Kneeの起源についての一考察
- 銀河系外宇宙線からの寄与 -

Origin of the knee in the cosmic ray spectrum
- Contribution from the extragalactic cosmic rays -

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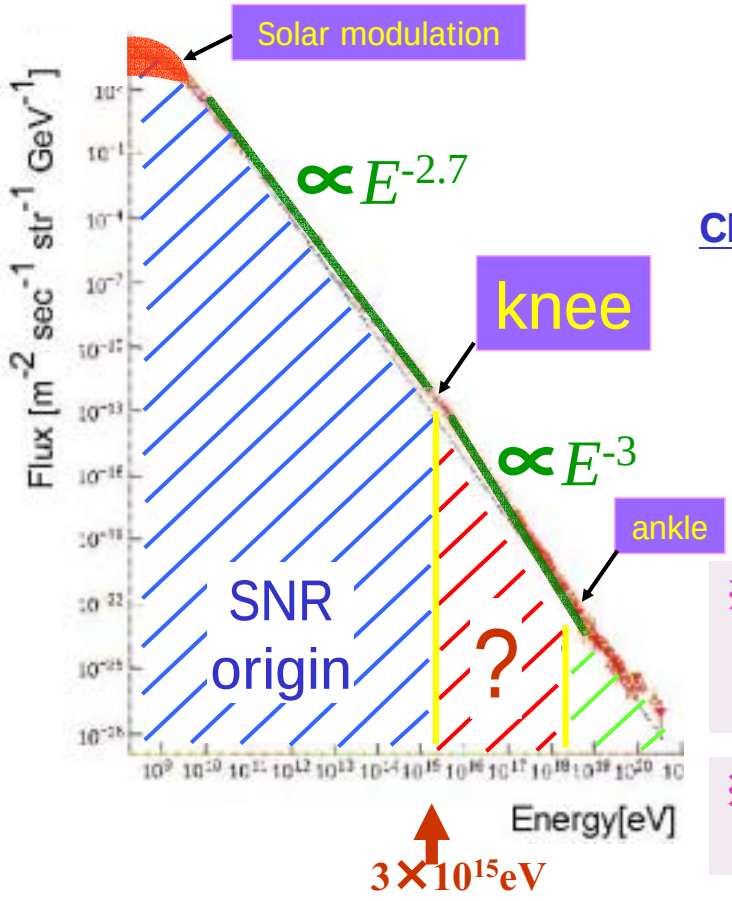
Contents

1. Introduction



Cosmic rays (CRs)

→Relativistic particles reaching the Earth from space
(p 90%, He 9%,...)

CR spectrum

→Power law spectrum
$\sim E^{-2.7}$ ($<3\times10^{15}$ eV)
$\sim E^{-3.0}$ (3×10^{15} - 10^{18} eV)
→Spectral break around 10^{15} eV
(refered to as the 'knee')

※CRs below the 'knee' have been believed to be originated in **Supernovae** in our Galaxy !

※CRs above the 'knee' is still unsettled !

General arguments of the Supernovae Origin of Galactic CRs

(1) Energetics (Hayakawa 1952, etc.)

✧Generating power of CRs

$$P_{CR} \approx 10^{40}\left(\frac{\rho_{CR}}{10^{-12}\,\mathrm{erg\,cm^{-3}}}\right)\left(\frac{V}{10^{67}\,\mathrm{cm^3}}\right)\left(\frac{\tau_{CR}}{10^{7}\,\mathrm{yr}}\right)^{-1}\mathrm{erg\,s^{-1}}$$

✧Power supply by SNe

$$P_{SNR} \approx 10^{42}\left(\frac{E_{CR}}{10^{-51}\,\mathrm{erg}}\right)\left(\frac{\xi_{SN\text{-}rate}}{1/30\,\mathrm{yr^{-1}}}\right)\mathrm{erg\,s^{-1}}$$

→ $P_{CR} \sim 0.01\,P_{SNR}$

(2) CR energy spectrum (Bell 1978, etc.)

✧Observed energy spectrum ∝ $E^{-2.7}$
✧Expected energy spectrum from the diffusive shock acceleration in SNR ∝ $E^{-\frac{r_c+2}{r_c-1}}$

SNRs have the necessary power and the Fermi shock acceleration mechanism provides the observed spectrum.

(3) Elemental and Isotopic Composition

(Yanagita, Hayakawa & Nomoto 1990)

Direct evidence

- Synchrotron radio emission from SNRs →**GeV electron**
- π^0 decay **γ**-rays from several SNRs by EGRET →**GeV proton**
  (Esposito et al. 1996)
- Synchrotron X-rays from several SNRs (SN1006, RXJ1713,...)
  (Koyama et al. 1995; Koyama et al. 1997, etc.) →**TeV electron**

Most direct evidence

- TeV **γ**-rays from three SNR have been detected !!

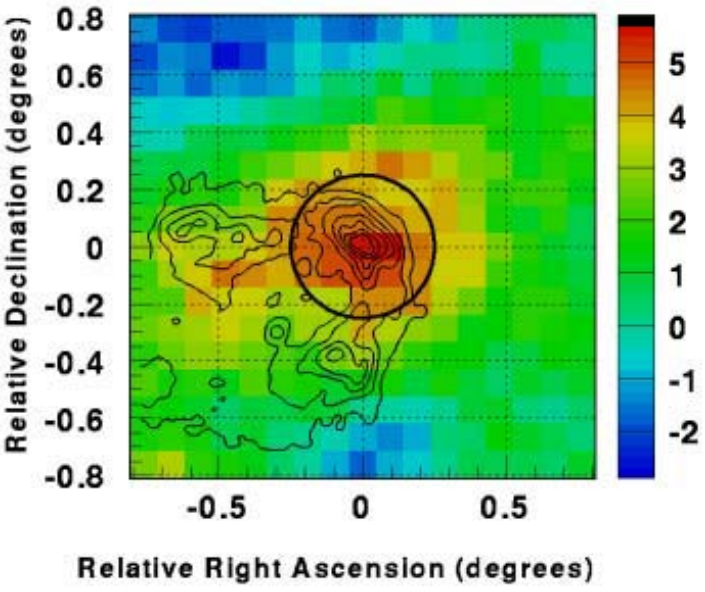
(1) SN1006 (by CANGAROO) :**TeV electron**
(Tanimori et al. 1998)

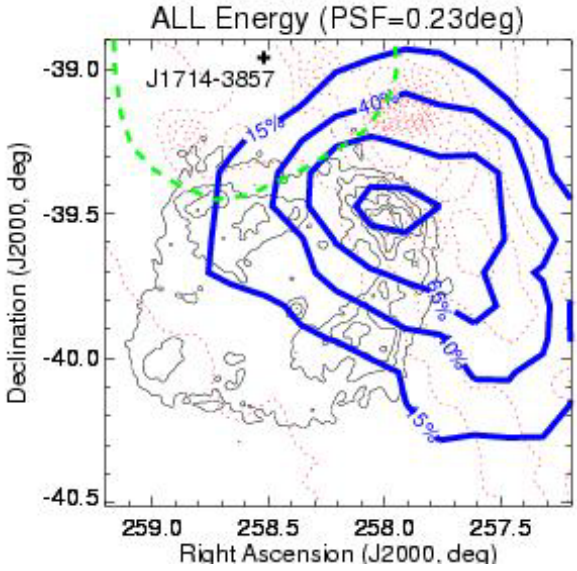
(2) RX J1713.7-3926 (by CANGAROO) :**TeV electron or proton?**
(Muraishi et al. 2000; Enomoto et al. 2002)

