超高エネルギー宇宙線と高エネルギー宇宙ニュートリノの理解への基礎的考察

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（阪大理理）

2001. 2.14 ICRR

- 超高エネルギー宇宙線
- AGN
- GRB

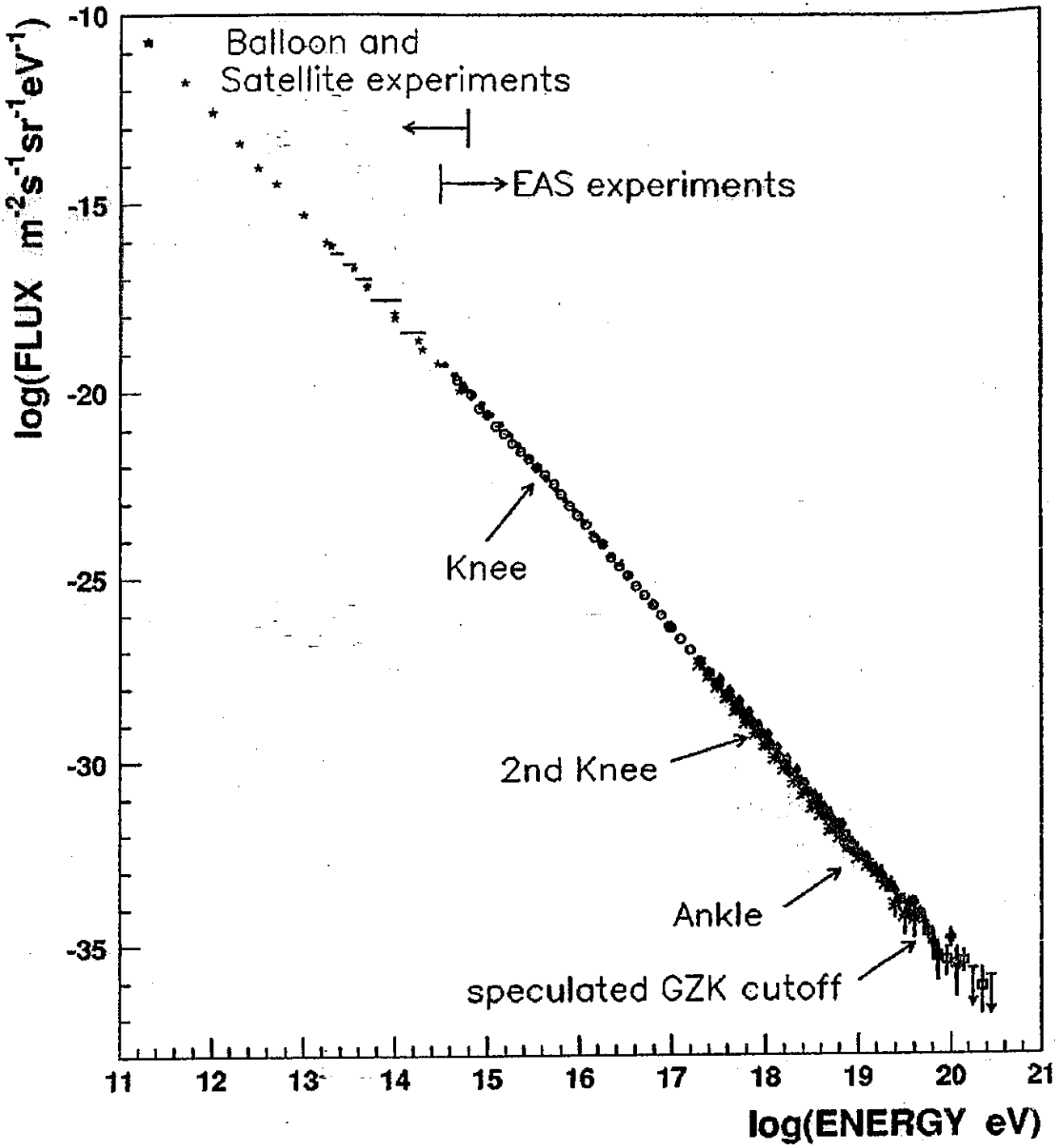


FIG. 1. Observed energy spectrum of primary cosmic rays. The spectrum is expressed by a power law from 10^{11} to 10^{20} eV with a slight change of slopes around $10^{15.5}$ eV (knee), $10^{17.8}$ eV (second knee), and 10^{19} eV (ankle). The integral fluxes above the "knee" and the "ankle" are approximately 1 per m^2 year and 1 per km^2 year. Details of the spectrum and sources of the data above 10^{17} eV are shown in Figs. 23 and 24.

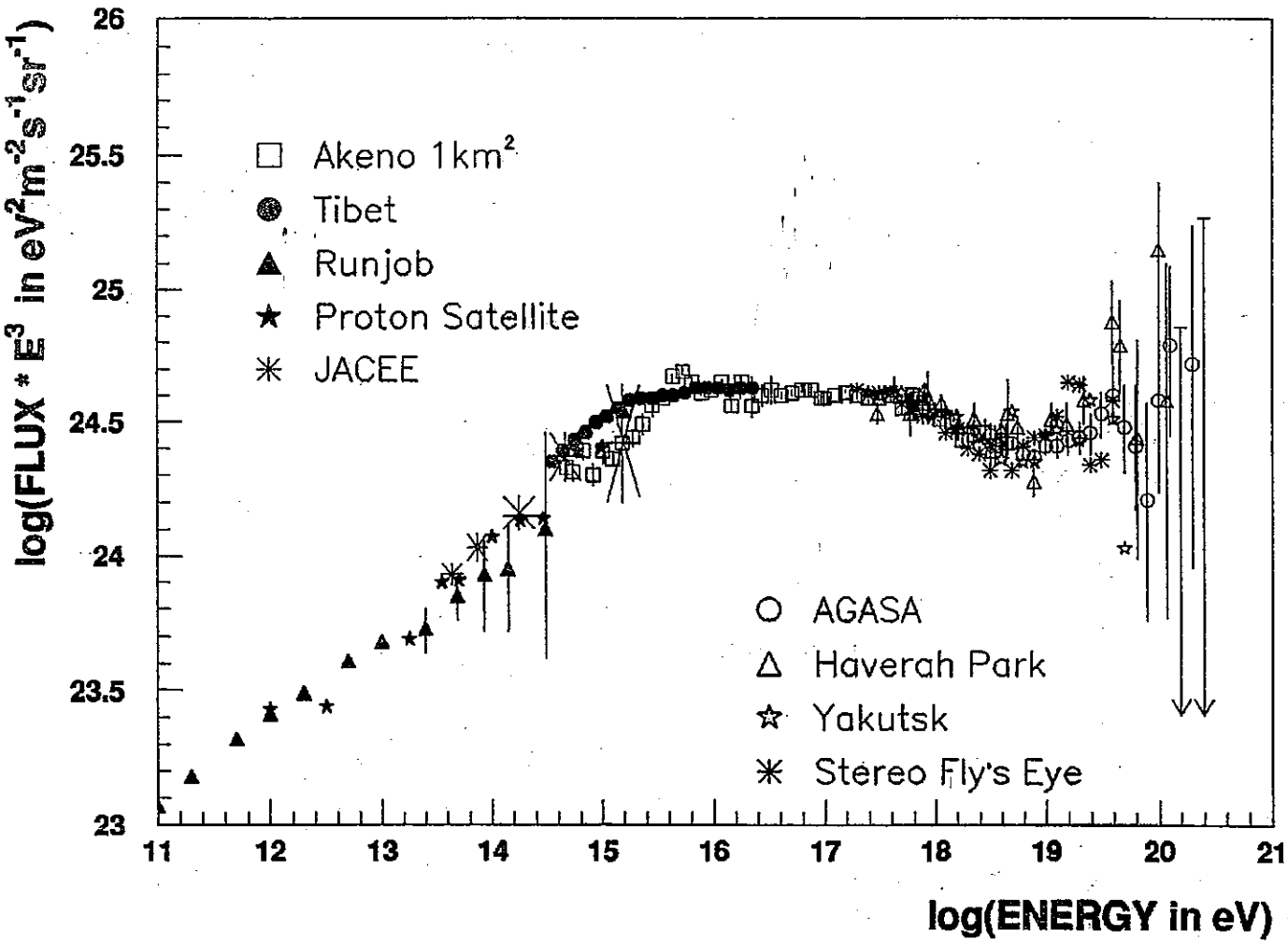


FIG. 24. Differential energy spectrum of primary cosmic rays over a broad energy range. Plots above 10^{18} eV are from four experiments (Haverah Park, Yakutsk, Fly's Eye, AGASA) and open squares are data from the Akeno 1-km^2 array. Other signals below 10^{16} eV are from Tibet at mountain altitude (Amenomori *et al.*, 1996a), direct measurements taken from balloons, JACEE (Asakimori *et al.*, 1993) and RUNJOB (Ichimura *et al.*, 1993), and the Proton Satellite (Grigorov *et al.*, 1971).

