occupies most of interstellar space. Gravitation in the z-direction compresses about 75 per cent of the gas into the cool, dense phase to form clouds. By choosing three parameters (the cosmic-ray ionization rate, the amount by which trace elements are depleted in sticking to dust grains, and the magnetic-field strength), we are able to predict six previously unrelated observational parameters to within a factor of 2.

McKee & Ostriker (1977) later introduced a dynamic third phase representing the hot (T ~ 10^6 K) gas that has been shock heated by supernova explosions and, in fact, constitutes most of the volume of the ISM.

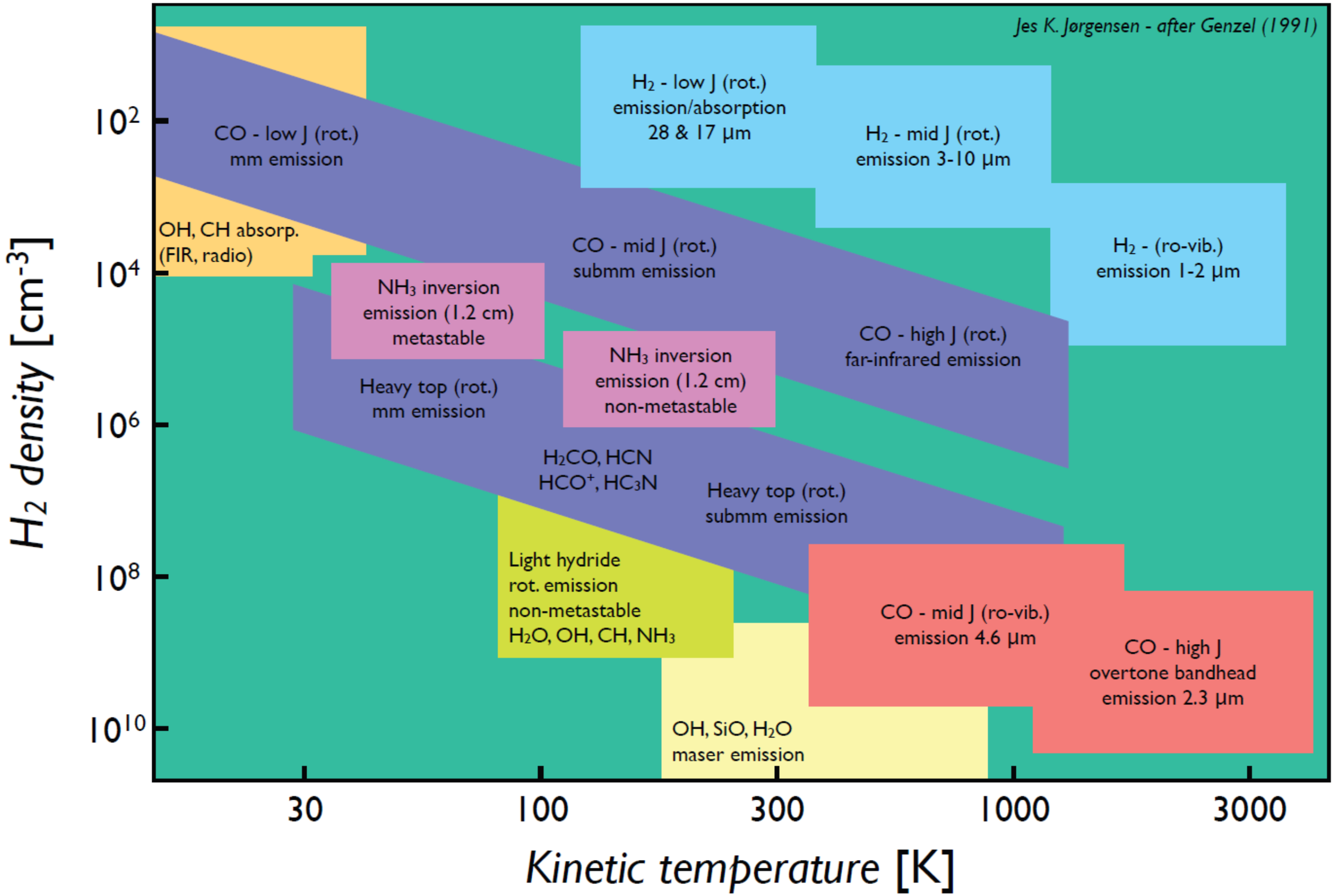
Slide courtesy of Jes Jørgensen

Molecular clouds in the Galaxy

- Traditionally divided according to size. Somewhat subjectively of course…

Type	**A_V [mag]**	$n_{\rm tot}$ [cm^{-3}]	L [pc]	T [K]	M [$M_\odot$]
Diffuse	**1**	500	3	50	50
Giant Molecular Cloud	**2**	100	50	15	10^5
Dark cloud: complex	**5**	500	10	10	10^4
Dark cloud: individual	**10**	10^3	2	10	30
Dense core/Bok globule	**10**	10^4	0.1	10	10

Slide courtesy of Jes Jørgensen



Slide courtesy of Jes Jørgensen

Support and lifetime of clouds

The Virial Theorem

- Generally aim to relate the kinematics of clouds (or gas in general) to the forces acting upon it.
- As the case for the equation of radiative transfer we will end with a very “simple” expression containing a whole lot of physics.
- Let us start with a simple expression just considering the kinematics of an ensemble of particles acting under gravity.

$$\frac{1}{2}\overset{\substack{\text{Generalised moment}\\ \text{of inertia}\\ \Downarrow}}{\frac{\partial^2 I}{\partial t^2}} = 2\underset{\substack{\Uparrow\\ \text{Total kinetic energy in bulk}\\ \text{motions}}}{\mathcal{T}} + 2\overset{\substack{\text{Total energy in thermal}\\ \text{motions}\\ \Downarrow}}{U} + \underset{\substack{\Uparrow\\ \text{Gravitational}\\ \text{potential energy}}}{\mathcal{W}} + \overset{\substack{\text{Magnetic energy}\\ \Downarrow}}{\mathcal{M}}$$

