Einführung in die Astronomie II

Teil 11

Peter Hauschildt
yeti@hs.uni-hamburg.de

Hamburger Sternwarte
Gojenbergsweg 112
21029 Hamburg

30. Oktober 2019

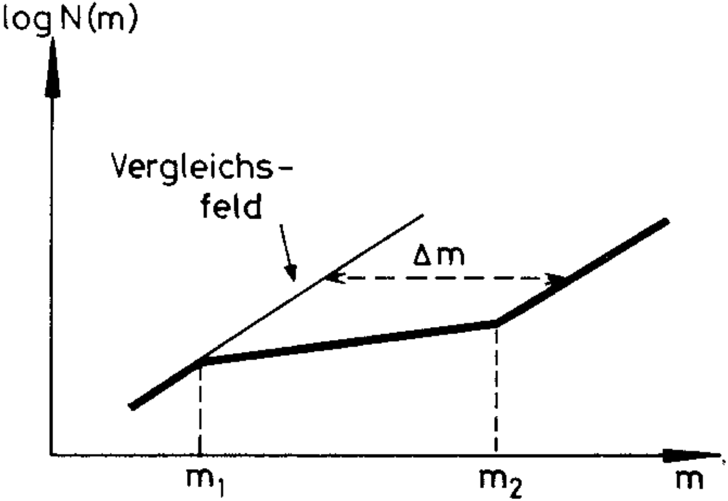
Overview part 11

- Interstellar Material
    - interstellar reddening
    - neutral H I
    - H II regions
    - molecules

The ISM

- Presence of ISM apparent through
    - bright reflection nebulae
    - dark clouds (star counts)
- Stars form out of the material in the ISM and return (processed?) material back to it.
- The next generation of stars forms from the ISM after it was enriched by the previous generations
  $\rightarrow$*chemical evolution*

Interstellar Extinction !!



Interstellar Extinction !!

- Interstellar dust clouds in the line of sight towards distant stars obscure the light
- changes the distance modulus equation:

$$m_\lambda = M_\lambda + 5 \log d - 5 + a_\lambda$$

  a_λ: the interstellar absorption in [mag]

- a_λ is related to the optical depth τ_λ of the cloud

$$I_\lambda / I_{\lambda,0} = \exp(-\tau_\lambda)$$

- with

$$m_1 - m_2 = -2.5 \log \left(\frac{F_1}{F_2} \right)$$

Interstellar Extinction !!

- thus

$$\begin{aligned} m_\lambda - m_{\lambda,0} &= -2.5 \log \left(\exp(-\tau_\lambda) \right) \\ &= 2.5 \tau_\lambda \log e \approx 1.086 \tau_\lambda \end{aligned}$$

- so that

$$a_\lambda \approx 1.086 \tau_\lambda$$

Interstellar Extinction !!

- optical depth is given by

$$\begin{aligned}\tau_\lambda &= \int_0^s n(s)\sigma_\lambda \, ds \\ &= \sigma_\lambda \int_0^s n(s) \, ds \quad \equiv \sigma_\lambda N_d\end{aligned}$$

  - σ_λ: extinction cross section of the cloud
  - $n(s)$: number density of absorbing/scattering particles in the cloud
  - N_d: *column density* of absorbing/scattering particles in the cloud
  - → number of particles in a cylinder with cross section of 1 cm^2 in the line of sight towards the observer.

Interstellar Extinction !!

- Most of the extinction in the ISM originates from *dust* particles.
- optical properties of spherical, homogeneous dust grains are described by the *Mie theory* (G. von Mie, 1908).

Mie Theory

- *geometrical cross section* of a dust particle with radius a

$$\sigma_g = \pi a^2$$

- dimensionless *extinction coefficient* Q_λ

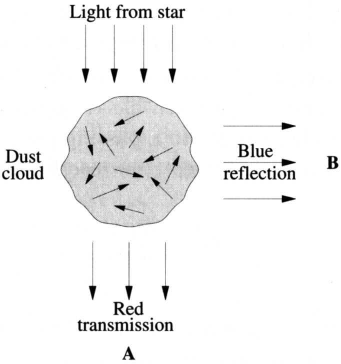
$$Q_\lambda \equiv \frac{\sigma_\lambda}{\sigma_g}$$