(3) Cas A (by HEGRA) :**TeV proton?**

→ Clear evidence for proton acceleration is still lacked.
→ New synchrotron X-ray SNRs (RCW86, RXJ0852).
→ Stereoscopic Observations will start soon
by H.E.S.S., CANGAROO-III, VERITAS, and others

Significance map around RXJ1713 (CANGAROO observation)





3.8m telescope

Muraishi et al., A&A 357, L57 (2000)

10m telescope

Enomoto et al., Nature 416, 823 (2002)

Possible origin of CRs between 10^{15} and 10^{18} eV

(1) Escape from the Galaxy of more energetic particles
(Peters 1960)

(2) Z dependence of the maximum energy in shock acceleration (Drury 1983, Lagage & Cesarsky 1983)

(3) Reacceleration of GCRs (Jokipii & Morfill 1985)

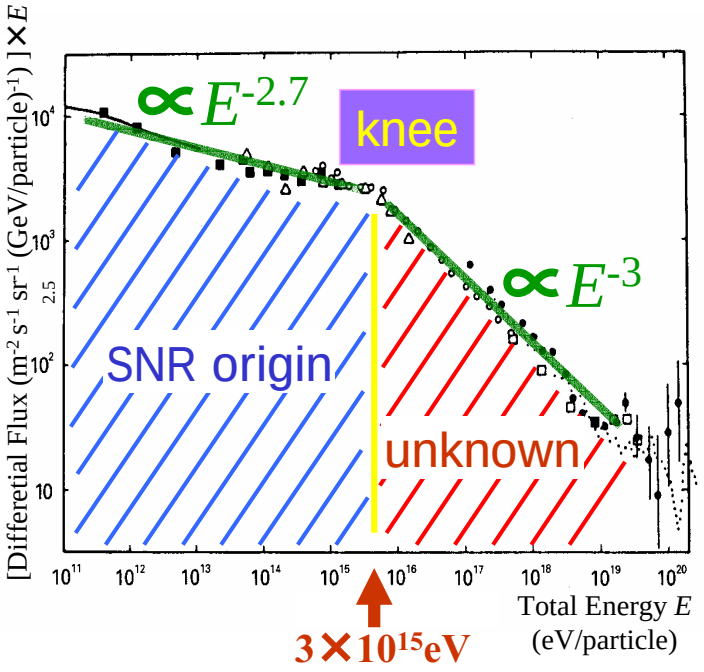
(4) Change of the interaction models in EAS
(Erlykin & Wolfendale 2000)

(5) Necessity of anomalous (extragalactic) CRs ??
(Fichtel & Linsley 1986)

2. Galactic modulation of extragalactic CRs

Motivation

-Possible existence of V.H.E. CRs in IGS -



◯CRs in intra-cluster medium (ICM)

✧EUV and hard X-ray emissions from ICM (Ensslin et al. 1999)

✧Isotropic extragalactic γ-ray background (Loeb & Waxman 2000)

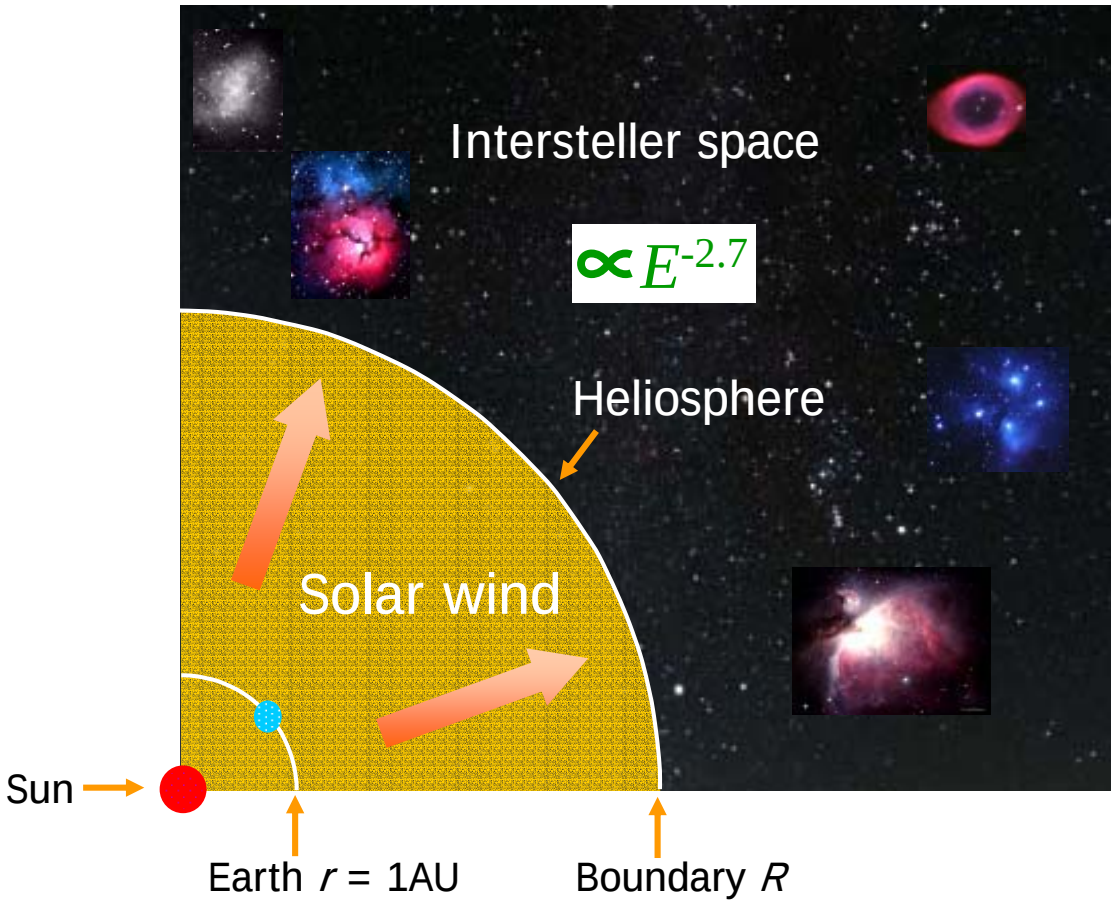
→Existence of L.E. CR electron

If nuclear components with energy up to 10^{18} eV also exist around our Galaxy,

↓ ↓ ↓ ↓ ↓

these components modulated by the galactic wind might be directly observable !!!

