気球による宇宙線観測

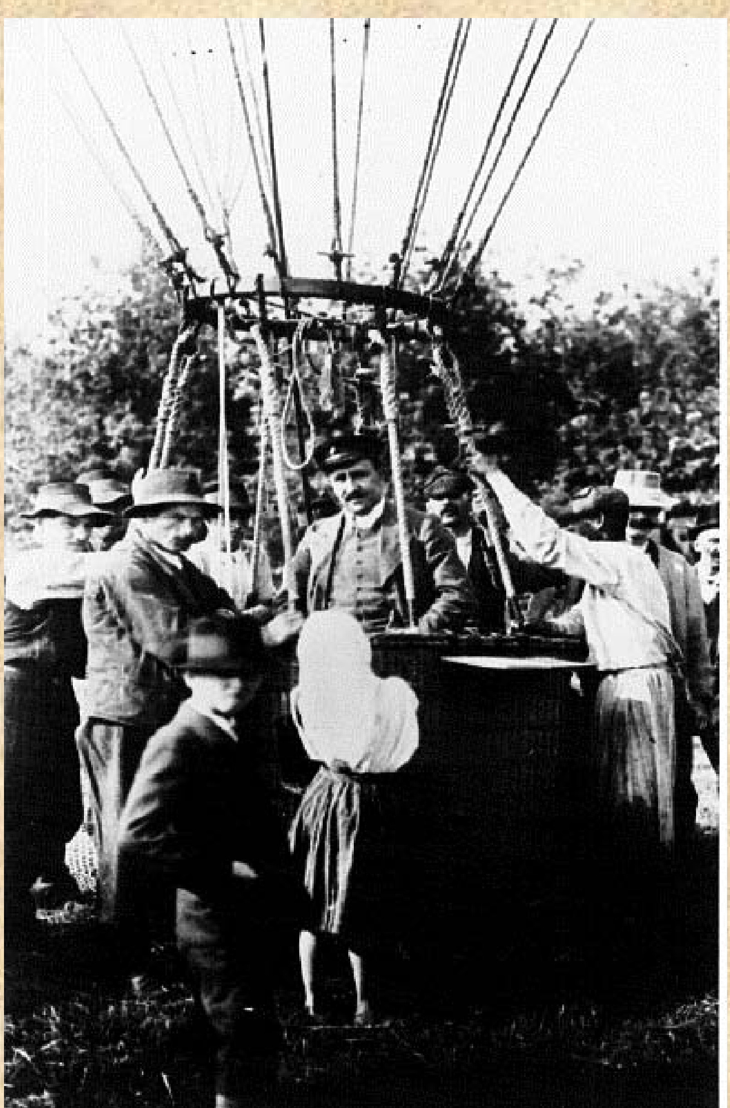
気球による宇宙線観測の成果と展望　ー極地実験を中心にー

神奈川大学工学部
鳥居祥二

日本物理学会　2004年秋季大会 (高知大学)　平成16年9月29日

- 気球による宇宙線実験
- 長期間気球実験
- これまでの実験のまとめ
- ２０００年以降の南極での宇宙線観測
- 今後の展望

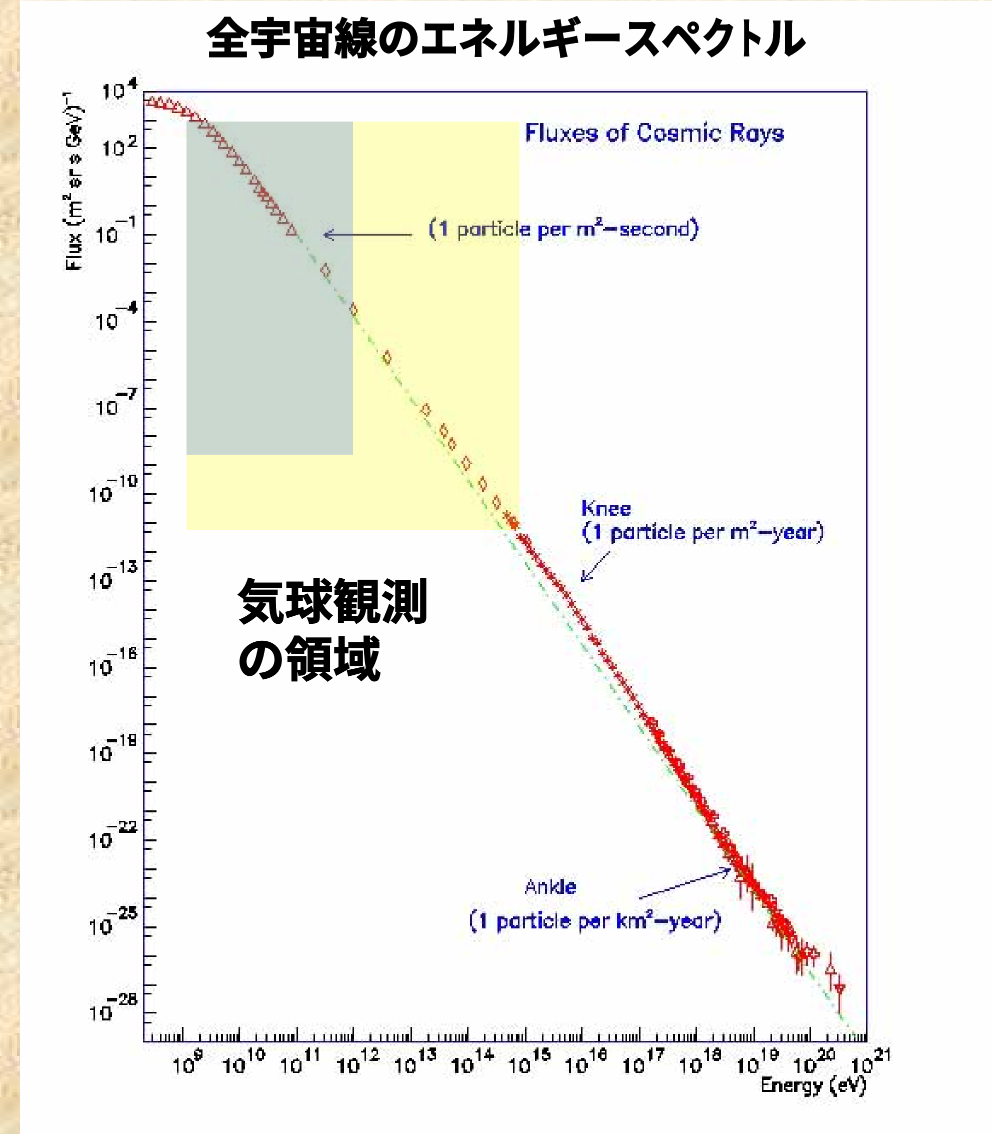
この後の講演：
昭和基地における南極周回気球
PPBによる電子観測
反陽子、陽電子、同位体
気球技術