1. 序論

エネルギースペクトル

- べき型　$N(E) \propto E^{-p}$
- 折れ曲がり　knee
  ankle

エネルギー密度

~1 eV cm^{-3}　at GeV

~10^{-4} eV cm^{-3}　knee

~10^{-8} eV cm^{-3}　ankle

~10^{-9} eV cm^{-3}　10^{20} eV

組成

p, He, C, O, ---, Fe, ---

spallation　p+(C,O)→Li, Be, B

unstable isotope　^{10}Be→^{10}B

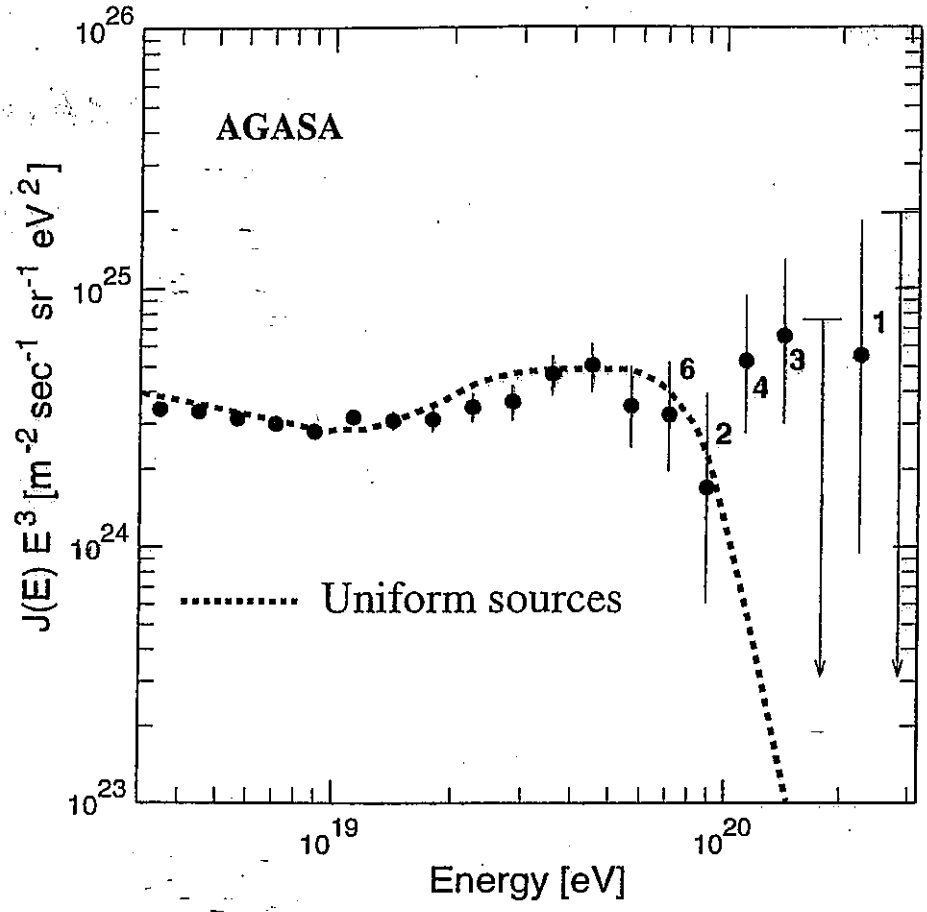
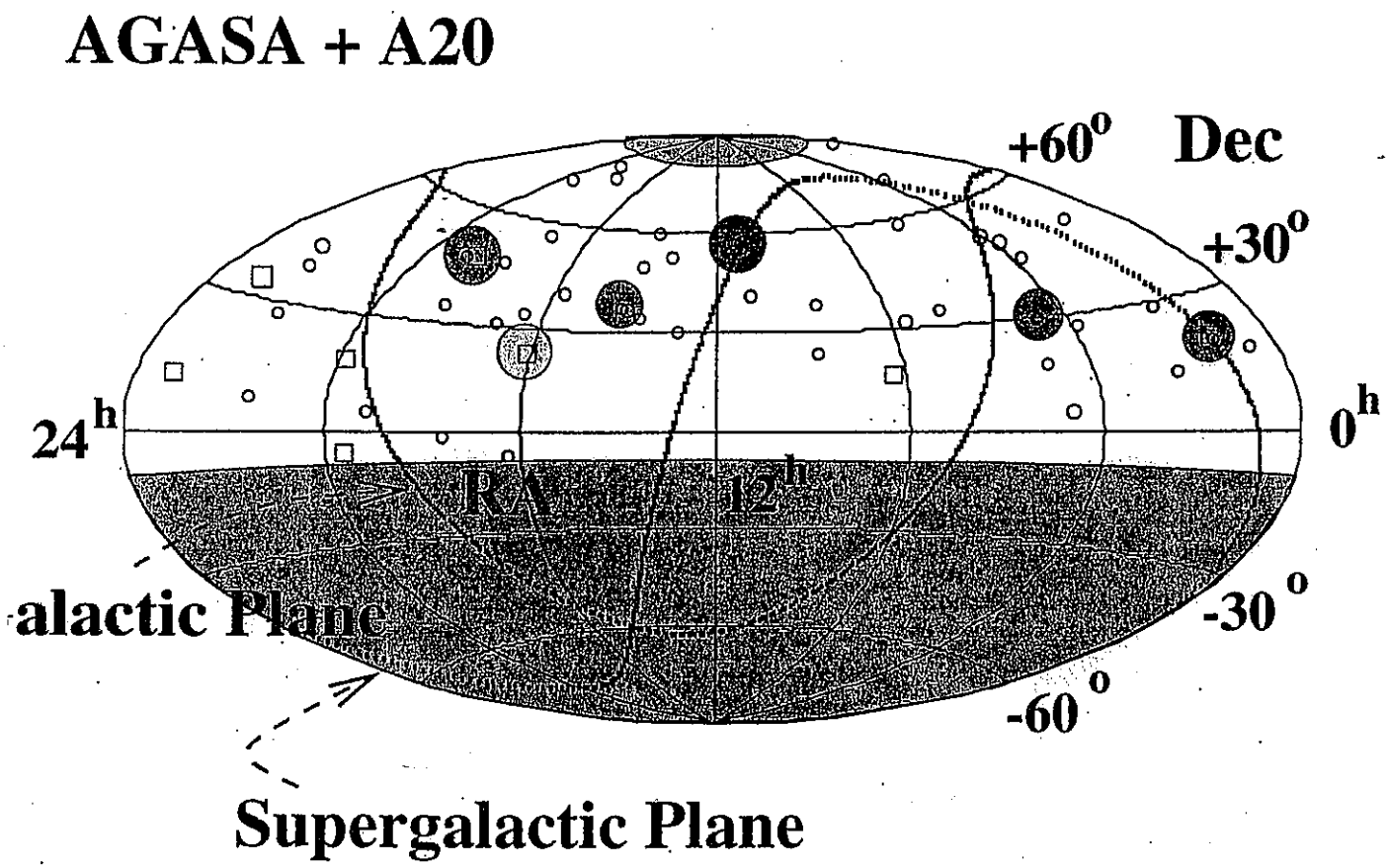
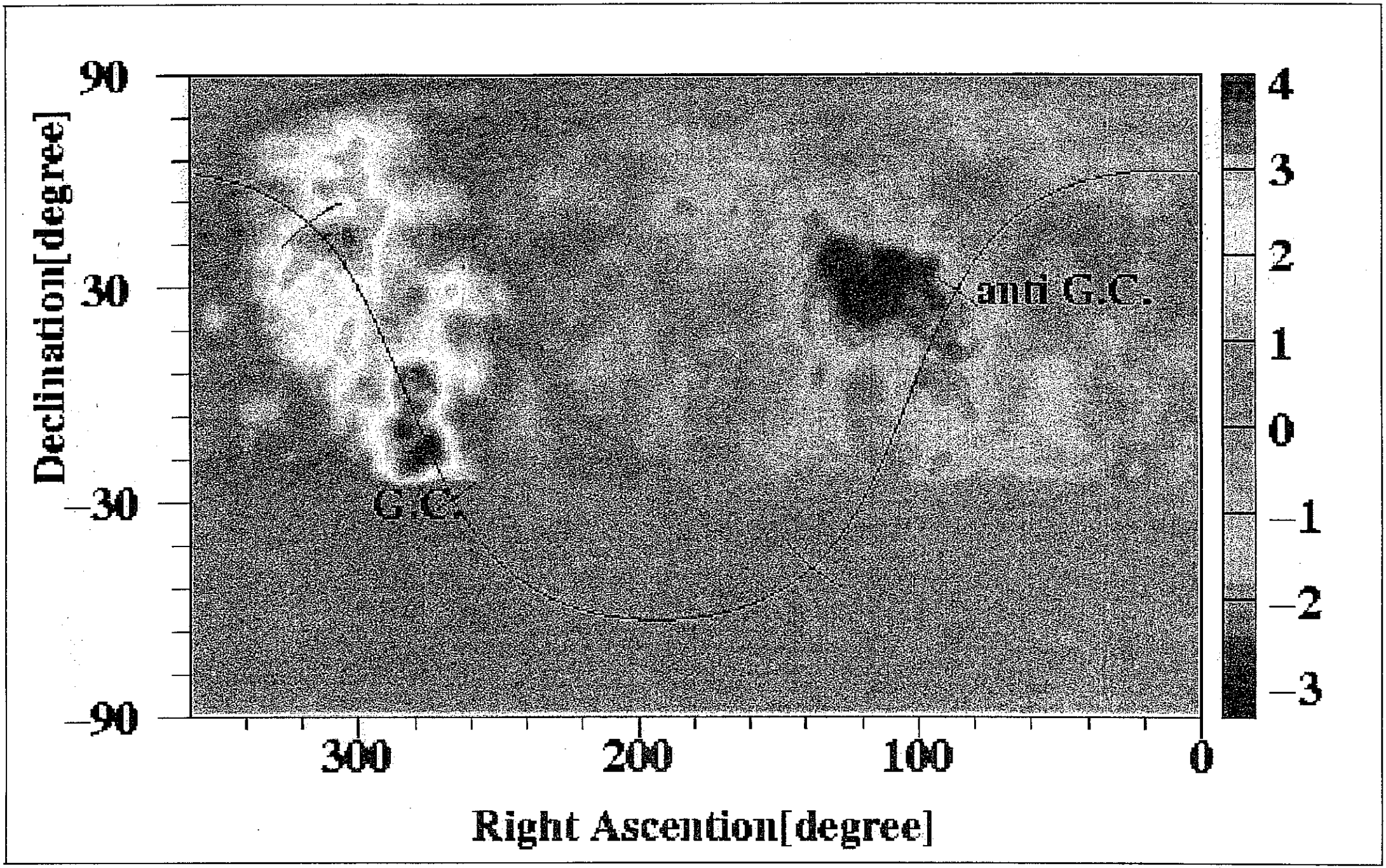
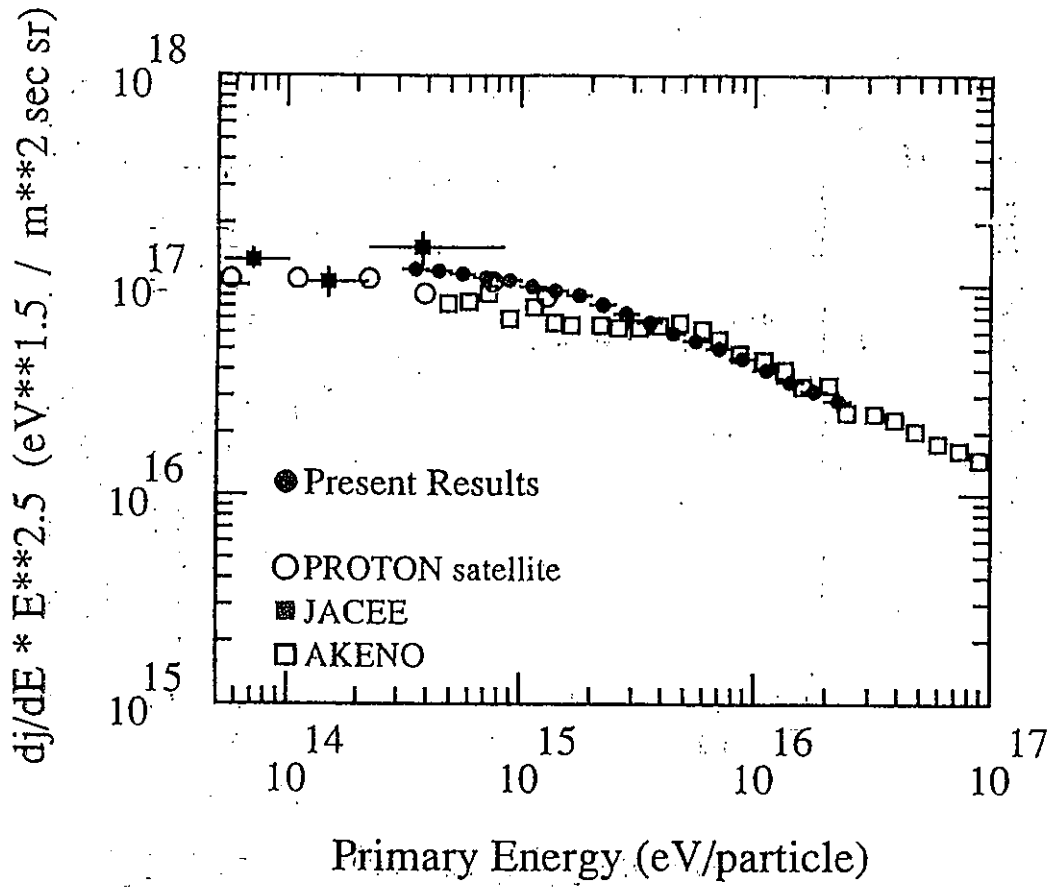


Fig. 1. The energy spectrum observed by AGASA. The vertical axis is multiplied by E^3. Error bars represent the Poisson upper and lower limits at 68% and arrows are 90% C.L. upper limits. Numbers attached to points show the number of events in each energy bin. The dashed curve represents the spectrum expected for extragalactic sources distributed uniformly in the Universe, taking account of the energy determination error. The primary spectrum is assumed $\propto E^{-2.3}$.




90
30
−30
−90
Declination[degree]
G.C.
anti G.C.
4
3
2
1
0
−1
−2
−3
300
200
100
0
Right Ascention[degree]