Solar modulation



— Fokker-Plank Eq.(spherical symmetry) —

(Parker 1965)

$$\frac{\partial f}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \kappa \frac{\partial f}{\partial r}\right) - V\frac{\partial f}{\partial r} + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 V\right)\frac{p}{3}\frac{\partial f}{\partial p}$$

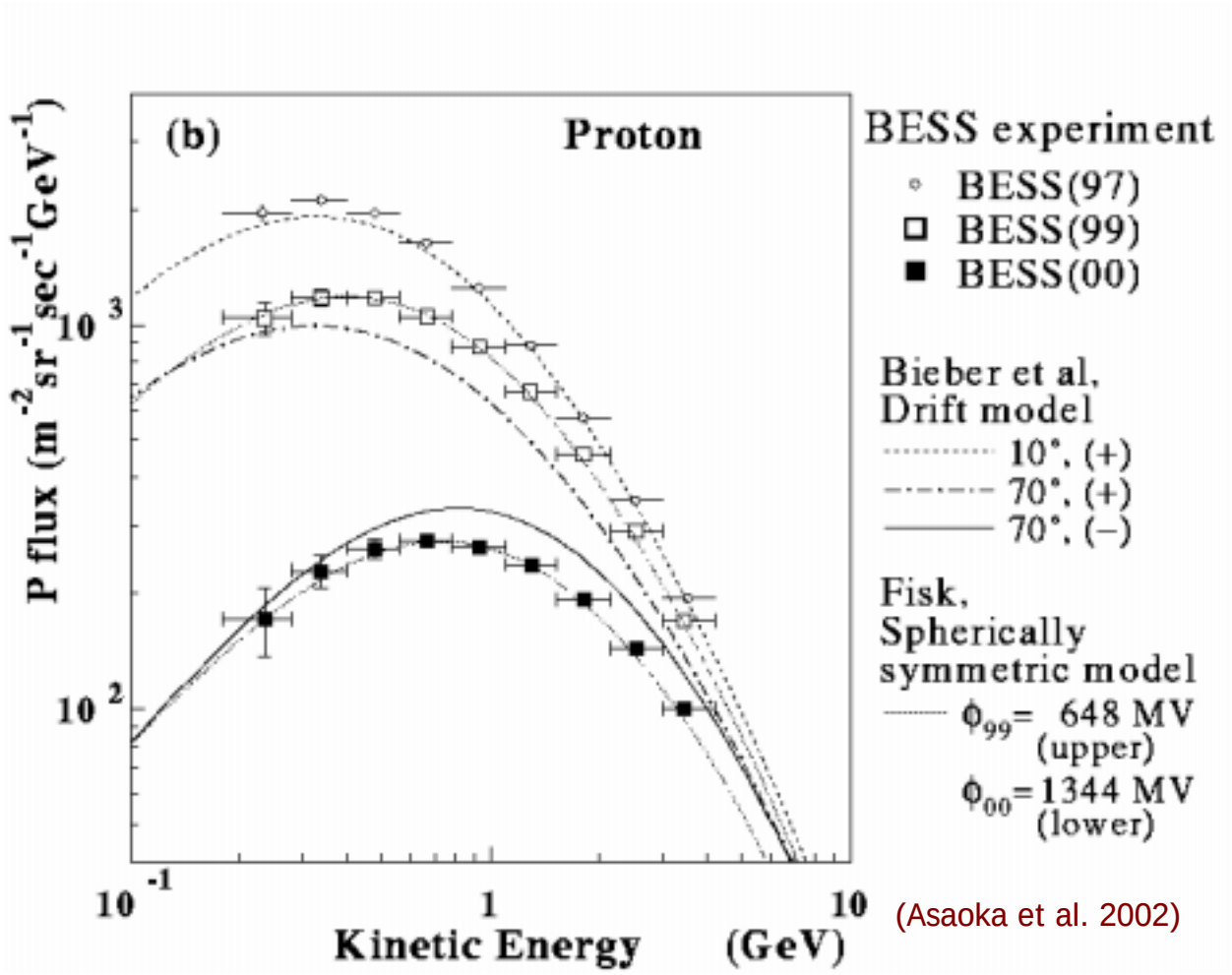
t: time
r: radial distance
f: distribution function
V: speed of the galactic wind
p: particle momentum
κ: diffusion coefficient

— SDEs equivalent to F-P eq. —

(Yamada, Yanagita & Yoshida 1998)

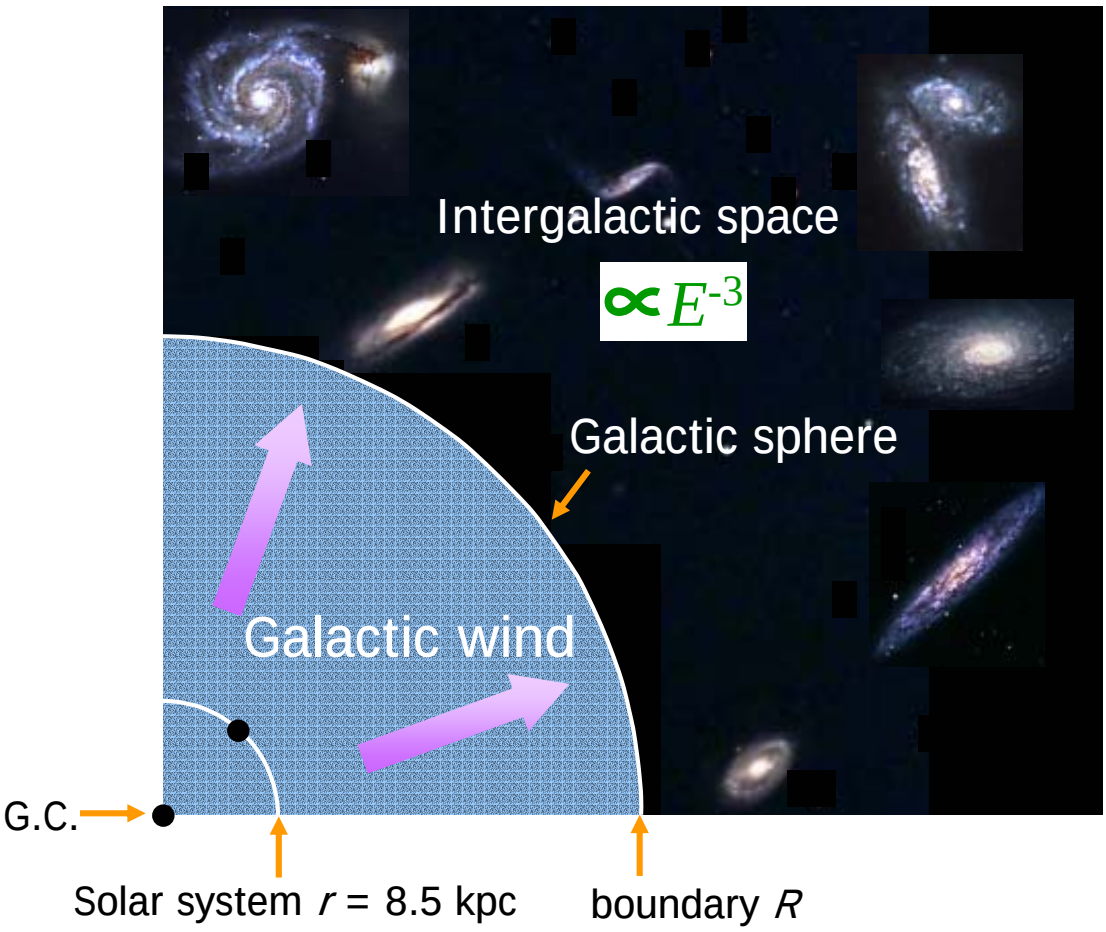
$$\begin{cases} dr = \left(V + \dfrac{2\kappa}{r} + \dfrac{\partial \kappa}{\partial r}\right)dt + \sqrt{2\kappa}\,dw \\ du = -\dfrac{2V}{3r}dt \qquad \left(u \equiv \ln(p/mc)\right) \end{cases}$$

dw: Wiener process given by a Gaussian distribution



(Asaoka et al. 2002)