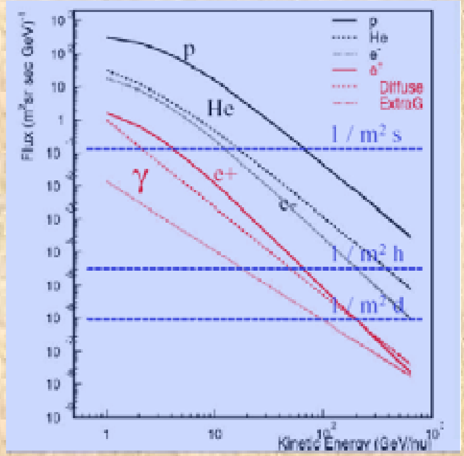


宇宙線観測は気球で始まった！！！

1912年
HESS による宇宙から飛来する
放射線の発見

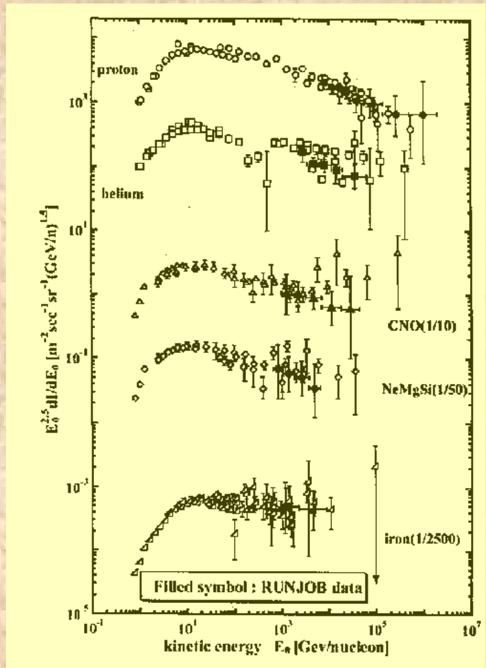
気球観測のエネルギー領域とフラックス





1〜1000GeV
電子、二次粒子

陽子に対する比
電子　~　1%
(一次)
陽電子 ~ 0.1%
(二次)
反陽子~ 0.1%
(二次)



Exotic Particles
(Dark Matter)
の検出

1~10^6GeV
陽子、原子核

長期間気球実験

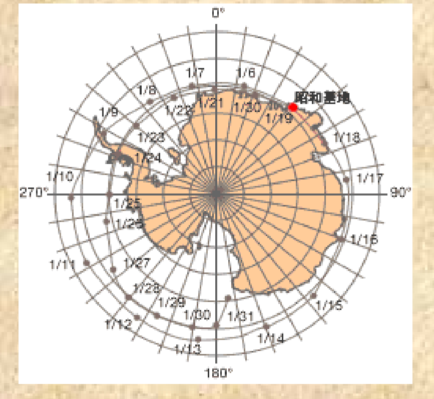
長期間気球実験　(LDB)　　１４～３０日間

南極周回気球　　PPB実験 (極地研/宇宙研)　　　１９８８年　昭和基地

LDB実験 (NASA)　　　　　　　　１９９０年　マクマード基地 (JACEE0)

北半球横断　　LDB実験 (ロシア)　(5~6日間)　　１９９５年　カムチャッカ (RUNJOB01)

PPB



NASA/LDB

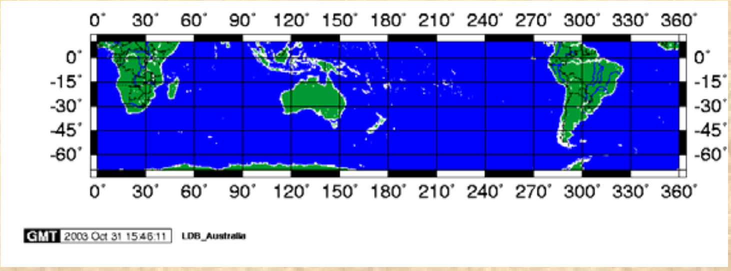
Russia/LDB

超長期間気球実験 (ULDB)　　１００日間　(南半球周回)

