A systematic study on escaping of cosmic rays from SNR shocks through observations of thermal X-ray plasmas

Hiromasa Suzuki[1],
Aya Bamba[1], Hirokazu Odaka[1], Ryo Yamazaki[2], Hiroya Yamaguchi[3], Yutaka Ohira[1]
1: The University of Tokyo; 2: Aoyama Gakuin Univeristy, 3: ISAS/JAXA
Email: suzuki@juno.phys.s.u-tokyo.ac.jp

1. Introduction

- Cosmic-ray escape from SNR shocks
  - Detections of soft GeV emission from old SNRs = Direct evidence for proton acceleration. (e.g. Abdo et al. 2010)
  - How, and what timescale can protons escape and become cosmic rays ?
- Common properties of old GeV-emitting SNRs
  - Interaction with dense molecular clouds (MCs)
  - About half have rapidly-cooled plasmas (RCPs; $kT_e < kT_z$) (e.g. Yamaguchi et al, 2009)

→ Our hypothesis: **(Suzuki et al. 2018)**
Shock-MC collision triggers both Escaping & Rapid cooling (Figure 1)

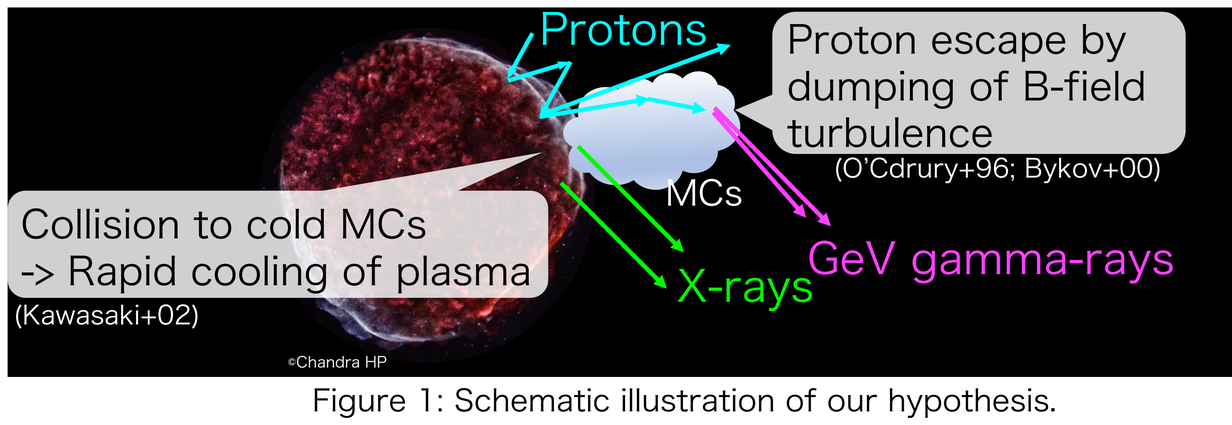

Figure 1: Schematic illustration of our hypothesis.

2. Analysis and Results

- Analysis:
  In our escaping scenario, after the shock-MC collison,
  ① **GeV breaking-energy** gradually becomes smaller.
  ② RCP gradually approachs ionization equiliblium. (Figure 2)
  → We estimated GeV breaking-energies of GeV SNRs which also have RCPs (12 objects; Table 1). (*Fermi* data; e.g. Acero et al. 2016)
  We investigated a correlation between **GeV breaking-energies and RCP ages**. (*Suzaku* data; e.g. Uchida et al. 2012)

