SHOCK ACCELERATION IN PARTIALLY IONIZED PLASMAS

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TeV Particle Astrophysics
Paris, July 19th - 23th, 2010

OUTLINE

- **Acceleration at collisionless shocks propagating in partially neutral plasmas**
  - ***Why it is relevant: the environment of SNRs***
  - ***Balmer shocks***
  - ***Observational evidences of CRs influence onto Balmer shocks***
  - ***Theoretical model***

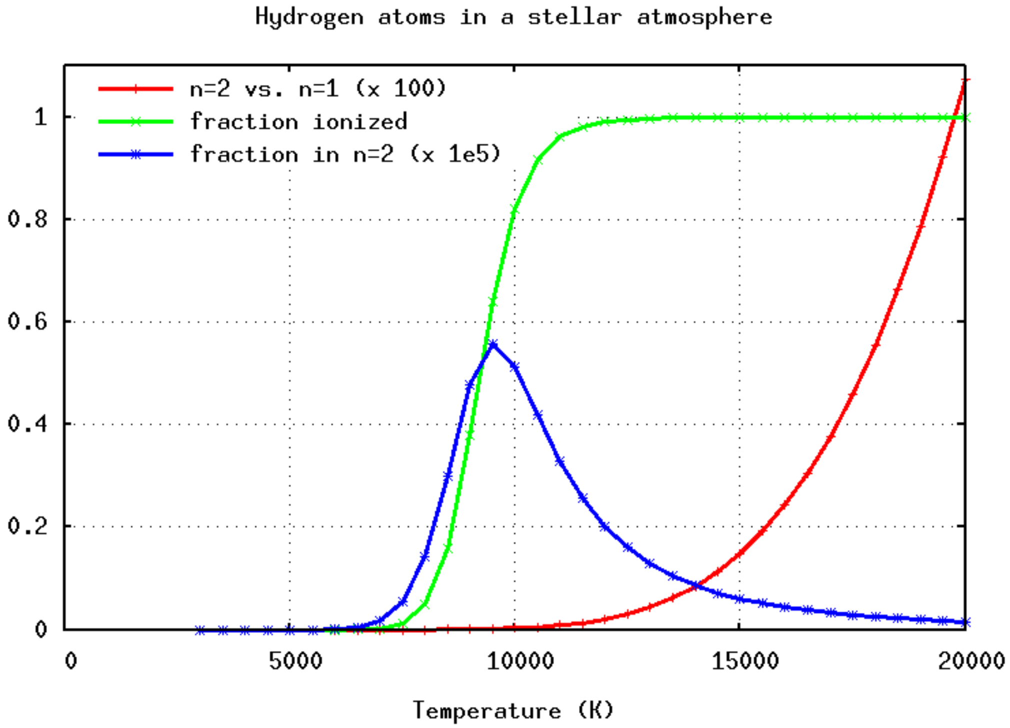
- **Conclusions**

Why Shocks in Partially Neutral Plasmas are Important?

Theory of shock acceleration is usually developed in <u>totally ionized plasma</u>

- Good approximation for Type II SNR which expand in the pre-stellar wind
(T~ 10^5-10^7 K)
→ hydrogen is totally ionized

- Bad approximation for Type I/a SNR which expand in the ISM (**T~ 10^4 K**)
→ hydrogen is partially ionized
→ even if T < 10^4 K → minimum degree of ionization for young SNR is ~20% due to the ionizing radiation coming from the remnant itself

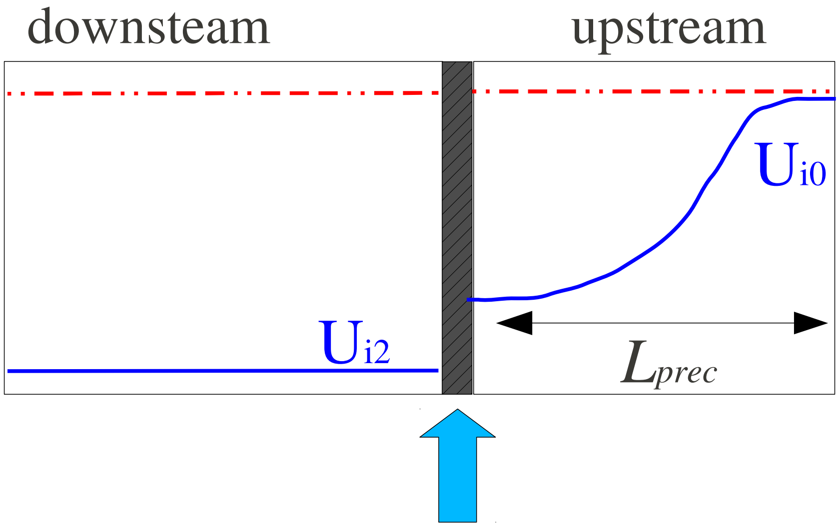


Why Shocks in Partially Neutral Plasmas are Important?

1) Does the shock structure change when expanding in partially neutral plasma?

2) Can neutral particle affect the CR production efficiency?

At zeroth order the neutral component does not feel the electromagnetic shock discontinuity



Velocity of neutral component

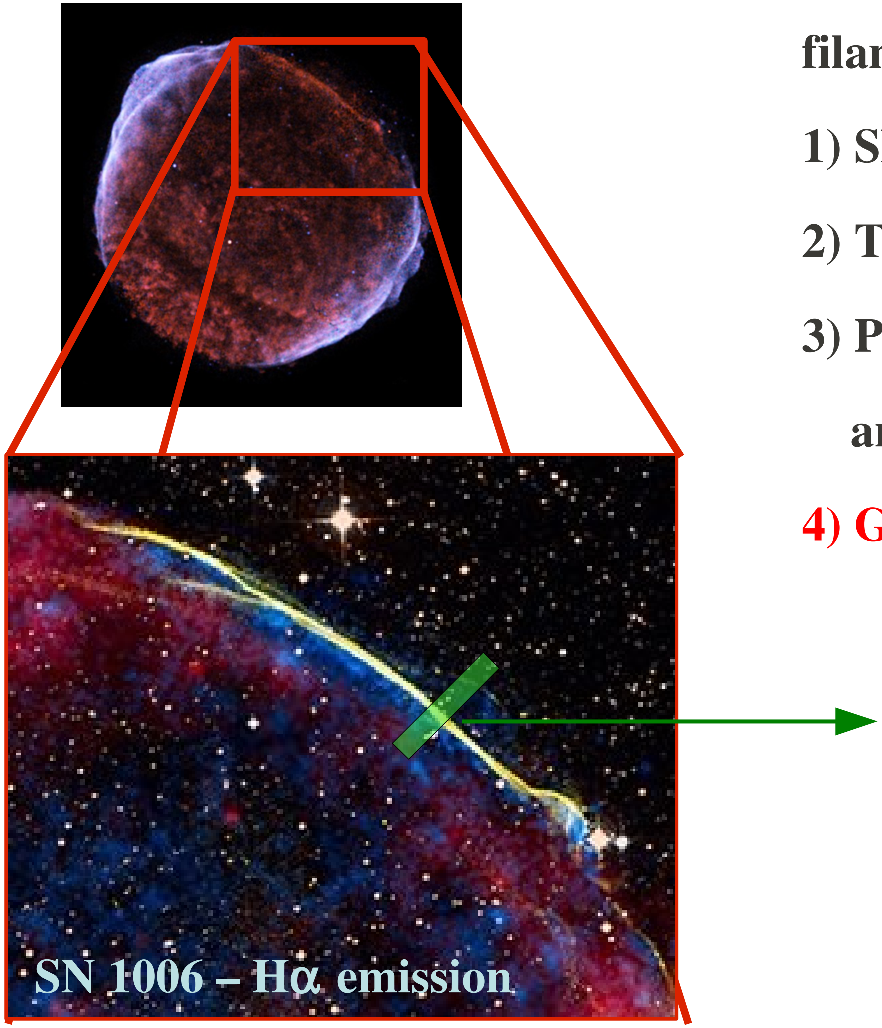
Velocity of ionized component

Collisionless subshock

BUT...