NASAのテストフライトはまだ成功していない。

総重量　２．７トン　　高度　３４km

NASA/ULDB



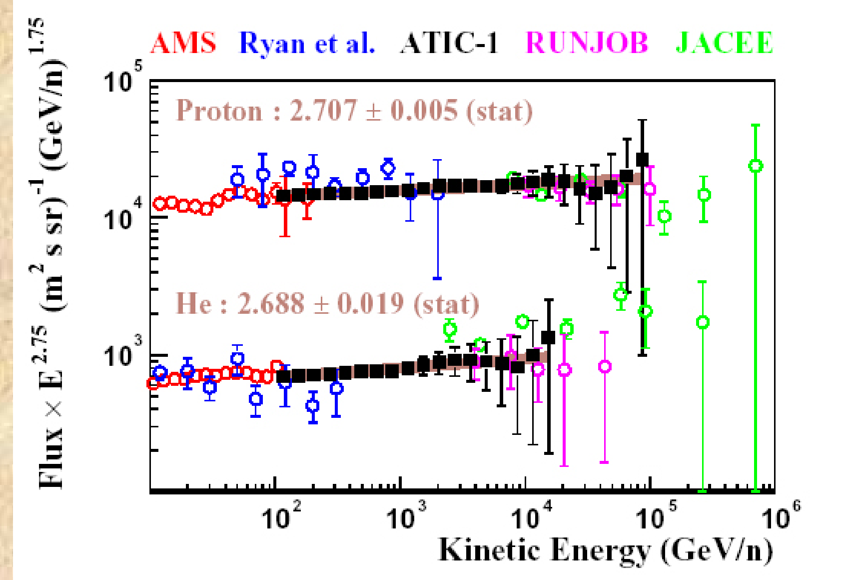
2000年以前の長期間気球を用いた宇宙線の観測は、エマルション・チェンバー実験に限られていたが、

1） 高度なエレクトロニクスを駆使した装置の開発、

2） 気球実験技術の高度化と、GPS、衛星通信テレメトリーの利用、

により、従来の衛星実験をしのぐレベルでの観測が安定的に行われるようになり、宇宙線観測にブレークスルーをもたらしている。

最近の南極でのLDB実験（ATIC-1) とRyan et al. 、JACEE、RUNJOBで得られたP、Heのエネルギースペクトルの比較。



The Cosmic Ray Antarctic Payloads in NASA

- ANITA (Anita Lite)：Antarctic Impulsive Transient Antenna (SMEX Mission)
  Origin of the highest energy particles in the Universe

- ATIC: Advanced Thin Ionization Calorimeter
  Measuring the cosmic proton and helium spectra from below
  5×10^{10} eV to more than 10^{14} eV

- BESS (Polar): Balloon Borne Experiment with Superconducting Solenoidal Spectrometer
  Search for anti-helium nuclei and studies of Z=1 and Z=2 components - identifying anti-protons, measuring proton and helium spectra and separating isotopes

- CREAM: Cosmic Ray Energetics and Mass (ULDB)
  Investigate ultra high energy (10^{12} to > 5×10^{14} eV) cosmic rays over the elemental range from protons to iron

- TIGER: Trans-Iron Galactic Element Recorder
  Measure GCRs with atomic number (Z) between 26 (Iron) and 40 (Zirconium).

- TRACER： Transition Radiation Array for Cosmic Energetic Radiation
  Measurements of heavy cosmic ray nuclei (oxygen to iron) in the energy range from 10^{13} to several 10^{14} eV per nucleus.