- Q_λ depends on the *composition* and the *size* of the dust particles.
  1. if $\lambda \approx a$ then $Q_\lambda \propto a/\lambda$ so that $\sigma_\lambda \propto \lambda^{-1}$
  2. if $\lambda \gg a$ then $Q_\lambda \to 0$
  3. if $\lambda \ll a$ then $Q_\lambda \to \mathrm{const.}$ (independent of λ)

Mie Theory

- the above implies a wavelength dependent effect of the dust.
- dust *scatters* blue light stronger than red light.
- it also *absorbs* more blue light than red light.
- *Rayleigh scattering*: special case of Mie scattering for molecules with $\ll \lambda$, giving $\sigma_\lambda \propto \lambda^{-4}$.
- combined effects lead to

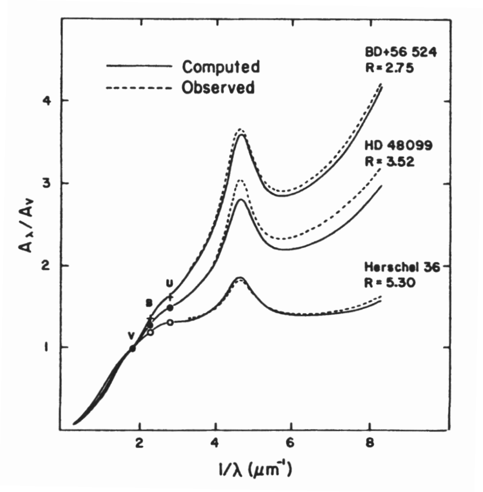
Interstellar Reddening !!



Interstellar Reddening

- stars seems behind a cloud of dust appear *redder* than without the cloud
- blue light will be scattered into the line of sight leading to *reflection nebulae*
- typical dust grain sizes in the ISM are $0.2\,\mu$ and densities (in the plane of the Galaxy) are about $10^{-13}\,\mathrm{cm}^{-3}$.
- Mie theory works well in visible to IR light
- at *shorter* wavelengths (UV) there are larger discrepancies:

Interstellar Reddening



ratio a_λ / a_V as function of $1/\lambda$

Color Excess !!

- *color excess* $E_{\mathrm{B-V}}$ is defined as

  $$E_{\mathrm{B-V}} = (B - V) - (B - V)_0$$

  where $(B - V)_0$ is the unchanged color index of the star related to the a_λ through

  $$E_{\mathrm{B-V}} = a_B - a_V$$

- therefore

  $$\frac{E_{\lambda-\mathrm{V}}}{E_{\mathrm{B-V}}} \to \frac{-a_V}{E_{\mathrm{B-V}}} \quad \mathrm{for} \quad \lambda \to \infty$$

Color Excess !!

- observed:

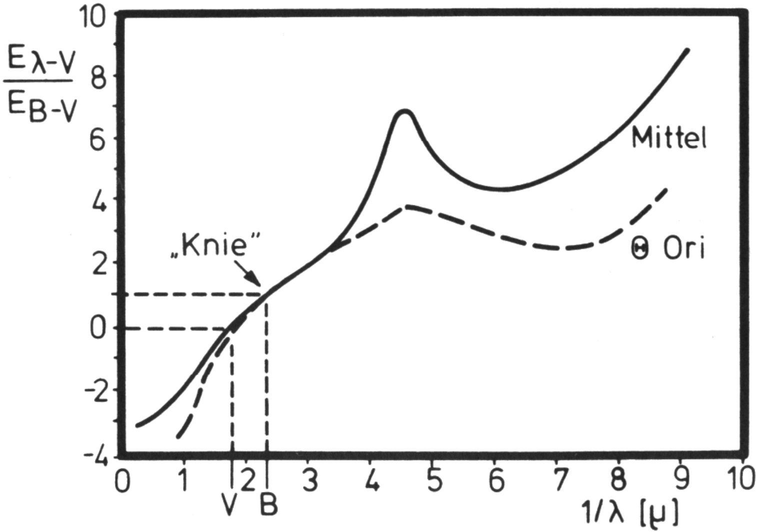
$$\frac{E_{\lambda-\mathrm{V}}}{E_{\mathrm{B-V}}} \rightarrow \approx -3 \quad \mathrm{for} \quad \lambda \rightarrow \infty$$