Balmer-Dominated Shocks

… neutral particles do produce radiation associated with shock transition



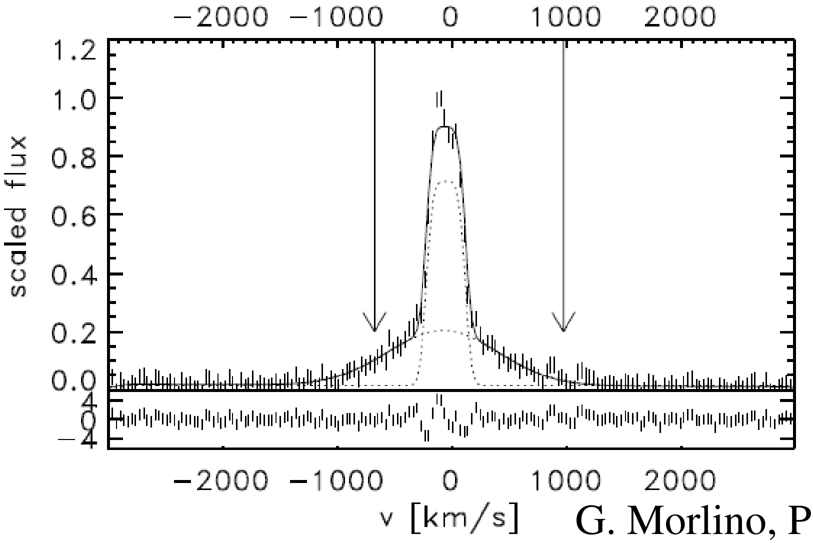
Balmer-dominated shocks are associated with faint optical filaments observed around young SNRs

1) Shock speed ~ 200 - 9000 km/s

2) Typical ISM density ~ 0.1 - 1 cm^{-3}

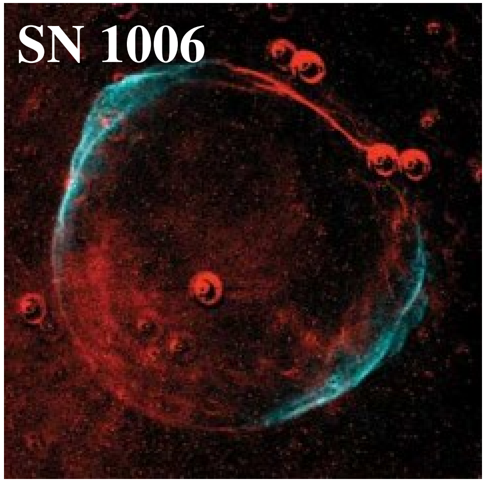
3) Presence of strong hydrogen lines with *narrow* (10 km/s) and *broad* (1000 km/s) components

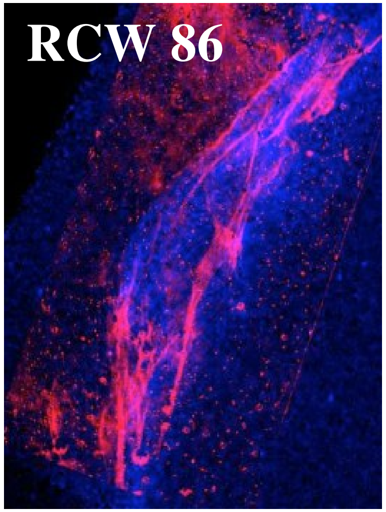
4) General lack of non-thermal X-ray emission

