宇宙線を効率的に加速する超新星残骸衝撃波からの水素原子輝線の偏光放射モデル

Polarized Hα Emission from Supernova Remnant Shock Waves Efficiently Accelerating Cosmic Rays

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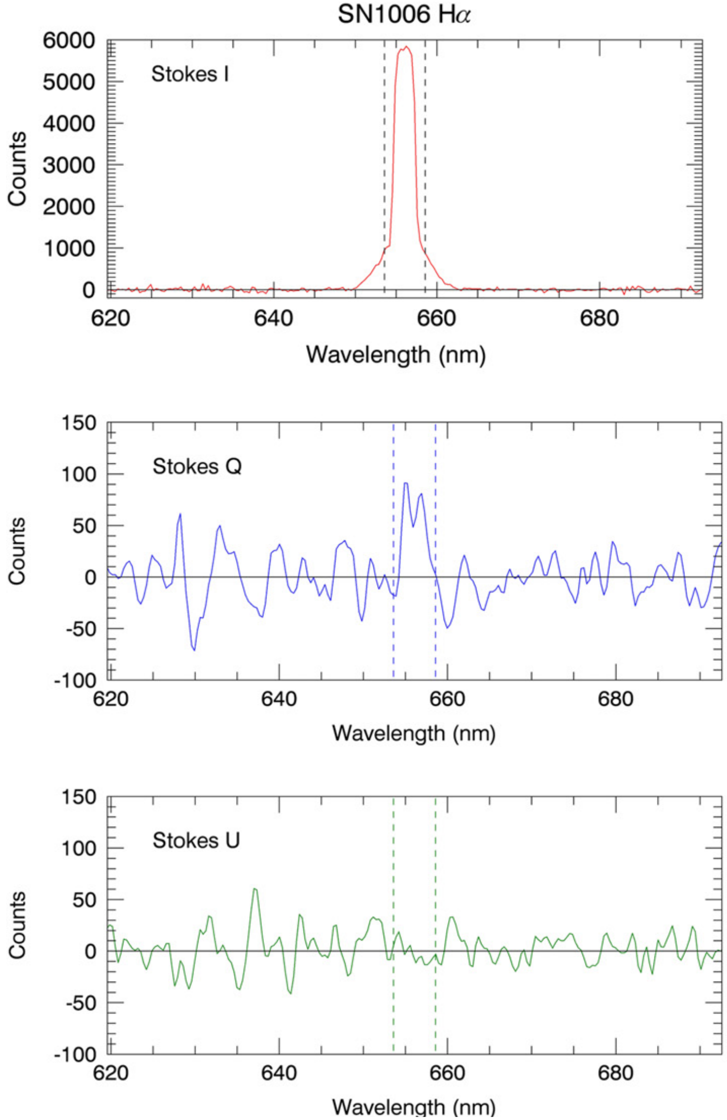
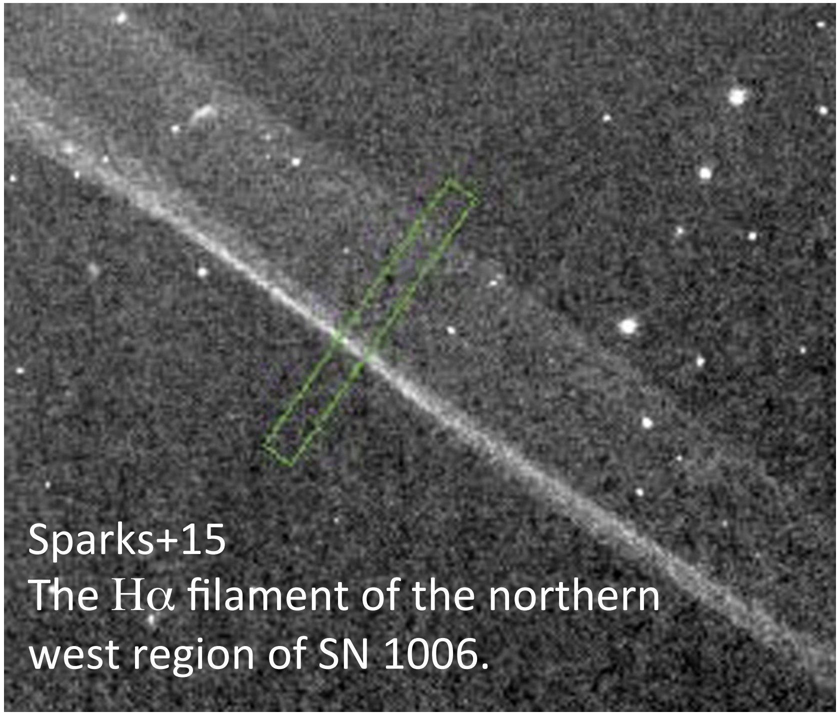
Discovery of the polarized Hα emission from SNR



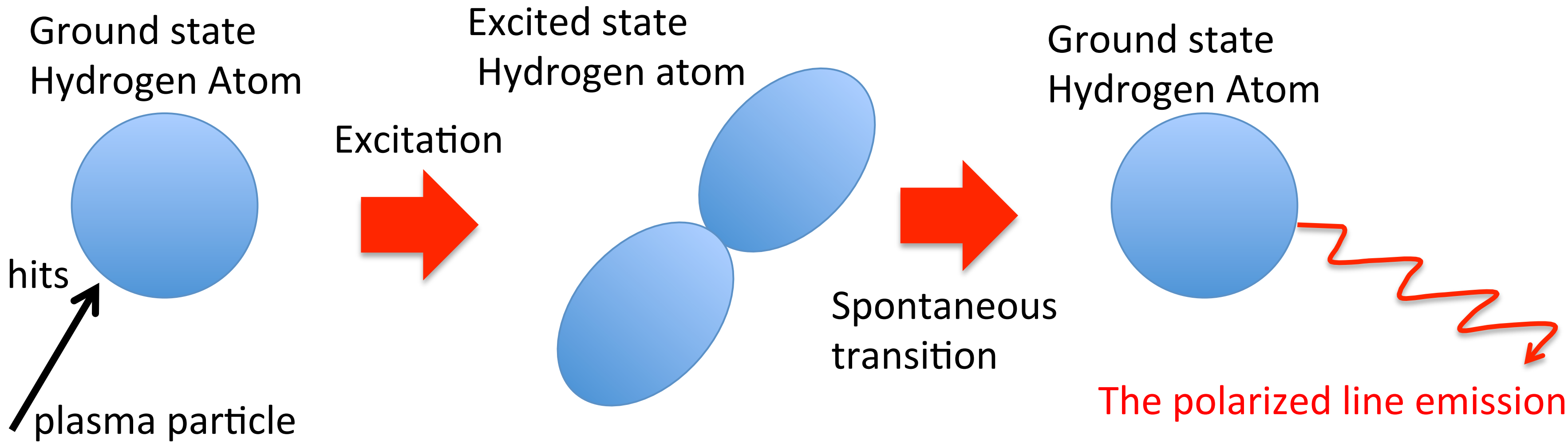
Sparks+15



Sparks+15
The Hα filament of the northern west region of SN 1006.

- ✓ Recently, Sparks et al. (2015) discovered the polarized Hα emission in northern east region of SN 1006.
- ✓ The polarization degree is 2.0±0.4%.

The polarized line emission



a) The hydrogen atoms entering the shock will collide with the downstream plasma particles.

b) Resulting from the collision, the bound electron of the hydrogen atom obtains an energy and an orbital angular momentum.

c) By the conservation of the angular momentum, the radiated line emission can be linearly or circularly polarized.

- If the colliding plasma particle has the anisotropic velocity distribution in the hydrogen atom rest frame, the orbital angular momentum direction obtained by the atomic electrons is polarized.
- The anisotropic orbital angular momentum distribution can yield the polarized line emission.

e.g.) Experiment of the polarized Hα

The polarization degree of Hα resulting from the collision between electron beam and hydrogen atoms（Kleinpoppen & Kraise 1968）.

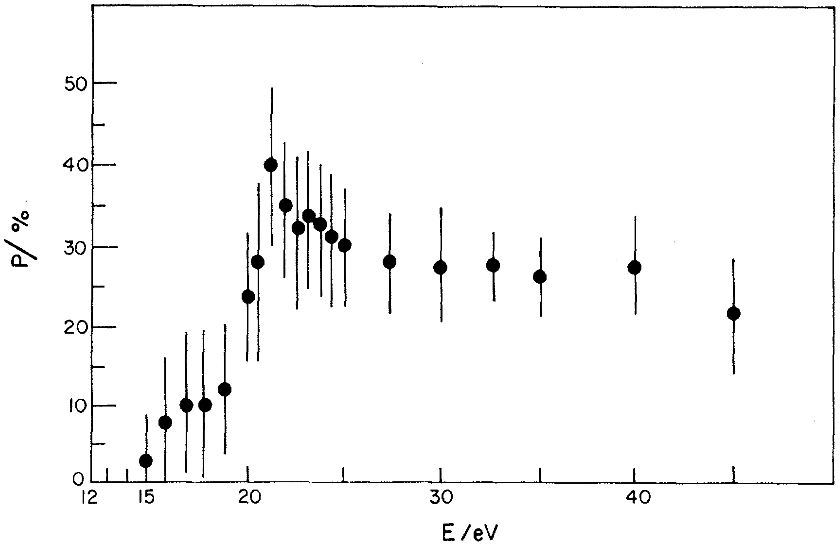


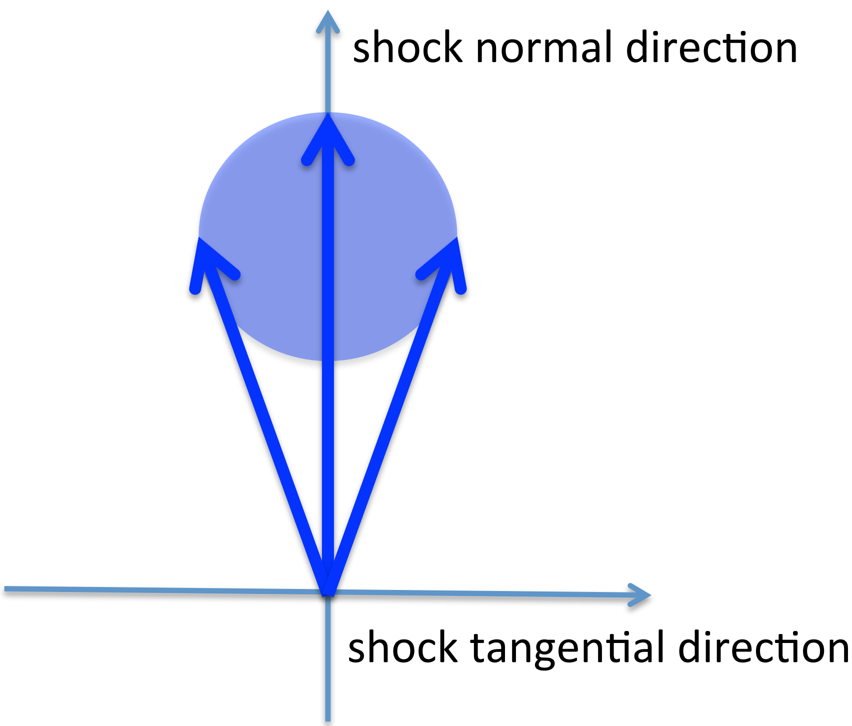
FIG. 1. Polarization of the hydrogen Balmer line H_α as a function of the electron energy (the error bars include 2×rms error plus an estimated systematic error).