Slide courtesy of Jes Jørgensen

Time-scale for free-fall

- Let us say that there are no thermal (microscopic) or bulk motions in our cloud and also no magnetic field, our cloud will of course just collapse under gravity…

$$\frac{1}{2}\frac{\partial^2 I}{\partial t^2} = \cancel{2\mathcal{T}} + \cancel{2\mathcal{U}} + \mathcal{W} + \cancel{\mathcal{M}}$$

$$\frac{1}{2}\frac{\partial^2 I}{\partial t^2} = \frac{1}{2}\frac{\partial^2 (MR^2)}{\partial t^2}$$

$$t_{\rm ff} = \sqrt{\frac{R_{\rm eff}^3}{GM}} \approx \underline{6 \times 10^6 \rm{yr}} \left(\frac{M}{10^5\, M_\odot}\right)^{-1/2} \left(\frac{R_{\rm eff}}{25\,\rm pc}\right)^{3/2}$$

Slide courtesy of Jes Jørgensen

Support: thermal motions

Support through the random motions of the particles in the cloud (thermal pressure)

$$U = \frac{\overset{\text{Number of molecules}}{\overset{\Downarrow}{M}}}{\mu\, m_{\mathrm{H}}}\, \underset{\underset{\text{Boltzmann constant}}{\Uparrow}}{k_{\mathrm{B}}}\, \overset{\text{Gas temperature}}{\overset{\Downarrow}{T}}$$

$$\begin{aligned} \frac{U}{|\mathcal{W}|} &\approx \frac{M}{\mu m_{\mathrm{H}}} k_{\mathrm{B}} T \left(\frac{GM^2}{R}\right)^{-1} \\ &= 3\times 10^{-3} \left(\frac{M}{10^5 M_\odot}\right)^{-1} \left(\frac{R}{25\,\mathrm{pc}}\right) \left(\frac{T}{25\,\mathrm{K}}\right) \end{aligned}$$

Slide courtesy of Jes Jørgensen

Support: magnetic fields

Support through magnetic fields:

$$\mathcal{M} = \frac{|\mathbf{B}|^2}{8\pi} V$$

Volume

Magnetic pressure

$$\frac{\mathcal{M}}{|\mathcal{W}|} = \frac{|\mathbf{B}|^2 R^3}{6\pi} \left(\frac{GM^2}{R}\right)^{-1}$$

$$= 0.3 \left(\frac{B}{20\mu\mathrm{G}}\right)^2 \left(\frac{R}{25\ \mathrm{pc}}\right)^4 \left(\frac{M}{10^5 M_\odot}\right)^{-2}$$