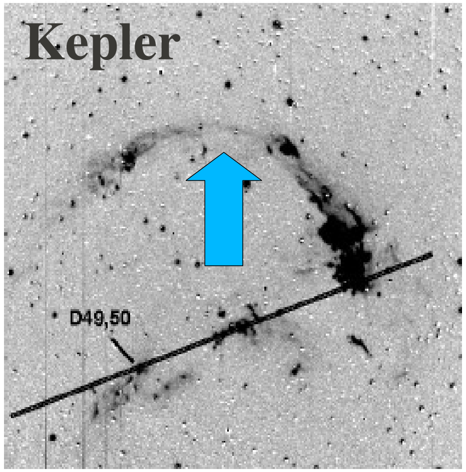


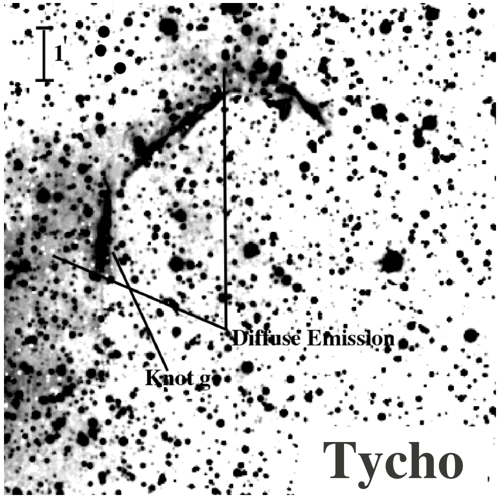
Balmer-Dominated Shocks

Optical Balmer shocks associated with SNRs

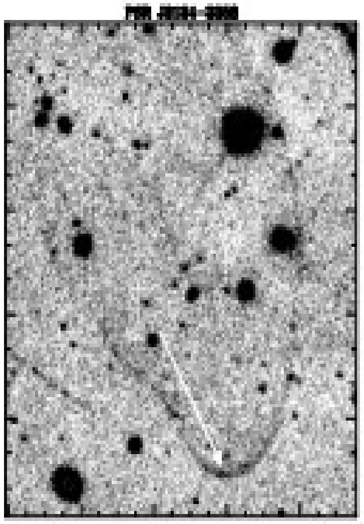


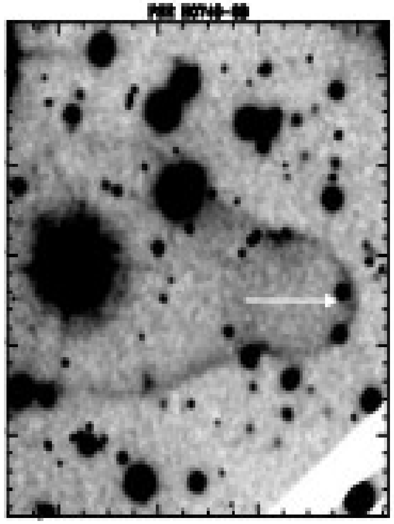


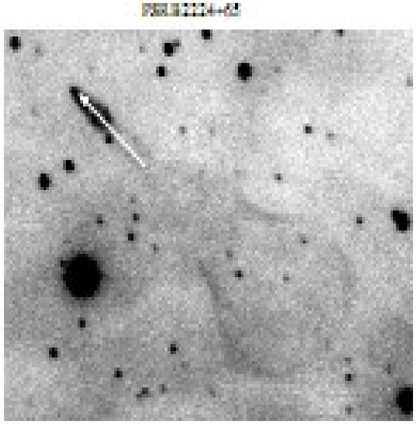


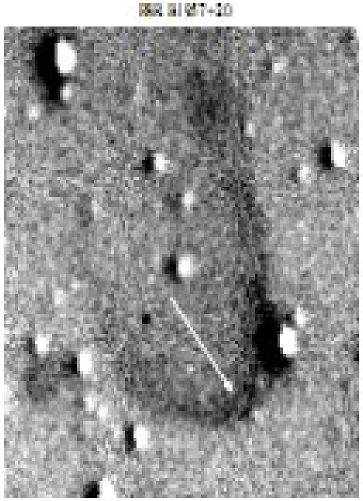


Optical bow shocks associated with PWNe

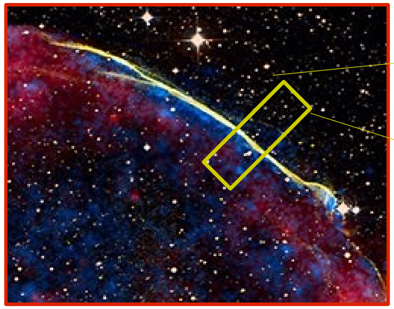




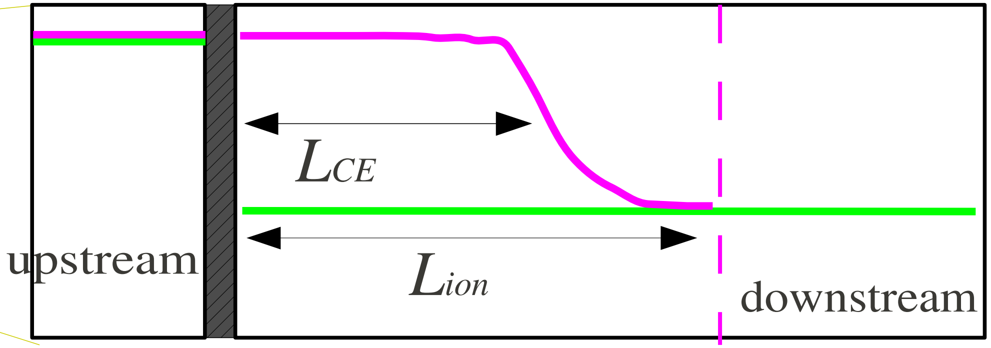




Balmer-dominated Shocks: Basic Principles

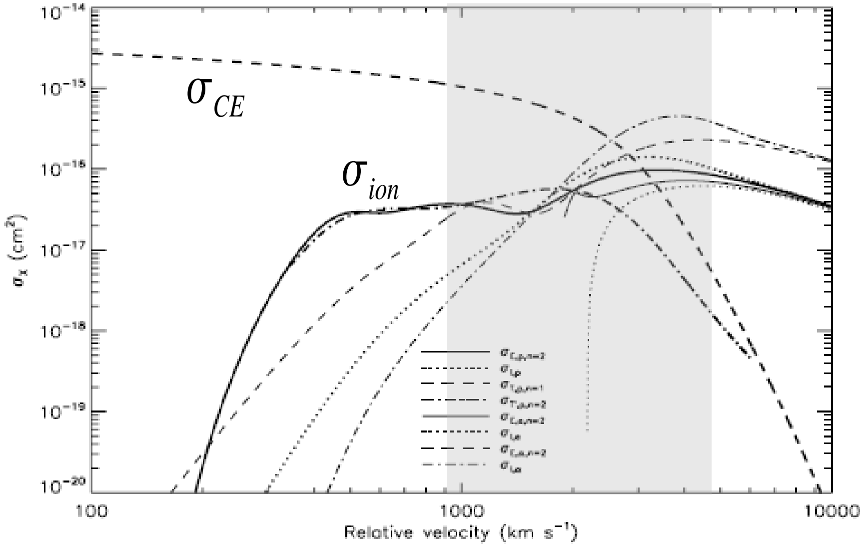


VELOCITY PROFILE

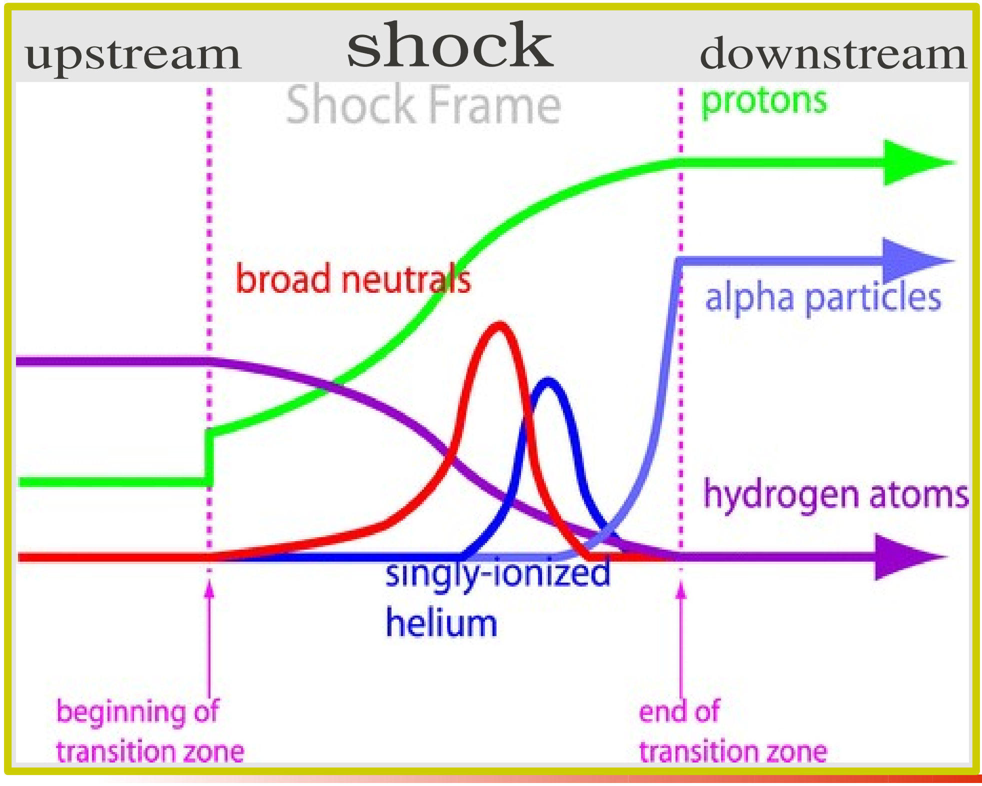


Downstream of the shock cold hydrogen atoms can charge exchange with hot shocked protons, giving rise to a population of hot hydrogen atoms