Name	Diameter (pc)	n_e (cm^{-3})	RCP age (kyr)	Refs. (X-ray)	Refs. (GeV-TeV)
N132D	14x14	3	9.3 (7.4-10)	Bamba+18	Ackermann+16; HESS collaboration 18
Kes17	35x35	0.9	39 (32-50)	Washino+16	Wu+11
G359.1-0.5	28x28	0.2	19 (17-21)	Suzuki+ in prep., Ohnishi+11	Hui+16; Aharonian+08
IC443	20x20	1.6	12 (11–13)	Yamaguchi+09, Matsumura+18	Ackermann+13; Acciari+09; Albert+08;Tavani+10
W44	24x31	1	20 (18-23)	Uchida+12	Ackermann+13
W49B	7x9	2.7	5.2 (4.7-5.7)	Ozawa+09, Matsumura 18	Abdo+10; HESS collaboration 18
3C391	16x21	0.9	45 (38-49)	Sato+14, Ergin+14	Ergin+14
W28	28x28	1	35 (32-41)	Sawada & Koyama+12, Okon+18	Cui+18; Aharonian+08
CTB37A	44x44	0.8	52 (48-64)	Yamauchi+14	Abdollahi+17
G166.0+4.3	51x80	0.9	68 (64-74)	Matsumura+17	Araya 13
MSH 11-61A	28x39	0.7	59 (55-65)	Kamitsukasa+15	Auchettl+15
HB 21	45x60	0.06	170 (110–250)	Suzuki+18	Ambrogi+19

Table 1: Properties of 12 GeV SNRs which have RPs.

- Results:
  - We found that GeV spectra had roughly a same photon index ~2.45. (Figure 3)
  - Assuming an uniform photon index of 2.45, we estimated GeV breaking-energies of GeV SNRs. (Figure 3)
  - We discovered a **positive correlation between GeV breaking-energies and RCP ages.** (Figure 4 (a, b))

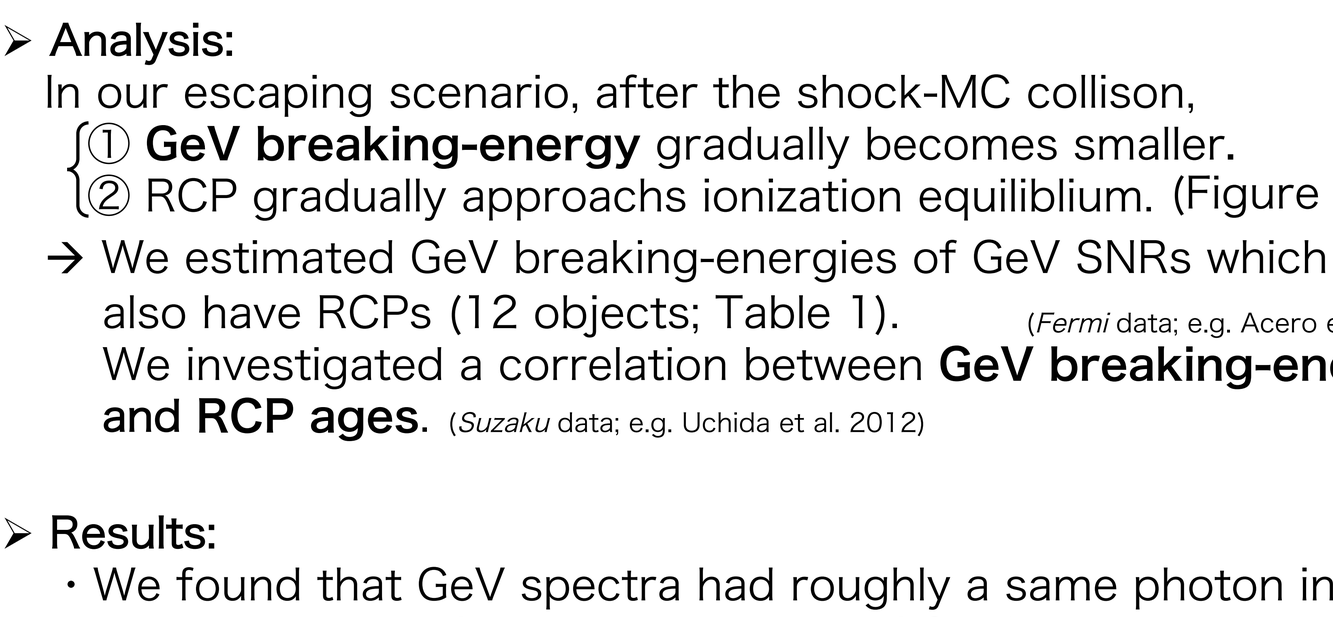

Figure 2: Time evolution of X-rays and GeV gamma-rays in our hypothesis.

