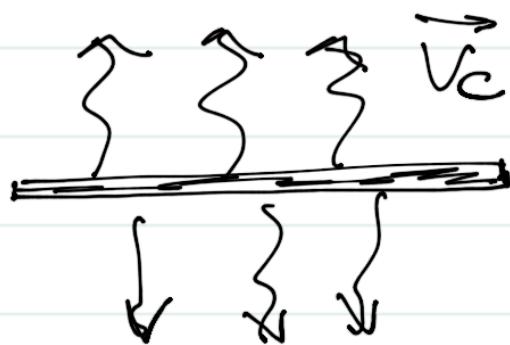


# CONVECTION in the GALAXY

It has been recognized for a long time that a THIN disc configuration would be disrupted by CR pressure. It can be stabilized by the presence of a HALO.

The stellar activity and the energetic phenomena associated to late stages of stellar evolution may push the IS plasma and the magnetic field associated with it OUT of the galactic plane. The net result is a convective current directed outwards from the gal. plane and called GALACTIC WIND. It adds a convective term to the diffusion equation.



The convective wind has been observed in external galaxies by radio observations. In ours, it is more

difficult to establish. The form is not clear, however it makes sense to model it as increasing with the distance from the disc. A speed of  $O(10 \text{ km/s})$  is reasonable.

The convection enters in the transport equation via a

$$\vec{J}_c = \vec{v}_c N(r, t) \quad \text{DRIFT CURRENT}$$

$$\Rightarrow \frac{\partial}{\partial t} - \vec{\nabla} \left\{ D \vec{\nabla} N + \vec{v}_c N \right\} = 0.$$

One has also to add ADIABATIC LOSSES in the expanding plasma:

$$\frac{dE}{dt} = -\frac{1}{3} (\vec{\nabla} \cdot \vec{v}_c) E$$

## ENERGY LOSSES

Nuclei and leptons ( $e^+, e^-$ ) lose energy by different mechanisms. These are typically QED processes.

For nuclei, there are two types of <sup>ENERGY</sup> losses which are relevant:

- 1) IONIZATION losses in the neutral ion
- 2) COULOMB losses in a fully ionized plasma

## Energy losses by IONIZATION

They are given by:

$$\left( \frac{dE}{dt} \right)_{\text{ion}} (\beta > \beta_0) \simeq - \frac{2\pi r_e^2 m_e c^3}{\beta} \sum_{S=H,He} n_s B_s$$

$$B_s = e n \left( \frac{2m_e c^2 \beta^2 \gamma^2 Q_{\max}}{I_s^2} \right) - 2\beta^2$$

$$Q_{\max} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e/M}$$

$\beta_0$  = typical velocity of bound  $e^-$  in the H atom

$I_s$  = ion. potentials ( $I_H = 19 \text{ eV}$ ,  $I_{He} = 44 \text{ eV}$ )

$M \gg m_e$  = incident nucleus (mass)

$n_s$  = density of the target atom in the ISM

$r_e$  = classical radius of  $e^-$

## Energy losses by COULOMB scattering

$$\left( \frac{dE}{dt} \right)_{\text{Coul}} \approx -4\pi r_e^2 c m_e c^2 Z^2 n_e (\ln \Lambda) \frac{\beta^2}{x_m^3 + \beta^3}$$

$$x_m = (3\pi/4)^{1/3} \sqrt{2kT_e/m_e c^2}$$

$$\ln \Lambda \approx \frac{1}{2} \ln \left( \frac{m_e^2 c^4}{\pi r_e^2 h^2 c^2 n_e} \cdot \frac{M \gamma^2 \beta^4}{M + 2\gamma m_e} \right) \quad (\sim 40-50)$$

$$\begin{cases} \langle n_e \rangle \approx 0.033 \text{ cm}^{-3} \\ T_e \sim 10^4 \text{ K} \end{cases} \quad \text{astroph. quantities}$$

These losses enter in the transport equation for nuclei -  
 They are not to be considered for  $e^\pm$ .  
 $e^+, e^-$  instead suffer dramatic energy losses, that we  
 are going to see the next page.

## Energy losses for $e^+e^-$ .

These particles undergo chamaic radiative cooling, which in many situations dominate over diffusion effects (depending i.e. on  $e^\pm$  energy).