- important general result:

$$\frac{a_V}{E_{\mathrm{B-V}}} \equiv R \approx 3.1 \pm 0.1$$

- relates the interstellar reddening to the interstellar extinction

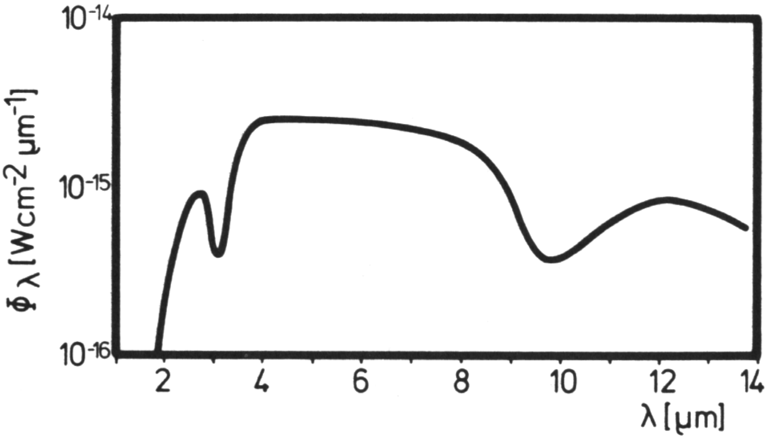
Interstellar Dust



Interstellar Dust

- *interstellar absorption feature* or “bump” at $\approx 2175\,\text{Å}$
- hints about the *composition* of the dust
  - *Graphite* interacts strongly with photons around $\lambda = 2175\,\text{Å}$
  - it is unclear how such large graphite particles form in the ISM!
  - the *interstellar extinction curve* depends on the line-of-sight:

Interstellar Dust



Interstellar Dust

- presence of other interstellar absorption features $\rightarrow$
- ISM also contains other kinds of dust
- $\approx 3.1\,\mu$: water ice?
- $\approx 10\,\mu$: (also at $\approx 18\,\mu$) *silicate* features due to stretching of Si–O and bending of Si–O–Si bonds
- spectral features of dust tend to be broad and ill defined, so better statements about dust compositions are very hard to make.

PAH

- series of emission bands in the *diffuse* ISM
- *unidentified infrared emission bands* between 3.3 μ and 12 μ
- associated with vibrational transitions in C–C and C–H bonds
- $\rightarrow$ *polycyclic aromatic hydrocarbons (PAH)*
- organic molecules with a planar, benzene ring-like structure

Interstellar Polarization

- light from interstellar dust is (depending on wavelength) slightly polarized (a few percent)
- this implies that the dust particles are *non-spherical*
- the polarization vectors are preferentially aligned, that implies that the dust grains are *aligned* too.
- alignment is probably due to interaction with a weak B-field of the rotating dust particles.

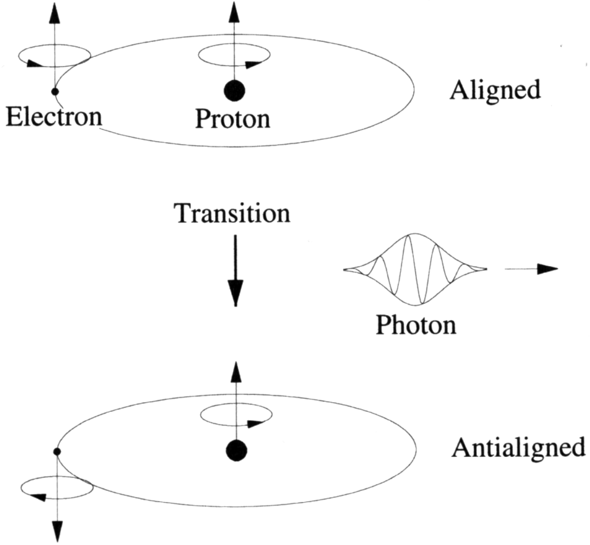
Interstellar Dust

- incomplete picture of the interstellar dust:
    - graphite, silicate and PAH particles
    - sizes range from 0.25 μ (graphite, silicates?) to a few Å (PAH)
    - dominant species in the ISM are H I, H II, and H_2 (70%), metals make up only a few %, He makes up the remaining mass

H I gas

- H I in the ground state → not observable in emission
- resonance lines → deep UV
- H I can be observed through radio hyperfine structure line:

21cm line !!



21cm line !!

- reversal of the electron spin relative to the proton spin in H I
  - spins anti-parallel: ground state
  - spins parallel: slightly higher energy due to *magnetic dipole moment* associated with the spins
- *magnetic dipole radiation* with a transition probability of $2.87 \times 10^{-15}\,\mathrm{s}^{-1}$
- *lifetime of 11 million years*.