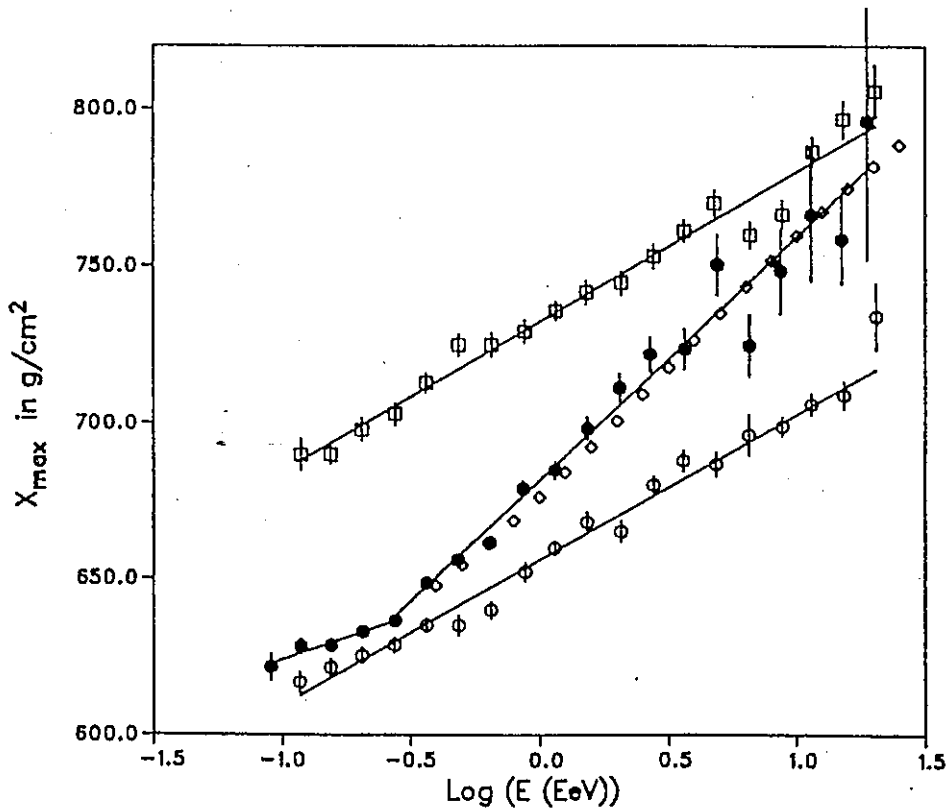
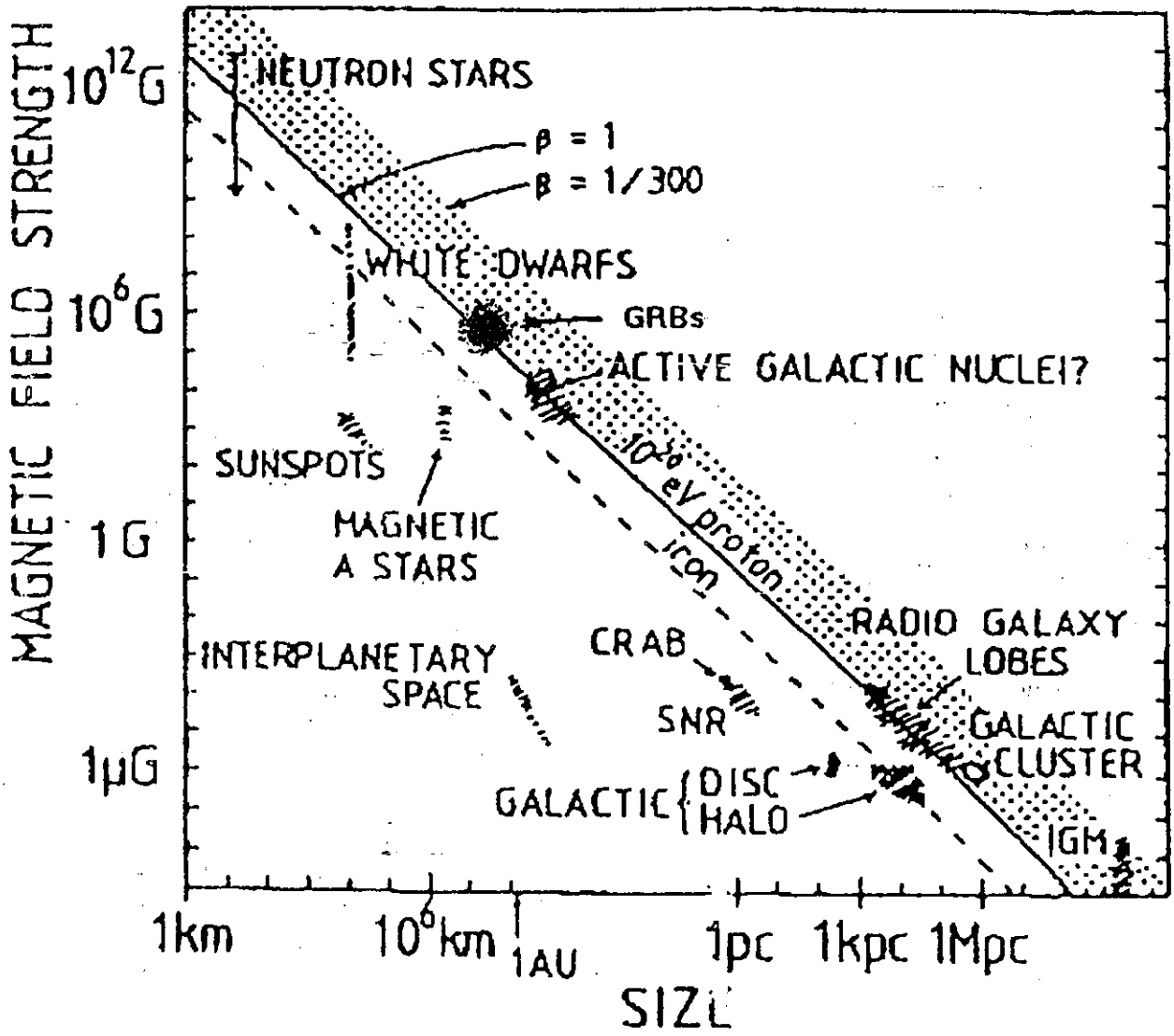


FIG. 3. X_{max} elongation rate are plotted against $\log_{10}E$. Black dots: Fly's Eye data. Open squares: proton X_{max} distribution based on QCD Pomeron model. Open circles: iron X_{max} distribution based on QCD Pomeron model. Diamonds: expected mean X_{max} distribution based on a simple two-component assumption of cosmic rays.


MAGNETIC FIELD STRENGTH
10^{12}G
10^{6}G
1G
1μG
NEUTRON STARS
β = 1
β = 1/300
WHITE DWARFS
GRBs
ACTIVE GALACTIC NUCLEI?
SUNSPOTS
MAGNETIC A STARS
10^{20} eV proton
iron
INTERPLANETARY SPACE
CRAB
SNR
RADIO GALAXY LOBES
GALACTIC CLUSTER
GALACTIC DISC HALO
IGM
1km
10^{6}km
1AU
1pc
1kpc
1Mpc
SIZE

Above the ankle

- **GZK cutoff**

$$p + \gamma \rightarrow p + \pi^0$$
$$n + \pi^+$$
$$\cdots$$

threshold $E_p E_\gamma = \frac{m_p m_\pi}{2}$

$E_\gamma \sim$ meV

$E_p \sim 6 \times 10^{19}$ eV

$$\ell \sim \frac{1}{n_\gamma \sigma} \sim 10\,\mathrm{Mpc}$$

- **原子核の光分解**

$$^4He + \gamma \rightarrow {}^3He + n$$
$$^3H + p$$
$$\cdots$$

(Giant Dipole Resonance)

$E_{th} \sim 20$ MeV

$$\text{meV} \times \frac{10^{20}\,\text{eV}}{4\,\text{GeV}} \sim 25\,\text{MeV}$$

Fe, C, O 等でも同様

CMB, CIB 等がまく

I. Observational requirements

* spectrum — continuation up to $\sim 10^{20.5}$ eV ($d \lesssim 25-100$ Mpc)
* composition — proton dominance ?
* anisotropy — basically isotropic

deflection angle

$$\theta \sim \sqrt{\frac{d}{\lambda}}\,\frac{\lambda}{R_L} \sim \frac{10^{20}\,\mathrm{eV}}{E}\,\frac{B}{10^{-9}\,\mathrm{G}}\,\frac{\sqrt{d\lambda}}{10^{2}\,\mathrm{Mpc}}$$

d : source distance

λ : coherence length of B

If clustering is real, $\theta \ll 1$ and

$n \sim 6 \times 10^{-3}\ \mathrm{Mpc}^{-3}$ (Dubovskij et al. 2000)

$\sim n$ (bright galaxies)

* energetics $u(>10^{19}\text{eV}) \sim 10^{-20}\ \text{erg cm}^{-3}$

$u(>10^{20}\text{eV}) \sim 10^{-21}\ \text{erg cm}^{-3}$

$$n L_{CR} \tau \sim u$$

$E > 10^{19}\text{eV}$, $\tau \sim 10^{17}\text{sec}$

$$\Rightarrow \frac{n}{\text{Mpc}^3} \cdot \frac{L_{CR}}{10^{45}\text{erg/s}} \approx 10^{-8.5}$$

$E > 10^{20}\text{eV}$, $\tau \sim 10^{15.5}\text{sec}$

$$\Rightarrow \frac{n}{\text{Mpc}^3} \frac{L_{CR}}{10^{45}\text{erg/s}} \approx 10^{-8}$$

source spectrum of EHECR must be very hard.

harder than $N(E) \propto E^{-1.5}$

incompatible with observation

E^{-3}

$\Rightarrow$ two-component { galactic at $E < E_*$?
extragalactic at $E > E_*$?

E^{-1}

$E_* \sim 10^{19.5}\text{eV}$

II. Possible acceleration processes

Confinement and Modulation

* $R_L = \frac{E}{qB} < R$

for $E = 10^{20}$ eV , $BR > 0.1$ G·pc

* electro-static potential

$$q\Delta\Phi \approx q\frac{V}{c}BR \approx 10^{21}\,eV\left(\frac{V}{c}\right)\cdot\frac{B}{G}\,\frac{R}{pc}$$

ex.

Earth magnetosphere

$B \sim 1$ G, $R \sim 10^{-10}$ pc $\Rightarrow E_L \sim 10^{11}$ eV

geo-magnetic cutoff

Heliosphere

$B \sim 10^{-5}$ G, $R \sim 10^{-5}$ pc $\Rightarrow E_L \sim 10^{11}$ eV

modulation of galactic cosmic rays

$\frac{V}{c} \sim 10^{-3}$ $\Rightarrow$ $q\Delta\Phi \sim 10^{8}$ eV

acceleration of anomalous cosmic rays

Galaxy

$B \sim 10^{-5}\,G$, $R \sim 10^{3-4}\,pc \Rightarrow E_L \sim 10^{19-20}\,eV$

modulation of extra-galactic cosmic rays ?

$\frac{V}{c} \sim 10^{-3}$ $\Rightarrow q\Delta\Phi \sim 10^{16-17}\,eV$

between the knee and ankle ?

Radio galaxies

hot spots $B \sim 10^{-3}\,G$, $R \sim 10^{3}\,pc \Rightarrow E_L \sim 10^{21}\,eV$

$\frac{V}{c} \sim 10^{-1}$ $q\Delta\Phi \sim 10^{20}\,eV$

cocoons $B \sim 10^{-4}\,G$, $R \sim 10^{5}\,pc \Rightarrow E_L \sim 10^{22}\,eV$

$\frac{V}{c}$?

Clusters of galaxies

$B \sim 10^{-7}\,G$, $R \sim 10^{1}\,pc \Rightarrow E_L \sim 10^{20}\,eV$

$\frac{V}{c} \sim 10^{-2}$ $q\Delta\Phi \sim 10^{18}\,eV$

GRB

$B \sim 10^{2}\,G$, $R \sim 10^{-2}\,pc \Rightarrow E_L \sim 10^{21}\,eV$

$\frac{V}{c} \sim 1$ (relativistic shock) $q\Delta\Phi \sim 10^{21}\,eV$

	加速	光度	等方性
Radio Galaxies	○	○	△

$n_{RG} \sim 10^{-5}\ \mathrm{Mpc}^{-3}$

$L_{CR} \sim 10^{42}\ \mathrm{erg\ s}^{-1}$

* FRII vs FRI

GRB	△	○	△

$\dot{n}_{GRB} \sim 1\ \mathrm{day}^{-1} \cdot \mathrm{Gpc}^{-3} \sim 10^{-14}\ \mathrm{s}^{-1} \cdot \mathrm{Mpc}^{-1}$

$E_{GRB} \sim 10^{51}\ \mathrm{erg}$

$\dot{n}E \sim 10^{37}\ \mathrm{erg\ s}^{-1}\ \mathrm{Mpc}^{-3}$

* 到達時間 $\tau \sim \theta^2 \frac{d}{c} \sim \theta^2 \times 10^8\ \mathrm{yr}\ \frac{d}{30\mathrm{Mpc}}$

Clusters of Galaxies	?	○	△

* 加速時間 ≈ 宇宙時間
  源ごの GZK cutoff

Normal Galaxies	?	○	○

* our Galaxyは何故 $\sim 10^{18\text{-}19}$ eV まで粒子を
  加速できるのか?

(Massive Black Holes Radiatively Quiescent)	?	?	?