Slide courtesy of Jes Jørgensen

Support: bulk motions

- Random (macroscopic) motions within the clouds:

$$\mathcal{T} = \frac{1}{2} M \underset{\Uparrow}{\Delta V^2}$$

Speed of macroscopic motions

$$\begin{aligned}\frac{\mathcal{T}}{|\mathcal{W}|} &\approx \frac{1}{2}M\Delta V^2 \left(\frac{GM^2}{R}\right)^{-1} \\ &= 0.5 \left(\frac{\Delta V}{4\,\mathrm{km\ s^{-1}}}\right)^2 \left(\frac{M}{10^5 M_\odot}\right)^{-1} \left(\frac{R}{25\,\mathrm{pc}}\right)\end{aligned}$$

Slide courtesy of Jes Jørgensen

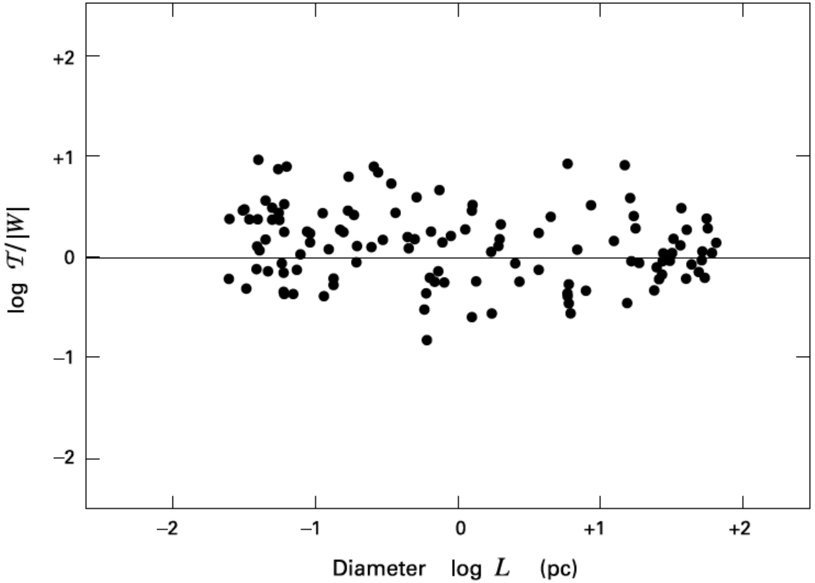
Comparing the kinematics and gravity

$$\frac{\mathcal{T}}{|\mathcal{W}|} \approx \frac{1}{2} M \Delta V^2 \left(\frac{GM^2}{R}\right)^{-1}$$

- The ratios of the kinematical to gravitational energies are constant over a wide range of scales.
- The typical clouds have velocities that are close to the virial velocity:

$$V_{\rm vir} \equiv \left(\frac{G\,M}{R}\right)^{1/2} .$$

- Relatively few magnetic field measurements – but those imply a similar constancy with gravity.