- ✓ The polarization is directed along the incident electron beam.
- ✓ For SNR, the charge particles hit hydrogen atoms from various directions in the downstream region.
- ✓ In the rest frame of hydrogen atoms, the colliding particles are seen as a "mildly-collimated beam" due to a finite temperature.
- ✓ This anisotropy eventually causes the net polarization with the degree of a few %.

e.g.) Experiment of the polarized Hα

The polarization degree of Hα resulting from the collision between electron beam and hydrogen atoms（Kleinpoppen & Kraise 1968）.

- Velocity distribution of electrons in hydrogen atom rest frame



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✓ This anisotropy eventually causes the net polarization with the degree of a few %.

The polarized Hα line emission from the SNR shock

- ✓ The downstream velocity distribution function of the (thermal) plasma particle "q" in the hydrogen atom rest frame.

anisotropy

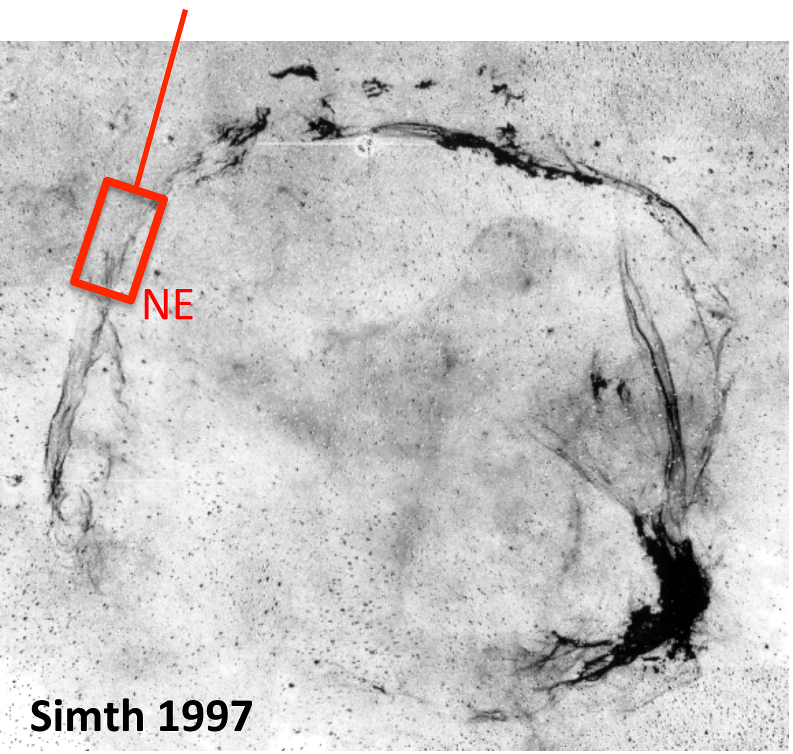
$$f_q(\boldsymbol{v_q}, \boldsymbol{u_2}) = \left(\frac{m_q}{2\pi k T_q}\right)^{\frac{3}{2}} \exp\left(-\frac{m_q(\boldsymbol{v_q} - \boldsymbol{u_2})^2}{2kT_q}\right),$$

- ✓ Laming (1990) predicted the polarized Hα emission from the SNR shock without CR acceleration.

The CR acceleration efficiency at SNR

The energy density of CR around the Earth is explained if ~ 10 % of SN kinetic energy is used for CR acceleration.

Observations of the northeastern region of the young SNR RCW 86 imply that the efficiency is higher than ~ 50 % (Helder+ 09, 13)!?



The Hα image of RCW 86, whose radius is ~10 pc.

- ✓ The measurement principle of the efficiency

  Rankine-Hugoniot relations:

$$kT_{\rm RH} = \frac{3}{16}\mu m_{\rm p} {V_{\rm sh}}^2$$

- ✓ The SNRs shock is loosing the energy due to the CR acceleration.
- ✓ If the actual downstream temperature $T_{\rm down}$ and the shock velocity $V_{\rm sh}$ can be measured individually, we get the CR acceleration efficiency as a missing thermal energy $T_{\rm RH} - T_{\rm down}$.

The polarized Hα line emission from the SNR shock

- ✓ The downstream velocity distribution function of the (thermal) plasma particle "q" in the hydrogen atom rest frame.

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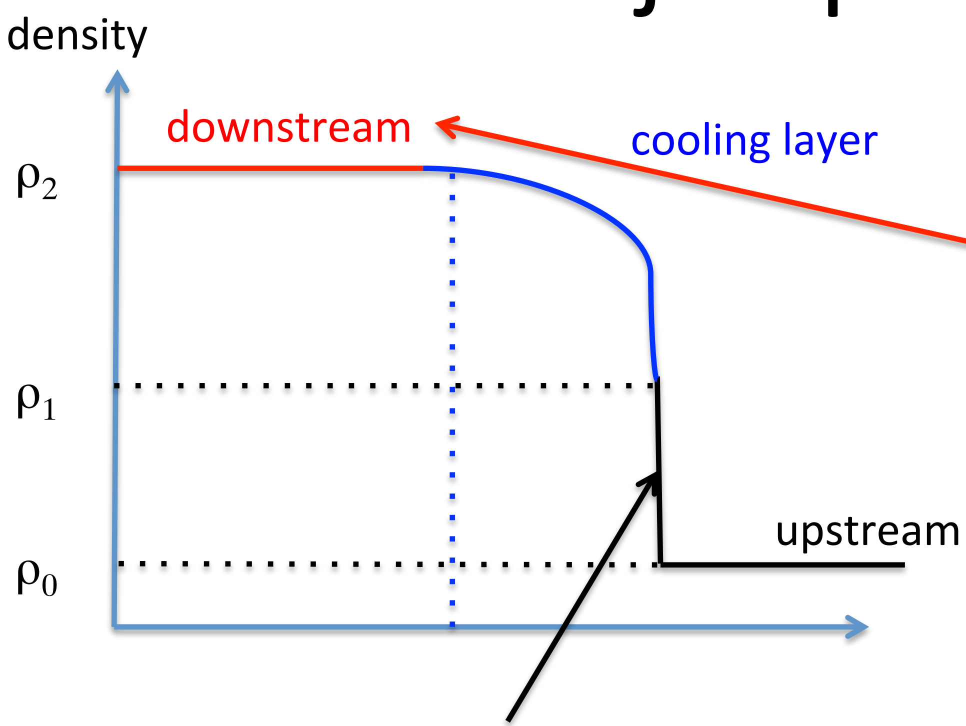
- ✓ Laming (1990) predicted the polarized Hα emission from the SNR shock without CR acceleration.

- ☐ When the SNR shock accelerates efficiently CRs, the downstream temperature becomes lower than the adiabatic shock case, that is, the anisotropy of the velocity distribution becomes larger.
- ☐ A large anisotropy yields a large polarization degree.
- ☐ We calculate the polarized Hα emission from the SNR shock with CR acceleration.

Shock jump conditions



$$\rho_1 = \frac{\gamma+1}{\gamma-1}\rho_0,$$

$$u_1' = \frac{\gamma-1}{\gamma+1}V_{\rm sh},$$

$$p_1 = \frac{2}{\gamma+1}\rho_0 {V_{\rm sh}}^2,$$

Cohen, Piran & Sari (1998) provided the shock jump conditions for a radiative shock.

$$\rho_2 = \frac{\rho_1 u_1'}{u_2'} = \frac{\gamma+1}{(\gamma-1)(1-\delta)}\rho_0,$$

$$p_2 = (\rho_1 u_1')(u_1' - u_2') + p_1 = \frac{2+(1-\gamma)\delta}{\gamma+1}\rho_0 {V_{\rm sh}}^2,$$

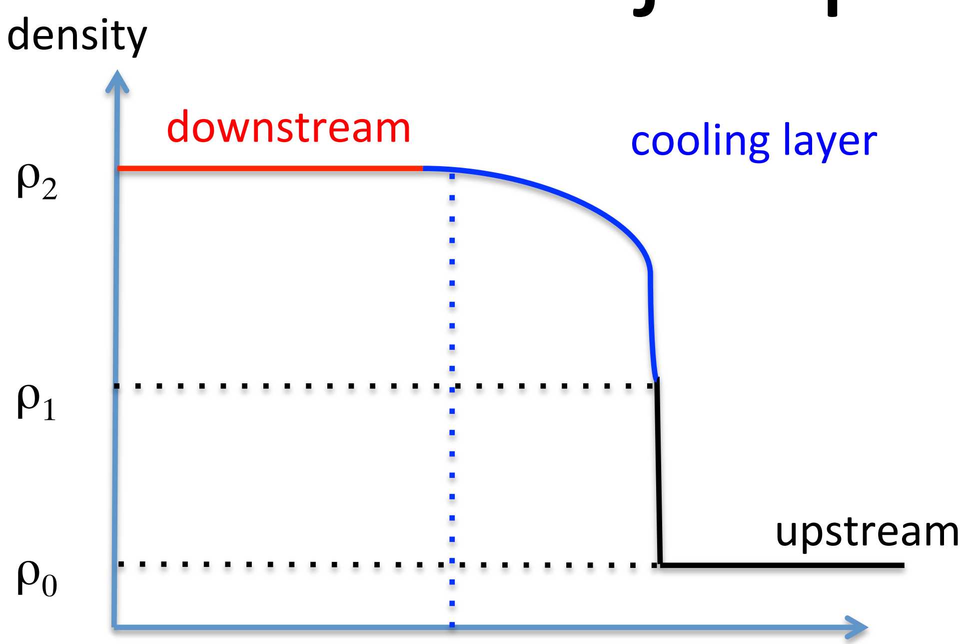
$$\varepsilon = 1 - \frac{F(u_2')}{F(u_1')} = \frac{\delta}{1+\gamma}\left[2+(\gamma-1)\delta\right].$$