Junor, Biretta & Livio

nature letters to nature 401, 891 (1999)

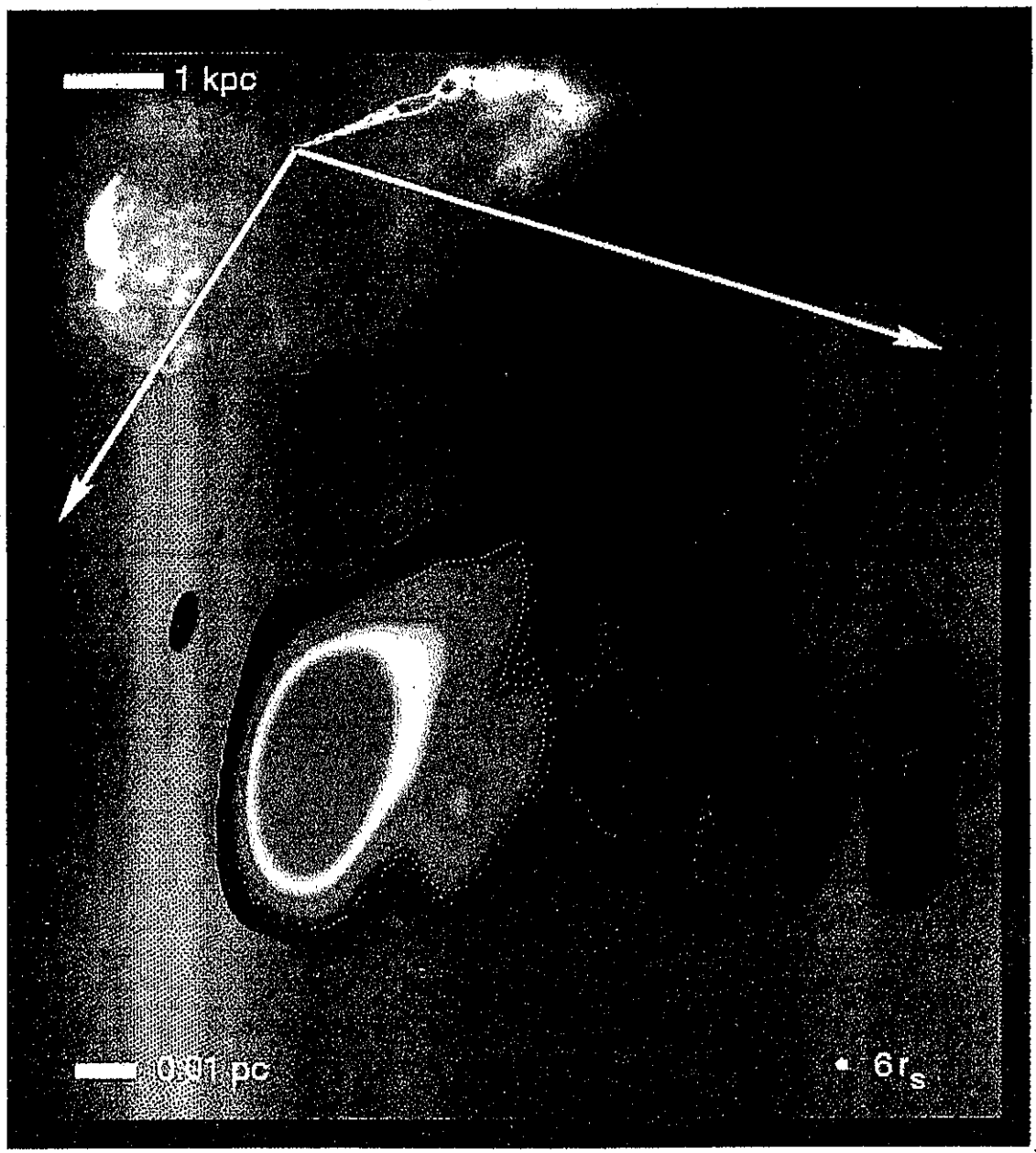


Figure 2 Pseudo-colour rendition of the nucleus of M87 at 43 GHz on 3 March 1999. See Fig. 1 for details. The filled white circle at lower right indicates $6r_S$, which is the diameter of the last stable orbit around a non-rotating black hole. The inset (top left) is a 15-GHz VLA image illustrating the large-scale jet.

← item →

Cyg A

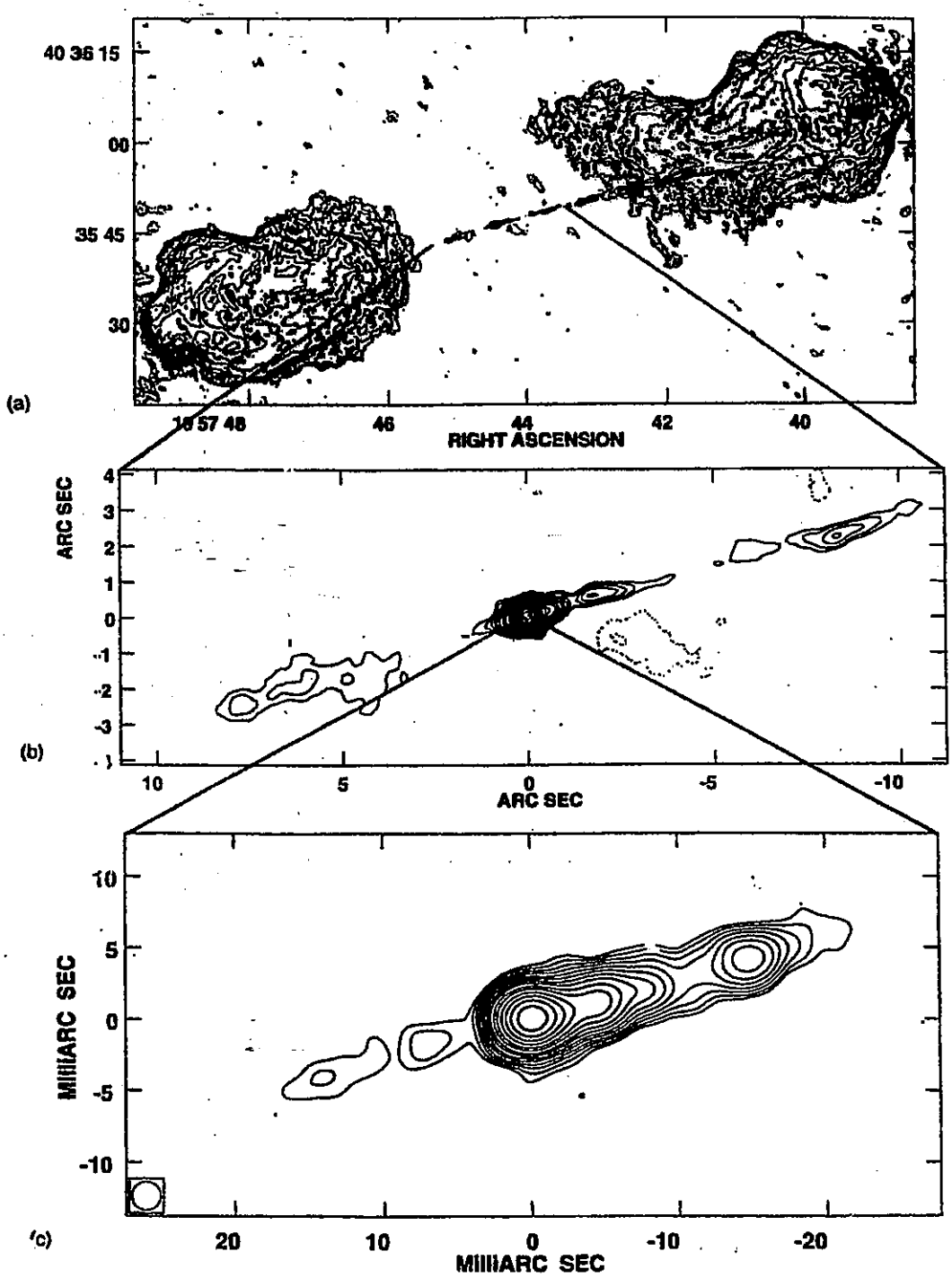
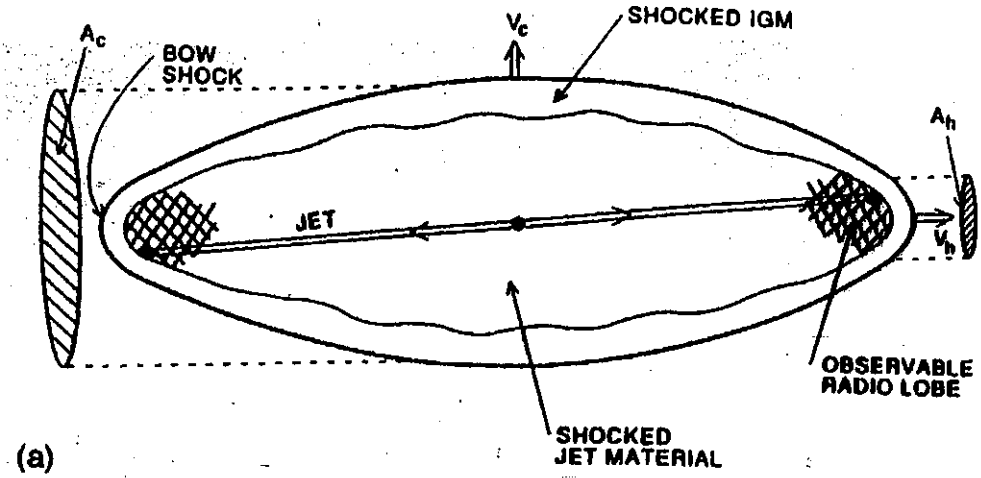


FIG. 4. Contour images of the Cygnus A radio jet on various scales, reproduced from Carilli *et al.* (Ref. 65). The top image shows the kpc-scale radio source at 5 GHz with a resolution of 0.4 arc sec. The contour levels are a geometric progression in $\sqrt{2}$, which implies a factor of 2 rise in surface brightness every two contours. The middle image is of the inner kpc-scale jet of Cygnus A with the same contouring as above. The bottom image shows the pc-scale jet of Cygnus A at 3mas resolution (FWHM).

Begelman & Cioffi Model?



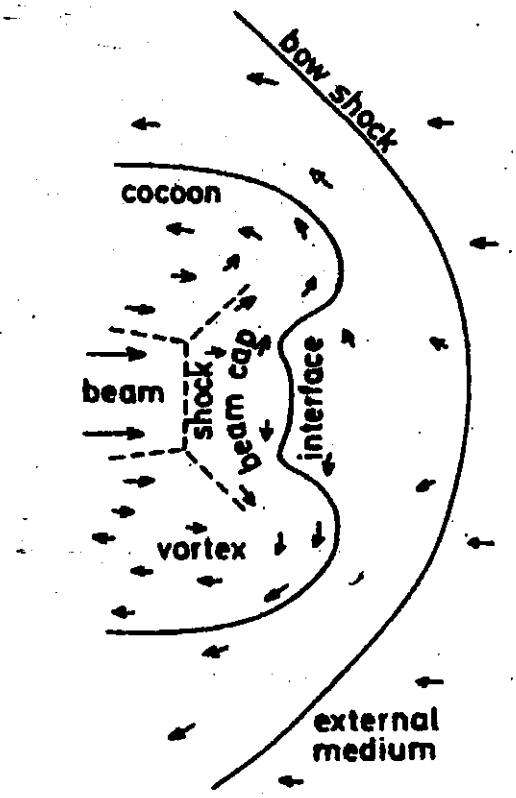


FIG. 3. A schematic representation showing the effect an expanding radio source will have on the external medium. (a) is reproduced from Begelman and Cioffi (Ref. 63), and shows the expected large-scale distribution of shocked ambient gas enveloping the radio lobes. (b) is reproduced from Smith *et al.* (Ref. 64) and shows a detail of the expected double-shock structure at the jet terminus. The interface is the contact discontinuity between shocked jet material and shocked intracluster material (ICM). The beam shock and cap correspond to the radio hotspots, and the cocoon corresponds to the radio lobe.

ERROR: undefined
OFFENDING COMMAND:

STACK:

Chandra X-Ray Observatory Center

Harvard-Smithsonian Center for Astrophysics
60 Garden Street, Cambridge, MA 02138
http://chandra.harvard.edu

Cygnus A: A galaxy, some 700 million light years away, with a central black hole.
Credit: NASA/UMD/A. Wilson et al.

Chandra's image shows a giant football-shaped cavity within X-ray emitting hot gas surrounding the galaxy Cygnus A. The cavity in the hot gas has been created by two powerful jets emitted from the central black hole region. The jets themselves terminate in radio and X-ray emitting "hot spots," some 300,000 light years from the center of the galaxy. Scientists believe that fast atomic particles and magnetic fields from the jets spill out into the region, providing pressure that continuously inflates the cavity.

Scale: Image is 3.3 x 2 arcmin.