Slide courtesy of Jes Jørgensen

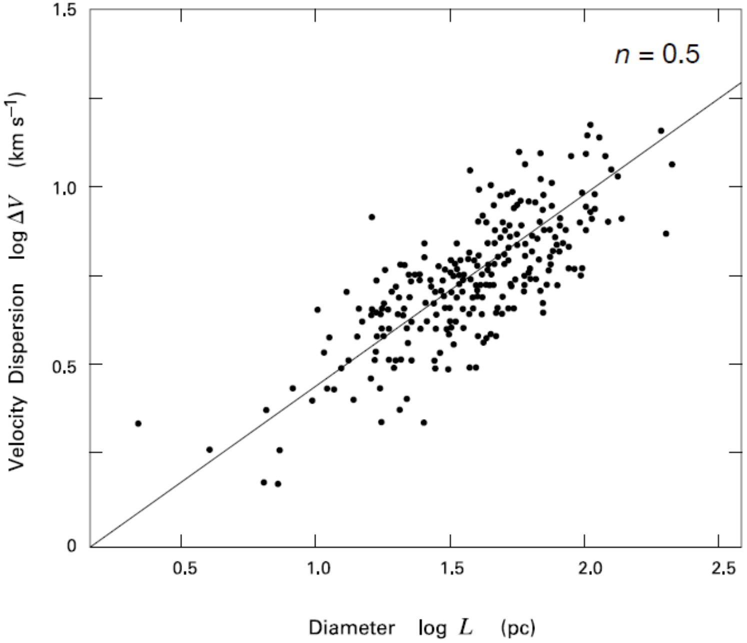
Larson's law

- Good correlation between velocity dispersion and size of cloud over wide range of scales, following power-law:

$$\Delta V = \Delta V_\circ \left(\frac{L}{L_\circ}\right)^n ,$$

- At smaller scales the velocity decreases until it reaches the thermal sound speed.

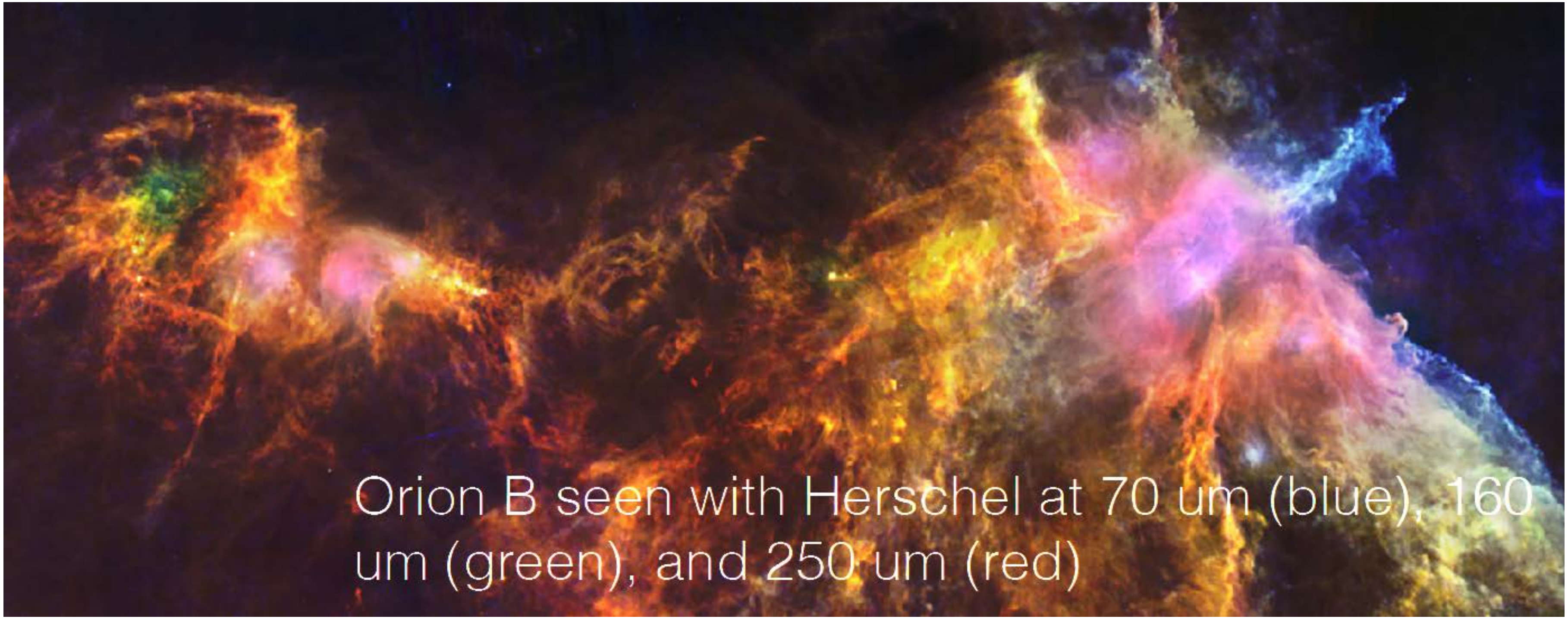
$$L_{\rm therm} = \frac{3\,\mathcal{R}\,T\,L_\circ}{\mu\,\Delta V_\circ^2} = 0.1\ {\rm pc}\left(\frac{T}{10\ {\rm K}}\right) .$$