Schematic view of our model



☆diffusion coefficient

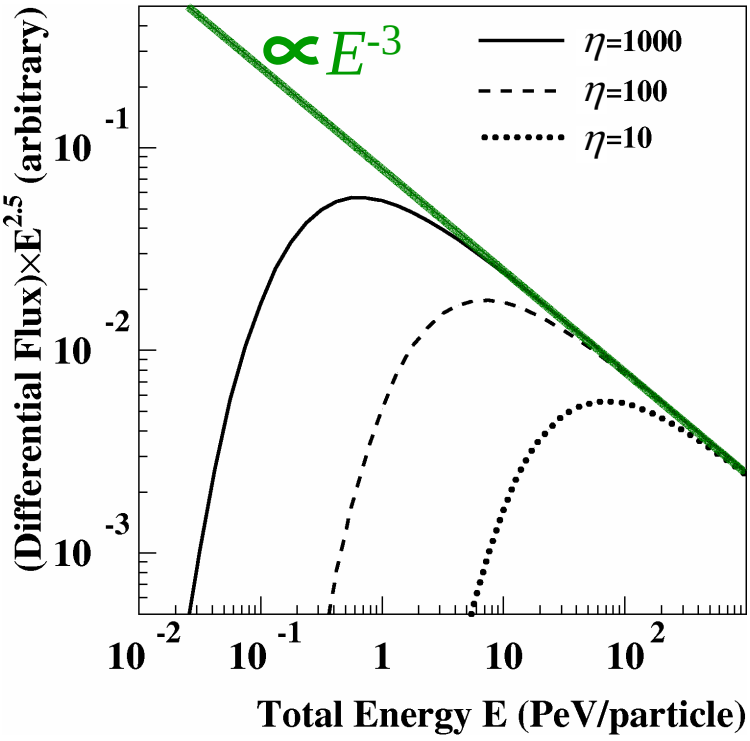
$$\kappa = \eta \kappa_{\mathrm{Bohm}} \approx 3.3\times10^{28}\,\eta Z^{-1}\left(\frac{E}{1\mathrm{PeV}}\right)\left(\frac{B}{1\mu\mathrm{G}}\right)^{-1}\ \mathrm{cm^2 s^{-1}}$$

κ_{Bohm} : Bohm diffusion coefficient

η : the ratio of diffusion mean free path to Larmor radius

B : magnetic field in the Galactic halo

Modulated spectra of protons near at the earth (r=8.5kpc)



- radial distance of the galactic sphere:

$$R = 100\,\mathrm{kpc}$$

(Zirakashvili et al. 1996)

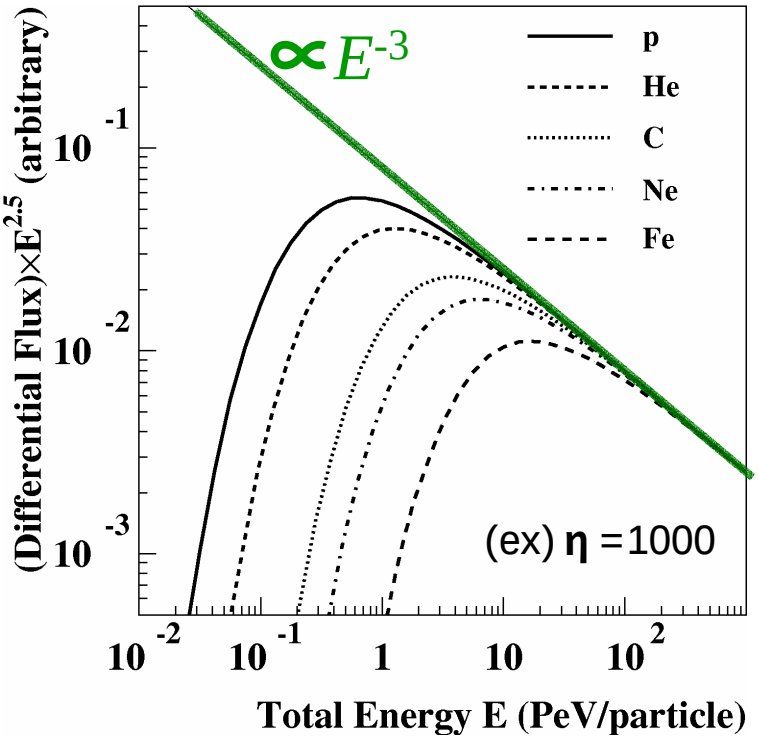
- speed of the galactic wind:

$$V = 300\,\mathrm{km\,s^{-1}}$$

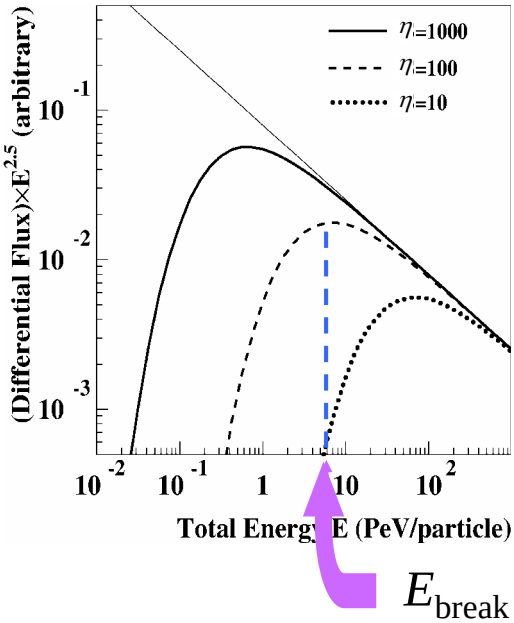
- magnetic field:

$$B = 1\,\mu\mathrm{G}$$

Modulated spectra of various nuclear components



Break point in the modulated spectrum of the hypothetical extragalactic CRs



$$E_{\text{break}}(\eta,B,R,V,Z) \approx 6\times10^{15}\,Z\left(\frac{\eta}{100}\right)^{-1}\left(\frac{B}{1\mu G}\right)\left(\frac{R}{100\text{kpc}}\right)\left(\frac{V}{300\,\text{kms}^{-1}}\right)\text{eV}$$