Chandra X-ray Observatory ACIS image

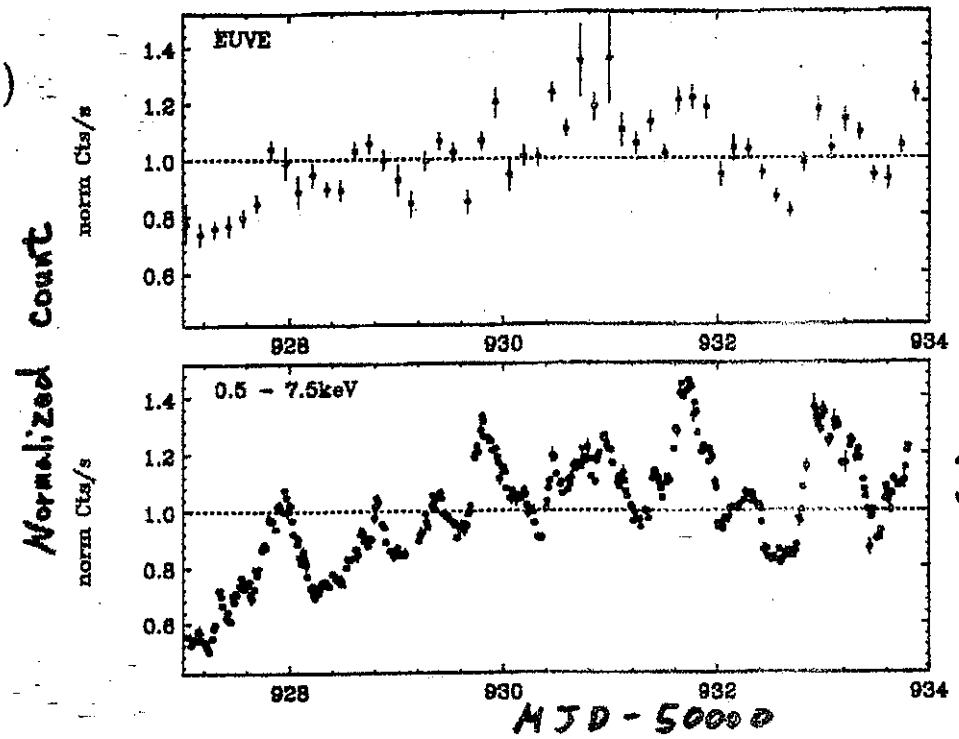
Two big campaings of TeV blazars

- 7 days continuous observation of Mrk 421

(PI: T.Takahashi)

1998 Apr

EUVE
ASCA

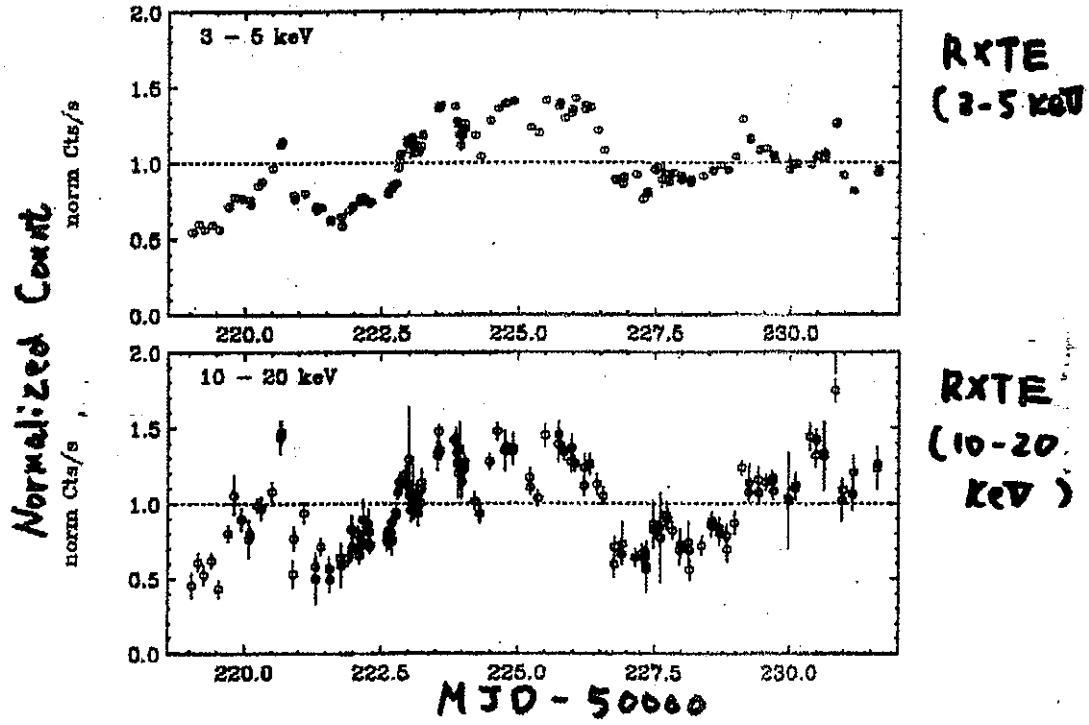


- 12 days continuous observation of PKS2155-304

(PI: C.M.Urry)

1996 May

RXTE

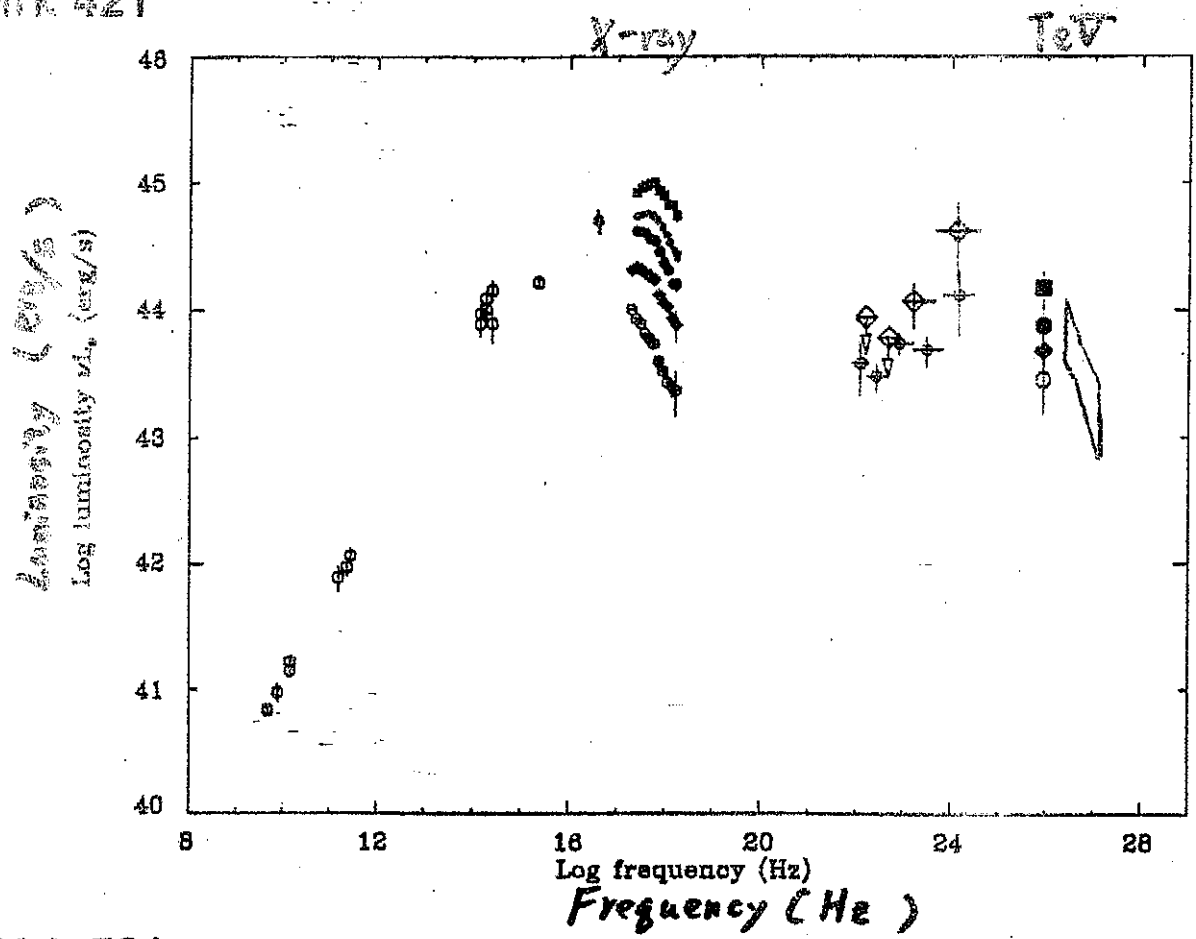


(1) Light curves include ~ 10 day-by-day flares
(2) Amplitude of variation becomes larger at higher energy band
(3) Many of flare events have symmetric time profiles

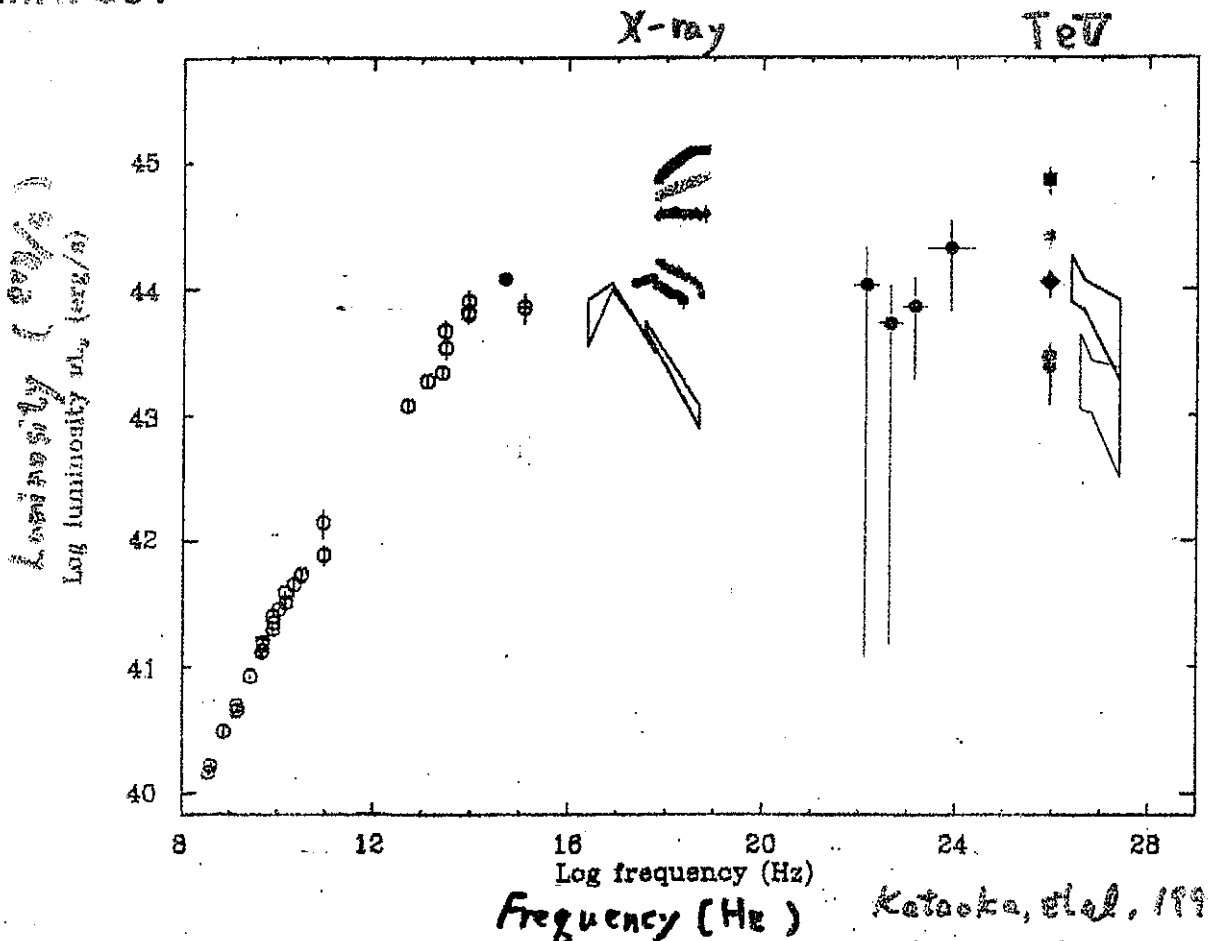
片岡

Evolution of the Multifrequency Spectra

(1) Mrk 421



(2) Mrk 501



Katoaka, et al., 1999
ApJ 514

Relativistic Beaming

- superluminal expansion ($v_{app} \sim 10c$)
- rapid time variability ($\Delta t \sim 10^3$–10^5 s)
- high polarization
- featureless continuum dominated