Slide courtesy of Jes Jørgensen

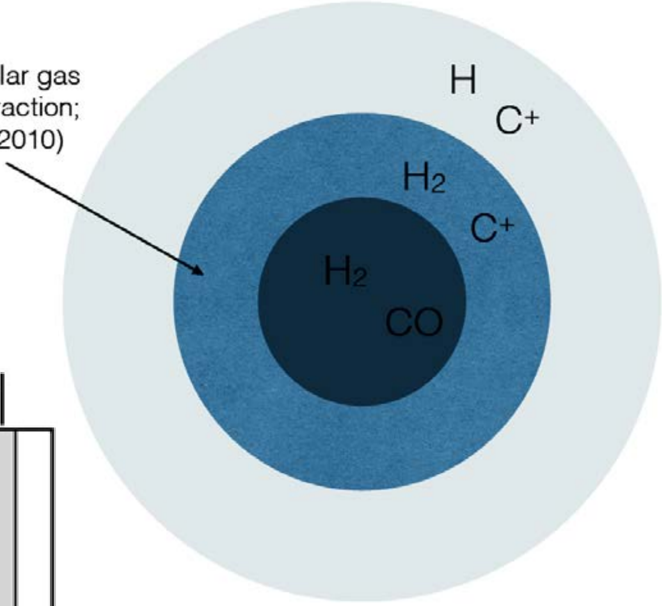
Photo-dissociation regions

- “Photon-dominated regions” or
  “photo-dissociation regions”, either one works
- Broadly speaking regions where radiation impinges on molecular cloud, but specifically regions where UV radiation impinges



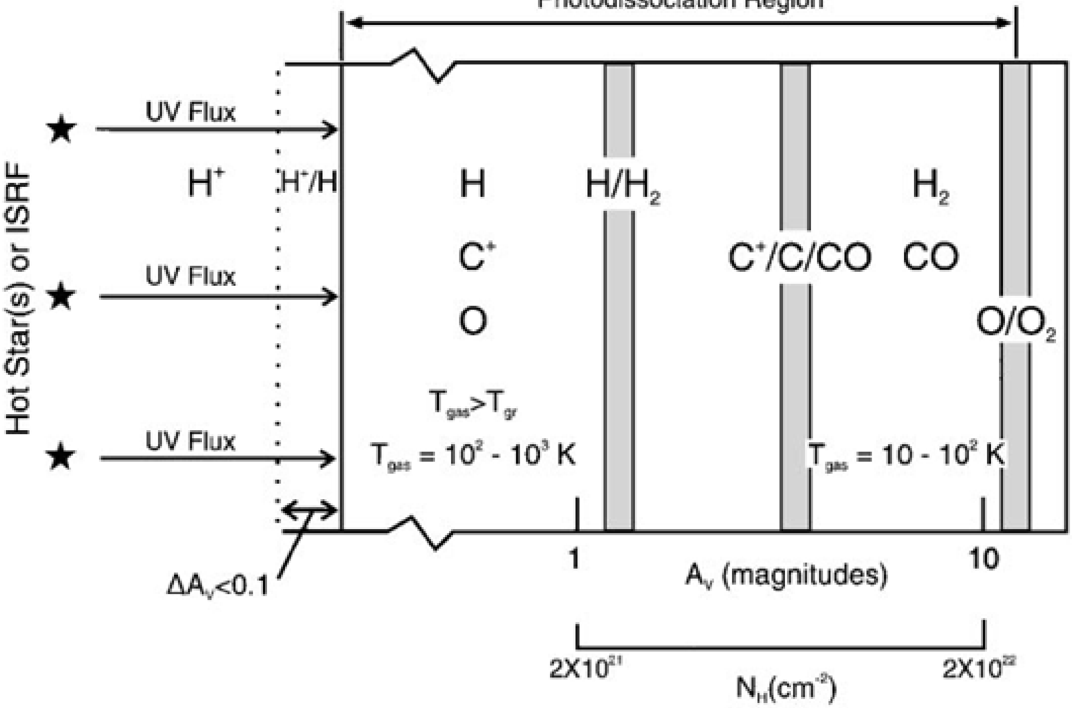
Orion B seen with Herschel at 70 um (blue), 160 um (green), and 250 um (red)