3. A model of the all-particle spectrum near the knee region

$$F_{\mathrm{Total}}(E) = F_{\mathrm{Modul}}(E) + F_{\mathrm{SNR}}(E)$$

F_{Total} : expected all-particle spectrum

F_{Modul} : modulated spectrum of the hypothetical extragalactic CRs

F_{SNR} : all-particle spectrum of the GCRs from SNRs

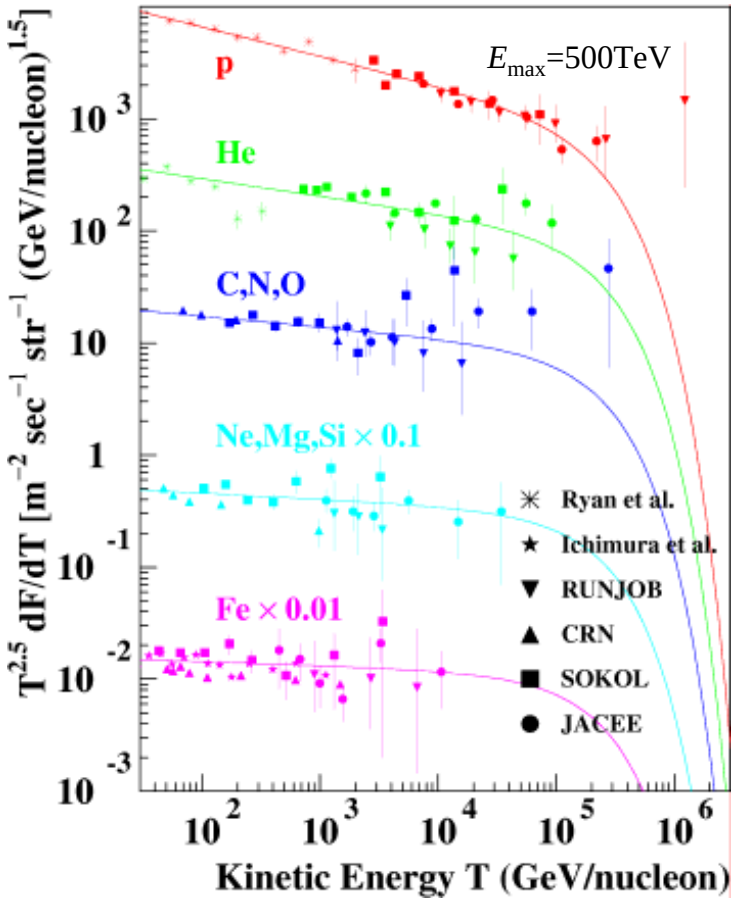
$$F_{\mathrm{SNR}}(E) = \sum_{Z} f_z(E)$$

$$f_z(E) \propto E^{-\alpha} \exp\left(-E/\left(Z E_{\max}\right)\right)$$

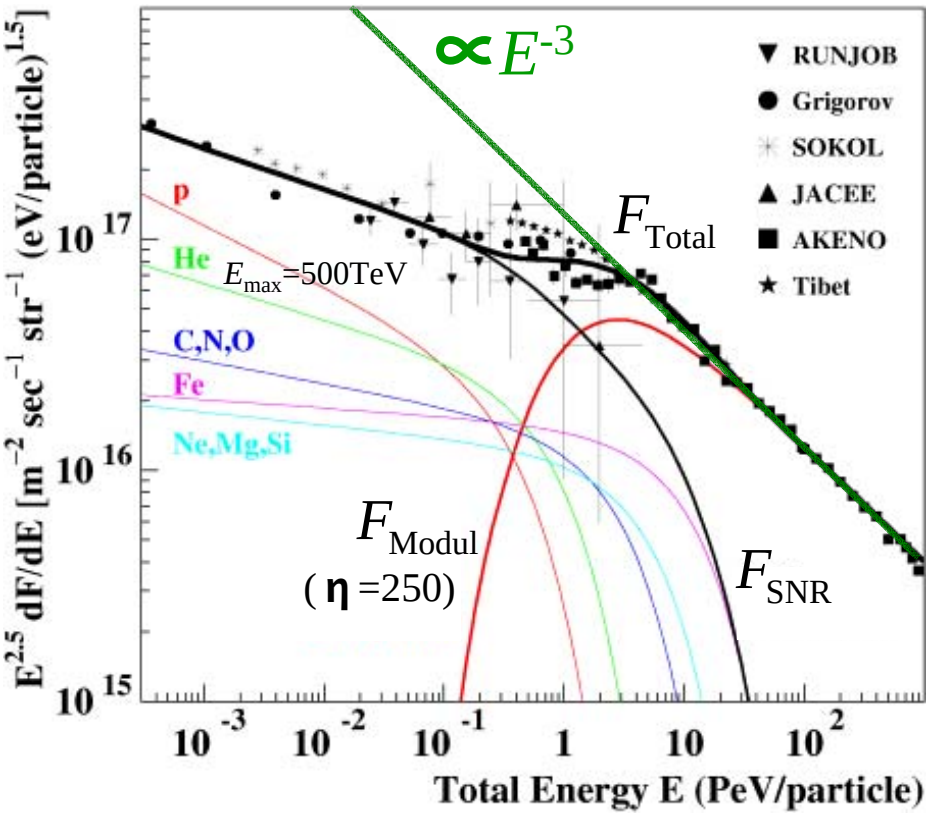
Z : atomic number

$E_{\max}$: maximum energy attained by protons in SNRs

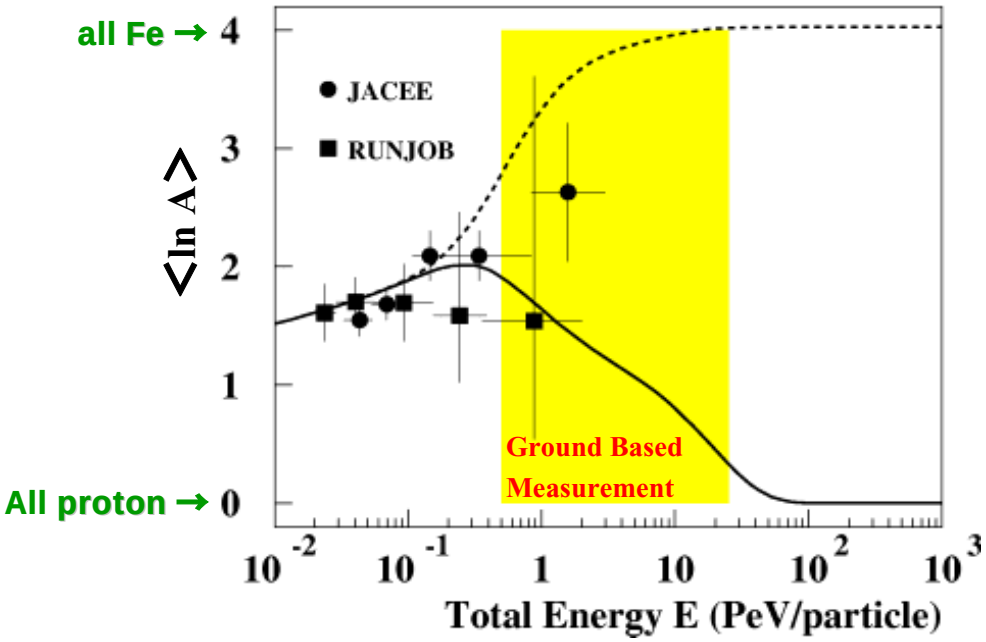
Energy spectra of GCRs and the fitted curves



Comparison of the model spectrum with the observations



Expected mean mass of CRs around the knee region



(····· $F_{SNR} + F_{modul}$(all Fe)
— $F_{SNR} + F_{modul}$(all proton))