synchrotron radiation

relativistical boosted emission from jets

dominates over thermal components

- GeV–TeV γ-rays

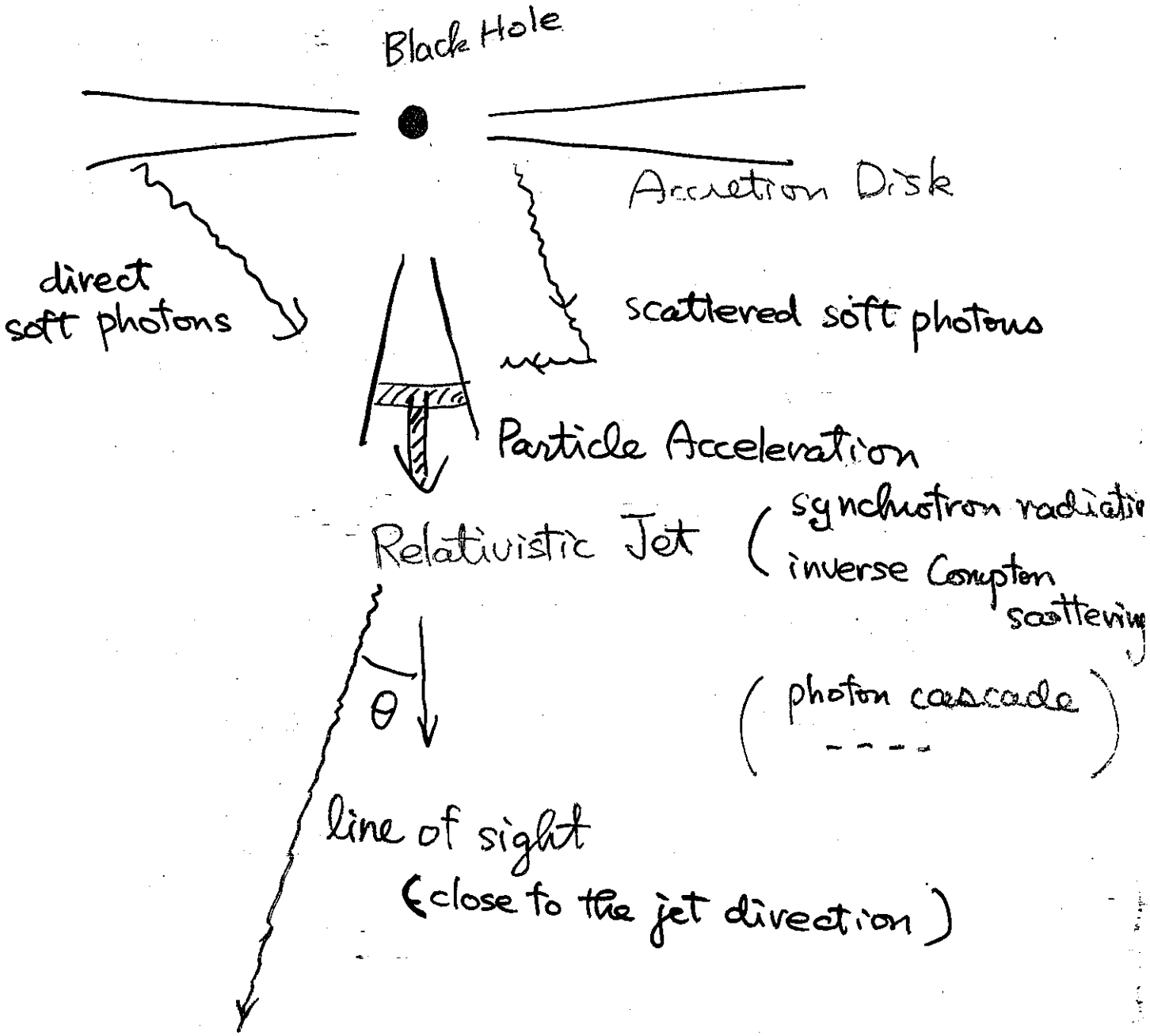
inverse Compton scattering

no evidence for internal γ–γ absorption

also means relativistic beaming

$$\Gamma \sim 10 \quad , \quad R \sim 10^{-2}\,pc \sim 10^2 r_g$$

◎ Model Ingredients



beaming factor

$$\delta \equiv \frac{1}{\Gamma(1-\beta\cos\theta)}$$

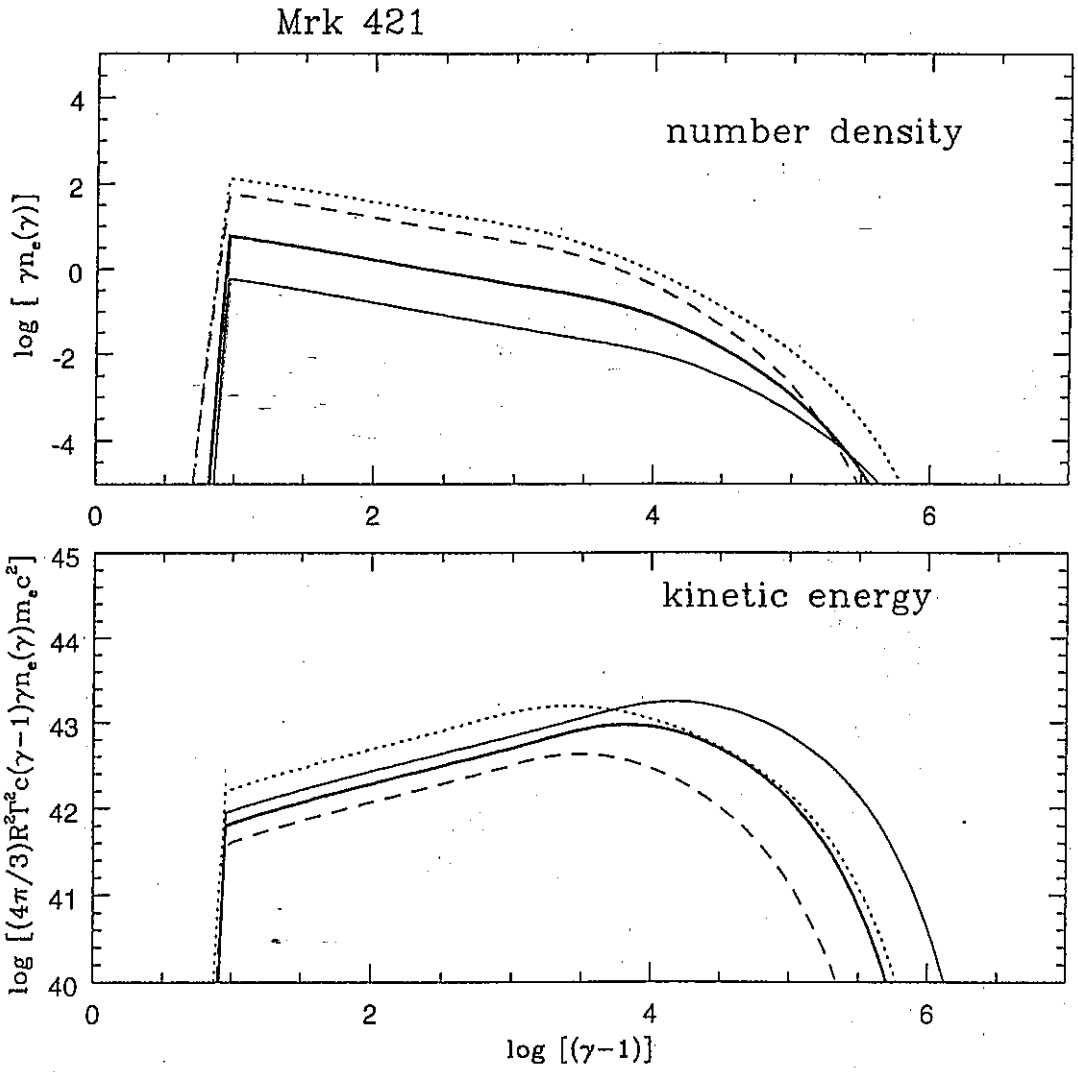


Fig. 5.— Electron energy spectrum and kinetic power of Mrk 421 corresponding to Figure 4.

$\frac{u_e}{u_B} = 11$

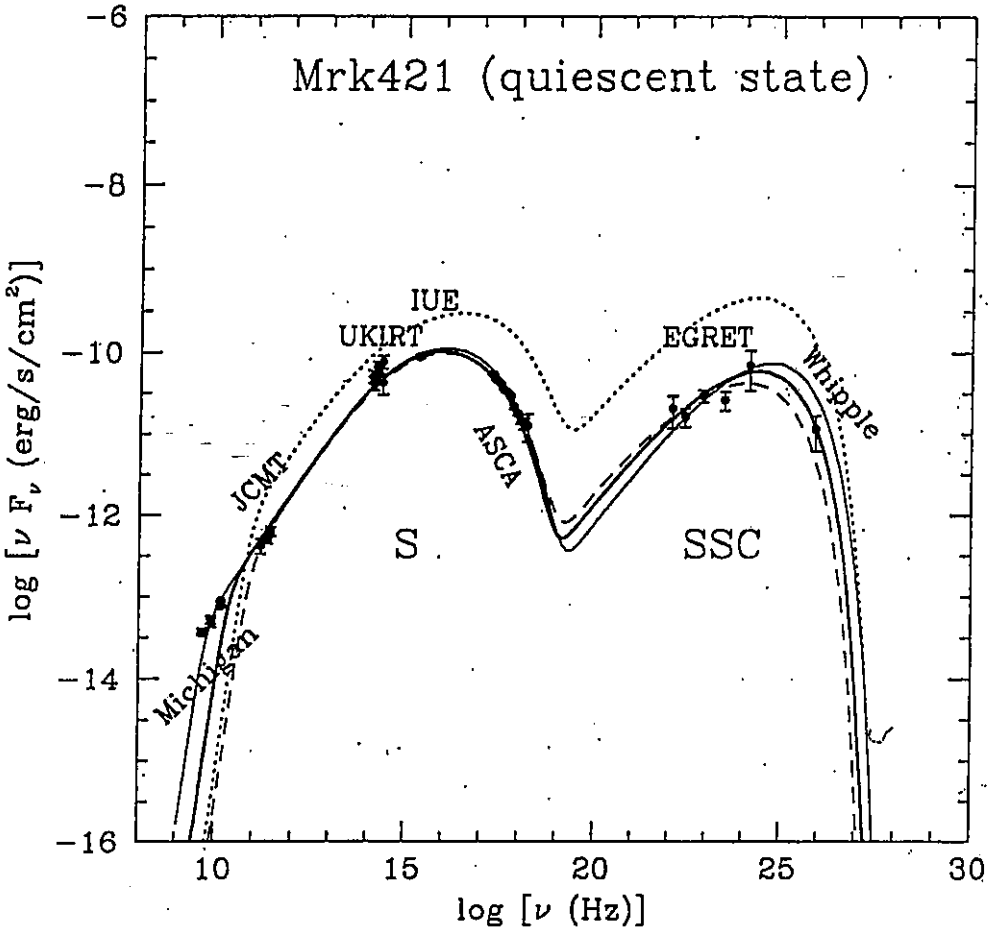


Fig. 4.— One-zone SSC model spectra for the steady state emission of Mrk 421. Thick solid line shows the best fit spectrum, where adopted parameters are $\delta = 12$, $R = 2.8 \times 10^{16}$ cm, $B = 0.12$ G, $\gamma_{\rm max} = 1.5 \times 10^5$, $q_{\rm e} = 4.1 \times 10^{-6}$ cm^{-3} s^{-1}, $s = 1.6$, and $u_{\rm e}/u_{\rm B} = 11$. Dotted line shows the spectrum obtained using the analytic estimates for Mrk 421. Thin solid and dashed lines show the spectra of low and high injection models, respectively, to indicate the uncertainty range of the spectral fitting.

* γ_{max} cooling limited

$$t_{acc} = \frac{3}{V_1 - V_2}\left(\frac{K_1}{V_1} + \frac{K_2}{V_2}\right)$$ for standard non-relativistic shocks

various complications for relativistic shocks
obliqueness, non-diffusive return for upstream
Böhm diffusion for downstream

guess $V_2 = \frac{V_1}{3}$, $K_2 = \frac{r_g c}{3}$, $K_1 = 0$

$$t_{acc} = \frac{9}{2}\frac{r_g}{c} \qquad r_g = \frac{\gamma m_e c^2}{eB}$$

$t_{acc} = t_{cool}$

$$\gamma_{max} = 1.1 \times 10^7 \left(\frac{B}{U_{sqft}}\right)^{1/2} \Rightarrow$$ correct tendency of higher γ_{max} for less luminous sources