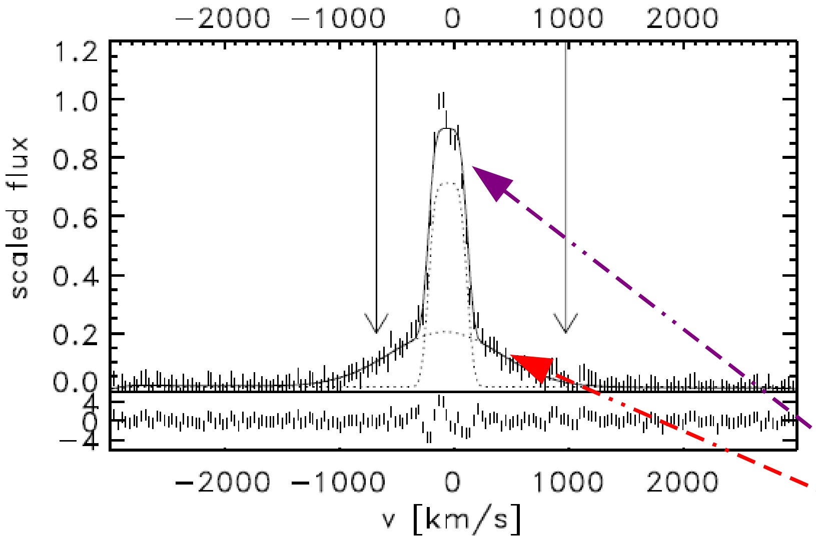
$$\boxed{\text{Interaction Rate} = n_p v_{rel} \sigma_{CE}(v_{rel})}$$



DENSITY PROFILE



Balmer-dominated Shocks: Basic Principles



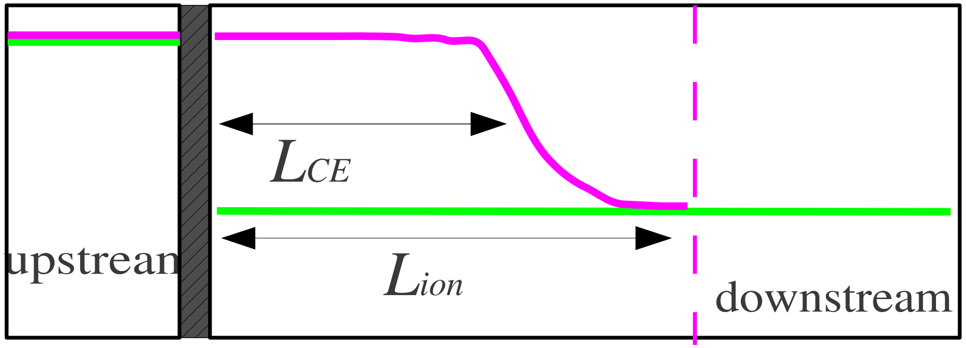
FWHM of narrow line

$$W_n = \sqrt{8 \ln 2 \frac{k T_0}{m_H}} = 21\, km/s \left(\frac{T_0}{10^4\, K} \right)^{1/2}$$

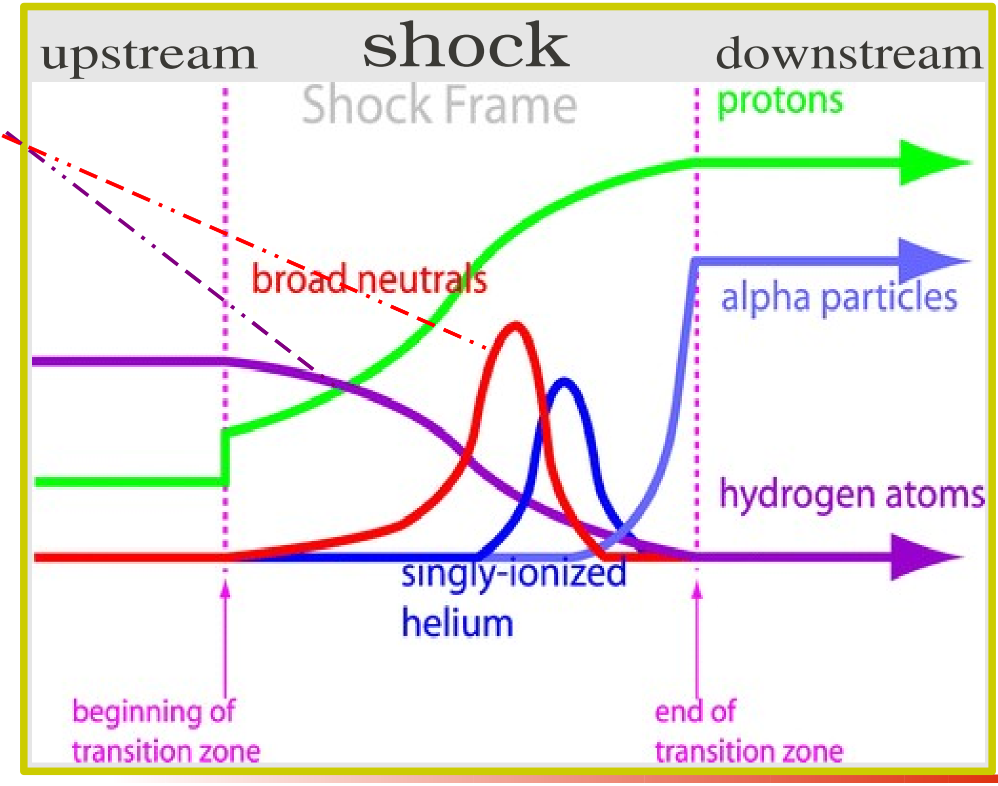
FWHM of broad line

$$W_b = \sqrt{8 \ln 2 \frac{k T_2}{m_H}} = \frac{4 v_{sh}}{\gamma + 1} \sqrt{\ln 2 (\gamma - 1)} = 1.02\, v_{sh}$$