4. Discussion

✧ Energetics of the hypothetical CRs

Upper limit

- Energy spectrum of the hypothetical CRs
  at the boundary of the galactic sphere

$$F_{\mathrm{CR}}(E) \approx 4.3\times10^{20}\,E^{-3}\ \mathrm{cm^{-2}s^{-1}sr^{-1}eV^{-1}}$$

$$\longrightarrow\ \rho_{\mathrm{CR}} = \int_{E_{\mathrm{m}}}^{\infty} \frac{4\pi}{v} F_{\mathrm{CR}}(E)\,E\,dE \approx \underline{294\ \mathrm{eV\,cm^{-3}}}$$

- Corresponding density parameter

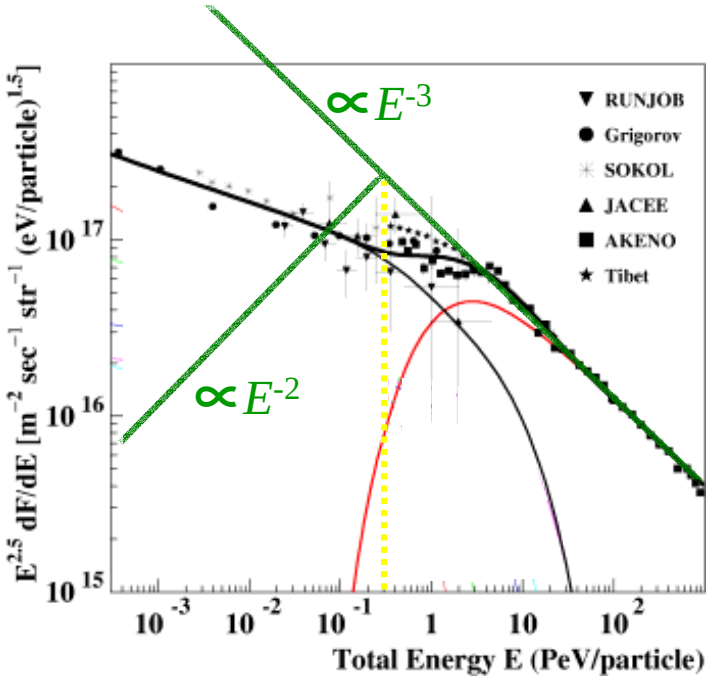
$$\Omega_{\mathrm{CR}}\,h_{70}^{2} \approx \underline{0.057} \quad (\sim\ \Omega_{\mathrm{B}}h_{70}^{2} \approx \underline{0.041}\ )$$

(Burles et al. 2001)

→The spectrum becomes harder in the energy lower than the knee and/or CRs are confined in local regions

→Contribution of CRs to Dark Matter ??

Lower limit



$$\text{If}\quad F_{\mathrm{CR}}(E) \approx \begin{cases} 4.3\times10^{20}\,E^{-3}\ \mathrm{cm^{-2}s^{-1}sr^{-1}eV^{-1}} & (\geq 10^{14.5}\,\mathrm{eV}) \\ 1.3\times10^{6}\,E^{-2}\ \mathrm{cm^{-2}s^{-1}sr^{-1}eV^{-1}} & (\leq 10^{14.5}\,\mathrm{eV}) \end{cases}$$

$$\longrightarrow\ \rho_{\mathrm{CR}} = \int_{E_{\mathrm{m}}}^{\infty} \frac{4\pi}{v} F_{\mathrm{CR}}(E)\,E\,dE \approx \underline{0.0078\ \mathrm{eV\,cm^{-3}}}$$

→much small !

✧ Origin of the hypothetical extraglactic CRs

- Reacceleration of GCRs ? (Jokipii & Morfill 1985)
- Early starburst ? (Voelk & Atoyan 2000)
- Cluster merger ? (Blasi 2001)
- Shock acceleration in large-scale structure formation ? (Miniati et al. 2000)

More energetic !

✧ Search for hypothetical extragalactic CRs

Recently

- Association of galaxy clusters with EGRET unidentified γ -ray sources (Totani & Kitayama 2000, Colofrancesco 2002)

  →**Evidence for the existence of extragalactic GeV CRs ?**

In the future

- PeV γ -ray observation from SMC

  →**search for the extragalactic PeV CRs???**
- CANGAROOIII observation from cluster merger

  →**search for the extragalactic TeV CRs???**

(ex) A violent cluster merger Abell3376

Introduction of Abell 3376

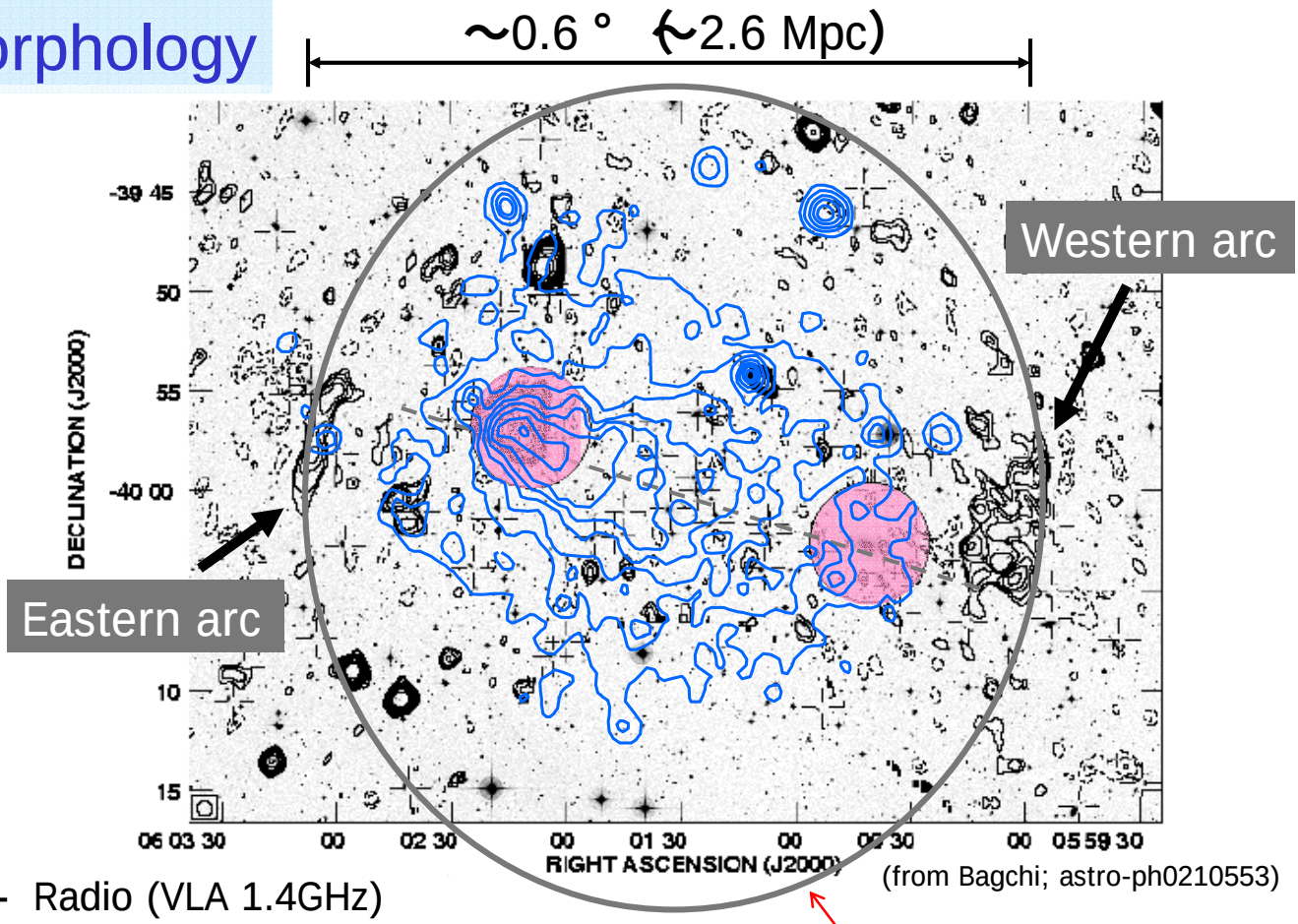
- Cluster of Galaxy
- Evidence for cluster merger (radio, optical, X-ray)
- Z=0.046 (200 Mpc)
- No EGRET un-ID source around Abell3376