$$\delta \equiv 1 - \frac{u_2'}{u_1'}$$

We parameterize the downstream velocity as

$$u_2' = \frac{\gamma_1 - 1}{\gamma_1 + 1}V_{\rm sh}.$$

Shock jump conditions

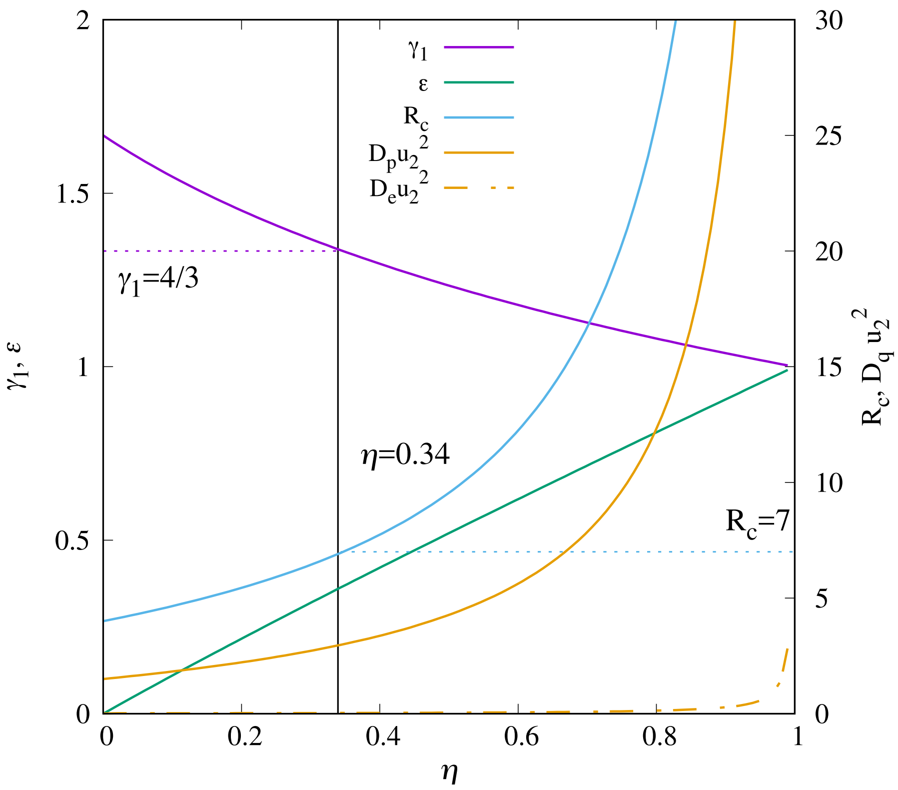


The downstream values are rewritten as

$$\begin{aligned}
\delta &= 1 - \frac{u_2'}{u_1'} = 1 - \frac{\gamma+1}{\gamma-1}\frac{\gamma_1-1}{\gamma_1+1}, \\
\rho_2 &= \frac{\gamma_1+1}{\gamma_1-1}\rho_0, \\
p_2 &= \frac{2}{\gamma_1+1}\rho_0 {V_{\rm sh}}^2, \\
\varepsilon &= \frac{4(\gamma-\gamma_1)}{(\gamma_1+1)^2(\gamma-1)}.
\end{aligned}$$

$$R_c = \frac{\rho_2}{\rho_0} = \frac{\gamma_1+1}{\gamma_1-1}.$$

Shock jump conditions



The downstream temperature and velocity are set as

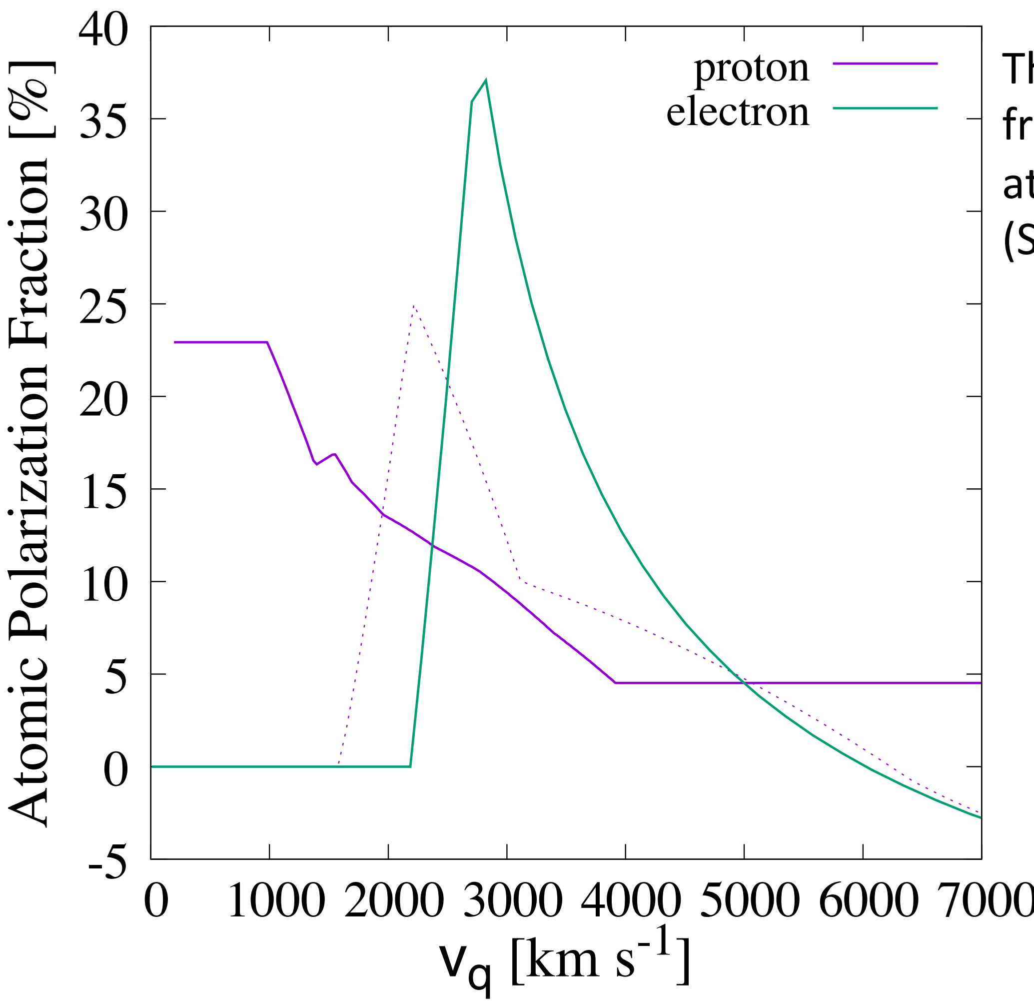
$$kT_{\mathrm{p}} = \frac{3}{16}(1-\eta)\mu m_{\mathrm{p}} V_{\mathrm{sh}}^2$$

$$kT_{\mathrm{e}} = \beta k T_{\mathrm{p}}$$

$$u_2 = \left(1 - \frac{1}{R_c}\right) V_{\mathrm{sh}} = \left(1 - \frac{1}{R_c}\right) \sqrt{\frac{(\gamma+1)^2}{2(\gamma-1)} \frac{kT_{\mathrm{p}}}{(1-\eta)\mu m_{\mathrm{p}}}}.$$

Setting the parameter T_p, η, and β, we calculate the polarized Balmer line emissions.

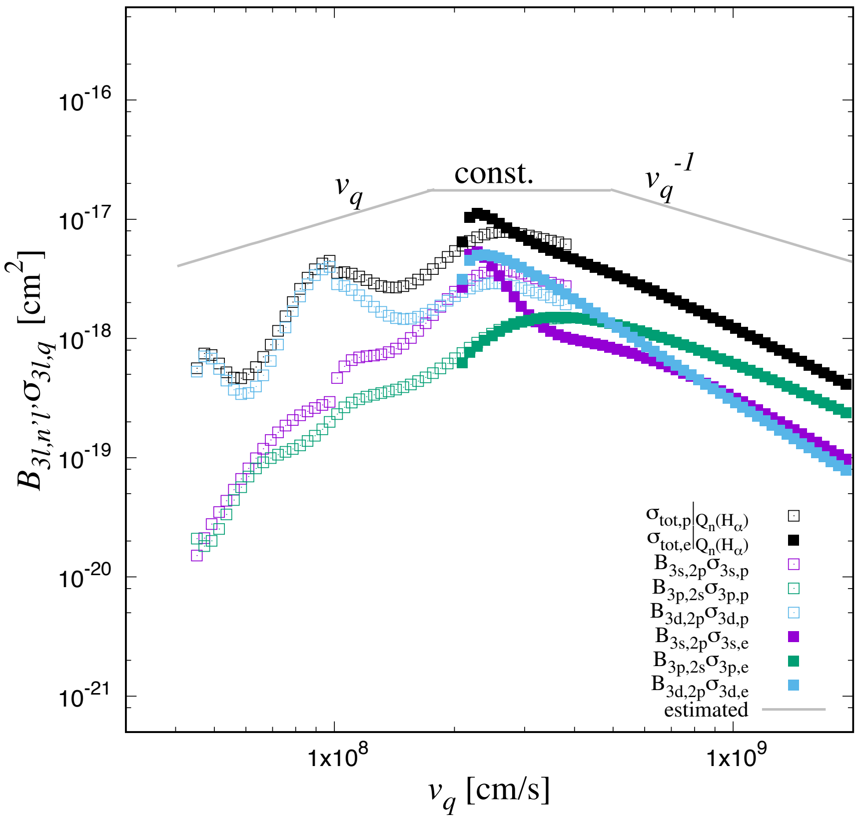
Atomic Polarization Fraction



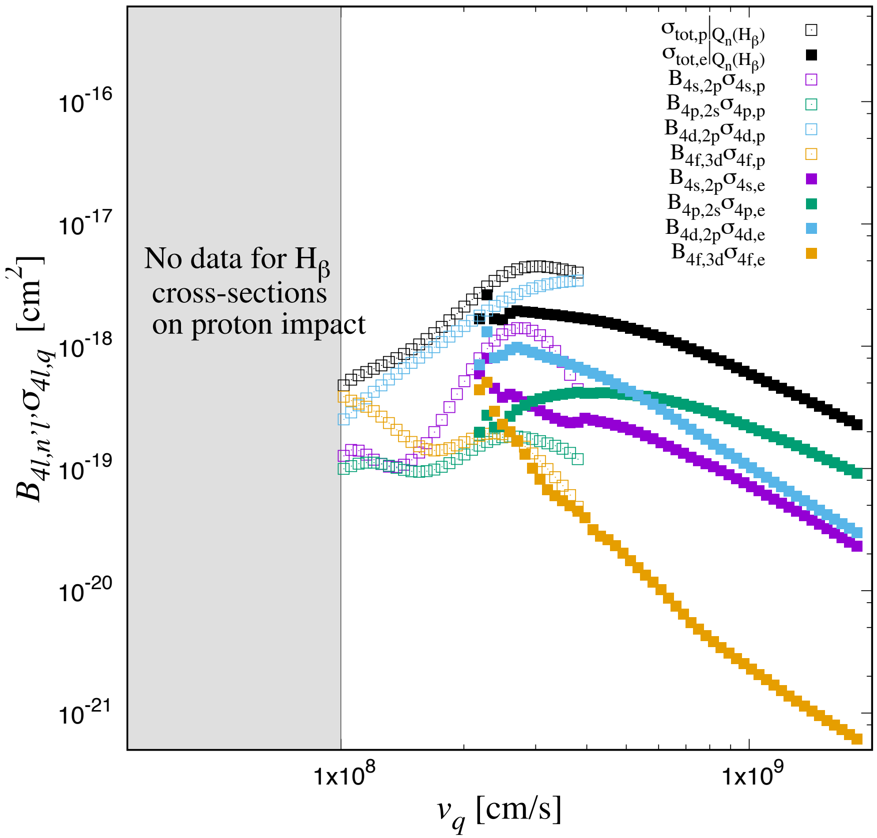
The polarization fraction of Hα resulting from the collision between hydrogen atoms and electron/proton beam (Syms+ 75, Laming 90).