VELOCITY PROFILE



DENSITY PROFILE

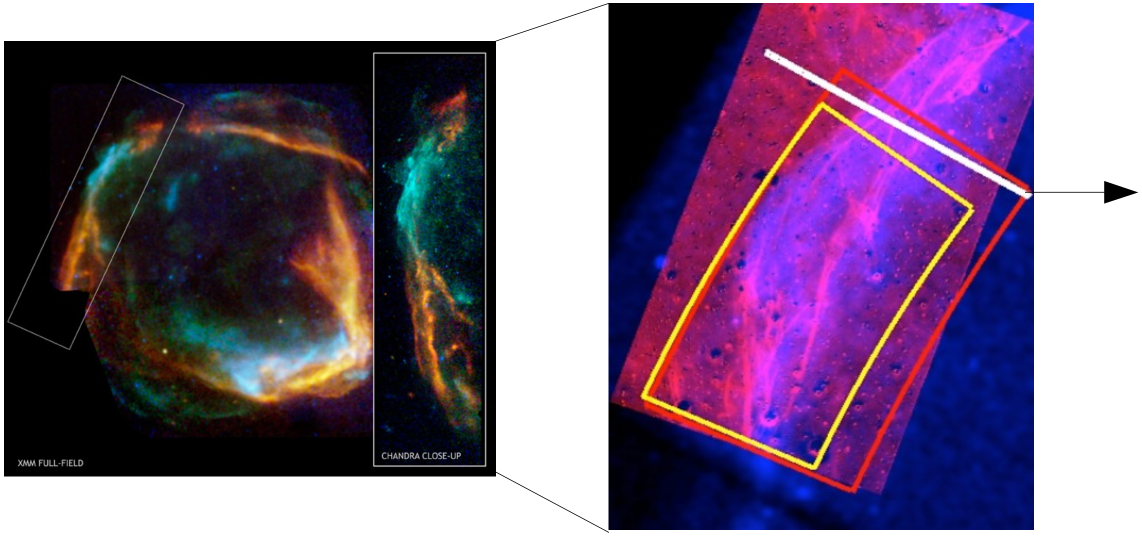


Balmer-dominated Shocks: Basic Principles

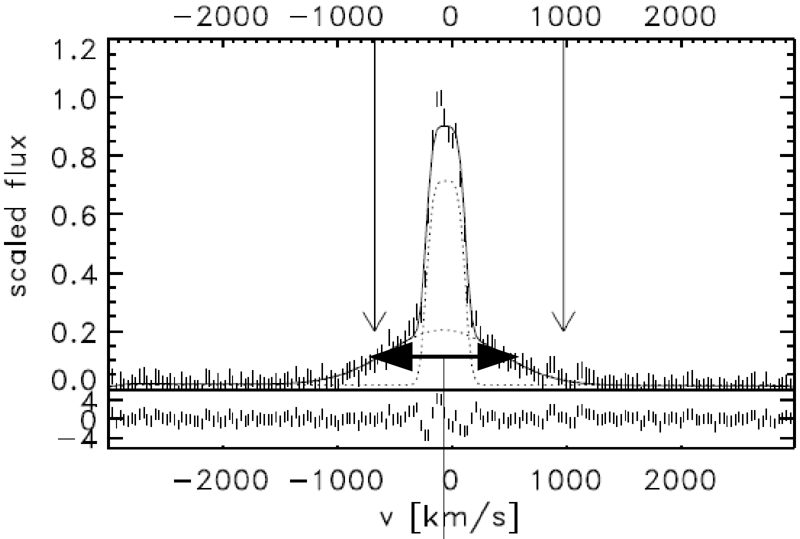
There are evidences that Balmer shock physics is not so simple...

Let analyse three different observational evidences of shock modification

1) Balmer-Dominated Shocks associated with X-ray Emission



From Helder et al., 2009



Dowstream temperature from broad Hα line

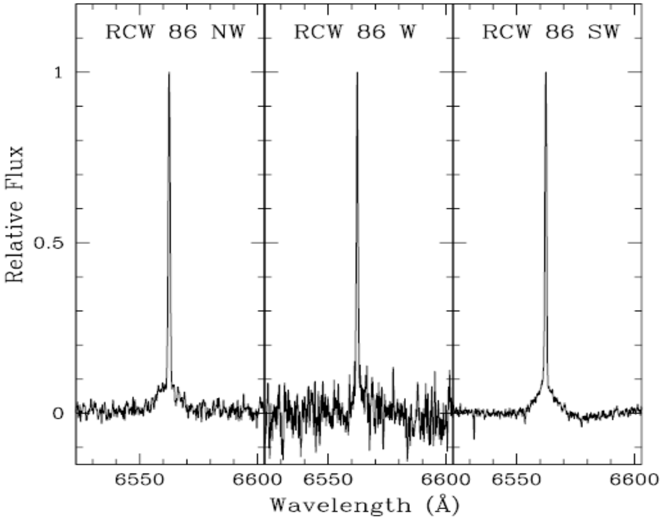
$$W_{broad} = 1100 \pm 63\, km/s \;\rightarrow\; T_2 = 2.3 \pm 0.3\, keV$$

Shock speed from proper motion

$$v_{shock} = 6000 \pm 2800\, km/s \left(\frac{d}{2.5 \pm .5\, kpc} \right) \left(\frac{\dot{\theta}_{obs}}{0.5 \pm .2''\, yr^{-1}} \right) \;\rightarrow\; T_2 = \begin{matrix} 20-150\, keV\, (no\, equilibration) \\ 12-90\, keV\, (equilibration) \end{matrix}$$

Helder et al. infer that > 50% of the post shock pressure is due to CRs.

2) Narrow Hα Lines with Unusual Broad Width



From Sollerman at al., 2003

SNR	Shock velocity (km s^{-1})	Narrow component *FWHM* (km s^{-1})
Cygnus Loop	300–400	28–35
RCW 86 SW	580–660	32 ± 2
RCW 86 W	580–660	32 ± 5
RCW 86 NW	580–660	40 ± 2
Kepler D49 & D50	2000–2500	42 ± 3
0505-67.9	440–880	32–43
0548-70.4	700–950	32–58
0519-69.0	1100–1500	39–42
0509-67.5	–	25–31
Tycho	1940–2300	44 ± 4
SN 1006	2890 ± 100	21 ± 3

The Hα FWHM of narrow lines measured from Balmer Shocks gives an estimate of upstream temperature

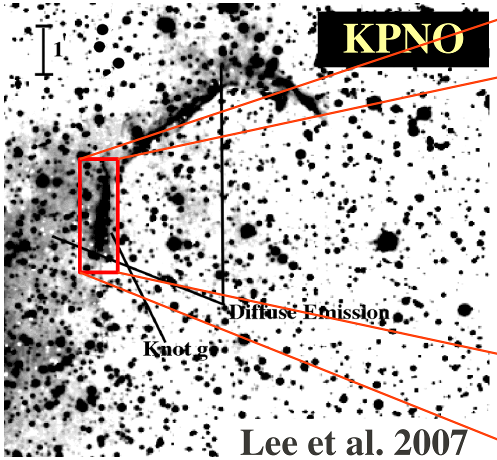
$$W_n = \sqrt{8\ln 2\,\frac{k T_0}{m_H}} = 21\,km/s\left(\frac{T_0}{10^4\,K}\right)^{1/2}$$

$$W_n \sim 30-50\,km/s \rightarrow T \sim 2-6\,10^4\,K$$

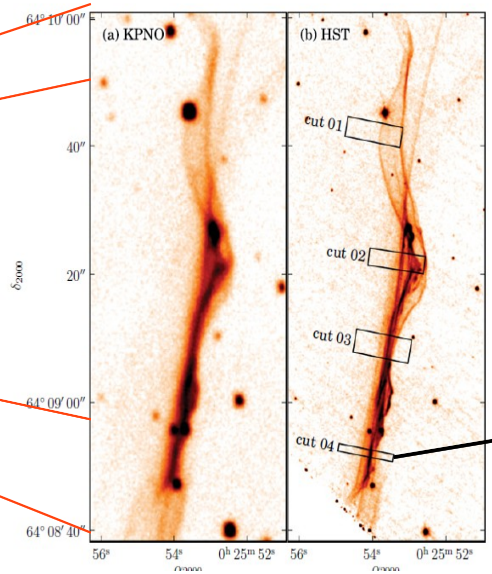
But for temperature above 10^4 K hydrogen is expected to be completely ionized

→ We need a mechanism able to heat the neutral ISM component in a time less than the ionization time

3) Precursor in Balmer-Dominated Shocks: the Case of Tycho

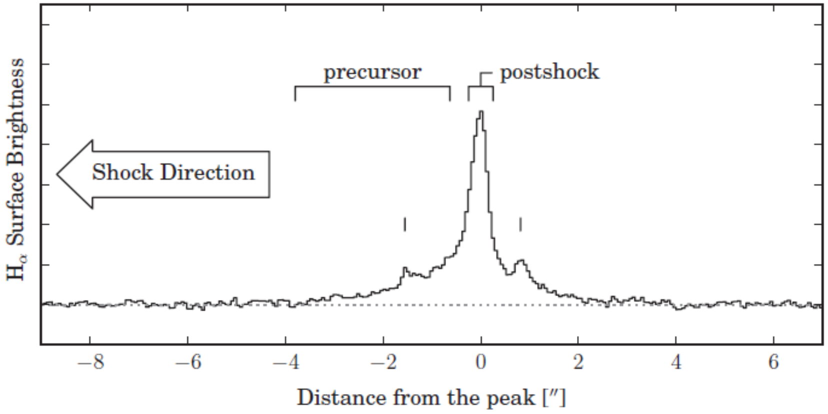


Lee et al. 2007

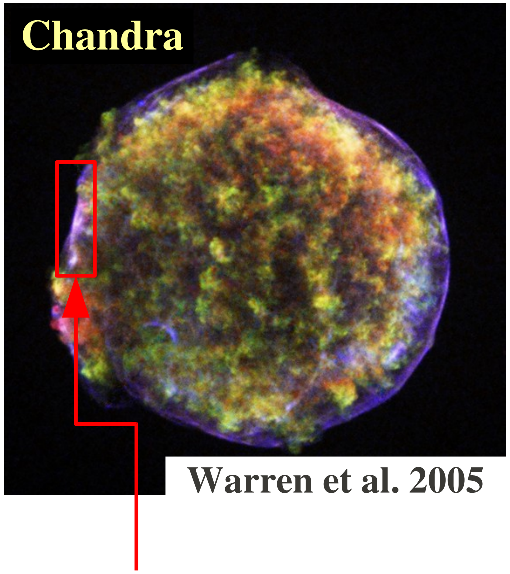


Lee et al., 2010

(Observation with the Hubble Space Telescope)