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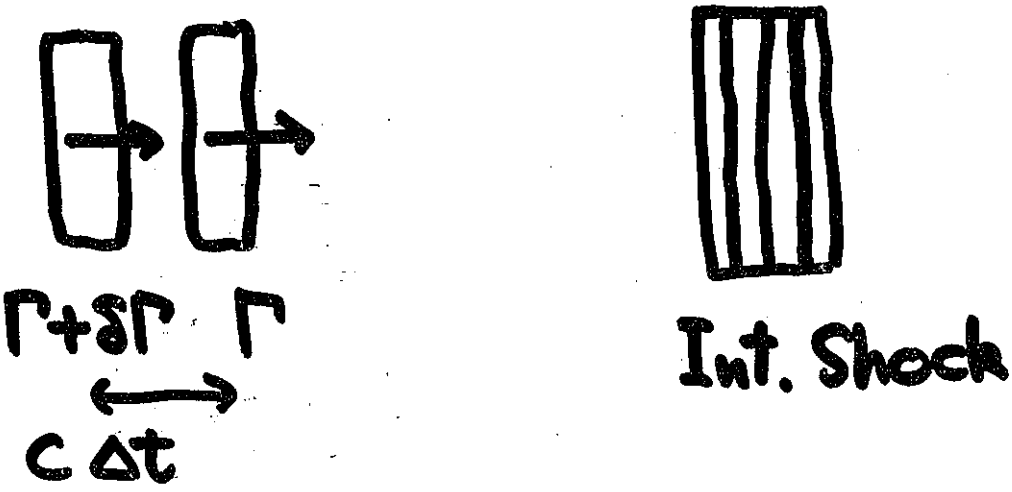
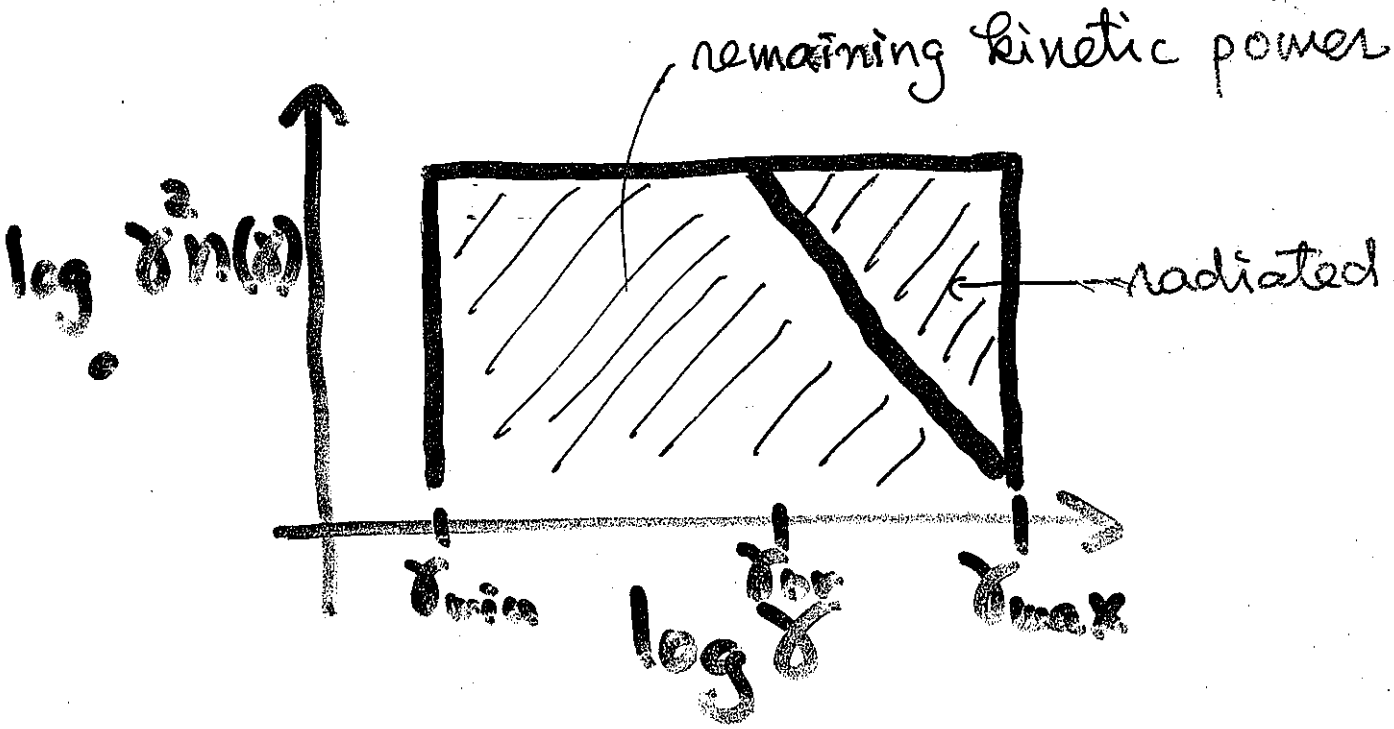
If γ_{max} is escape limited

$$\gamma_{max} mc^2 = \frac{2}{27} eBR$$ (in the shock rest frame)



$$d_{ss} \approx c\Delta t\, \Gamma^2 \frac{\Gamma}{3\Gamma}$$

- shock acceleration
- injection to cooling region



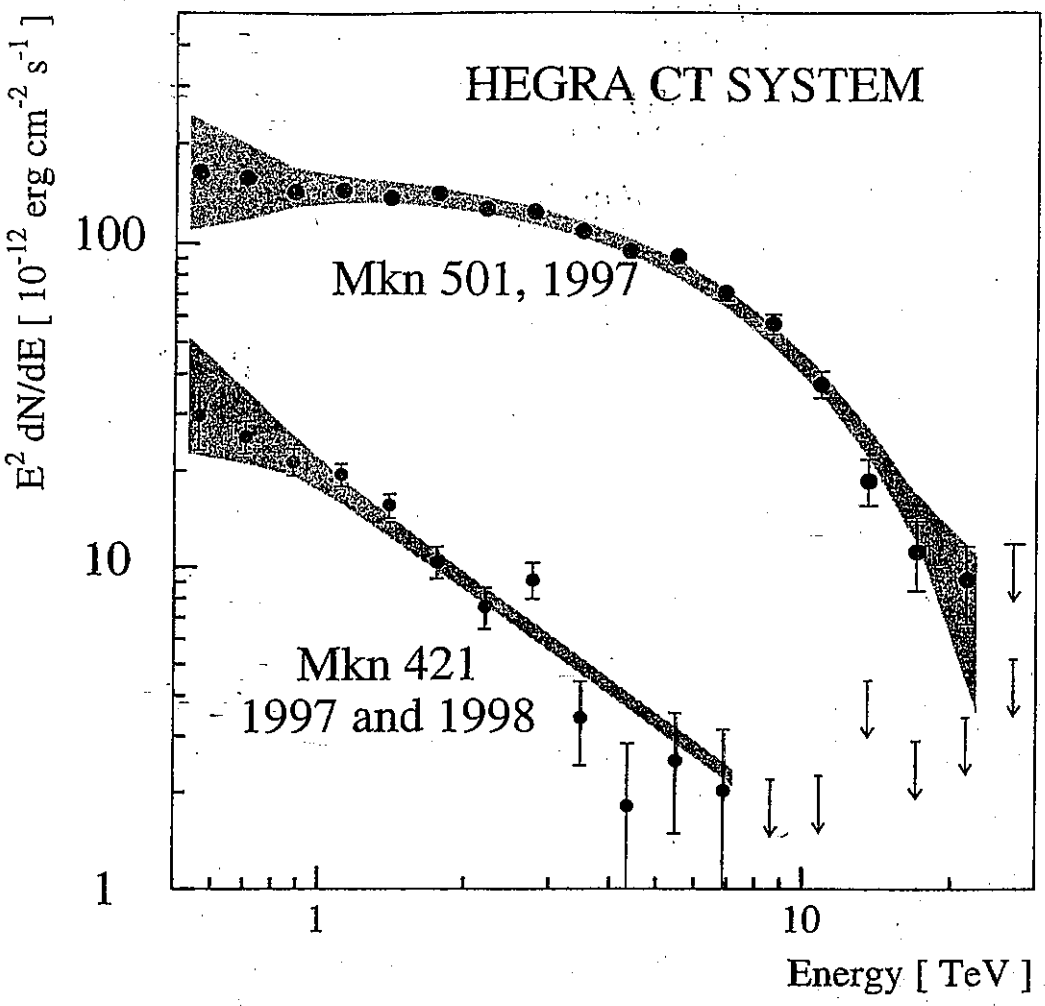


Fig. 9. The 1997 Mkn 501 and the 1997–1998 Mkn 421 spectral energy distributions. The hatched areas give the estimated systematic errors, except the 15% uncertainty in the absolute energy scale. Upper limits are at 2σ confidence level.

Blazar で陽子加速は起こっているか？

◉電子（陽電子）モデルの根拠

* X線と TeV との同時変動

* TeV スペクトルは Mrk421 と Mrk 501 とで異なる.

* jet の組成
  - $e^{\pm}$ 説
    - 電波の偏光の性質
    - $L_{\rm Bin}$ の評価
    - bulk acceleration の容易さ
  - e/p 説

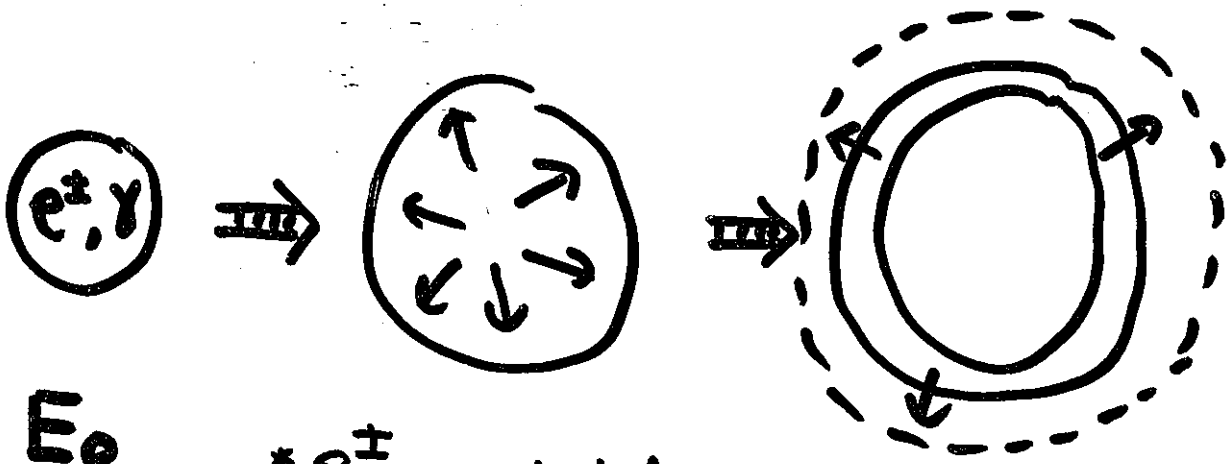
◎陽子モデル

*電子モデルでは TeV-γ-ray spectrum の再現に問題
p-γ initiated shower, proton synchrotron を考える.

* 陽子モデルでは大きな磁場で fit する
  - 磁場加速派の逃げ道
  - 必要なパワーは何桁も増大

* 陽子モデルはニュートリノ放射を伴なう
  - ν-astronomy の target 探し
  - 中性子の役割などの新奇さ

Cosmological Fireball



E_0

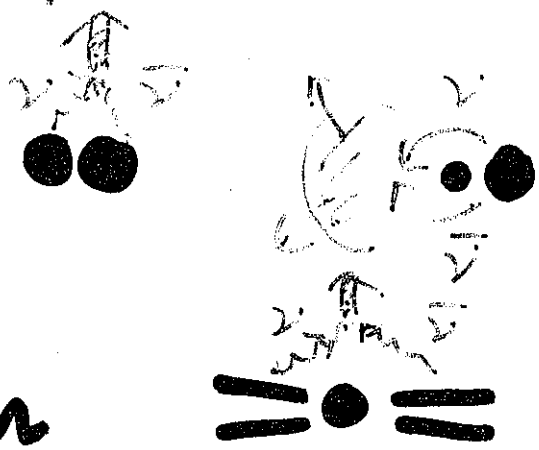
production

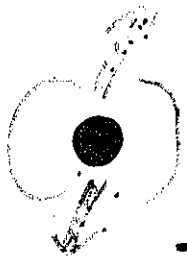
* $e^{\pm}$ annihilation
* $\tau_T \lesssim 1$
* Radiation → Matter dominance

deceleration by ambient medium

production processes

* NS merger
* Failed SN
* Newly Born Pulsar
* ....





$$t_{MDR} \sim 200 \left(\frac{B}{3\cdot 10^{15}}\right)^{-2} \left(\frac{P}{1\,msec}\right)^{2} \text{ sec}$$

基本的なパラメータ

$$\eta \equiv \frac{E_0}{M_0 c^2} \sim 10^{-3} \frac{E_0/10^{51}\,\mathrm{erg}}{M_0/M_\odot}$$

$$\begin{cases} M_0 \gtrsim 10^{-3} M_\odot & : \text{非相対論膨張} \\ 10^{-3} \gtrsim \dfrac{M_0}{M_\odot} \gtrsim 10^{-9} & ; \text{相対論的膨張} \\ 10^{-9} M_\odot \gtrsim M_0 & ; \text{prompt } \gamma\text{-rays} \end{cases}$$

$\eta \gg 1$ を考える.