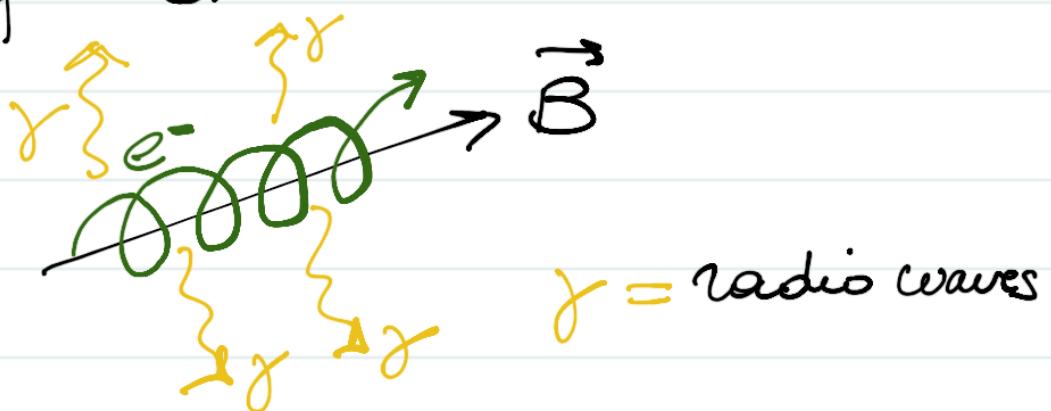
$e^\pm$  lose energy by:

- 1) SYNCHROTRON EMISSION
- 2) INVERSE COMPTON SCATTERING

Bremssstrahlung, ionization and Coulomb en. losses are instead negligible.

# SYNCHROTRON ENERGY LOSSES (WHICH IS also an EMISSION)

This energy loss is caused by the interaction of an  $e^-$  on a magnetic field  $B$ .



Electrons spiraling in a magnetic field radiate photons with energy typically in the RADIO band

$$\frac{dE_{\text{Sync}}}{dt \, dv} = \frac{\sqrt{3} e^3 B}{m_e c^2} G(x)$$

where  $x = \gamma/\gamma_c$ ,  $\gamma = E/\gamma/h$ ,  $\gamma_c = \frac{3eBc^2}{4\pi m_e^3 c s}$

and  $G(x)$  is a dimensionless integral.

$$G(x) = \int \sin \theta \, F(\gamma/\sin \theta) \frac{d\Omega}{4\pi}, \quad F(x) = x \int_x^\infty k_{S_3}(t) dt$$

One can derive the frequency  $\nu_{\max}$  corresponding to the maximum of the emitted power:

$$\nu_{\max} = \nu(P_{\max}) \sim 2\gamma^2 \frac{B}{\mu G}$$

Let's compute  $\nu_{\max}$  for electrons.

$$\gamma = \frac{1}{\sqrt{1 - \beta^2}} = \frac{E}{mc^2}$$

If  $E = 100 \text{ MeV}$ , for  $B$  with a typical value for the Galaxy  $2 \mu \text{G} \lesssim B \lesssim 6 \mu \text{G}$ , we have:

$$\gamma = \frac{100 \text{ MeV}}{0.5 \text{ MeV}} = 200$$

$$\nu_{\max} \simeq 2 \cdot (200)^2 \cdot 4 \text{ Hz} = 2 \cdot 4 \cdot 10^4 \cdot 4 \text{ Hz} = \\ \simeq 300 \text{ Hz}$$

If  $E = 10 \text{ GeV} \Rightarrow \nu_{\max} \simeq 30 \text{ GHz}$   
 This are typical emissions in the radio band.

The approximated formula for synchrotron emission is:

$$\left(-\frac{dE}{dt}\right)_{\text{sync}} \propto \sigma_T B_\perp^2 \gamma^2.$$

We can also derive the typical emission time:

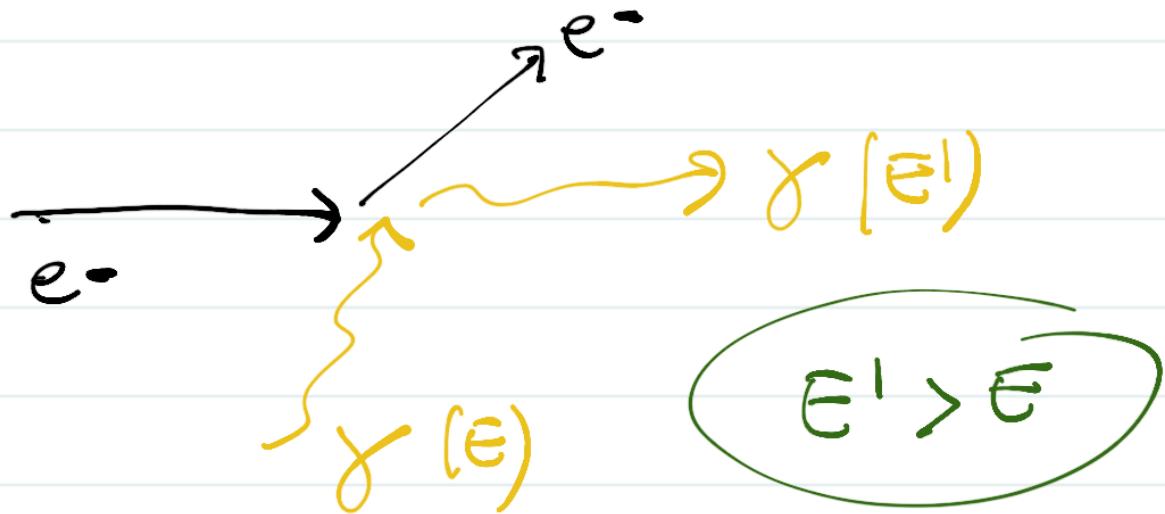
$$t_{\text{sync}} \simeq 300 \left(\frac{E}{1 \text{ GeV}}\right)^{-1} \left(\frac{B_\perp}{3 \mu \text{G}}\right)^{-1} \text{Myr}$$

If  $E = 1 \text{ TeV} \Rightarrow t_{\text{sync}} \simeq 0.3 \text{ Myr}$

High energy electrons lose energy via synch. emission very quickly.

## INVERSE COMPTON energy losses (which is also an emission)

This process is the upscattering of a background photon by an energetic electron.



We have relativistic electrons propagating in a gas of photons, called the Inter Stellar Radiation field (ISRF). One has to outline 2 regimes:

- Thomson
- Klein-Nishina

Thomson approximation is valid for  $\gamma e \lesssim \frac{m_e c^2}{E_\gamma}$ .

The photon energy  $E_\gamma$  depend on the photon population:

- 1) CMB, with  $E_\gamma \approx 2.35 \cdot 10^{-4}$  eV
- 2) Infrared (IR) light,  $E_\gamma \approx 3.45 \cdot 10^{-3}$  eV
- 3) Starlight (optical) radiation,  $E_\gamma \approx 0.3$  eV

Therefore, the Thomson regime is valid for:

1.  $E_e \lesssim 10^6$  GeV for IC scattering on CMB
2.  $E_e \lesssim 8 \cdot 10^4$  GeV for " " " " IR
3.  $E_e \lesssim 8.7 \cdot 10^3$  GeV for " " " " SL

So the Thomson approximation is no longer valid for  $e^\pm$  energies of the Earth above few tens of GeV. A fully relativistic treatment is needed.

$$\left( -\frac{dE}{dt} \right)_{IC} = \int dE_\gamma \int dE_{\gamma_1} (E_{\gamma_1} - E_\gamma) \frac{dN_{coll}}{dt dE_f dE_j}$$

The collision rate is given by:

$$\frac{dN_{\text{coll}}}{dt dE_\gamma dE_{\gamma_1}} = \frac{3}{4} \frac{\sigma_T c}{\gamma^2} \left\{ \frac{dn(\bar{E}_\gamma)}{d\bar{E}_\gamma} \right\} \frac{1}{E_\gamma} .$$

$$= \left\{ 1 + 2q \left( \ln q - q + \frac{1}{2} \right) + \frac{(1-q)}{2} \frac{(Mq)^2}{1+Mq} \right\}$$

We have QED convolved with the  $\gamma$  distributions in the Galaxy (or where we are considering  $e^\pm$ ).

$$\rightarrow \frac{dn}{d\bar{E}_\gamma} = 2 \cdot \frac{4\pi \bar{E}_\gamma^3}{(2\pi \hbar c)^3} \left\{ \exp \left( -\frac{\bar{E}_\gamma}{k_B T} - 1 \right) \right\}^{-1}$$

is the PHOTON DENSITY in the range  $d\bar{E}_\gamma$ .

Here it is assumed to follow a blackbody emission.

$$q = \frac{\hat{E}_1}{M(1-\hat{E}_1)} ; \quad \hat{E}_1 = \frac{E_{\gamma_1}}{\gamma m_e c^2} ; \quad M = \frac{4\gamma E_\gamma}{m_e c^2}$$

which include  $e^\pm$  and photon properties.