Other Astrophysical Antarctic Payloads in NASA

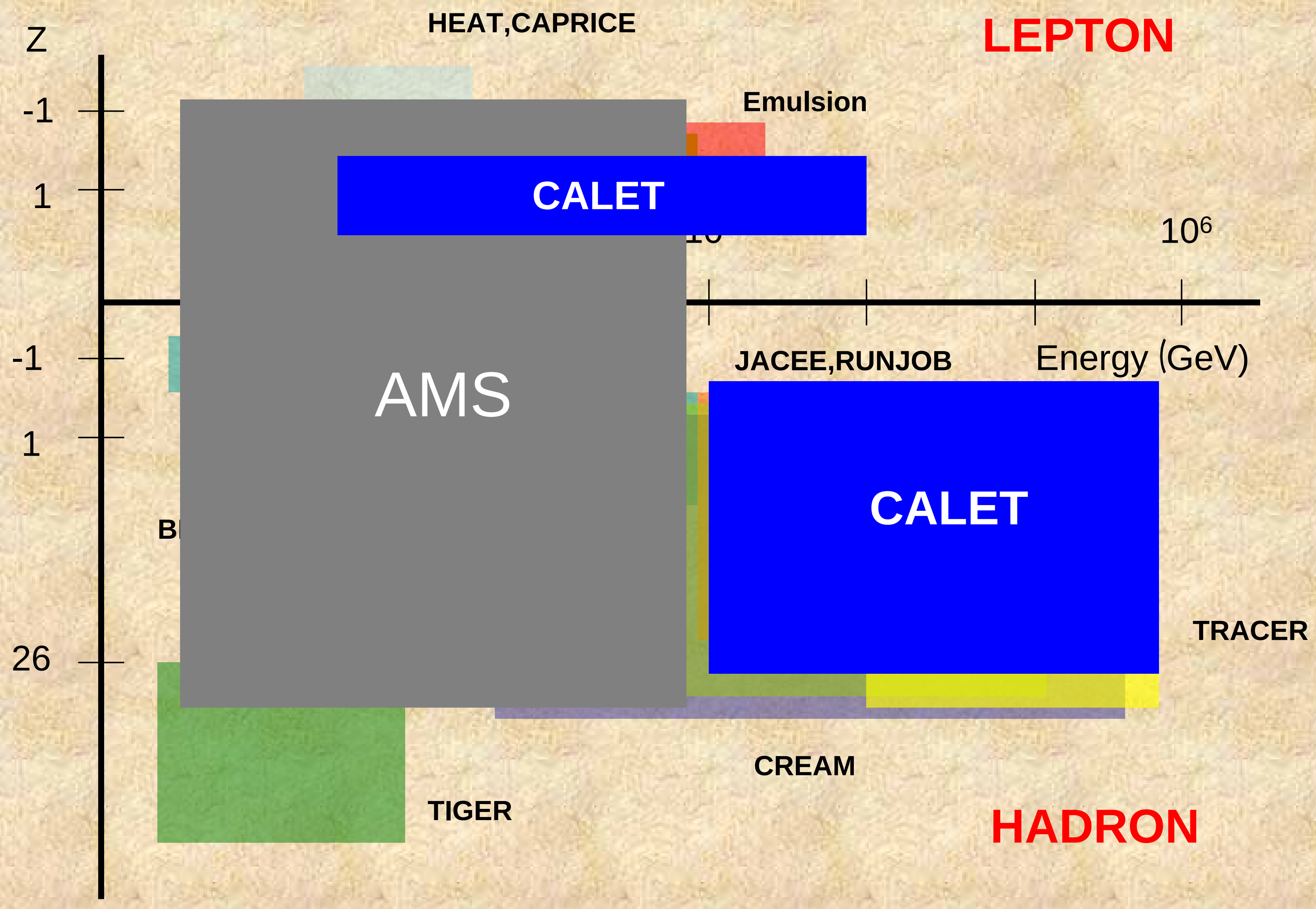
- Boomerang:
  Balloon Observations of Millimetric Extragalactic Radiation and Geophysics
  Mapping the Cosmic Microwave Background (CMB)

Polar Patrol Balloon Payload in NIPR/JAXA

- **PPB-BETS:**
  Polar Patrol Balloon – BETS
  Observing Primary Electron in 10 -1000 GeV

Emulsion Chamber Experiments

- JACEE:
  Japanese American Cooperative Emulsion Experiment
- RUNJOB:
  Russian Nippon Joint Balloon Experiment
  Measurement of H to Fe in 1-1000 TeV
- Primary Electron:
  Observation of Primary Electrons in 100 -1000 GeV



HEAT,CAPRICE
LEPTON
Z
-1
1
Emulsion
CALET
10^6
-1
JACEE,RUNJOB
Energy (GeV)
AMS
1
CALET
26
TRACER
CREAM
TIGER
HADRON

Summary of Long Duration Cosmic-Ray Balloon Flights

Emulsion Chamber

Primary Electron	1968~2002	9.2 m^2 day sr	Electron (100~ 1000 GeV)
RUNJON	1995~1999	24 m^2 day	H to Fe (1 ~ ∗100 TeV)
JACEE (including LDBs)	1979~1995	60 m^2 day	H to Fe (1 ~ ∗100TeV)

NASA Long Duration Flights in Antarctica

1998/1999	BOOMERANG	10.5 days	CMB
2000/2001	ATIC	14 days	H, He to Fe (0.1~100 TeV)
2001/2002	TIGER	31.5 days	26 < Z < 40
2002/2003	ATIC(2)	17 days	
	BOOMERANG(2)	15 days	
2003/2004	TIGER (2)	18 days	
	+ ANITA Lite		Neutrinos
	TRACER	14 days	O to Fe (10~∗100TeV)
2004/2005	BESS-Polar		anti-P
(scheduled)	CREAM		H to Ni (Z=28) (1~500 TeV)
	ATIC(3) (Backup)		

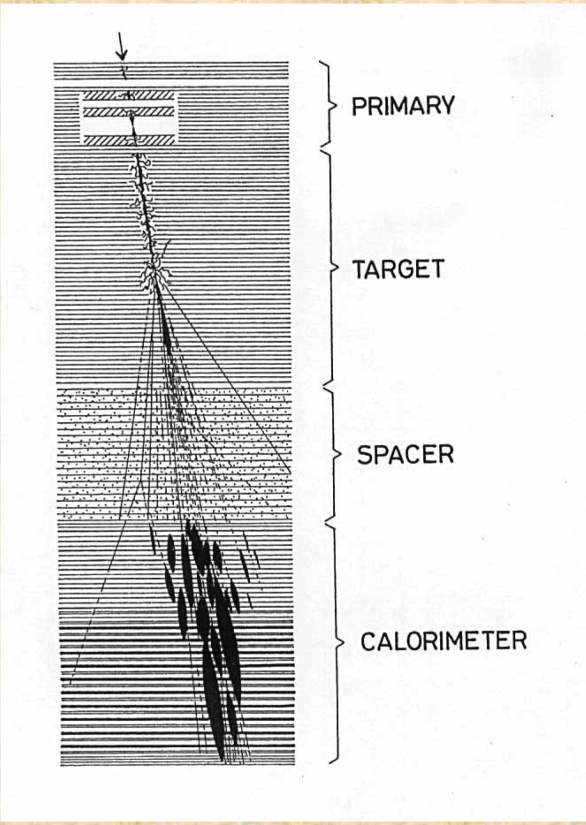
NIPR/ISAS Polar Patrol Balloon Flight in Antarctica