Chandra



Warren et al. 2005

Knot g

1) Evidence of Hα emission from the precursor which contribute up to 30-40% of the total narrow Hα emission:

→ different temperature and/or different bulk speed between ions and neutrals in the precursor region

2) The knot g in Tycho remnant is associated with non-thermal X-ray emission

→ the shock may accelerate particles efficiently

3) Precursor in Balmer-Dominated Shocks: the Case of Tycho

Can we explain all these features with the presence of accelerated CRs?

1) Shock speed inferred from Broad lines < measured speed

→ a fraction of kinetic energy is converted into nonthermal particles

2) Broad narrow component imply upstream $T_0 > 10^4$ K

→ neutral hydrogen has to be heated ahead of the shock in a time < collisional time

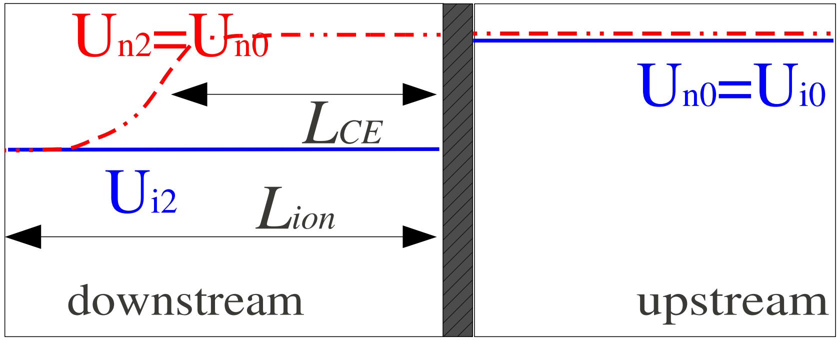
3) Evidence of Hα (narrow line) emission ahead of the shock:

→ protons and neutral hydrogen have different temperatures and/or different bulk velocities in the precursor

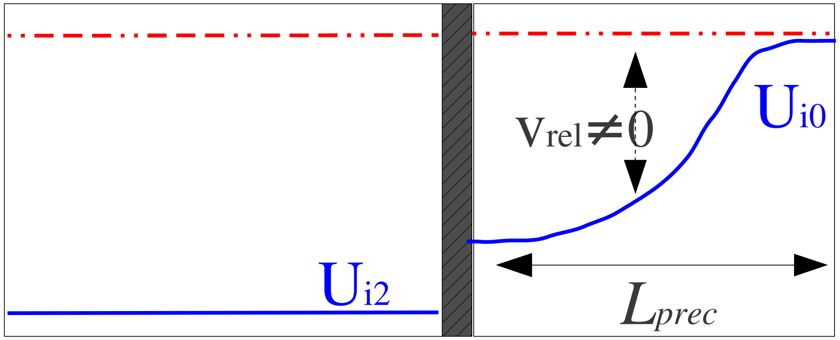
Need the presence of a precursor

Balmer-Dominated Shocks with CRs Acceleration

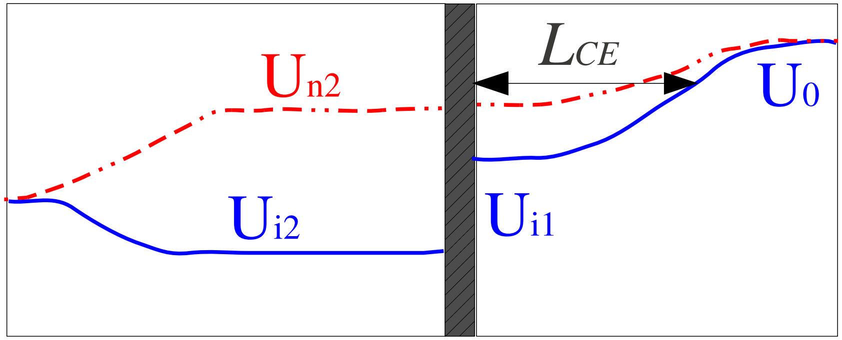
velocity profile u(x) in the shock frame



Unmodified shock



Shock modified by CRs



Shock with CRs and neutrals

Sub-shock thickness

$$L_s \sim r_L(p_{th}) \simeq 10^{10}\,cm \left(\frac{B}{\mu G}\right)^{-1} \left(\frac{u_0}{3000\,km/s}\right)$$

Ionization and charge-exchange length

$$L_{ion} \sim u_0 \tau_{ion} = \frac{u_2}{n_p \sigma_{ion} v_{rel}} \simeq 10^{16}\,cm \left(\frac{n_p}{1\,cm^{-3}}\right)^{-1}$$

$$L_{CE} \sim u_0 \tau_{CE} = \frac{u_2}{n_p \sigma_{CE} v_{rel}} \simeq 10^{15}\,cm \left(\frac{n_p}{1\,cm^{-3}}\right)^{-1}$$

Precursor length

$$L_{prec} \sim \frac{D(p_{max})}{u_0} \simeq 10^{17}\,cm \left(\frac{B}{\mu G}\right)^{-1} \left(\frac{E}{TeV}\right) \left(\frac{u_0}{3000\,km/s}\right)^{-1}$$

Ionization and charge exchange length in the upstream

$$L_{prec}/L_{ion} \leqslant 0.1$$
$$L_{prec}/L_{CE} \sim 10-100$$

Modified Shocks in Plasma with Neutral Component: Fluid Equations

Time-independent Boltzmann equation

$$\cancel{\frac{\partial f}{\partial t}} + \vec{v}\cdot\nabla f = f(x,\vec{v})R(x,\vec{v})$$

Ionized component (interacting with CRs)

$$\frac{\partial}{\partial x}\left[\rho_i u_i\right] = q_M$$

$$\frac{\partial}{\partial x}\left[\rho_i u_i^2 + P_i + P_{CR}\right] = q_m$$

$$\frac{\partial}{\partial x}\left[\frac{1}{2}\rho_i u_i^3 + \frac{\gamma}{\gamma-1}u_i P_i\right] = -u_i\frac{\partial P_{CR}}{\partial x} + q_e$$