Cross Section

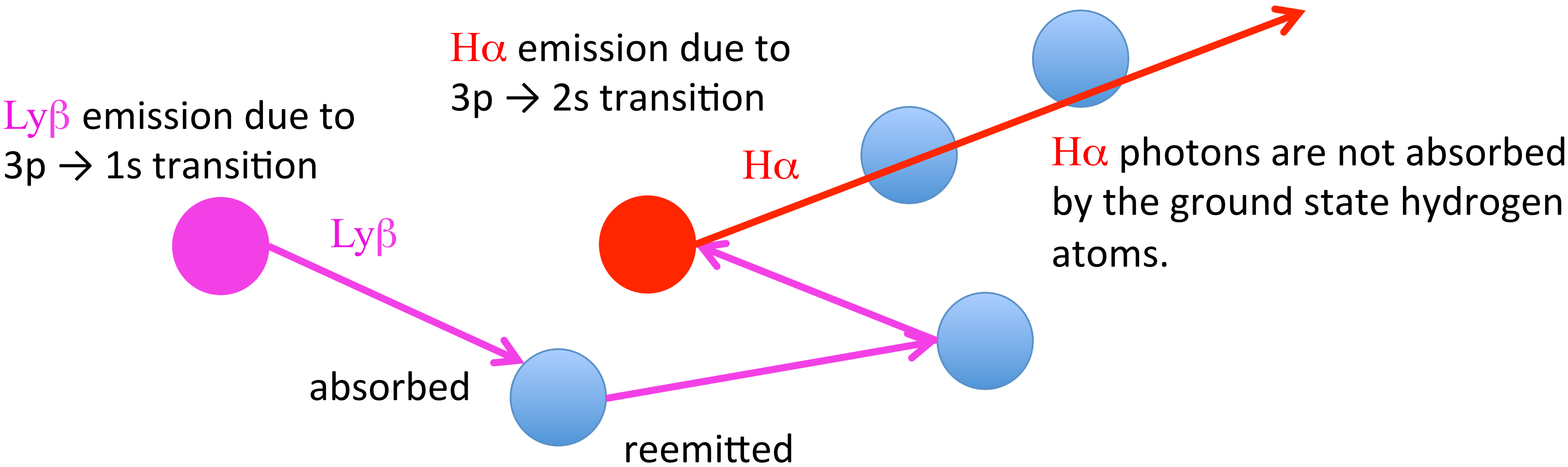
for Hα



for Hβ



Lyman Line Trapping



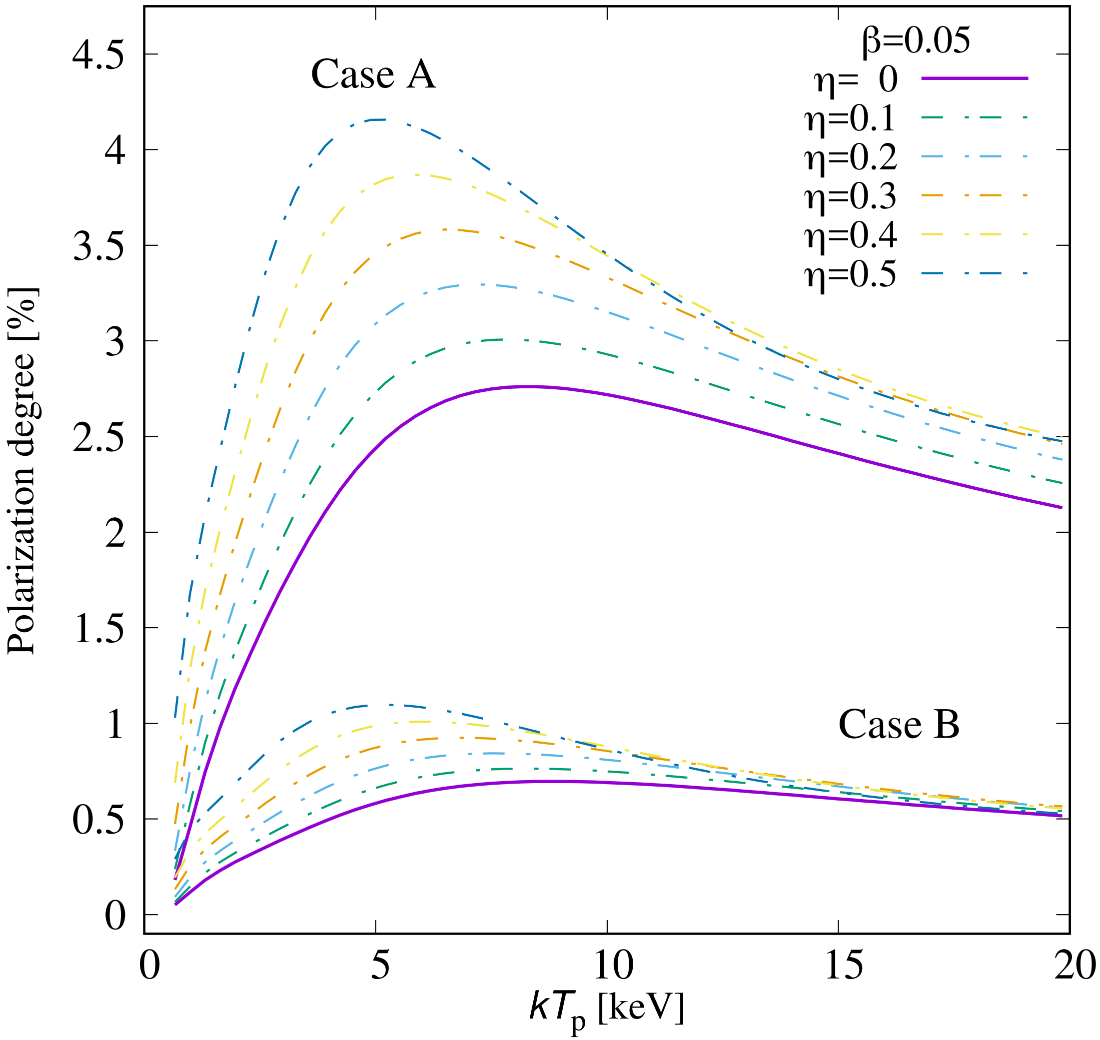
a) A part of hydrogen atoms in the state n=3 emit Lyβ photon due to 3p→1s transition.
b) The emitted Lyβ photons are absorbed by the ground state hydrogen atoms.
c) Eventually, the Lyβ photons are converted Hα photons, which are optically thin for the ground state hydrogen atoms.

Optically thin for Lyβ → "Case A"

Optically thick for Lyβ → "Case B"

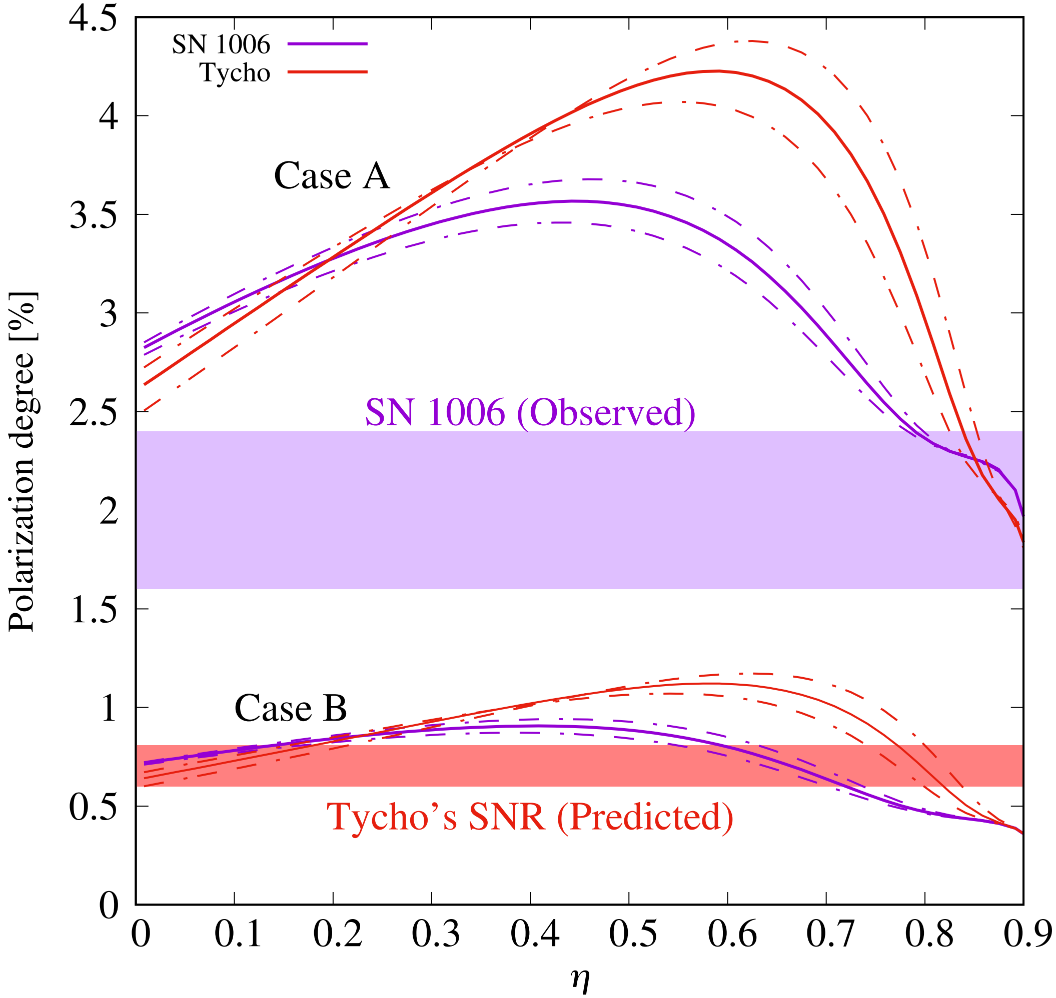
We assume that the converted Hα photons are unpolarized.

The polarized Hα line emission from the SNR shock



The polarization degree depends on the energy loss rate.