Slide courtesy of Jes Jørgensen



“Dark” molecular gas
(~30% mass fraction;
Wolfire et al. 2010)

Hollenbach & Tielens 1997, ARA&A

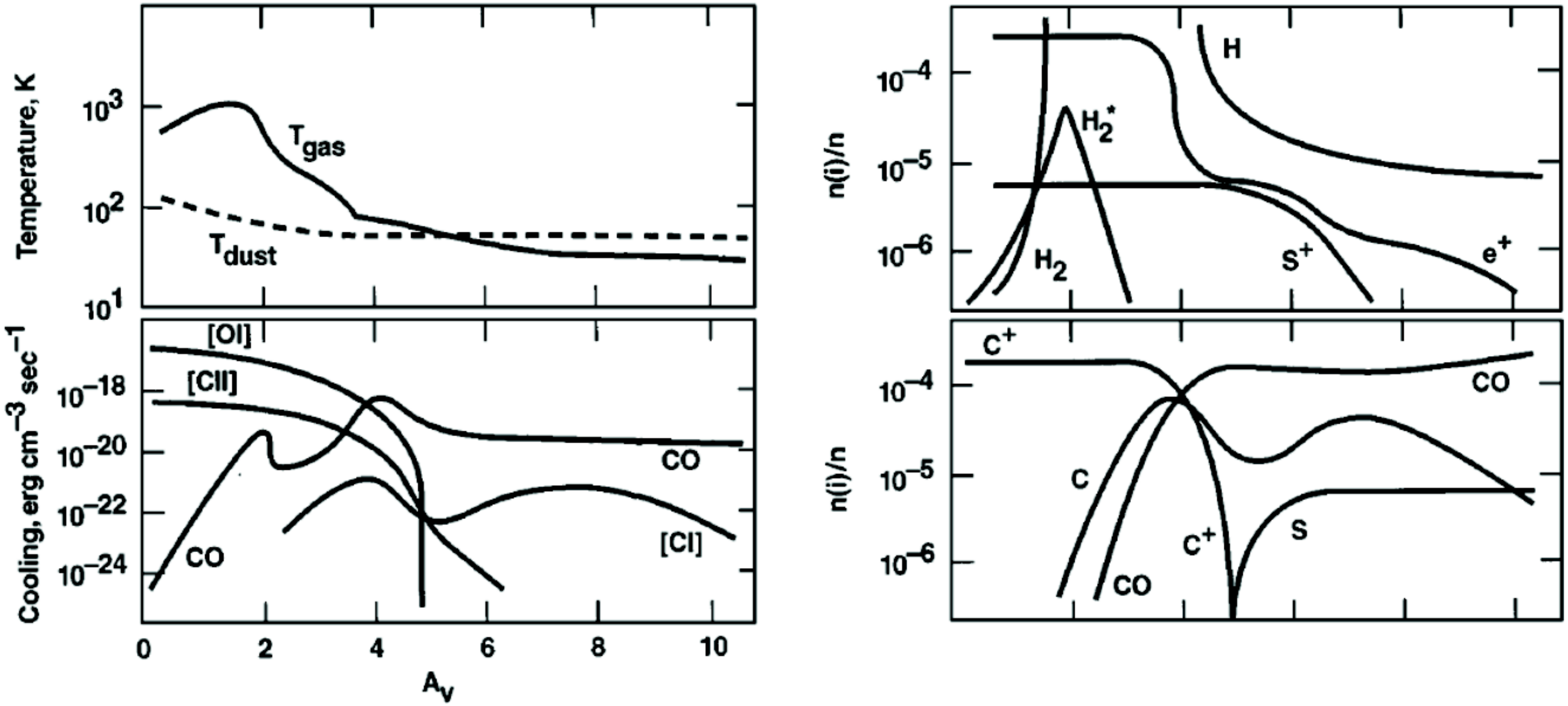


Self-shielding of H_2

- H_2 UV absorption lines leading to dissociation become very optically thick at small depth into the cloud: this is called self-shielding