- Discovery of giant 'synchrotron radio arcs'
  (Bagchi; astro-ph0210553 , submitted to MNRAS 2002)

→ Existence of Mpc scale shock-waves, which occur during cluster formation

Very interesting !

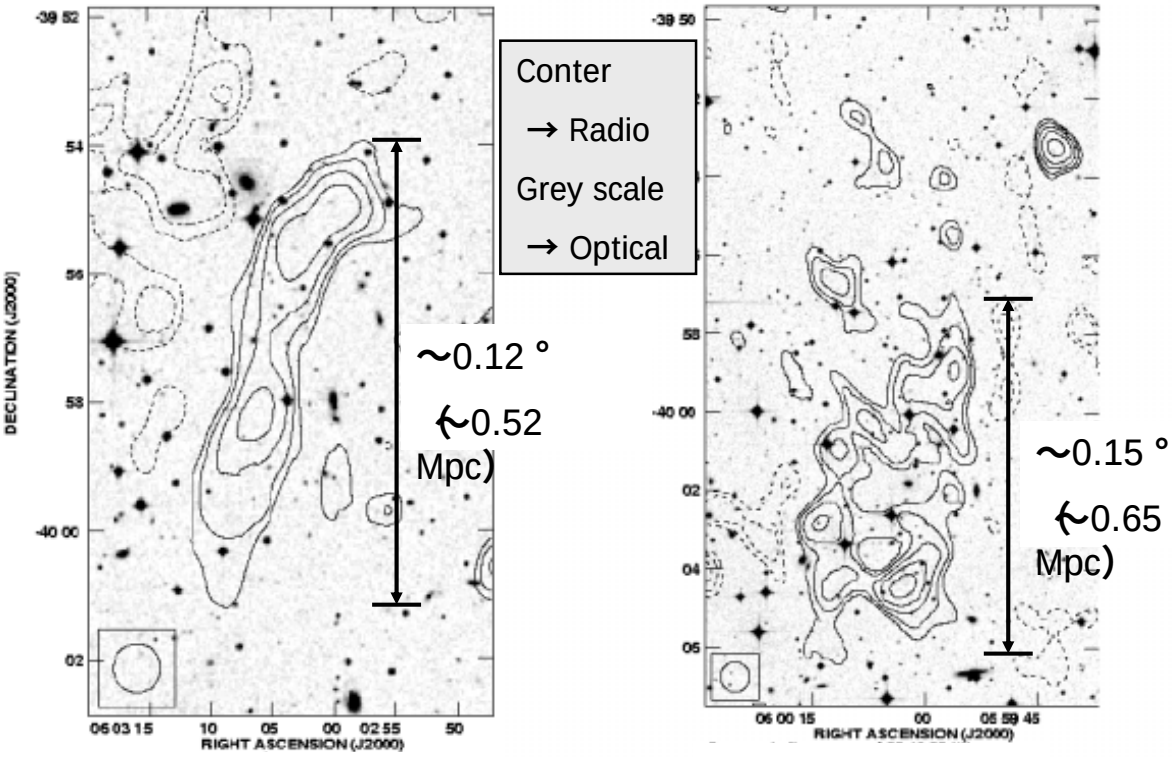
Morphology



(from Bagchi; astro-ph0210553)

Eastern arc

Western arc



※ Optically no counter part exist around the arcs. → Synchrotron radio emission!

→Evidence for Mpc scale shock-waves, which occur during cluster formation

Maximum energy in the arcs

Accerelation time for diffusive shock acceleration (Drury 1983)

$$t_{\mathrm{acc}} = \frac{r_{\mathrm{c}}(r_{\mathrm{c}}-1)}{r_{\mathrm{c}}-1}\frac{Ec}{eB\,\mathrm{v}_{\mathrm{shock}}}$$

E : particle energy $\mathrm{v}_{\mathrm{shock}}$: shock velocity

B : magnetic field strength in the arcs

r_{c} : compression ratio (=4 for strong shock)

By assuming the Bohm diffusion,

※ For proton : if $t_{\mathrm{acc}} \le t_{\mathrm{merger}} \approx 10^{9}\left(\frac{d}{1.8\mathrm{Mpc}}\right)\left(\frac{\mathrm{v}_{\mathrm{shock}}}{2000\ \mathrm{km\ s^{-1}}}\right)^{-1}\mathrm{yr}$ then

$$E_{\mathrm{max}}^{\mathrm{proton}} \le 4.8\times10^{18}\left(\frac{B}{1\mu\mathrm{G}}\right)\left(\frac{\mathrm{v}_{\mathrm{shock}}}{2000\mathrm{km\,s^{-1}}}\right)^{2}\mathrm{eV}$$

→Origin of UHECR ?

※ For electron : if $t_{\mathrm{acc}} \le t_{\mathrm{radiation\,(IC)}} \le t_{\mathrm{merger}}$ then

$$E_{\mathrm{max}}^{\mathrm{electron}} \le 7.4\times10^{13}\left(\frac{B}{1\mu\mathrm{G}}\right)^{0.5}\left(\frac{\mathrm{v}_{\mathrm{shock}}}{2000\mathrm{km\,s^{-1}}}\right)\mathrm{eV}$$

→ Possible to emit subTeV-TeV γ rays by IC !

Detectability of TeV γ-rays from the arcs

～Analogy with the results for SN1006～

Relation between synchrotron and IC losses

$$\frac{F_{\rm syn}}{F_{\rm IC}} = \frac{U_B}{U_{\rm ph}}$$

$F_{\rm syn}$: Synchrotron flux　$U_{\rm ph}$: Photon density (CMB)

$F_{\rm IC}$: IC flux　U_B : Magnetic energy density $(= B^2/8\pi)$

※ Radio flux from the arcs in A3376

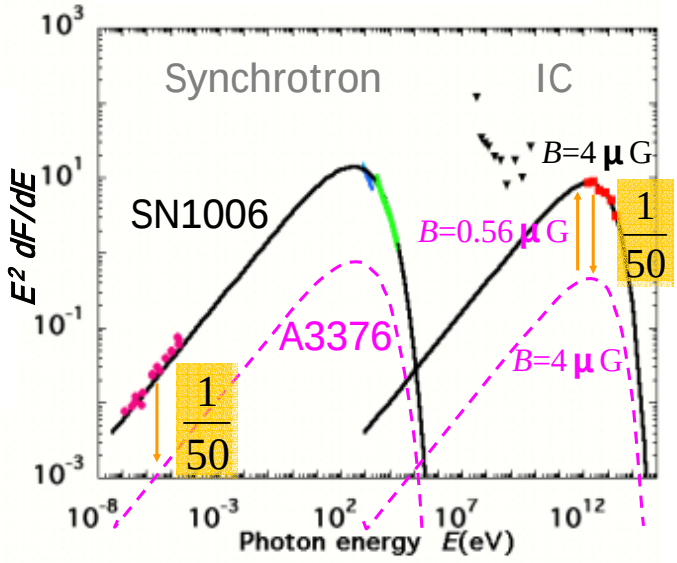
→ 1/50 smaller than that for SN1006 NE-rim