2004.1	PPB-BETS	13 days	Electron (10~1000 GeV)

JACEEによる宇宙線観測

JACEE 10

エマルションチェンバー



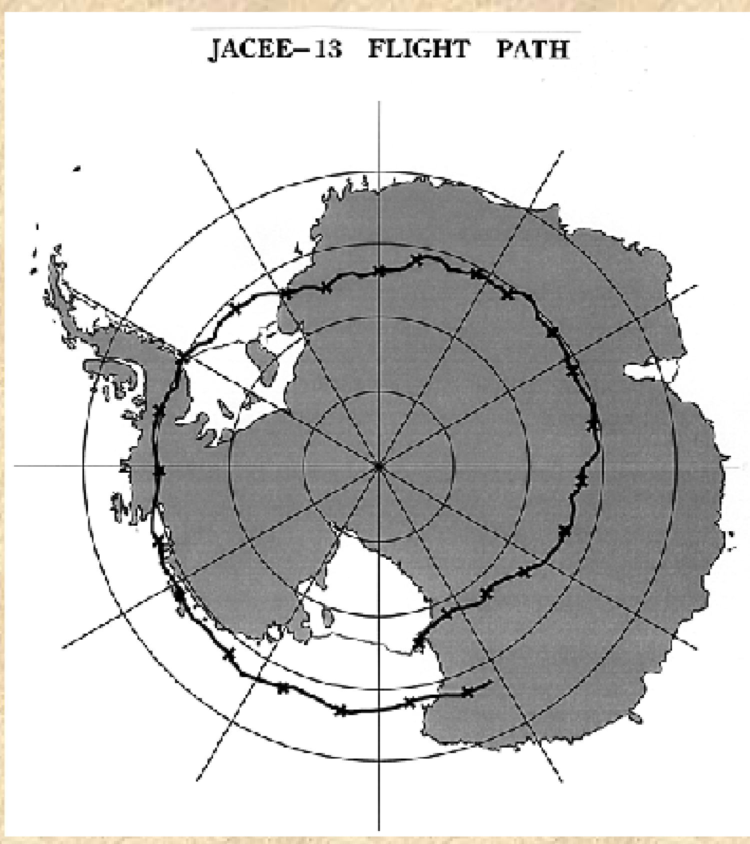
- 電荷決定層 (Primary section)
- 標的層 (Target section)
- 間隙層 (Spacer section)
- エネルギー決定層 (Calorimeter section)

JACEE BALLOON FLIGHT TABLE

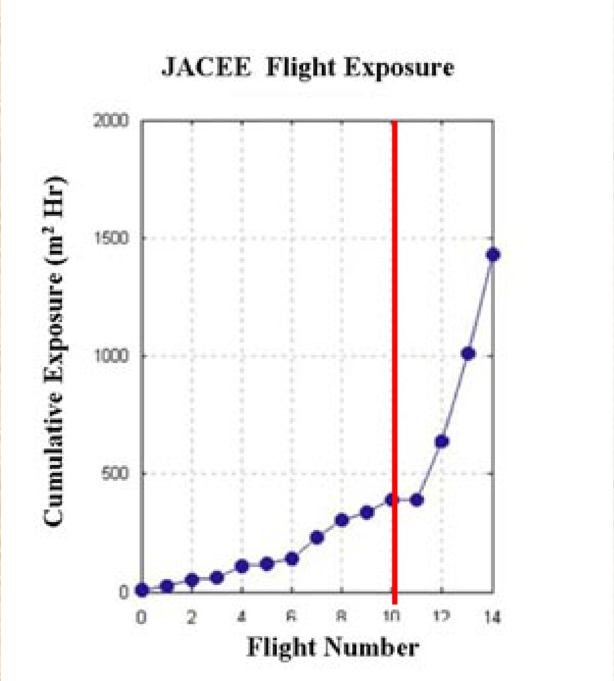
1434m^2hr (~60m^2day)

Flight	Launch Date	Launch Site	Altitude [g/cm^2]	Duration [hours]	Area [m^2]	Exposure [m^2·hr]
JACEE-0	May 1979	Sankiku(Japan)	8.0	29.0	0.2	5.80
JACEE-1	Sep 1979	Palestine(Texas)	3.7	25.2	0.8	20.16
JACEE-2	Oct 1980	Palestine(Texas)	4.0	29.6	0.8	23.68
JACEE-3	Jun 1982	Greenville(S.Carolina)	5.0	39.0	0.25	9.75
JACEE-4	Jun 1983	Palestine(Texas)	5.0	59.5	0.8	47.60
JACEE-5	Oct 1984	Palestine(Texas)	5.0	14.5	0.8	11.60
JACEE-6	May 1986	Palestine(Texas)	4.0	30.0	0.8	24.00
JACEE-7	Jan 1987	Alice Springs(Australia)	5.0	150.0	0.6	90.00
JACEE-8	Feb 1988	Alice Springs(Australia)	5.0	120.0	0.6	72.00
JACEE-9	Sep 1990	Fort Sumner(New Mexico)	4.0	44.0	0.8	35.20
JACEE-10	Dec 1990	McMurdo(Antarctica)	3.5	204.0	0.24	48.96
JACEE-11	Dec 1993	McMurdo(Antarctica)	4.5	217.5	1.2	261.00 Not recover
JACEE-12	Jan 1994	McMurdo(Antarctica)	5.0	211.0	1.2	253.20
JACEE-13	Dec 1994	McMurdo(Antarctica)	5.0	310.0	1.2	372.00
JACEE-14	Dec 1995	McMurdo(Antarctica)	5.0	350.0	1.2	420.00