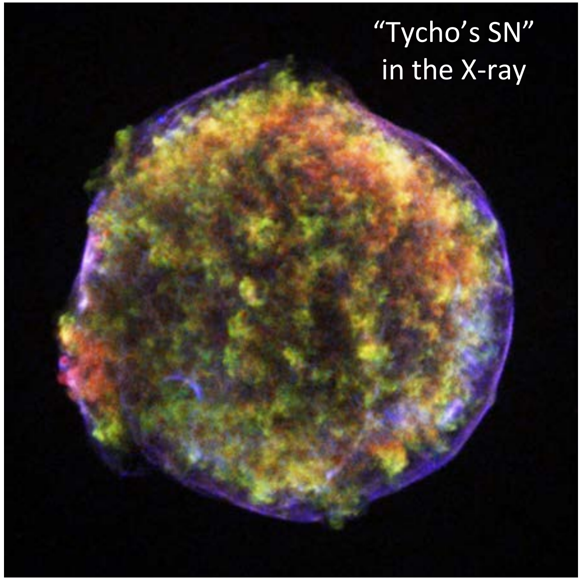
- H_2 molecules at the edge of the cloud absorb all available photons at specific wavelengths, so that molecules lying deeper in the cloud “see” virtually no photons at all and are not dissociated

Slide courtesy of Jes Jørgensen



Hollenbach & Tielens 1997

The physics of shock waves


“Tycho’s SN”
in the X-ray

From Alyssa Goodman's 201b course at Harvard

	NON-RADIATIVE (no radiative cooling post-shock)		RADIATIVE (treats cooling of post-shock gas)	
	"**viscous**" shock	*a fictitious, truly* "**adiabatic**" shock	*poorly named!* "**isothermal**" shock	"**radiative**" shock
continuity equation used (conservation of **mass**)	✔	✔	✔	✔
conservation of **momentum** equations used	✔	✔	✔	✔
conservation of **energy** equations used	✔	✔	✘	✘
entropy conserved ("isentropic" conditions)	✘	✔	✘	✘
energy loss via **radiative cooling**	✘	✘	✔	✔
Comments	a **"strong" shock** is one of these where Mach# >>1	*This is <u>impossible</u>! Shocks are irreversible processes, so entropy will go up.*	The "isothermal" part refers to the post-radiative-cooling T = to original T.	cooling due to radiation

Magnetic precursors

- $vA \sim n^{-1/2}$ => Alfven speed for decoupled ion-electron fluid can be much larger than Alfven speed for coupled neutral-ion-electron fluid:

$$v_{\mathrm{A}} = v_{\mathrm{A,ie}} = \frac{B}{\sqrt{4\pi\rho_{\mathrm{i}}}}$$

$$\approx 50\ \mathrm{km/s} \left(\frac{n_{\mathrm{i}}/n_{\mathrm{H}}}{10^{-4}}\right)^{1/2} \left(\frac{20 m_{\mathrm{H}}}{\rho_{\mathrm{i}}/n_{\mathrm{i}}}\right)^{1/2}$$