IC energy losses are  $\propto \gamma^2$  in the Thomson regime and  $\propto \ln(\gamma)$  in the KN one.

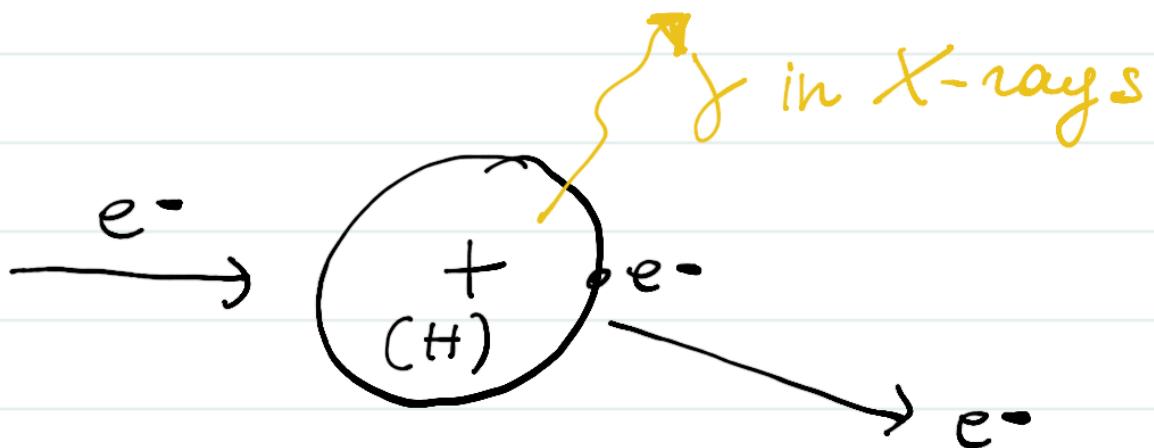
Approximatively,  $\left(-\frac{d\theta}{dt}\right)_{IC} \propto \sigma_T U_{rad} \gamma^2$  (Gh.)

and  $t_{IC} \simeq 300 \left(\frac{\epsilon}{1 \text{ GeV}}\right)^{-1} \left(\frac{U_{rad}}{0.3 \text{ GeV m}^{-3}}\right)^{-1} \text{ Myr}$

# BREMSSTRAHLUNG energy losses

or free-free emission

$\delta\Gamma$  is the loss of energy of a charged particle in atoms or in a plasma.



The scattering produces a photon, typically in the X-ray range.

$$\left(-\frac{dE}{dt}\right)_{\text{brem}} \propto \sigma_T \gamma n_{\text{ISM}}$$

$$E\gamma \sim \frac{E}{2} ; E^{-\alpha} \Rightarrow E\gamma^{-\alpha}$$

$$t_{\text{brem}} \simeq 300 \left(\frac{n_{\text{ISM}}}{1 \text{ cm}^{-3}}\right)^{-1} \text{ relevant in very dense regions}$$

⇒ Figure with  $\epsilon$  losses' effect on  $e^-$

⇒ Figure with SRF

⇒ Figure with typical loss times

Catastrophic losses by NUCLEAR destructions  
(which is a source as well)

This section only refers to NUCLEI.

The CR nuclei can undergo scatterings with the ISM,  
which is made of H and He.

Inelastic scattering:



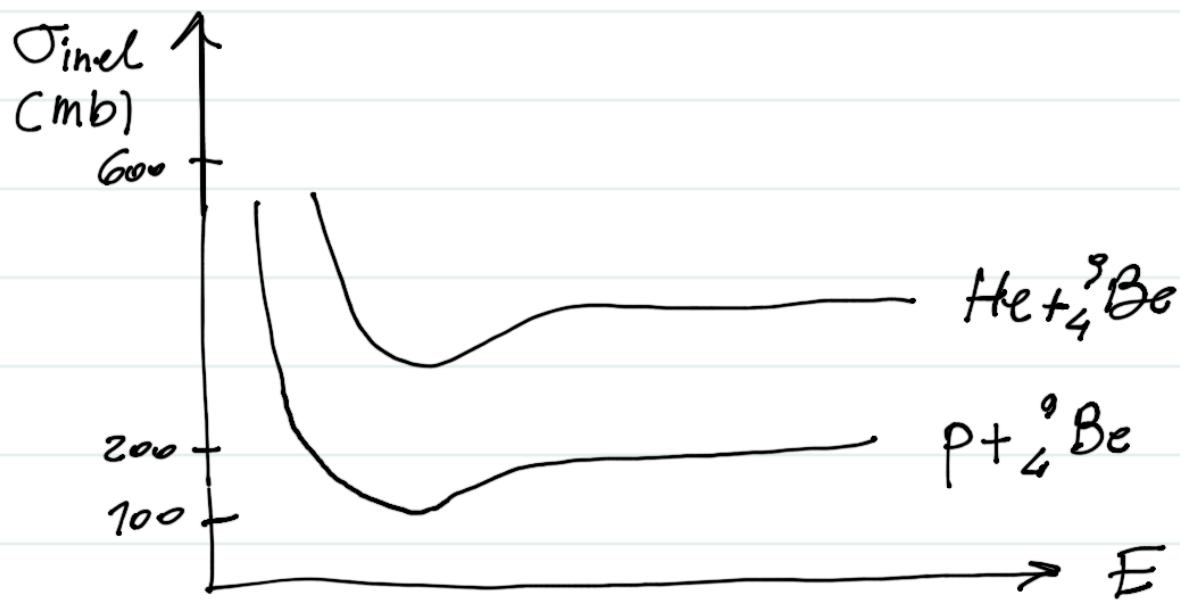
So N disappears, and creates a new nuclei or isotopes  
 $N'$  -  $N'$  is a newborn secondary nucleus.

The interaction rate is:  $\Gamma_{\text{inel}} = n_{\text{ISM}} \sigma \tau_{\text{inel}}$  \*  
and strongly depends on the DESTRUCTION cross section  
 $\sigma$ , which sizes the destruction of nucleus N on the ISM

$$\tau_{\text{inel}} \simeq 10^3 \left( \frac{n_{\text{ISM}}}{1 \text{ cm}^3} \right)^{-1} \left( \frac{\sigma_{\text{inel}}}{1 \text{ mbarn}} \right)^{-1} \text{ Myr}$$

The greater is the destruction cross section, the shorter is  
the relevant loss time, the more important is the loss of  
the nucleus due to nuclear destruction.

$$\sigma_{\text{inel}} = \sigma_{\text{tot}} - \sigma_{\text{el}}$$



The inelastic cross section is high for high- $Z$  nuclei.

$$\sigma_{\text{inel}} (\text{p, C, Fe}) \sim (40, 250, 750) \text{ mb}$$

The destruction time for Fe is much smaller than for p. This process is more relevant for Fe.

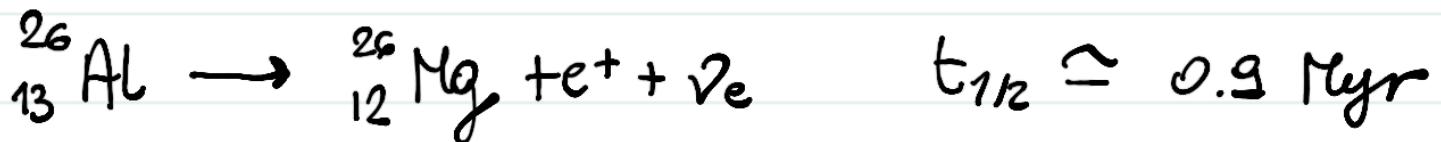
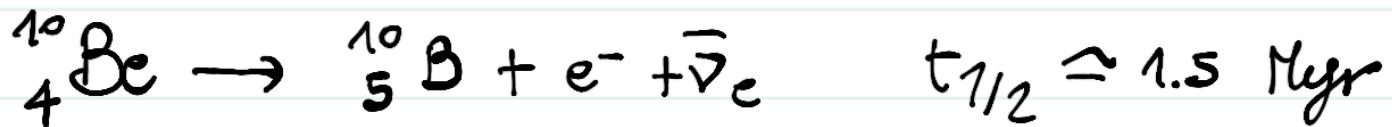
$\Rightarrow$  Figure with  $t$  vs  $E$  for various nuclei.

## Losses by $\beta$ -decay

Some isotopes are unstable by  $\beta$ -decay. They therefore disappear with times given by their  $t_{1/2}$ .

$$t_B \simeq E_{\text{kin}}/n \left( \frac{t_{1/2}}{1.51 \text{ Myr}} \right) \text{ Myr}$$

Among the most interesting  $\beta$ -decay isotopes:



$$\gamma_{\text{inel}} = \frac{\ln 2}{\tau t_{1/2}}$$
 is the decay rate