21cm line !!

- Collisions between particles are a competing process that can also flip the spins *without* emitting a photon.
- In the ISM, the time scales for collisions are a few 100 years so that most spin flips do not produce a 21 cm photon
- but there are still enough left to produce measurable 21 cm photons
- even under terrestrial "high vacuum" conditions, the particle densities are too high for 21 cm photons to be measured!

21cm line !!

- 21 cm line is used to measure
    - velocities (Doppler)
    - B-fields (Zeeman)
    - structure and kinematics of galaxies
- low transition probability of the hyperfine line
- competing collisional de-excitation processes
- → line *optically thin* over long line-of-sights through interstellar clouds

21cm line !!

- line profile is Gaussian, the optical depth in the line center is

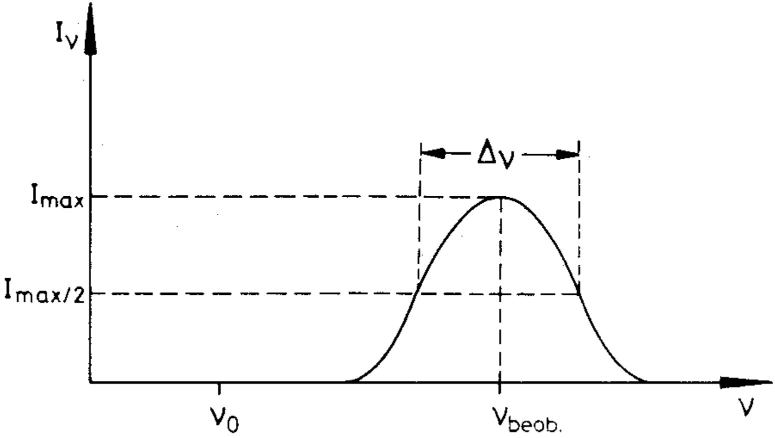
$$\tau_{21} = 5.2 \times 10^{-19} \frac{N_H}{T \Delta v}$$

  where

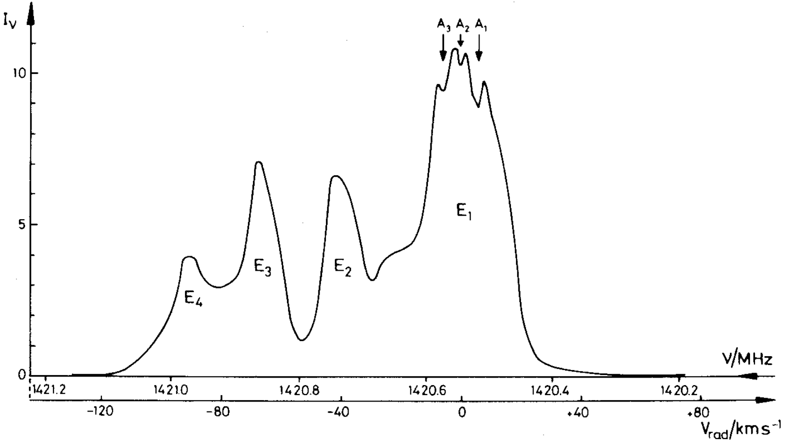
  - N_H: column density of H I in cm^{-2}
  - T: temperature
  - Δv: FWHM of the line in km/s ($\sim 10\,\mathrm{km\,s^{-1}}$)

- proportional to N_H

21cm line !!



21cm line !!



I_ν
10
5
0
A_3
A_2
A_1
E_1
E_2
E_3
E_4
V/MHz
1421.2
1421.0
1420.8
1420.6
1420.4
1420.2
-120
-80
-40
0
+40
+80
V_{rad}/kms^{-1}

diffuse H I clouds

- $T \approx 30 \dots 80\,\mathrm{K}$
- $n \approx 100 \dots 800\,\mathrm{cm}^{-3}$
- cloud masses $\approx 1 \dots 100\,\mathrm{M}_\odot$

H I clouds

- Comparing τ_{21} and a_V shows that

$$N_H \propto N_D$$

(N_D: dust column density) as long as

$$a_V < 1$$

  - suggests that dust and gas are distributed together in the ISM
  - breaks down for $a_V > 1$: N_H does *not* increase as fast as N_D does!