JACEEの露出量とLDB実験

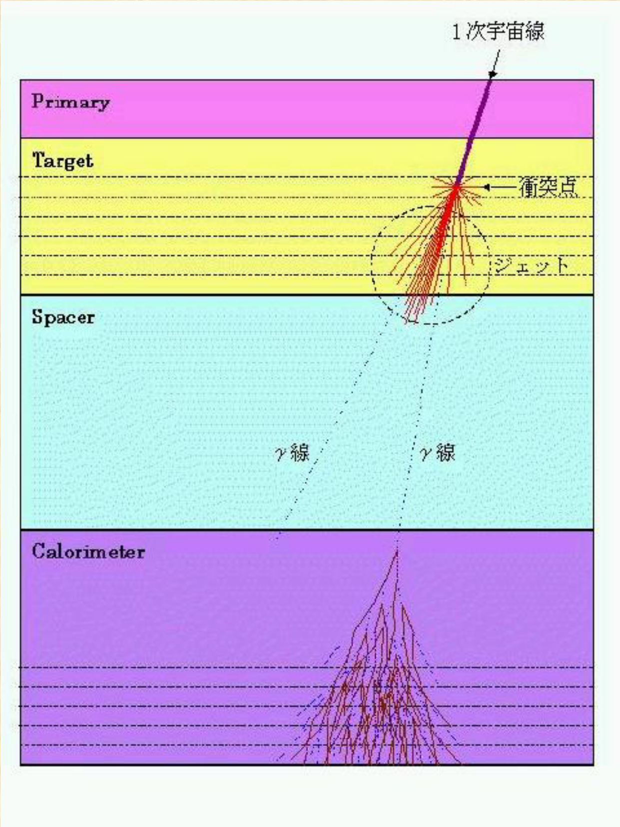


JACEEの露出量の変化。
JACEE11以降のLDB実験で
急速に露出量が増えている。



RUNJOB : RUssia Nippon JOint Balloon experiment

エマルションチェンバー



RUNJOBで使用した気球のフライト状況

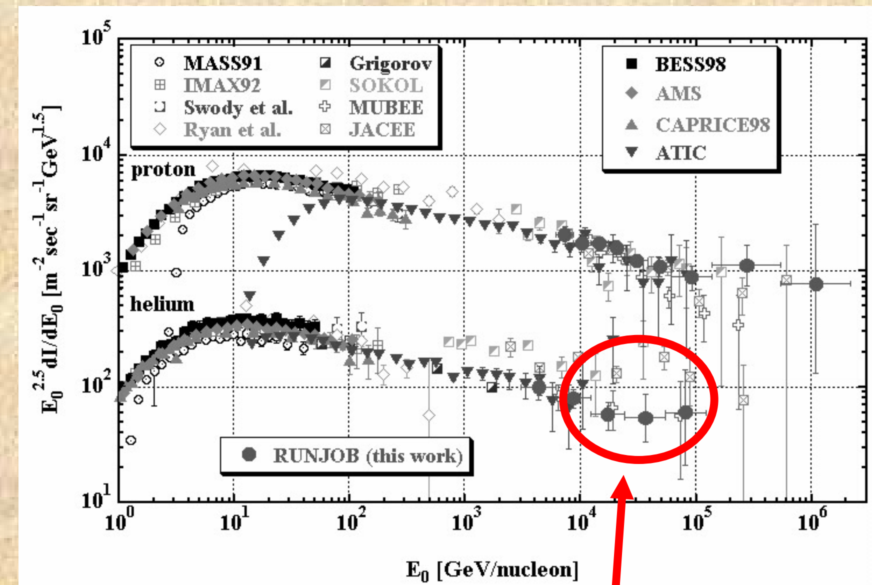
574.4 m^2 hr (~24m^{2}day)