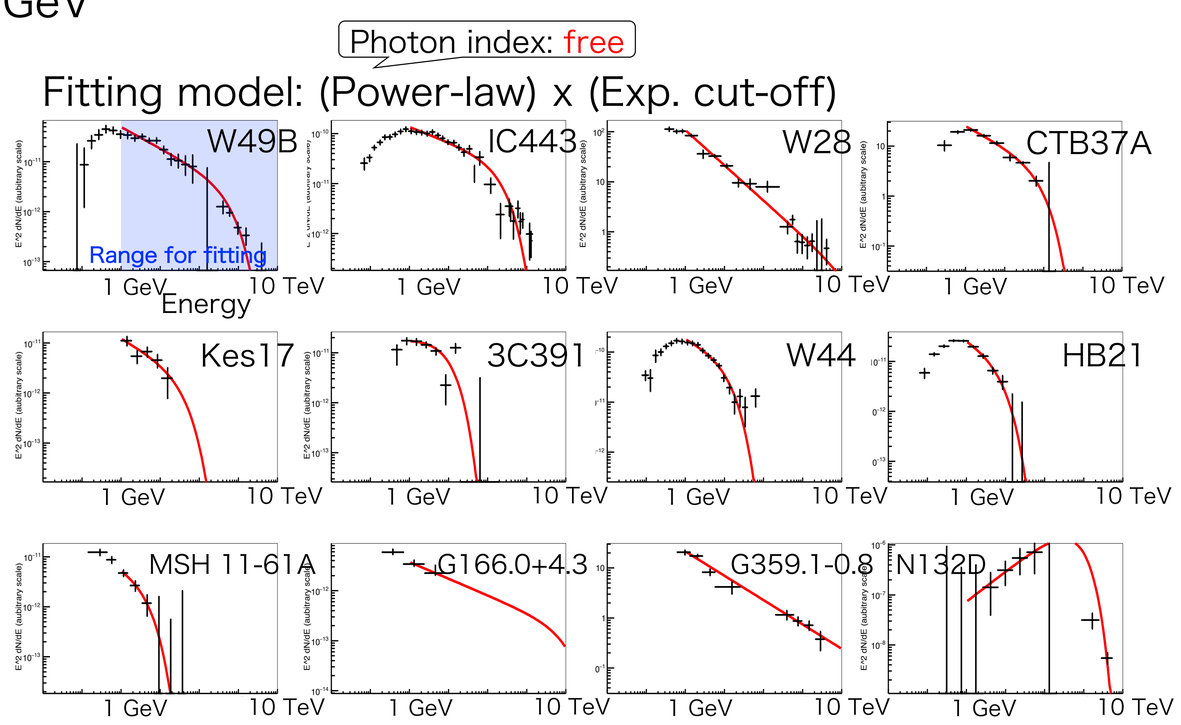

Figure 3: GeV spectra and the best-fit models for 12 SNRs.