H I clouds

- *Optically thick dust clouds* shield gas from UV radiation that can dissociate H_2 molecules.
- H_2 molecules can also form on the *surface* of dust grains easier
    - dust grain is a site for H atoms to "meet"
    - provides an energy reservoir for the binding energy set free by the formation of H_2
    - this energy heats the grain and can lead to an ejection of the molecule from the surface.

molecular clouds

- H I clouds with $N_h > 10^{21}\,\mathrm{cm}^{-2}$ also shield their inner regions from UV radiation so that H_2 forms → H_2 clouds are surrounded by a shell of H I.
- spectrum of H_2 molecules is very different from H I,
- does *not* emit something like the 21 cm radiation
- extremely hard to detect (H_2 has electronic transitions in the UV)
- therefore, N_H and a_v are not well correlated in *molecular clouds* ($a_v > 1$)

molecular clouds

- H_2 is very difficult to observe directly, but other molecules can be used as *tracers*:
    - CO (about 10^4 times less abundant than H_2), 2.6 mm transition
    - CH, OH, CS, C_3H_2
    - more than 50 interstellar molecules are known, some very complex and large: $HC_{11}N$ etc.
- collisions excite the tracer molecules, the subsequently emitted photons are detected.

molecular clouds

- collisional rates depend on temperature and density of the gas → tracers provide info on temperatures and densities in the gas phase.
- To calculate the emitted radiation field, *rate equations* very similar to the nuclear rate equations have to be solved (problem: non-locality of the radiation field!)

molecular clouds

- Results of tracer molecule studies show very different conditions:
- *translucent molecular clouds*:
  - H I gas
  - $a_V \approx 1 \ldots 5$
  - $T \approx 15 \ldots 50\,\mathrm{K}$
  - $n \approx 500 \ldots 5000\,\mathrm{cm}^{-3}$
  - $M \approx 3 \ldots 100\,\mathrm{M}_\odot$

molecular clouds

- *giant molecular clouds (GMC)*:
  - molecular gas and dust
  - 50 pc size
  - $T \approx 20\,\mathrm{K}$
  - $n \approx 100 \ldots 300\,\mathrm{cm}^{-3}$
  - $M \approx 10^6\,\mathrm{M}_\odot$
  - associated with young O and B stars → sites of star formation

molecular clouds

- *GMC cores*:
    - 0.05 . . . 1 pc size
    - $a_V \approx 50 \dots 1000$
    - $T \approx 100 \dots 200\,\mathrm{K}$
    - $n \approx 10^7 \dots 10^9\,\mathrm{cm}^{-3}$
    - $M \approx 100 \dots 1000\,\mathrm{M}_\odot$

molecular clouds

- *Bok globules*:
    - ≈ 1 pc size
    - $a_V \approx 10$
    - $T \approx 10\,\mathrm{K}$
    - $n > 10^4\,\mathrm{cm}^{-3}$
    - $M \approx 1 \ldots 1000\,\mathrm{M}_\odot$
    - have young stars in their centers (sites of active star formation)

Emission Nebulae !!

- emission nebulae appear close to O and B stars
- → hot stars ($> 20,000\,\mathrm{K}$) emitting large amounts of UV photons
- atoms in the gas absorb UV photons and are ionized
- → emission nebulae mostly H II (ionized hydrogen, H I: neutral H)
- → *H II regions*

Emission Nebulae !!

- H II regions emit light by *recombination* of H II to H I
- electrons are typically captured in high-energy levels
- subsequently cascade down towards lower levels
- $\rightarrow$ emit light in the spectral lines of the element

Emission Nebulae !!

- very important 3–2 transition in hydrogen, Hα line at 656 nm
- this line gives emission nebulae their characteristic red color
- each high-energy UV photon absorbed → several emitted photons in the visible
- → gigantic fluorescent tubes ...

Radiation from H II Regions

- strong emission lines over weak continuum
- continuum: recombination of ionized H II (and He II/III)
- free-free Bremsstrahlung
- emission lines: cascades after recombinations
- low density → collisions rare
- → meta-stable transitions can be observed

Radiation from H II Regions

- emission from H:
- proportional to number of electrons
- proportional to number of H II particles →

$$I \propto \int n_e^2 \, ds$$

- optically thin!
- define *emission measure*

$$\mathrm{EM} = \int n_e^2 \, ds$$

Extension of H II Regions !!