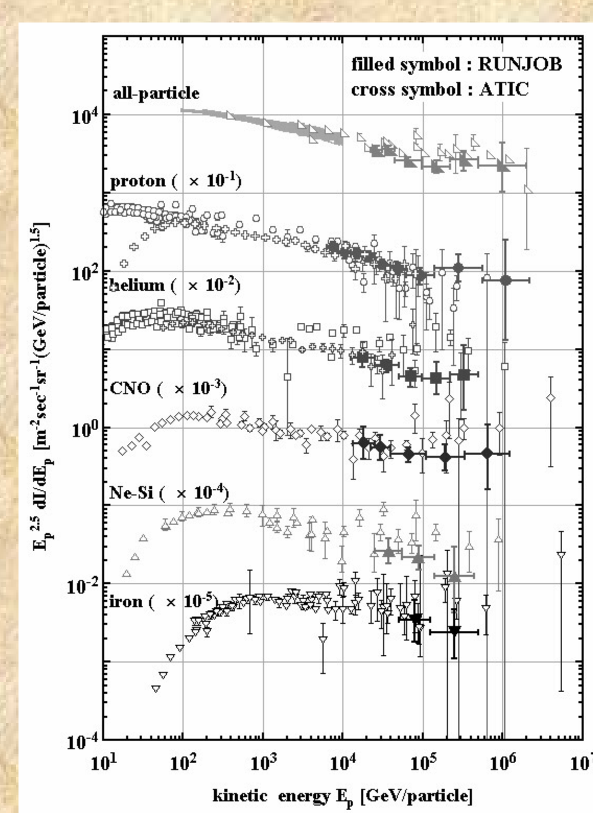
	気球体積 (m^3)	質量 (kg)	面積 (m^2)	放球日	着陸日	飛翔時間 (h)
RUNJOB1	180000	230	0.4	1995/7/15	1995/7/20	130
RUNJOB2	180000	230	0.4	1996/7/19	1996/7/25	167
RUNJOB3	180000	254	0.4	1996/7/17	1996/7/23	134
RUNJOB4	180000	254	0.4	1995/7/18	1995/7/24	147.5
RUNJOB5	180000	260	0.4	1997/7/ 9	1997/7/15	139.5
RUNJOB6	180000	270	0.4	1997/7/11	1997/7/17	139.5
RUNJOB7	180000	268	0.4	1997/7/16	墜落	ー
RUNJOB8	180000		0.4	1999/7/8	1999/7/14	142
RUNJOB9	180000		0.4	1999/7/12	1999/7/18	145
RUNJOB10	180000		0.4	1999/7/13	1999/7/19	146.5
RUNJOB11	180000		0.4	1999/7/14	1999/7/20	145