The polarized Hα line emission from the SNR shock

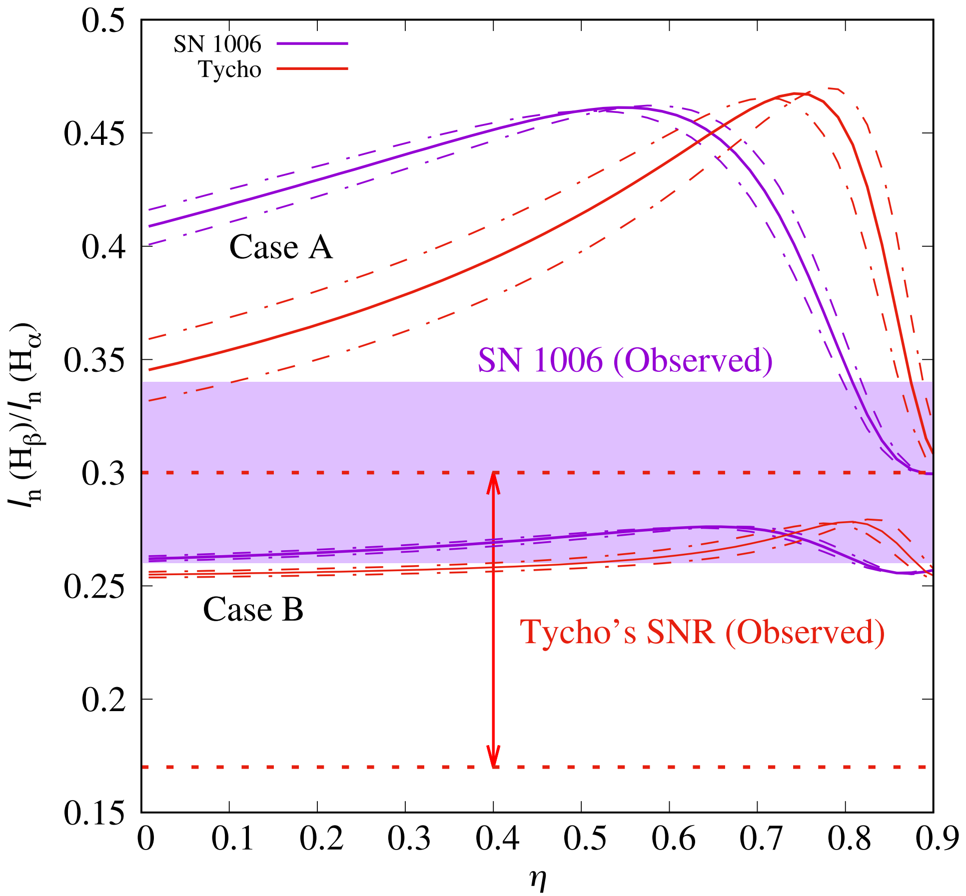


The polarization degree for SN 1006 and Tycho's SNR.

If SN 1006 is Case A, the energy loss rate is $\eta \approx 0.8$.

Extending the model to an arbitrary optical depth of Ly β photon is required.

The polarized Hα line emission from the SNR shock

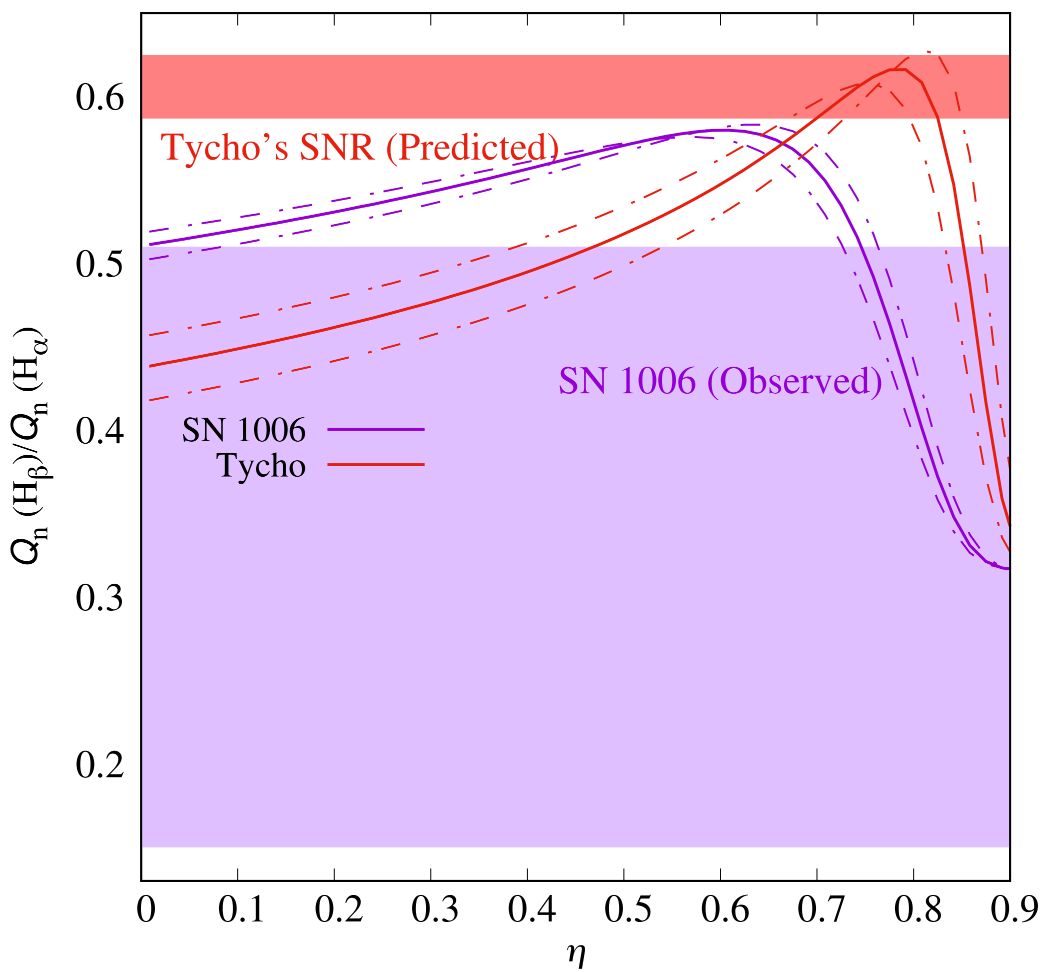


The total intensity ratio for SN 1006 and Tycho's SNR.

If SN 1006 is Case A, the energy loss rate is η≈0.8.

Extending the model to an arbitrary optical depth of Ly β photon is required.

The polarized Hα line emission from the SNR shock



The polarized intensity ratio of Hβ to Hα is also calculated.

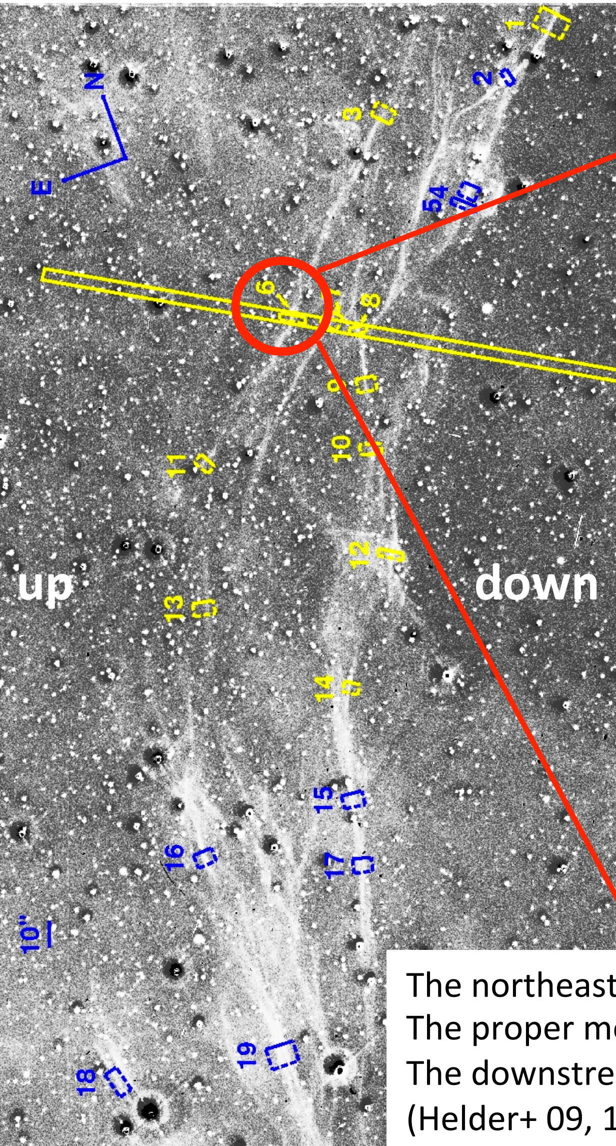
The ratio is not affected by the Lyman line trapping.

For SN 1006, the acceleration efficiency is not constrained.

Summary

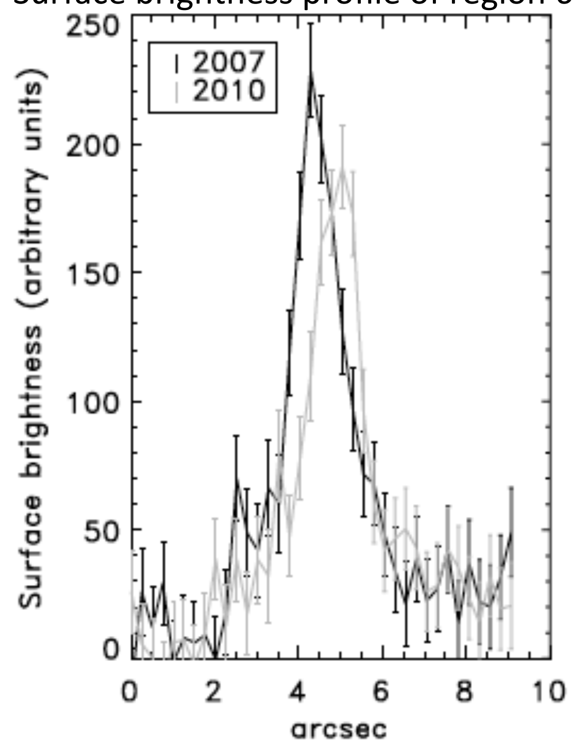
- SNRs are believed as acceleration sites of Galactic CRs.
- The energy density of CR around the Earth can be explained if the 10% of SN kinetic energy is used for CR acceleration.
- We show that the polarization measurements of the Balmer line emissions from SNR shock could provide the CR acceleration efficiency (without the argument of the distance).
- For precise measurement of the efficiency, we must extend the model to an arbitrary optical depth of Lyman line emissions.
- The observation of Tycho's SNR by SUBARU is coming soon (Katsuda et al. 2019-).

Measurements of the shock velocity



- ✓ The shock velocity V_{sh} is measured by the proper motion of Hα filaments.