※ To get the same TeV flux as 1006

$$B_{\rm Abell3376} = \sqrt{\frac{1}{50}} B_{\rm SN1006} = 0.56\,\mu{\rm G}$$

$(\because B_{\rm SN1006} = 4\,\mu{\rm G})$

→ It's a reasonable value in the arcs



Energetics

✧Power supply by cluster merger

$$P_{\rm G} \approx \frac{E_{\rm G}}{t_{\rm merger}} = 2\times10^{47} \left(\frac{\rm M}{2\times10^{14}\,{\rm M}_\odot}\right)\left(\frac{d}{1.8{\rm Mpc}}\right)^{-2}\left(\frac{v_{\rm shock}}{2000{\rm km\,s^{-1}}}\right)^{-1} {\rm erg\,s^{-1}}$$

✧Emissivity of TeV γ-rays by IC

If $F(>1{\rm TeV}) \approx 10^{-11}\,{\rm erg\,cm^{-2}s^{-1}}$,

$$\longrightarrow P_{\rm TeV} \approx 4\pi r^2 \times F = 4\times10^{44}\left(\frac{r}{200{\rm Mpc}}\right)^2 {\rm erg\,s^{-1}}$$

$\therefore P_{\rm G} \sim 0.002\,P_{\rm TeV}$

→ Possible to detect TeV γ-rays from Abell3376 !

Motivation of CANGAROO observation from the cluster merger Abell3376

- Evidence for Diffusive shock acceleration in Cosmic shock
- Discovery of the Existence of high energy CRs in the intracluster space
- Search for the origin of HE. or UHECRs in cosmic shock
- New source in TeV γ-ray astronomy

5. Conclusion

- All-particle spectrum of CRs around "the knee" region is reproduced well by a superposition of the two components,

  GCRs of SNR origion and,
  the extragalactic CRs modulated by the galactic wind.

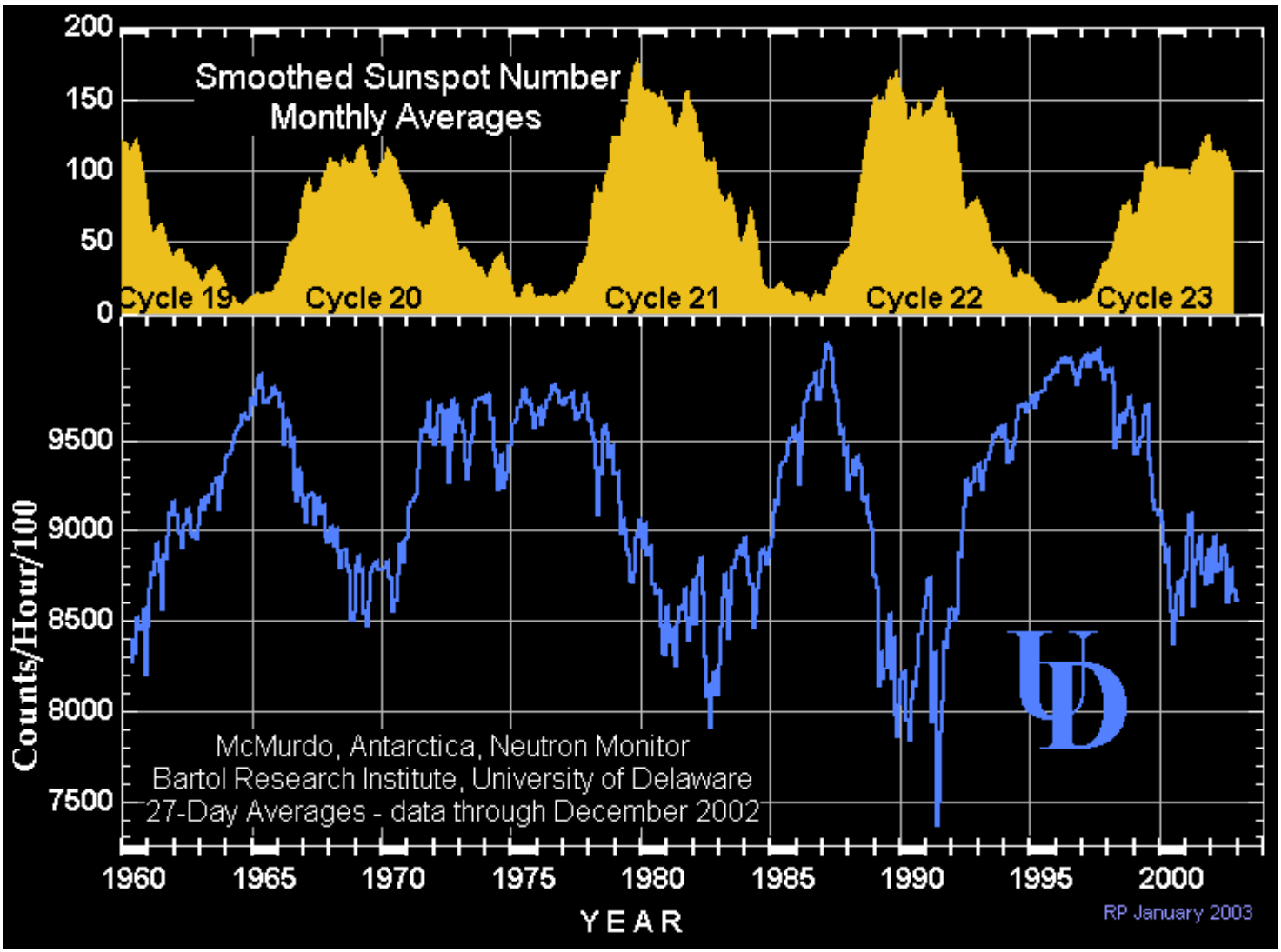
- The position of "the knee" may give us ideas on the structure of the galactic sphere (its size, the speed of the galactic wind, and etc.・・・・etc.) .

- Future observations of CRs above the knee region will tell us the chemical composition of the extragalactic CRs.

- Simulation experiments in more realistic setting for galactic structure are needed.

-The END-

補足


Smoothed Sunspot Number
Monthly Averages
200
150
100
50
0
Cycle 19
Cycle 20
Cycle 21
Cycle 22
Cycle 23
Counts/Hour/100
9500
9000
8500
8000
7500
McMurdo, Antarctica, Neutron Monitor
Bartol Research Institute, University of Delaware
27-Day Averages - data through December 2002
1960
1965
1970
1975
1980
1985
1990
1995
2000
YEAR
RP January 2003

Dependence of modulated spectra on the diffusion coefficient