- each H I ionization requires photon with $> 13.6\,\mathrm{eV}$
- $\rightarrow$ requires $T_{\mathrm{eff}} > 20\,000\,\mathrm{K}$
- balance ionization by recombination processes
- $\rightarrow$ max. size of H II region
- Recombination/sec $\rightarrow \alpha n_e$ per H II into excited states
- nebula of size s_0, constant density $\rightarrow$

$$N_R = \frac{4}{3}\pi s_0^3 n_{\mathrm{HII}} \alpha n_e \approx \frac{4}{3}\pi s_0^3 \alpha n_{\mathrm{H}}^2$$

Extension of H II Regions !!

- balance with number of ionizing photons $N_L \rightarrow$

$$s_0 = \left(\frac{3N_L}{4\pi\alpha n_{\mathrm{H}}^2} \right)^{1/3} = R_S \left(\frac{n_{\mathrm{H}}}{1\,\mathrm{cm}^3} \right)^{-2/3}$$

- *Strömgren sphere*
- excess energy of photons → heating
- H II regions reach 10^4 K

Expansion of H II Regions

- compared to H I region:
- T higher in H II region
- $\approx$ twice as many particles
- $P = NkT$ is larger in H II region!
- $\rightarrow$ H II region expands into H I region
- $v \approx 15\,\mathrm{km\,s^{-1}}$ (c_s in H II)

Expansion of H II Regions

- but that's Mach 10 for H I!
- → complicated shock structure interface
- H II gas thins out
- EM drops
- dissolved after $\approx 10^6$ years

Microscopic Proc. in the ISM !!

- clouds cool by emitting radiation: *radiative cooling*
- conduction or convection are usually unimportant
- basic mechanism:
  - collisional excitation of an atomic, ionic or molecular transition
  - subsequent emission of a photon
  - photon leaves (optically thin!) cloud
  - kinetic energy of the gas is reduced → cooling

Cooling of the interstellar gas

- In symbolic form:

$$\begin{aligned} A + B &\rightarrow A + B^* \\ B^* &\rightarrow B + h\nu \end{aligned}$$

Cooling of the interstellar gas

- Efficient cooling processes have the following characteristics:
  1. Frequent collisions → fairly abundant partners
  2. Excitation energies comparable to (or less than) the thermal kinetic energy
  3. large collisional cross-section (i.e., high probability for excitation during a collision)
  4. high radiative transition probability (i.e., photon is emitted *before* a second collision on the excited particle occurs)

Cooling by ions and atoms

- *first* criterion → collisions with H and other abundant elements (C, N, O), their ions and electrons are most likely.
- From the *second* criterion → excitation energy comparable to typical temperature of ca. 100 K for many low density clouds.
- predominant ion of C is C II with a $^2P_{1/2} \rightarrow ^2P_{3/2}$ transition with an energy difference corresponding to 92 K.
- This transition will be unimportant in clouds with $T = 20\,\mathrm{K}$!

Cooling by ions and atoms

- collisions with electrons will be important (why?)
- *third* criterion $\rightarrow$ requires QM calculation (very hard)...
- but typically the collisional cross-section is large when the radiative transition is *allowed*
- the same holds for the *fourth* criterion.
- for an allowed transition (i.e., a transition with a non-zero electric dipole moment) we can view the transition being caused by the electric field of the passing electron.

Important Cooling Processes

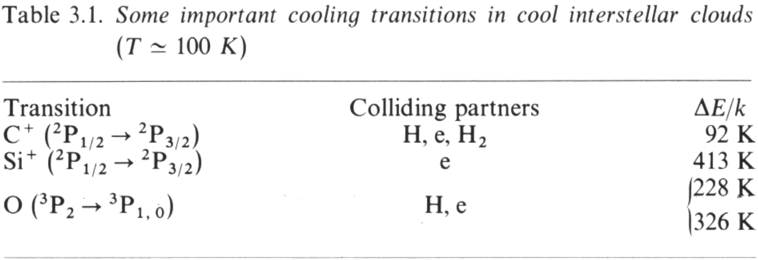


Table 3.1. *Some important cooling transitions in cool interstellar clouds* ($T \simeq 100$ K)

Transition	Colliding partners	$\Delta E/k$
C^+ $(^2P_{1/2} \rightarrow {}^2P_{3/2})$	H, e, H_2	92 K
Si^+ $(^2P_{1/2} \rightarrow {}^2P_{3/2})$	e	413 K
O $(^3P_2 \rightarrow {}^3P_{1,0})$	H, e	228 K 326 K