Surface brightness profile of region 6



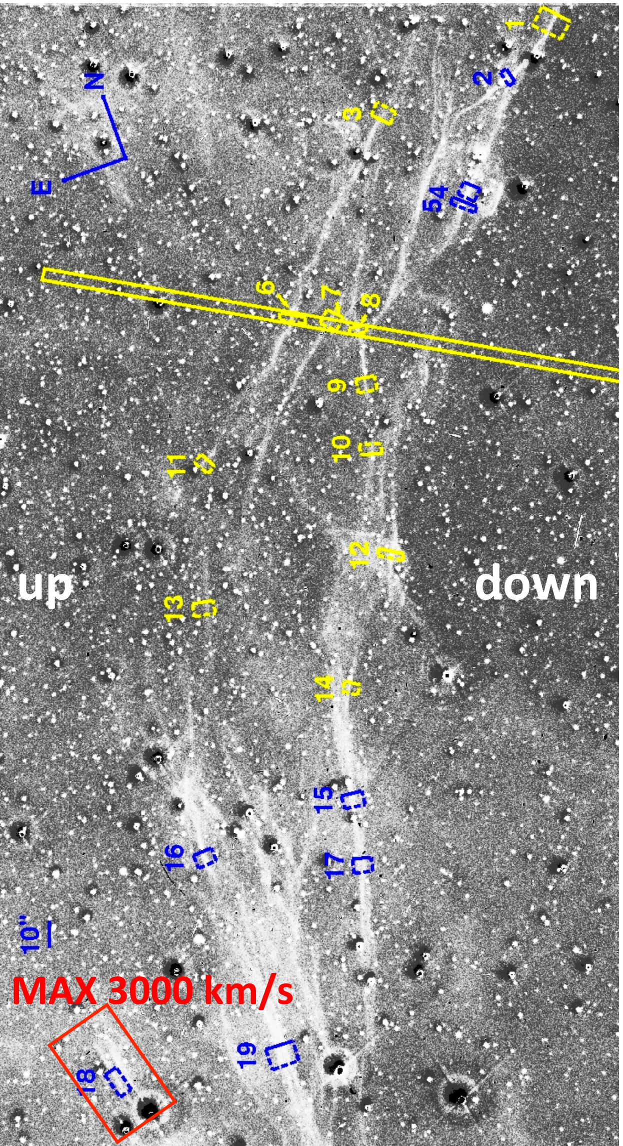
- ✓ The proper motion measured by the shift of surface brightness profile.

$$\chi^2 = \int dx \left(L_{2010}(x - \Delta x) - L_{2007}(x) \right)^2$$

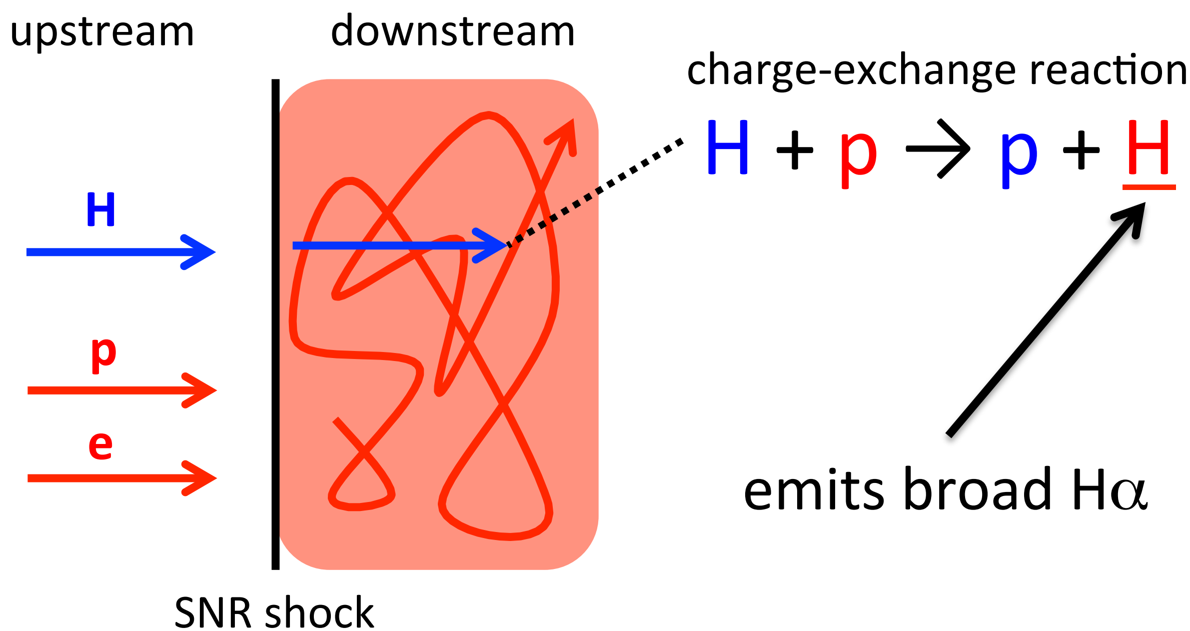
- ✓ The shift is determined so that the χ^2 takes minimum value (Helder+ 13).
- ✓ The distance of RCW 86 is estimated as 2.5 kpc (Helder + 09)

The northeastern region of RCW 86.
The proper motion is measured in boxes.
The downstream temperature measured along the long slit.
(Helder+ 09, 13)

Measurements of the downstream temperature

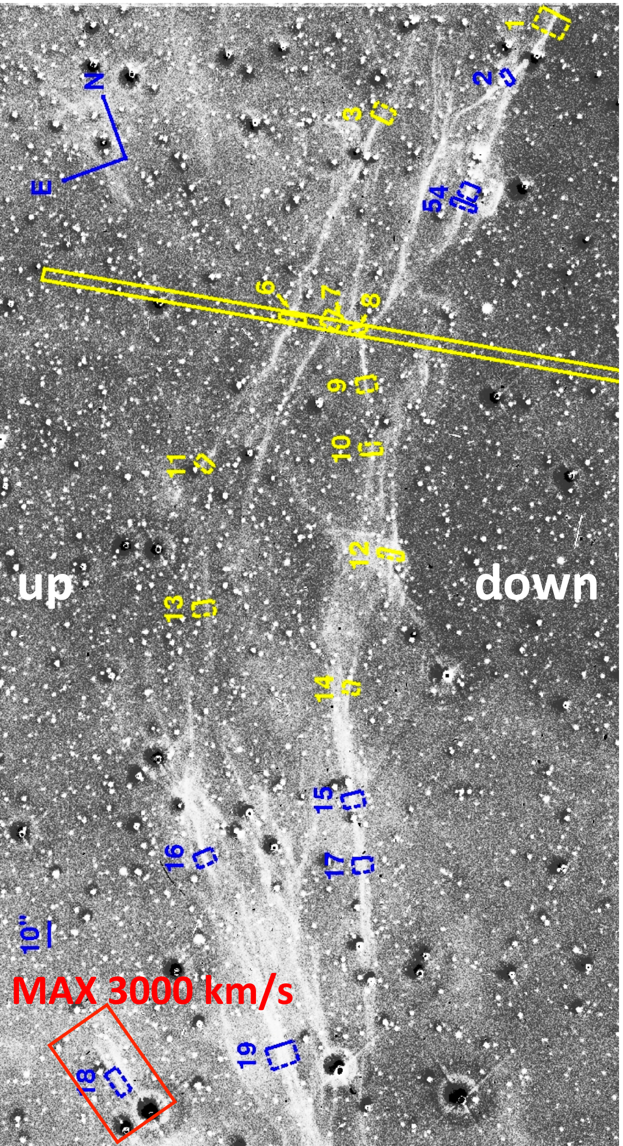


Hα emission emerged from charge-exchange reaction between hydrogen atoms and shocked protons

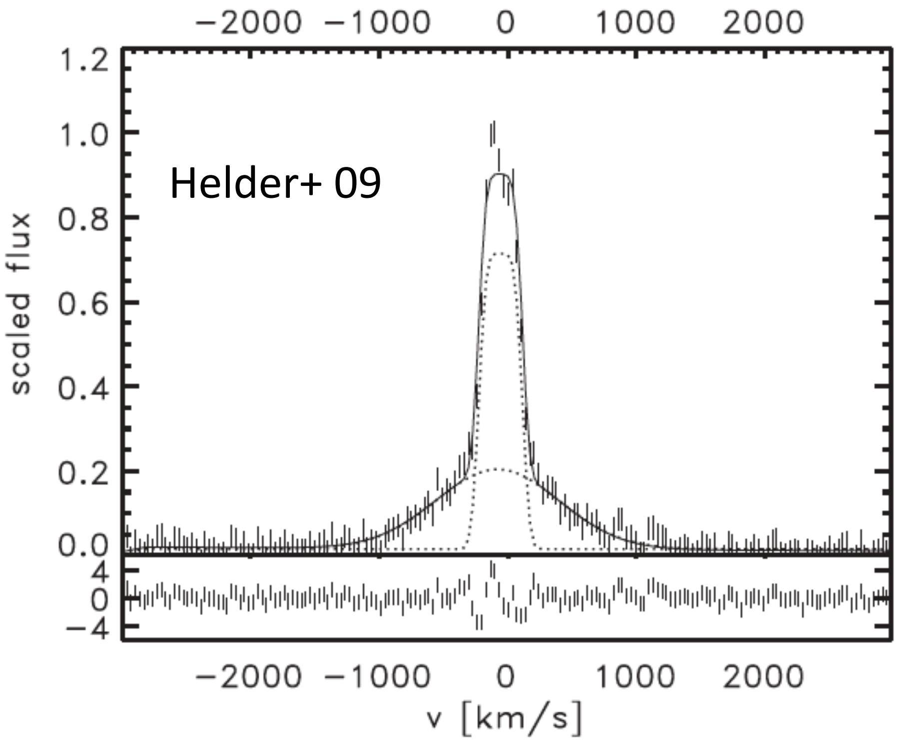


The downstream proton temperature T_{down} is measured directly by the spectrum of the broad component of Hα.

Measurements of downstream temperature

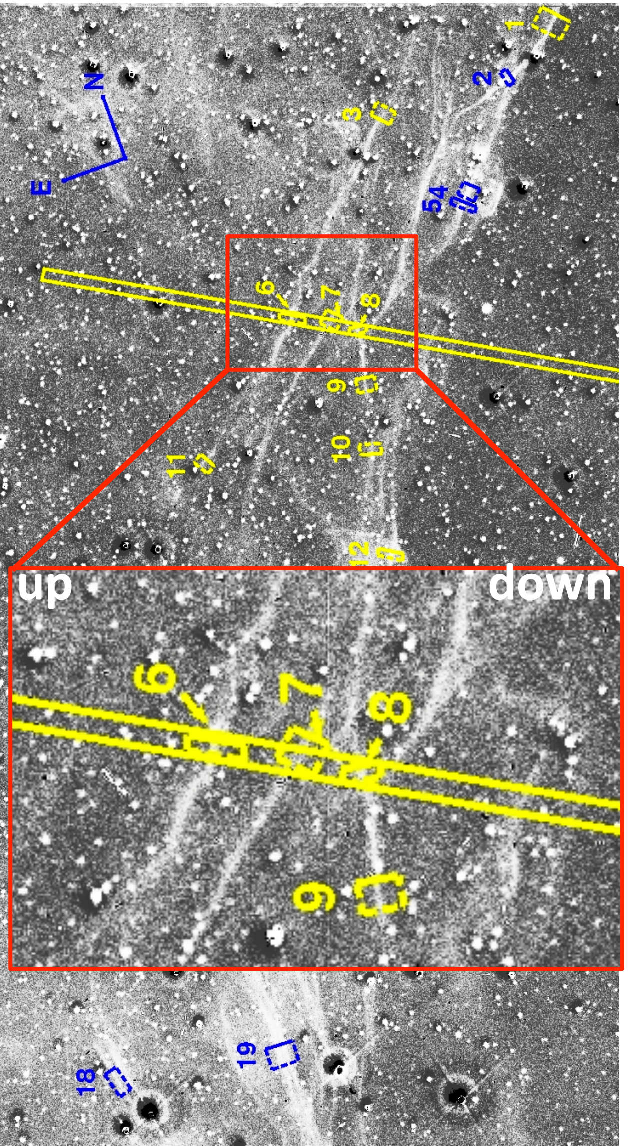


- ✓ The downstream temperature is measured by the spectrum of broad Hα component along the long slit.