MASS FLUX

MOMENTUM FLUX

ENERGY FLUX

Neutral component

$$\frac{\partial}{\partial x}\left[\rho_n u_n\right] = -q_M$$

$$\frac{\partial}{\partial x}\left[\rho_n u_n^2 + P_n\right] = -q_m$$

$$\frac{\partial}{\partial x}\left[\frac{1}{2}\rho_n u_n^3 + \frac{\gamma}{\gamma-1}u_n P_n\right] = -q_e$$

$$q_M(x) = \int dv_n dv_i \sigma_{ion}|v_{rel}| f_n(x,v_n) f_i(x,v_i)$$

MASS TRANSFER

$$q_m(x) = \int dv_n dv_i (v_n - v_i)(\sigma_{ion} + \sigma_{CE})|v_{rel}| f_n(x,v_n) f_i(x,v_i)$$

MOMENTUM TRANSFER

$$q_e(x) = \int dv_n dv_i \frac{1}{2}(v_n^2 - v_i^2)(\sigma_{ion} + \sigma_{CE})|v_{rel}| f_n(x,v_n) f_i(x,v_i)$$

ENRGY TRANSFER

We assume both the distribution functions to be maxwellian

Effect of Charge-Exchange in the Upstream

Initial conditions

$T_0 = 10^4 K;$
$B_0 = 10 \mu G$
$n_0 = 1 cm^{-3};$
$f_N = 0.5;$
$u_0 = 3000 km/s;$
$p_{max} = 10^4 m_p c$

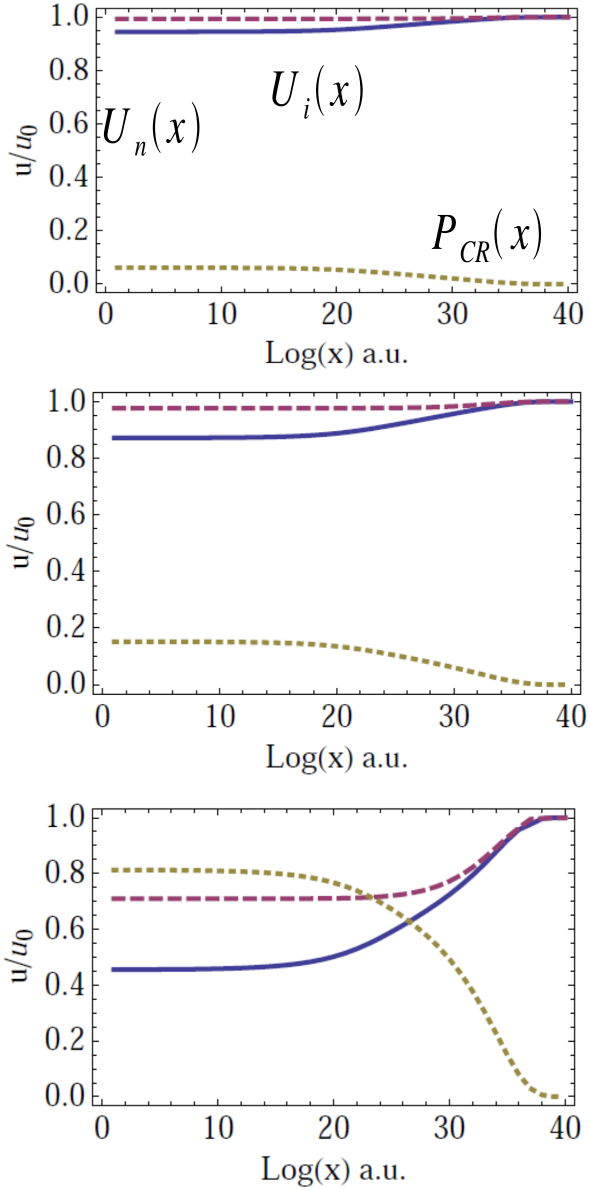
Acceleration efficiency

$\xi_{inj} = 4.0;$
$P_{CR}/(\rho_{i,0} u_0^2) = 0.06$

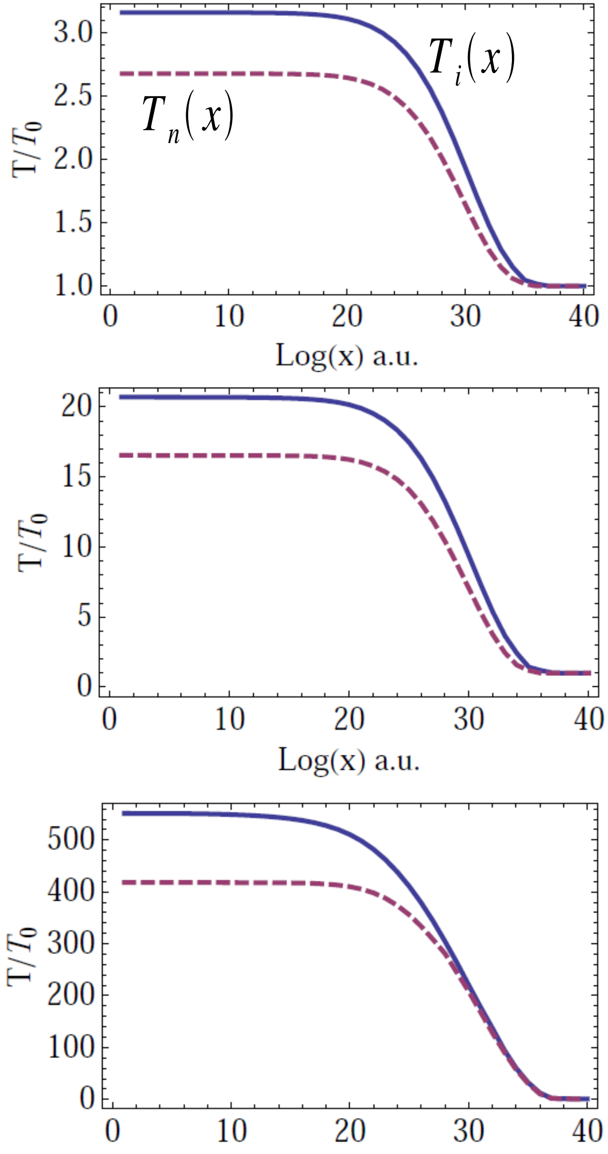
$\xi_{inj} = 3.9;$
$P_{CR}/(\rho_{i,0} u_0^2) = 0.15$