3. Discussion

- Our result suggests that SNRs with older RCPs have lower breaking-energies of accelerated protons.
  → **RCP age reflects time evolution of escape.**
- We compared the result to the theoretical predictions. (Ptuskin et al. 2003; Figure 4 (a, b))
  → ・B-field dumping by shock-MC interaction seems to be too efficient (= **Our hypothesis is unlikely**).
  ・**Shock-ISM interaction can explain time evolution of escape**, assuming RCP age ~SNR age.
- RCP ages have positive correlation with estimated SNR ages. (Figure 4 (c))
- → Possible scenario:
  Escape gradually proceeds with time,
  whereas RCPs are generated in early stages of evolution. (e.g. Katsuragawa 2019)

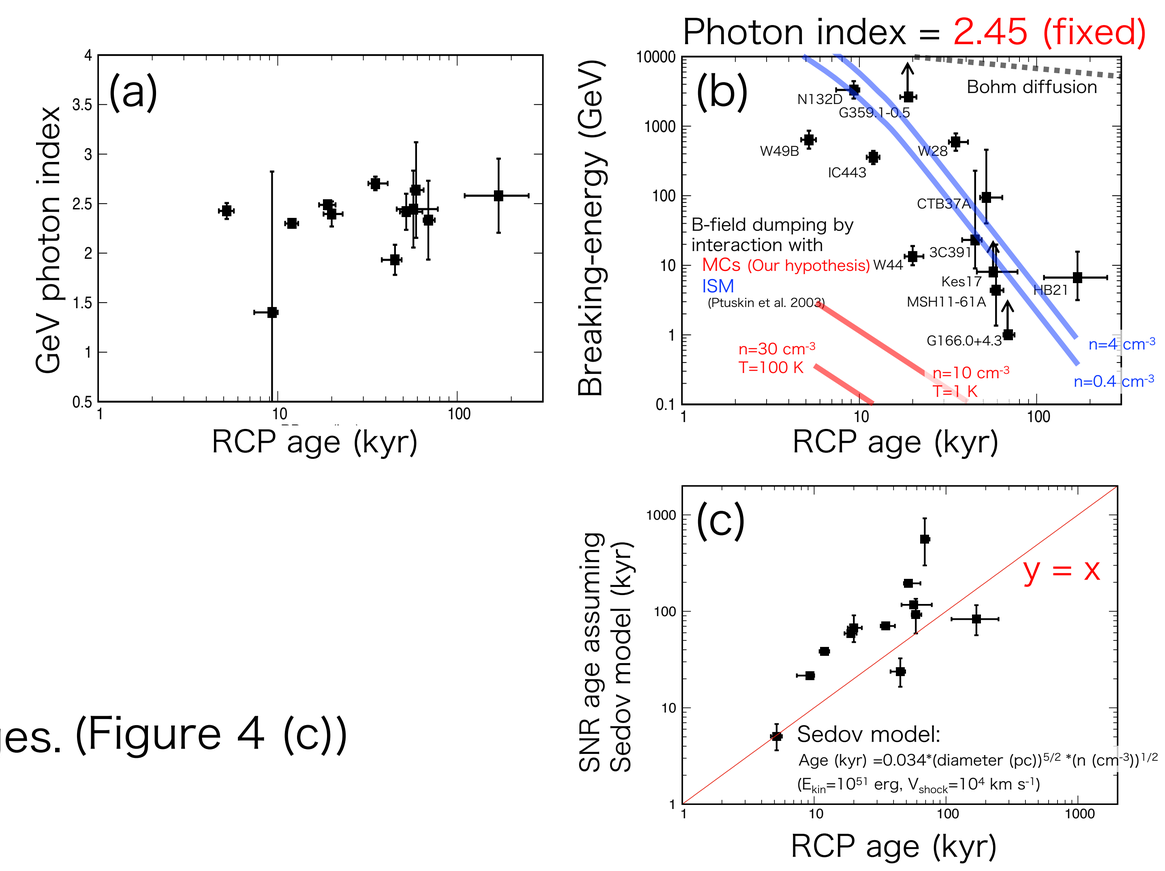

Figure 4: Panels (a) and (b): fitting results of GeV spectra, and their dependence on RCP ages. In panel (c), theoretical predictions are also shown. Panel (c): relation between RCP ages and estimated SNR ages.

References

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