$$E_0 \approx a T_0^4 R_0^3$$

$$T_0 \approx 3 \cdot 10^{11}\,\mathrm{K}\ \frac{E_0/10^{51}}{(R_0/10^6)^3}$$

膨張 (radiation dominated)

$$T = T_0 \frac{R_0}{R}$$

$$E_{th} = E_0 \frac{R_0}{R}$$

$$E_{kin} = E_0 = \Gamma E_{th}$$

$$\Gamma = \frac{R}{R_0}$$

- $kT_{ann} = kT_0 \frac{R_0}{R_{ann}} \sim m_e c^2$

$$R_{ann} \sim 10^8 \text{ cm}$$

- $E_{th} = E_0 \frac{R_0}{R_{bd}} \sim M_0 c^2 = \frac{E_0}{\eta}$

$$R_{bd} \sim \eta R_0$$

この時期以降は $\Gamma \approx \eta \approx$ const.
で膨張

- $\tau_T \sim n_e \sigma_T R \lesssim 1$ になる時期

$$n_e \sim \frac{M_0}{m_p R^3} \sim \frac{E_0}{R^3 \eta m_p c^2}$$

$$R_t \sim \left(\frac{E_0 \sigma_T}{\eta m_p c^2} \right)^{1/2} \sim 10^{15} \left(\frac{E_0}{10^{51}} \right)^{1/2} \eta^{-1/2} \text{ cm}$$

$$\begin{cases} R_t < R_{bd} & \text{for} \quad \eta \gtrsim 10^6 E_{51}^{1/3} R_6^{-2/3} \\ R_t > R_{bd} & \eta \lesssim \ \text{〃} \end{cases}$$

Deceleration by ambient matter

$$E_0 \sim \eta^2 n_{ext} m_p c^2 R_{dec}^3$$

$$R_{dec} \sim 10^{18} E_{51}^{1/3} n_{ext}^{-1/3} \eta^{-2/3} \ \mathrm{cm}$$

$$\Delta t_{obs} \sim \frac{R_{dec}}{c} \cdot \frac{1}{\eta^2}$$

$$\sim 3 \cdot 10^7 E_{51}^{1/3} n_{ext}^{-1/3} \eta^{-8/3} \ \mathrm{sec}$$

$10^2 < \eta < 10^3$ の時

$10^2 \mathrm{sec} > t_{obs} > 10^{-1} \mathrm{sec}$

* 粒子加速 → radiation は充分速くおこるか？
* micro-structure をどう説明するか？
* main burst と afterglow は何に対応するか？

通常のシナリオ

- Internal Shocks が GRB 本体
  External Shock は Afterglow に対応

- Shock加速で電子加速の効率が非常に大きく、
  電子のシンクロトロン放射で観測を説明する.

- 陽子加速も必ず起きるので、宇宙線、ニュートリノ
  も必ず生じる.

疑問

* Internal shock の効率

* 電子加速の効率

* GRB スペクトルの普遍性

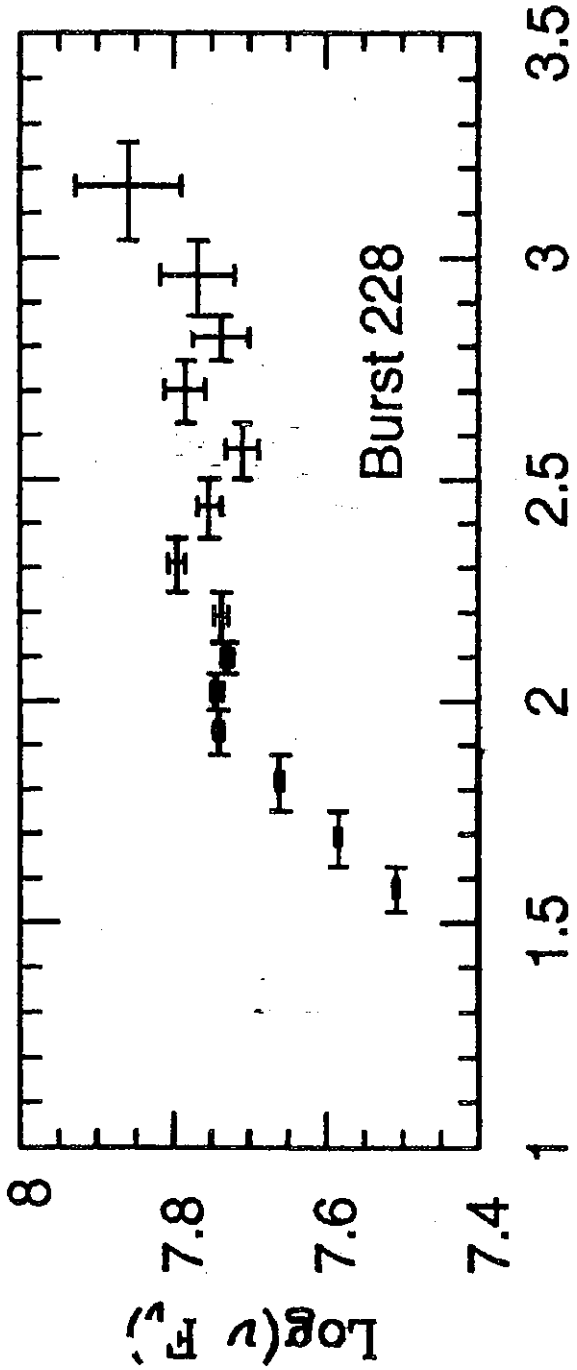


Figure 18.2: The spectrum of burst 228 from the BATSE 2 catalogue.

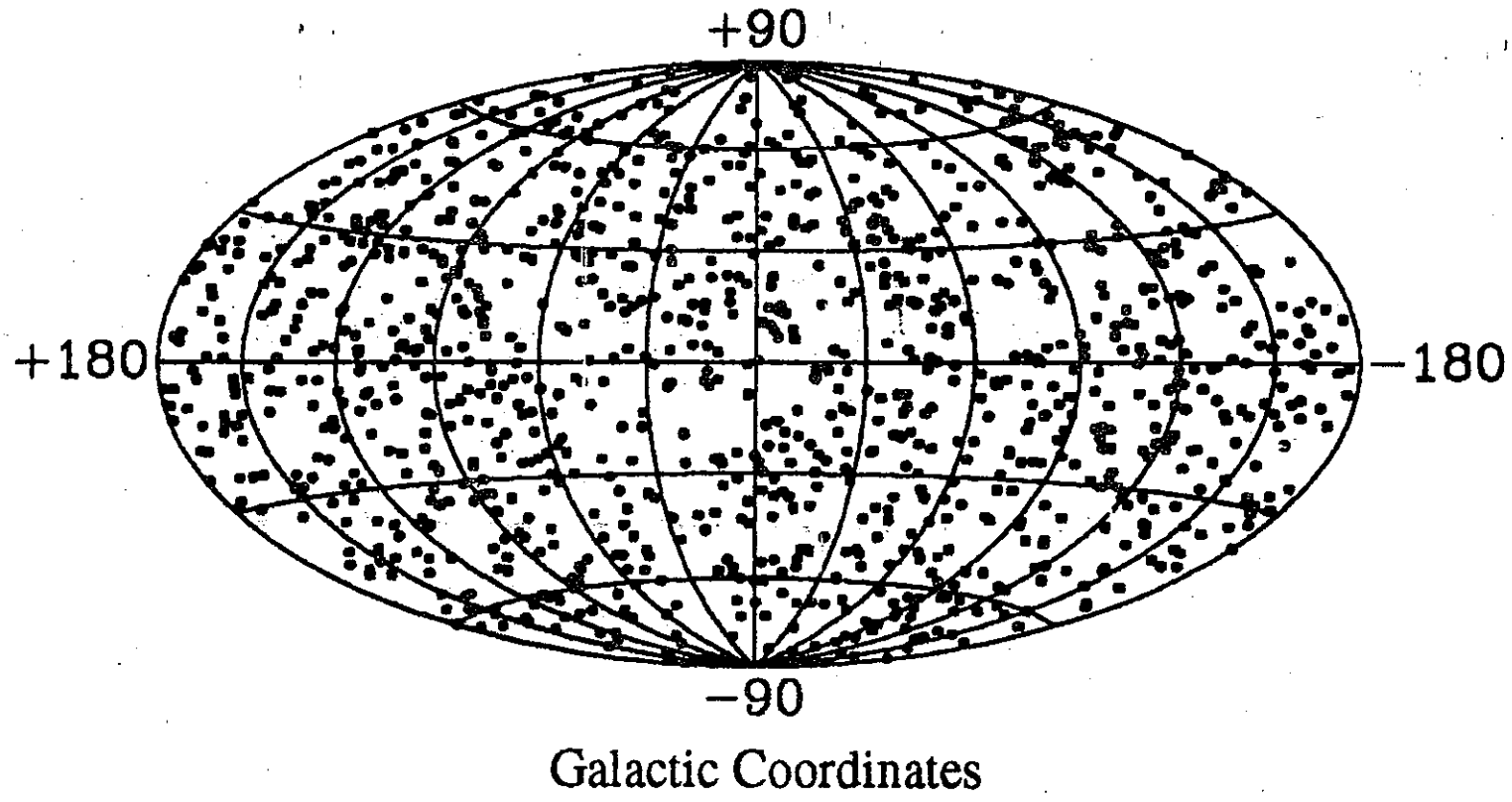


Figure 18.3: The Distribution of 1005 bursts on the sky.

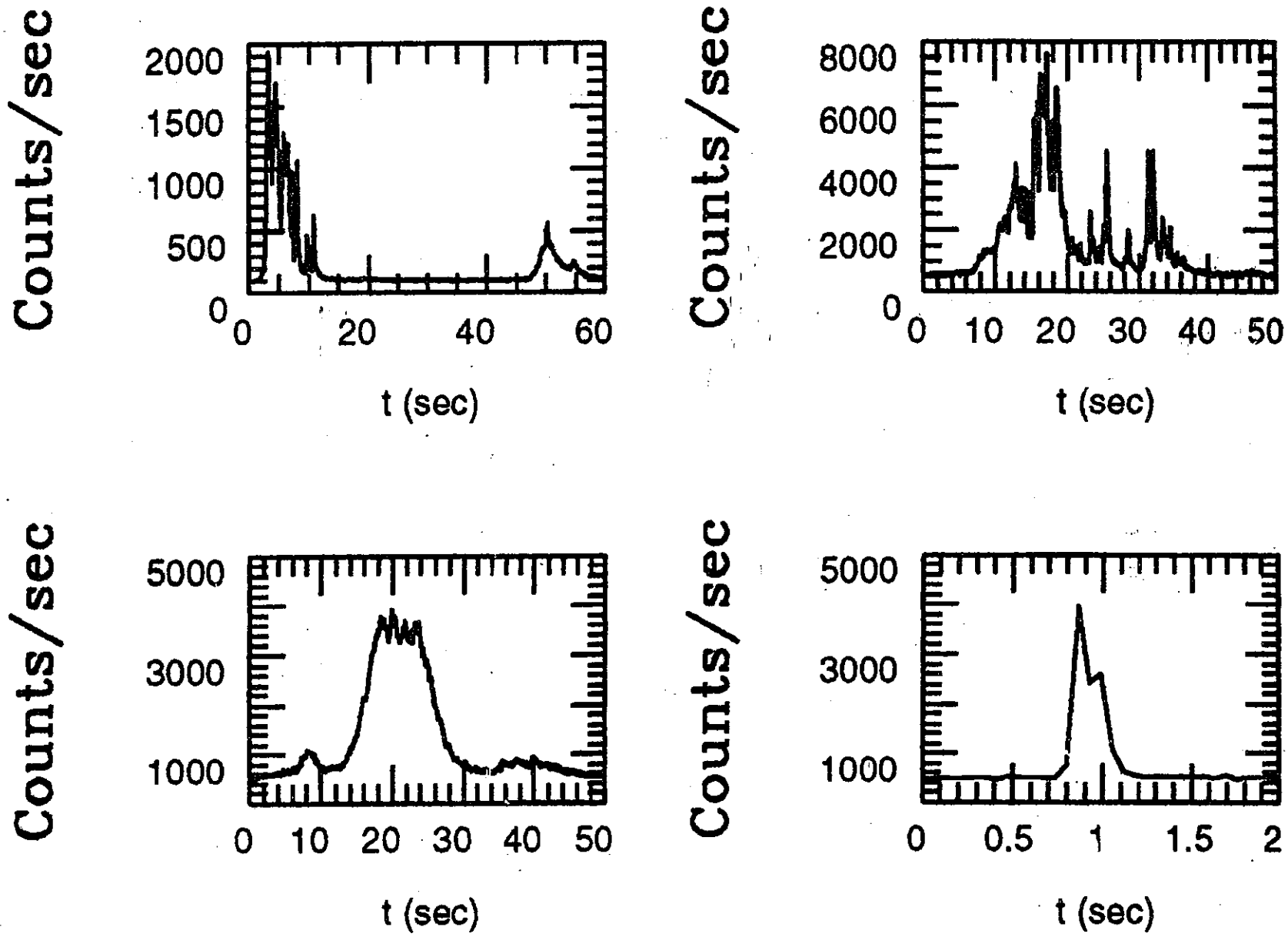


Figure 18.1: Temporal distribution of four bursts from the BATSE 2 Catalogue.