The observed downstream proton temperature kT_{down} = 2.3±0.3 keV (Helder+ 09).

The estimation of the CR acceleration efficiency.



- ✓ The expansion speed measured by the proper motion of the Hα filament:

$$V_{\rm sh} \approx 1871 \pm 250~{\rm km/s} \quad \text{(for Region 6)}$$

$$kT_{\rm RH} = \frac{3}{16}\mu m_{\rm p} {V_{\rm sh}}^2 \approx 4.5 \pm 1.2~{\rm keV}$$

- ✓ The downstream temperature :

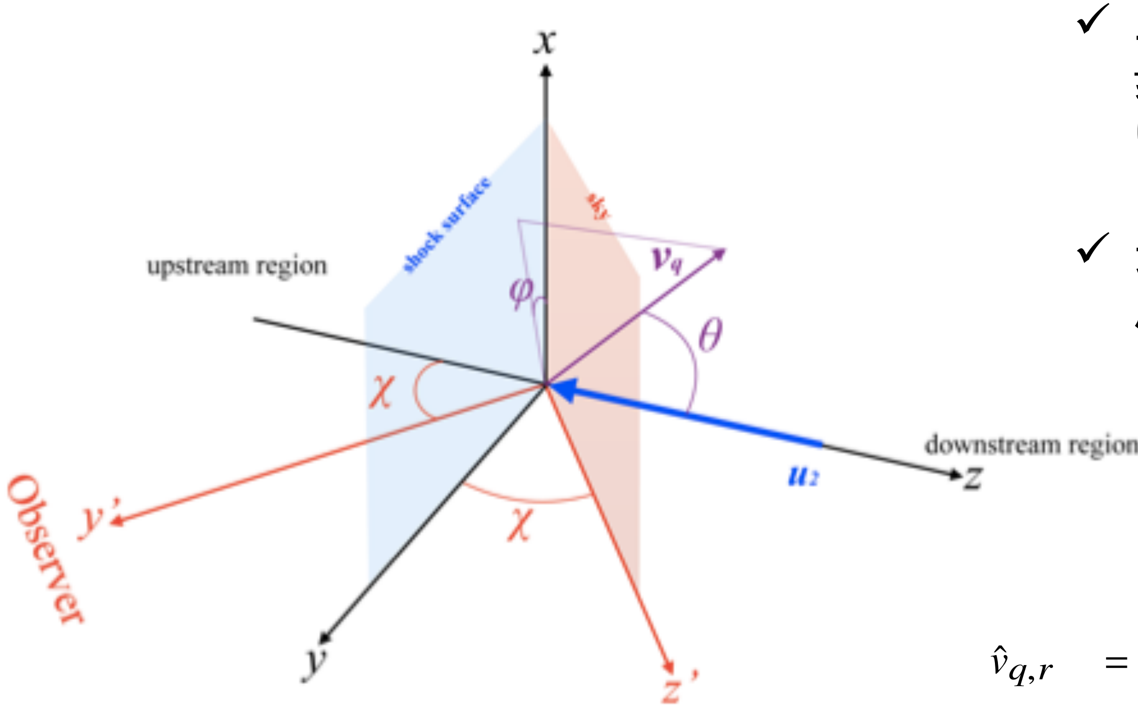
$$kT_{\rm down} \approx 2.3 \pm 0.3~{\rm keV}$$

- ✓ The CR acceleration efficiency:

$$\eta = \frac{T_{\rm RH} - T_{\rm down}}{T_{\rm RH}} \approx 0.6 \pm 0.1$$

Hα偏光放射モデル

- 偏光放射なので、ストークスパラメーターを計算する。



考えている座標

✓ 上流静止系を考え、衝撃波下流で水素原子が荷電粒子(q)との衝突によりどれだけ励起されるかを考える。

✓ 光子の偏極は粒子qの速度ベクトル成分を用いて表す。

$$\hat{\hat{d}}_0 = \hat{v}_{q,r} e^{i\omega_B t},$$

$$\hat{\hat{d}}_{\pm 1} = \frac{1}{\sqrt{2}}(\hat{v}_{q,\theta} \pm i\hat{v}_{q,\varphi})e^{i\omega_B t},$$

$$\begin{aligned}
\hat{v}_{q,r} &= (\sin\theta\cos\varphi, \sin\theta\sin\varphi, \cos\theta), \\
\hat{v}_{q,\theta} &= (\cos\theta\cos\varphi, \cos\theta\sin\varphi, -\sin\theta), \\
\hat{v}_{q,\varphi} &= \hat{v}_{q,r} \times \hat{v}_{q,\theta} = (-\sin\varphi, \cos\varphi, 0),
\end{aligned}$$

Hα偏光放射モデル

- 偏光放射なので、ストークスパラメーターを計算する。

$$Q = \langle E_{\mathrm{obs},z'} E_{\mathrm{obs},z'}{}^{*} \rangle - \langle E_{\mathrm{obs},x} E_{\mathrm{obs},x}{}^{*} \rangle$$

$$I = \langle E_{\mathrm{obs},z'} E_{\mathrm{obs},z'}{}^{*} \rangle + \langle E_{\mathrm{obs},x} E_{\mathrm{obs},x}{}^{*} \rangle$$

個々の水素原子が観測者視線方向に発する光子の偏極方向

$$\boldsymbol{E}_{\Delta m}(t) = \left\{ \hat{y}' \times (\hat{y}' \times \hat{\hat{d}}_{\Delta m}) \right\} E(t) \equiv \hat{\epsilon}_{\Delta m} E(t)$$

$$\hat{y}' = (0, \sin\chi, -\cos\chi)$$

光子の偏極を与える反応断面積

$$\sigma'_{\Delta m,q}(v_q) = \sum_{\Delta m} B_{nlm,n'l'm'} \sigma_{nlm,s}(v_q),$$

$$B_{nlm,n'l'm'} = \frac{A_{nlm,n'l'm'}}{\sum_{n',l'm'} A_{nlm,n'l'm'}},$$

放射強度はこの光子の偏極を与える反応をした水素原子の個数に比例するとする。

Hα偏光放射モデル

- 偏光放射なので、ストークスパラメーターを計算する。

$$
\begin{aligned}
Q &= \langle E_{\mathrm{obs},z'} E_{\mathrm{obs},z'}{}^{*} \rangle - \langle E_{\mathrm{obs},x} E_{\mathrm{obs},x}{}^{*} \rangle \\
&\propto \sum_q \int v_q f_q(\boldsymbol{v_q}, \boldsymbol{u_2}) \\
&\times \left[\sigma'_{0,q} |\boldsymbol{E}_{0,z'}|^2 + \sigma'_{1,q} |\boldsymbol{E}_{1,z'}|^2 + \sigma'_{-1,q} |\boldsymbol{E}_{-1,z'}|^2 \right. \\
&\left. - \left\{ \sigma'_{0,q} |\boldsymbol{E}_{0,x}|^2 + \sigma'_{1,q} |\boldsymbol{E}_{1,x}|^2 + \sigma'_{-1,q} |\boldsymbol{E}_{-1,x}|^2 \right\} \right] d^3\boldsymbol{v_q} \\
&\propto \sum_q \int v_q f_q(\boldsymbol{v_q}, \boldsymbol{u_2}) \\
&\times \left[\sigma'_{0,q} |\hat{z'} \cdot \hat{v}_{q,r}|^2 + \sigma'_{1,q} \left(|\hat{z'} \cdot \hat{v}_{q,\theta}|^2 + |\hat{z'} \cdot \hat{v}_{q,\varphi}|^2 \right) \right. \\
&\left. - \left\{ \sigma'_{0,q} |\hat{x} \cdot \hat{v}_{q,r}|^2 + \sigma'_{1,q} \left(|\hat{x} \cdot \hat{v}_{q,\theta}|^2 + |\hat{x} \cdot \hat{v}_{q,\varphi}|^2 \right) \right\} \right] d^3\boldsymbol{v_q},
\end{aligned}
$$

$$
\begin{aligned}
\hat{v}_{q,r} &= (\sin\theta\cos\varphi, \sin\theta\sin\varphi, \cos\theta), \\
\hat{v}_{q,\theta} &= (\cos\theta\cos\varphi, \cos\theta\sin\varphi, -\sin\theta), \\
\hat{v}_{q,\varphi} &= \hat{v}_{q,r} \times \hat{v}_{q,\theta} = (-\sin\varphi, \cos\varphi, 0),
\end{aligned}
$$

$$
\begin{aligned}
\hat{z'} &= (0, \cos\chi, \sin\chi), \\
\hat{x} &= (1, 0, 0).
\end{aligned}
$$

などと計算される。

Hα偏光放射モデル

- 偏光放射なので、ストークスパラメーターを計算する。

$$\chi = \pi/2$$
$$f_q = \delta(\boldsymbol{v_q} - \boldsymbol{u_2})$$

の場合は $\frac{Q}{I} = \sum_q \frac{\sigma'_{0,q} - \sigma'_{1,q}}{\sigma'_{0,q} + \sigma'_{1,q}}.$

ここで、

$$P_q = \frac{\sigma'_{0,q} - \sigma'_{1,q}}{\sigma'_{0,q} + \sigma'_{1,q}},$$

とおけば、粒子qのビームを照射したときに観測される偏光度となり、実験などで与えられている（e.g. Kleinpoppen & Krais 1968）。

$$\sigma_{\mathrm{tot},q} = \sigma'_{0,q} + 2\sigma'_{1,q}$$

だから、

$$\sigma'_{0,q} + \sigma'_{1,q} = \frac{2}{3 - P_q}\sigma_{\mathrm{tot},q},$$
$$\sigma'_{0,q} - \sigma'_{1,q} = P_q(\sigma'_{0,q} + \sigma'_{1,q}),$$