Cooling Rates

- to calculate the actual *cooling rate* the collisional cross-section must be known
- in general, the rates have forms somewhat similar to the C II cooling rate:

$$\Lambda_{\mathrm{C\ II}} = 8 \times 10^{33} n(e) n(\mathrm{C\ II}) T^{-1/2} \exp(-92/T)\ [\mathrm{Jm}^{-3}\mathrm{s}^{-1}]$$

- excitation of H I will be important (H is abundant!) but its transitions are very energetic ($n = 2$ level is 10.2 eV above the ground state!) and require $T \approx 10^4$ K.

Cooling Rates

- at intermediate temperatures ($T \approx 1000\,\mathrm{K}$), ions such as Fe II and Si II can be excited into *metastable* states $\rightarrow$ these act as new "ground-states" from which excitations can continue.

Cooling by molecules

- Molecular H (H_2) might be an important coolant:
  - *rotational energy levels* →

$$E_J = \mathrm{const.} J(J+1),\ \ J = 0, 1, 2, \ldots$$

  - H_2 does not have a permanent electric dipole moment → electric dipole transitions are forbidden
  - transitions occur through *electric quadrupole transitions* with $\Delta J = \pm 2$.
  - energy of the least energetic of those, $J = 0 \rightarrow J = 2$, corresponds to 510 K.

Cooling by molecules

- H_2 cooling process is very different from the atomic cooling processes because the *lifetimes* of the rotational levels are very long:
  $5 \times 10^{10}\,\mathrm{s}$ for the $J = 2$ level.
- collisions occur with a rate of $10^{11}/n\,\mathrm{s}$ → *shorter than the radiative lifetimes!*
- → levels are populated with

$$N_J \propto (2J + 1)\exp(-E_J/kT)$$

- → radiation "leaks" out slowly (only minor perturbation of the collisionally established equilibrium!).

Cooling by molecules

- these arguments do not apply to HD:
  - HD does have a (small) electric dipole moment
  - transitions with $\Delta J = \pm 1$ are *allowed*
  - $\rightarrow$ HD is *more* effective in cooling per molecule
  - but its abundances is down: $n(\mathrm{HD}) < 10^{-5} n(\mathrm{H}_2)$
  - $\rightarrow$ it will *not* add significantly to the H_2 cooling rate

Cooling by molecules

- the cooling rate for H_2 is

  $$\Lambda_{\mathrm{H}_2} = n(\mathrm{H}_2, J)\Delta E(J \to J-2)A(J \to J-2)$$

  where A is the transition probability (in 1/s).
- for $T = 100\,\mathrm{K}$ this gives about 3×10^{-33} J/s per H_2 molecule.

Cooling by molecules

- other molecules are very important:
- next abundant molecule: CO
  - dense clouds: $n(\mathrm{H}_2) \geq 10^{10}$
  - $n(\mathrm{CO}) \approx 10^{-5} n(\mathrm{H}_2)$
  - CO also significant in lower density clouds
  - CO is a *very* effective coolant because it has a dipole moment → allowed rotational transitions!
  - lowest rotational CO transition $J = 1 \rightarrow J = 0$ corresponds to 5.5 K!

Cooling by molecules

- CO can be an extremely efficient coolant in low temperature clouds!
- *but* CO can also get *optically thick* → reducing its cooling efficiency enormously (radiation is trapped!)

Important Cooling Processes

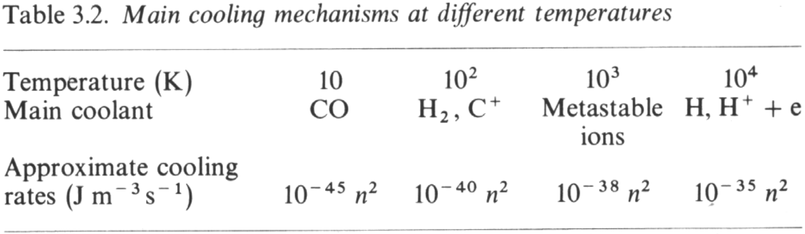


Table 3.2. *Main cooling mechanisms at different temperatures*

Temperature (K)	10	10^2	10^3	10^4
Main coolant	CO	H_2, C^+	Metastable ions	H, $H^+ + e$
Approximate cooling rates ($J\ m^{-3} s^{-1}$)	$10^{-45}\ n^2$	$10^{-40}\ n^2$	$10^{-38}\ n^2$	$10^{-35}\ n^2$

Cooling by molecules

- cooling is very rapid at high temperatures → large heating rates required to sustain high T's.
- if the gas is ionized, other cooling processes take over (PNe)

Heating of the interstellar gas !!