- Typically $C_S < v_{A,n} < v_S < v_{A,ie}$

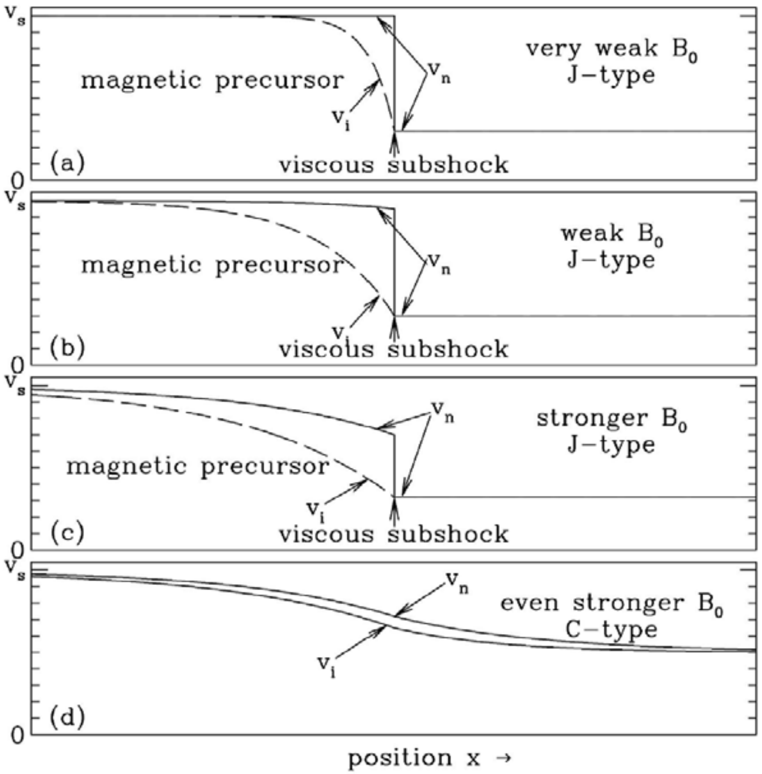
- Ion-electron plasma sends information ahead of disturbance to “inform” pre-shock plasma that compression is coming: magnetic precursor

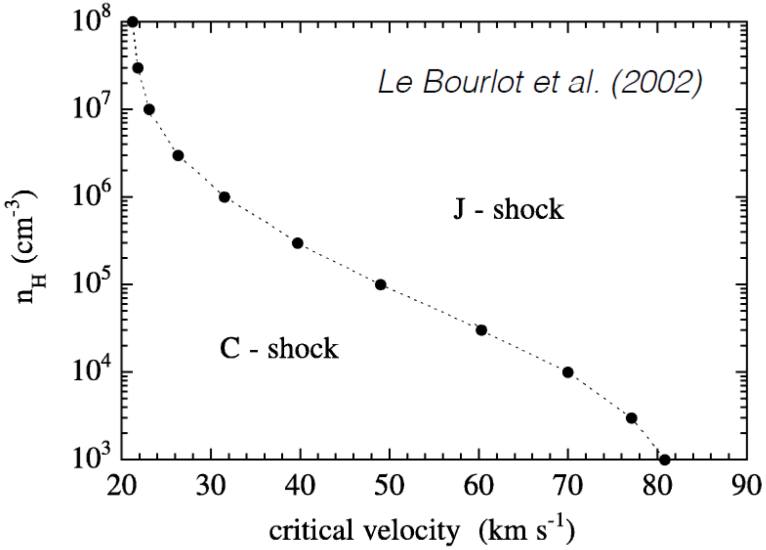
- Compression is subsonic and transition is smooth and continuous: C-shock

- Ions couple by collisions to neutrals

Slide courtesy of Jes Jørgensen

Schematic structure of J- and C-type shocks

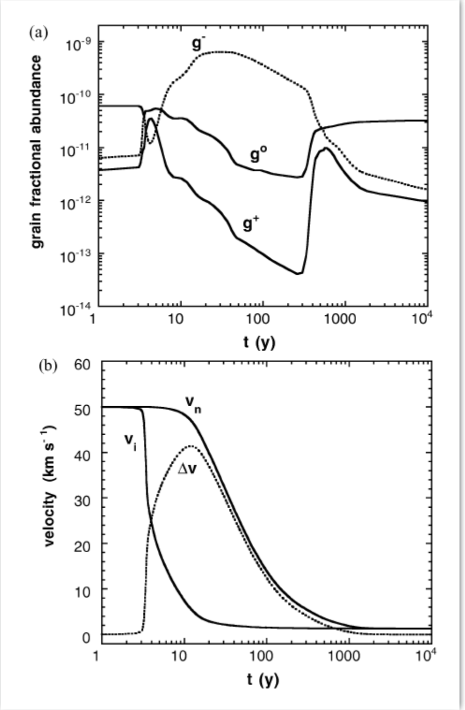



Le Bourlot et al. (2002)

Slide courtesy of Jes Jørgensen

Grain sputtering

- Primarily in C-type shocks
- Electrons accelerated, attach to grains, grains accelerated, stream past neutral gas
- J-type shocks: thermal sputtering only



Flower & Pineau des Forêts 2003

Slide courtesy of Jes Jørgensen

Questions…