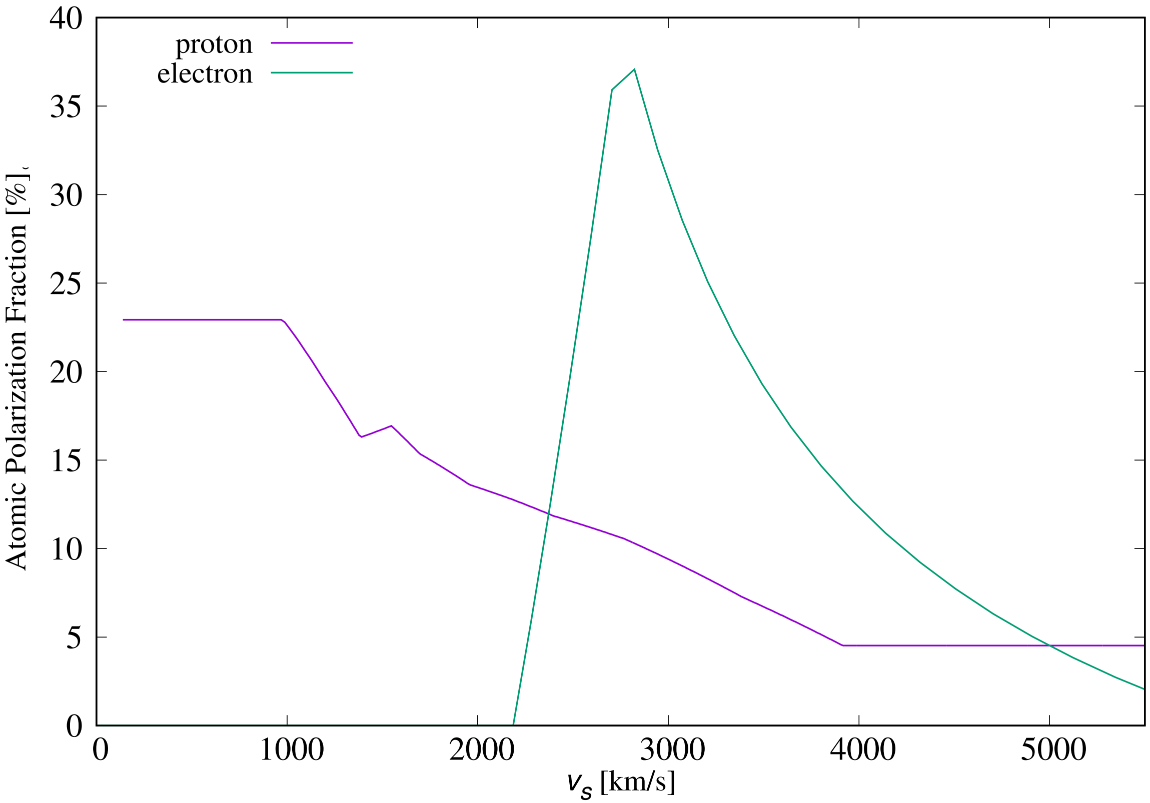
水素原子が光子を放出する全反応断面積

$$\sigma_{\mathrm{tot},q},$$

さえ求めれば、任意の粒子qの分布函数の下で計算できるようになる。

Hα偏光放射モデル

- 偏光放射なので、ストークスパラメーターを計算する。



$$P_q = \frac{\sigma'_{0,q} - \sigma'_{1,q}}{\sigma'_{0,q} + \sigma'_{1,q}},$$

の理論計算（Syms+1975 for proton、Laming1990 for electron）。
今後はこれを用いる。

Hα偏光放射モデル

- 水素原子がHα光子を放出する全反応断面積

選択則$l'=l\pm 1$に注意し、n=4からの影響まで考えて

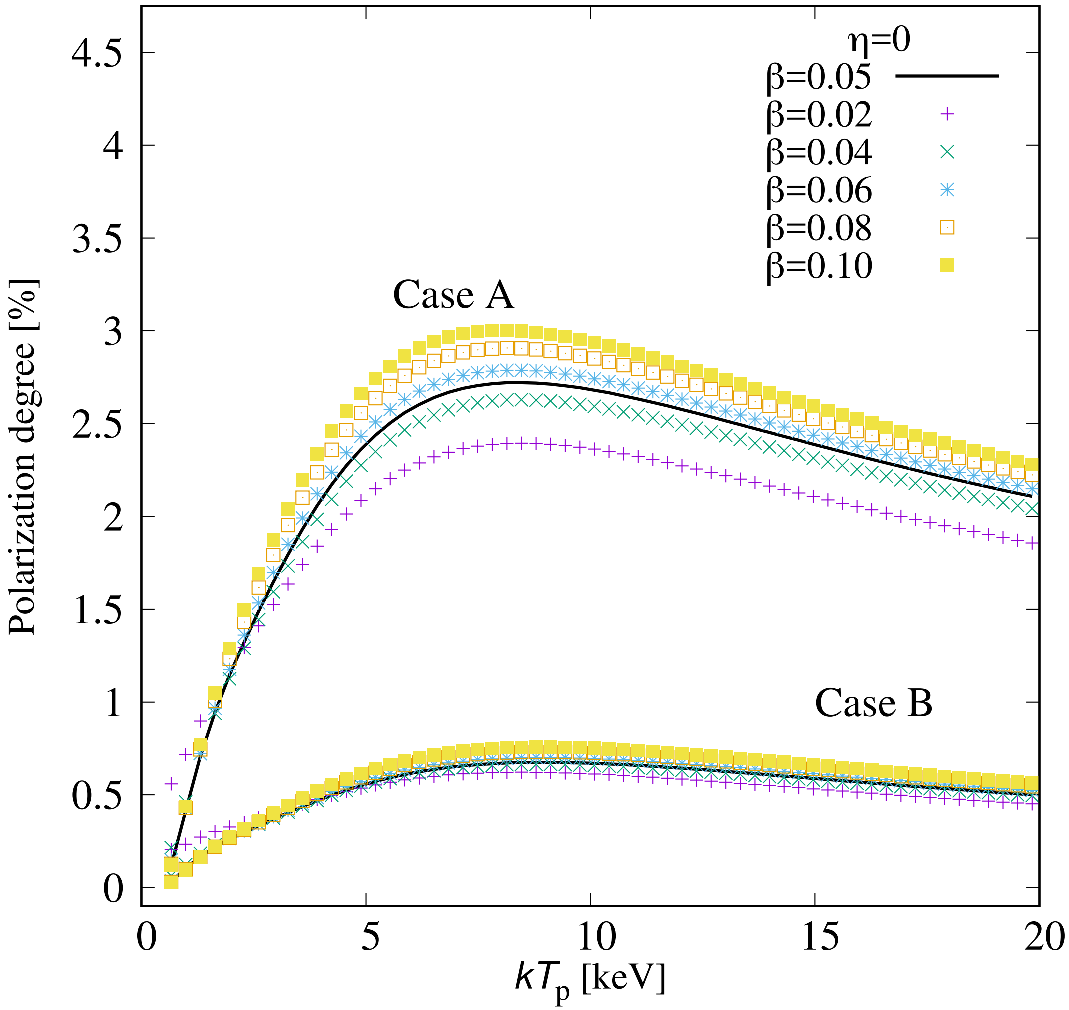
$$
\begin{aligned}
\sigma_{\text{tot},q}|_{Q(\mathrm{H}_\alpha)} &= \sigma_{3s,q} + B_{3p,2s}\sigma_{3p,q} + \sigma_{3d,q}, \\
\sigma_{\text{tot},q}|_{I(\mathrm{H}_\alpha)} &= \sigma^*_{3s,q} + B_{3p,2s}\sigma^*_{3p,q} + \sigma^*_{3d,q}, \\
\sigma^*_{3s,q} &= \sigma_{3s,q} + B_{4p,3s}\sigma_{4p,q}, \\
\sigma^*_{3p,q} &= \sigma_{3p,q} + B_{4s,3p}\sigma_{4s,q} + B_{4d,3p}\sigma_{4d,q}, \\
\sigma^*_{3d,q} &= \sigma_{3d,q} + B_{4p,3d}\sigma_{4p,q} + \sigma_{4f,q},
\end{aligned}
$$

$$(s, p, d, f, \ldots) = (0, 1, 2, 3, \ldots)$$

$B_{3p,2s}$	0.1183
$B_{4s,2p}$	0.5841
$B_{4s,3p}$	0.4159
$B_{4p,1s}$	0.8402
$B_{4p,2s}$	0.1191
$B_{4p,3s}$	3.643×10^{-2}
$B_{4p,3d}$	4.282×10^{-3}
$B_{4d,2p}$	0.7456
$B_{4d,3p}$	0.2544

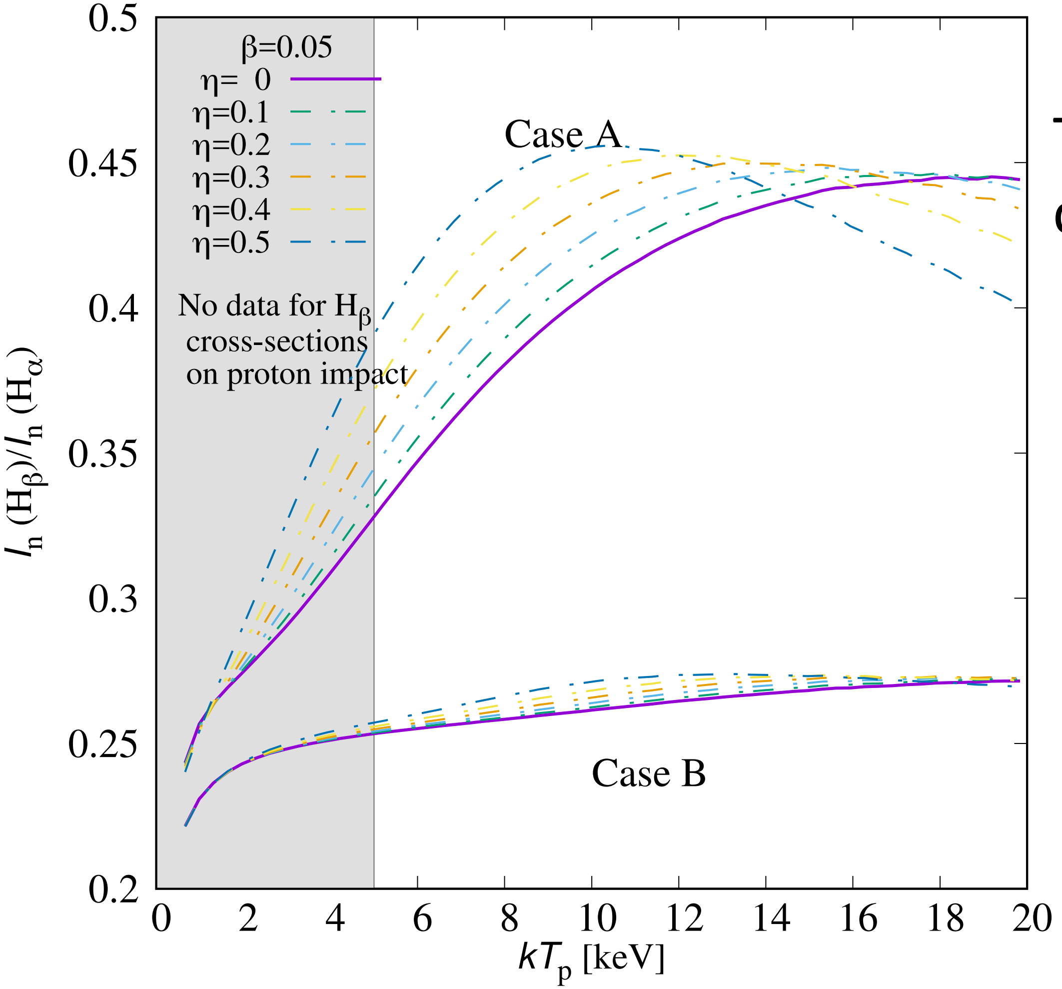
ライマン輝線捕獲によって変換される分を全て無偏光とした。
Case Aの場合の$B_{nl,n'l'}$は左の文献値を用いる。
Case Bの場合は$B_{nl,1s}=1$として計算する。
Hβ光子についても同様に計算する。

The polarized Hα line emission from the SNR shock



The polarization degree depends on the electron temperature.

The polarized Hα line emission from the SNR shock



The total intensity ratio (so-called Balmer decrement).