- several sources are important:
  1. starlight (local and “ambient”)
  2. cosmic rays
  3. X-rays
  4. novae & SNe
  5. if cloud is collapsing: compression

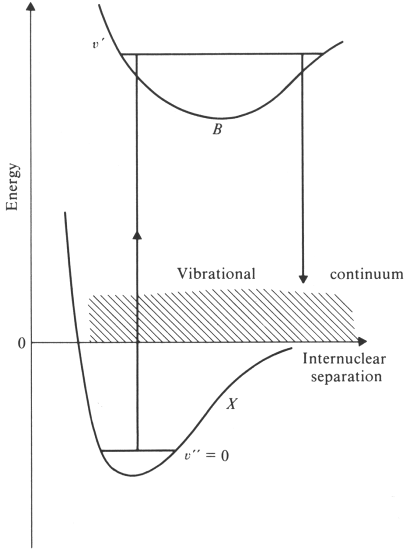
Heating by starlight

- photoionization:
  - $A + h\nu \rightarrow A^+ + e$
  - yields an electron with $E = h\nu - I$ (I: ionization energy of A)
  - electron interacts with the gas
  - → energy "thermalized" if most collisions are elastic
  - some collisions will excite atoms/ions/molecules (inelastic collisions)
  - → can lead to photon emission → energy lost!

Heating by starlight

- overall heating of clouds through b-f processes on C, Si, Fe.
- in H II regions, H ionizations are the most important heating source
- H ionizations “use up” all photons with $E > 13.6\,\mathrm{eV}$.
- in H I regions, C I ionizations ($I = 11.3\,\mathrm{eV}$) thus lead to a maximum deposited energy of about 2.3 eV per ionization.
- the mean value of deposited energy (for solar abundances) is about 2.1 eV

Photodissociation of H_2



Photodissociation of H_2

- excitation from ground state X to excited state B
- $\rightarrow$ cascade into vibrational continuum of X
- 23% of these excitations/de-excitations lead to H_2 dissociation
- dissociated H atoms take excess energy in form of kinetic energy
- thermalization → heating.
- about 0.4 eV deposited per photodissociation of H_2

Heating by cosmic rays and X-rays

- cosmic rays: high energy (few MeV) protons
- soft X-rays with range of photon energies peaking at $\approx 0.1\,\mathrm{keV}$.

- ionization of H by protons:

$$(\mathrm{p}, X) + \mathrm{H} \rightarrow (\mathrm{p}', X') + \mathrm{H}^{+} + \mathrm{e}$$

- a 2 MeV proton leads to electrons with a range of energies peaking at about 30 eV.
- if medium is already ionized → most of this energy is thermalized

Heating by cosmic rays and X-rays

- in a mainly neutral medium →

  $$\mathrm{e} + \mathrm{H(1s)} \rightarrow \mathrm{e} + \mathrm{H(2s)} \rightarrow \mathrm{e} + \mathrm{H(1s)} + h\nu$$

  or

  $$\mathrm{e} + \mathrm{H(1s)} \rightarrow \mathrm{e} + \mathrm{H}^+ + \mathrm{e}$$

- e-e collisions will slowly thermalize the energy
- when the e energy is $< 13.6\,\mathrm{eV}$ → no further H ionizations
- when the e energy is $< 10.2\,\mathrm{eV}$ → no further H excitations
- including the energy loss mechanisms
  $\rightarrow \approx 3.4\,\mathrm{eV}$ deposited per primary or secondary electron

Heating by cosmic rays and X-rays

- X-ray situation is similar but:
  - He (10% by number!) important because its X-ray cross-section is far larger than for H.
  - secondary electron's kinetic energy can be thermalized
  - or it produces further ionizations and excitations
  - a 50 eV X-ray photon absorbed by He $\rightarrow$ 25 eV electron
  - but only 6 eV are actually deposited as kinetic energy into the gas (for zero ionization)

Heating by grains

- photoelectric emission of electrons!
- creates electrons with a few eV energy
- this process is actually the *dominant* heating mechanism if it occurs rapidly enough!