$\xi_{inj} = 3.7;$
$P_{CR}/(\rho_{i,0} u_0^2) = 0.8$

Upstream Velocity profile

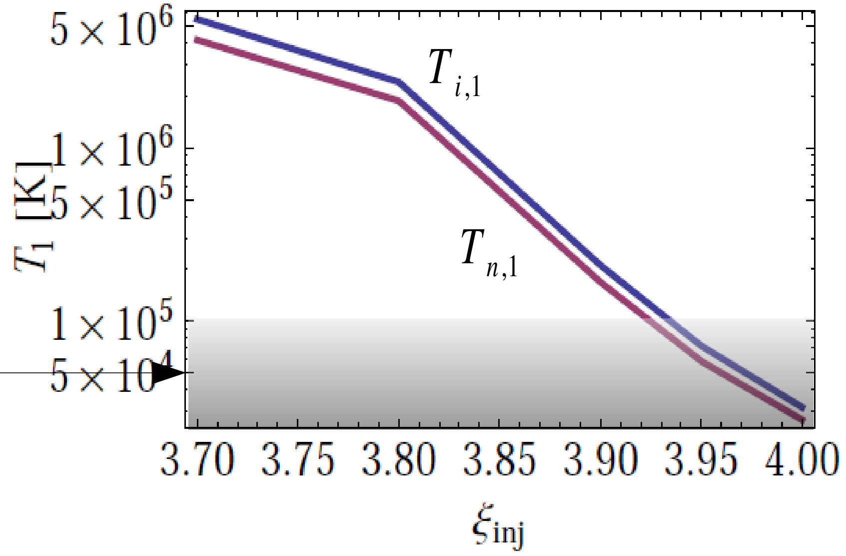


Upstream Temperature profile

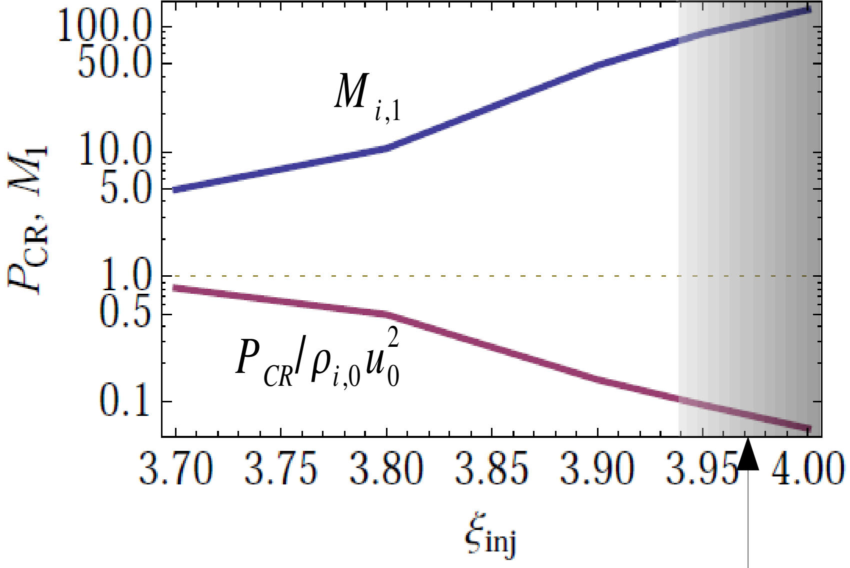


Temperature of Neutral Hydrogen

Upstream Temperature as function of injection efficiency



CR pressure and upstream Mach number as function of injection efficiency



Region of observed temperature

Region of inferred CR efficiency

Even a modest acceleration efficiency (around few %) is able to heat the neutral plasma

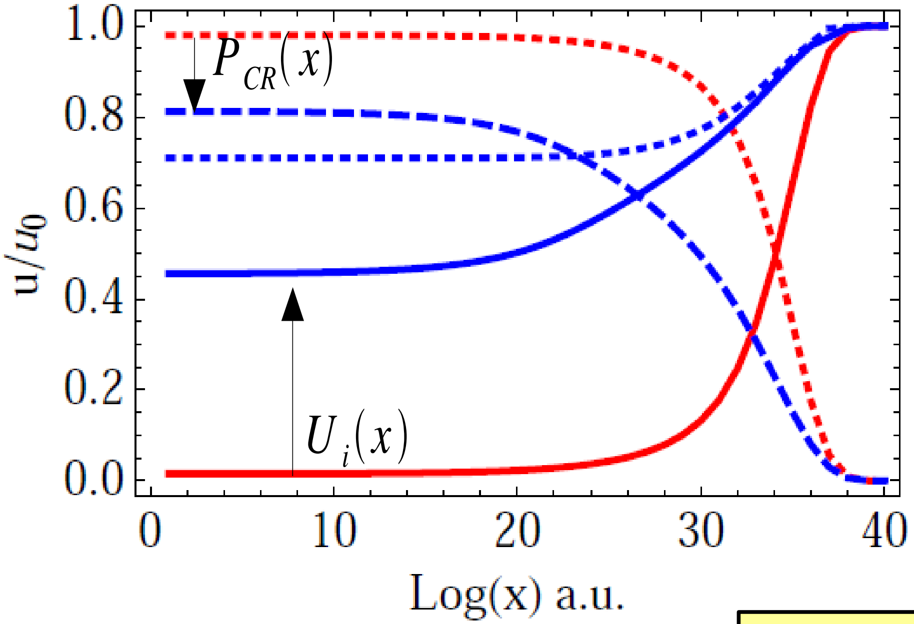
To explain the observed temperature of neutral hydrogen ($T < 10^5$) we need a CR efficiency < 10%

Which are the (indirect) effects of Neutral Hydrogen on CRs Spectrum?

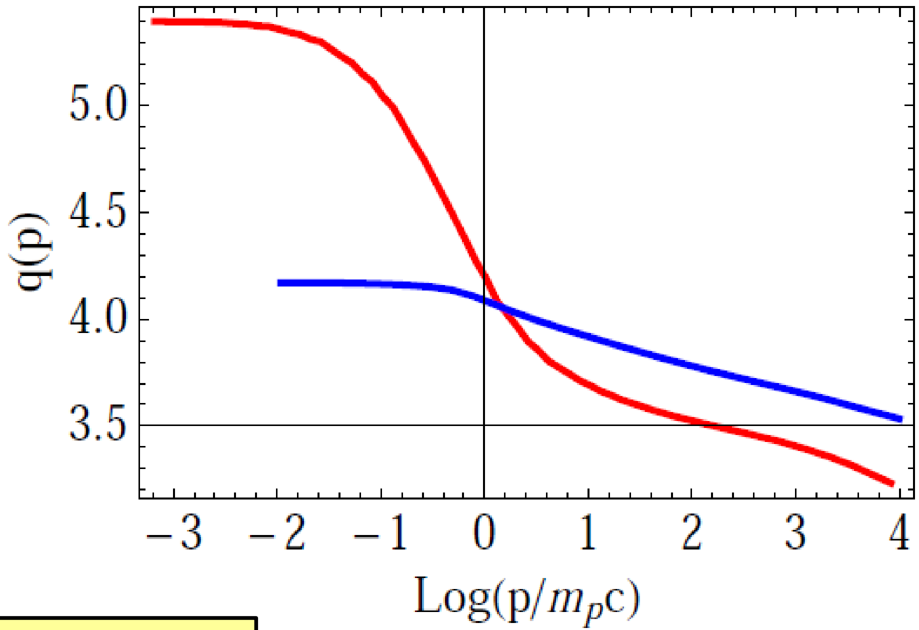
Initial conditions:

$$T_0 = 10^4 K;\ B_0 = 10 \mu G;\ n_0 = 1 cm^{-3};\ f_N = 0.5;\ u_0 = 3000 km/s;\ p_{max} = 10^4 m_p c; \xi_{inj} = 3.7;$$

Upstream Velocity profile
and CRs pressure



Spectrum slope $f(p) \propto p^{-q(p)}$



🟥 $f_N = 0;$

🟦 $f_N = 0.5;$

P_{CR}: 0.98 → 0.81;

R_t: 81 → 7.8;

R_s: 2.25 → 3.56;

T_1: $1.9\,10^5 K$ → $5.5\,10^6 K$;

CONCLUSIONS

CRs acceleration at shocks is strongly affected by the presence of a non negligible fraction of neutral hydrogen because the **charge exchange** process

1) The neutral hydrogen can be efficiently heated in the precursor even in the case of inefficient shock acceleration (ϵ_{CR}~few%)

→ this can explain the broad *narrow lines*

→ predicts the presence of narrow lines ahead of the shock

2) Also the ionized component is heated in the precursor and as a consequence

→ the shock modification and the CR spectrum concavity are reduced (the same effect is produced by *turbulent heating* and *magnetic field amplification*)

We are currently applying the theory to single SNR

→ detailed results will be available soon