JACEE、RUNJOB、ATICほかによる
H からFeまでのエネルギースペクトル

超新星における衝撃波加速の限界の検出　−＞　スペクトルの変化

陽子～100TeV　　原子核～100Z TeV

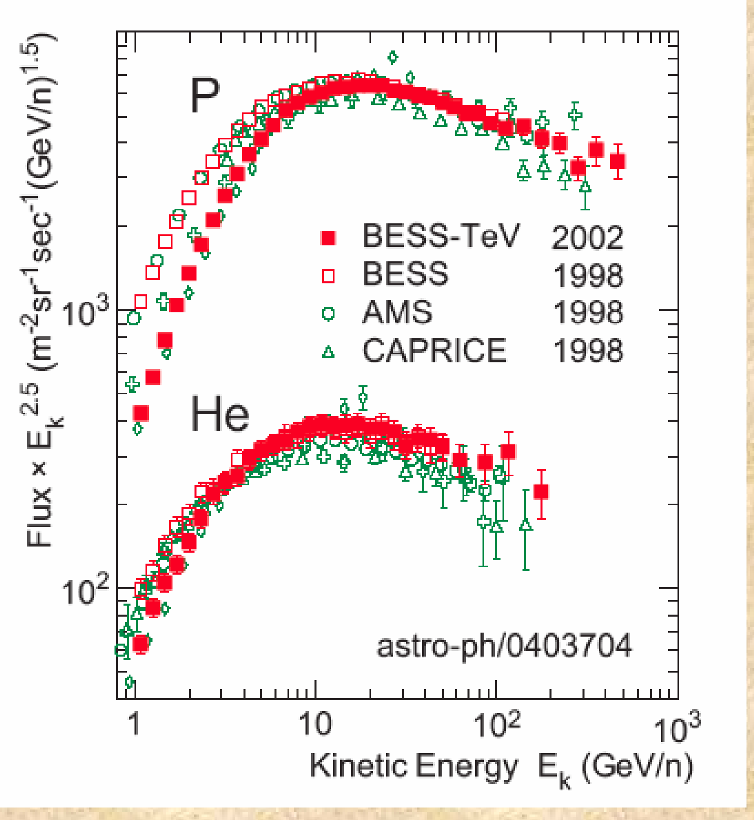




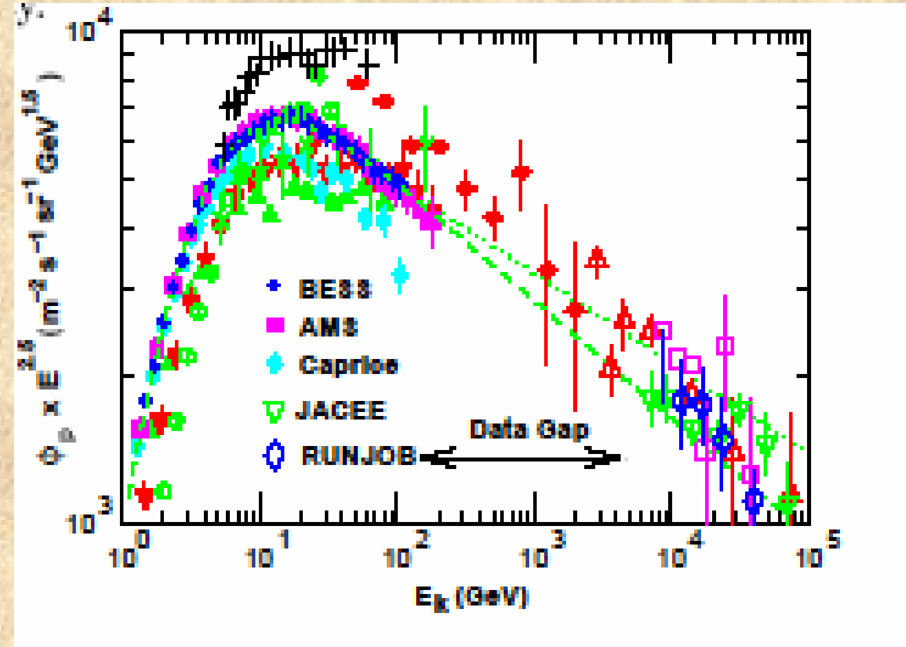
He **スペクトルの食い違い**
ATIC**の結果？**

エネルギースペクトル測定の今後の課題

マグネットペクトロメータに
匹敵するエネルギー分解能



１００GeV-1TeV間のギャップを埋める
(ニュートリノ振動実験のシミュレーションコード
の精度を高める。)



エマルションチェンバーによる一次電子観測量

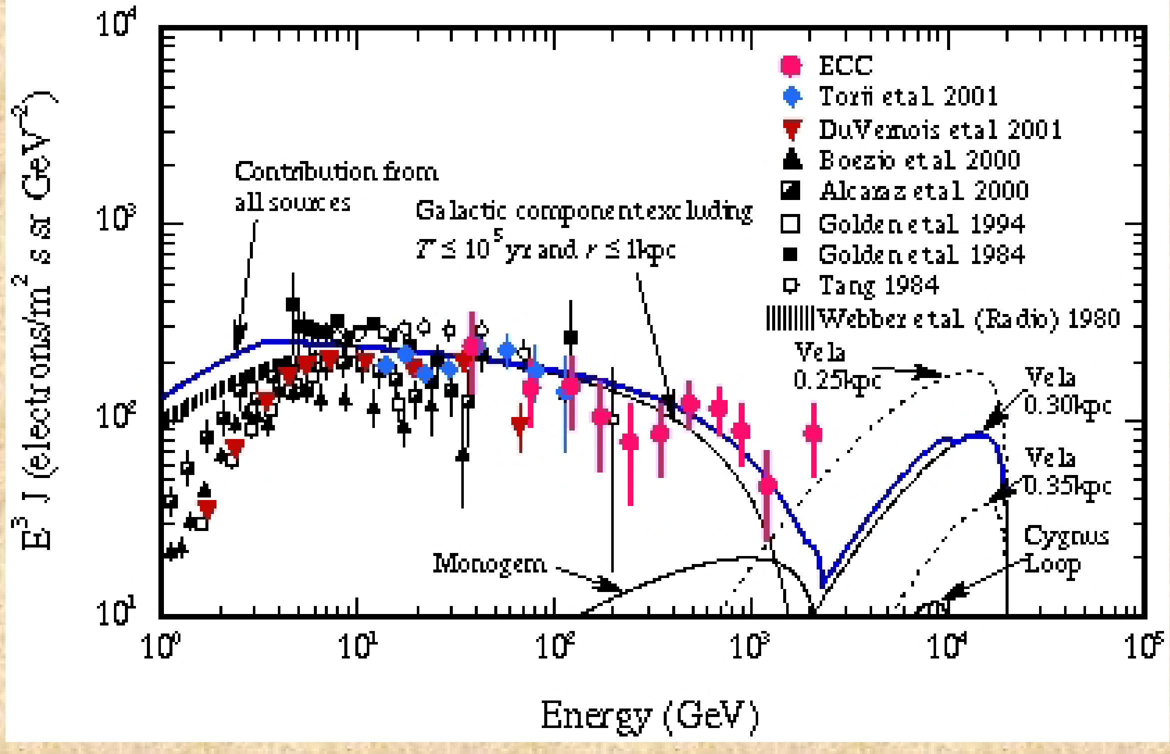
~ 9.2 m² day sr

List of Balloon Flights

Flight	Area (m^2)	Time (min)	Average Alutitude (g/cm^2)	$S\Omega T$ ($m^2 \cdot s \cdot sr$)	Launch Site
1968	0.05	380	6.1	1.826×10^3	Haranomachi, Japan
1969	0.05	267	7.1	1.283×10^3	Haranomachi, Japan
1970	0.05	1136	6.1	5.460×10^3	Sanriku, Japan
1973	0.20	833	8.2	1.934×10^4	Sanriku, Japan
1976	0.40	1526	4.0	7.084×10^4	Palestine, USA
1977	0.78	1760	4.5	1.572×10^5	Palestine, USA
1979	0.80	1680	4.9	1.539×10^5	Palestine, USA
1980	0.80	2029	7.8	1.884×10^5	Palestine, USA
1984	0.20	576	9.2	1.357×10^4	Sanriku, Japan
1985	0.40	940	9.4	4.614×10^4	Sanriku, Japan
1988	0.20	647	7.1	1.493×10^4	Uchinoura, Japan
1996	0.20	2092	4.6	4.874×10^4	Sanriku, Japan
1998	0.20	1178	5.6	2.729×10^4	Sanriku, Japan
1999	0.20	891	5.6	2.005×10^4	Sanriku, Japan
2001	0.20	1108	5.5	2.494×10^4	Sanriku, Japan
Total				$7.939\times10^5\, m^2 \cdot s \cdot sr$	$\sim 9.19 m^2 \cdot sr \cdot day$

電子観測による近傍ソースの検出

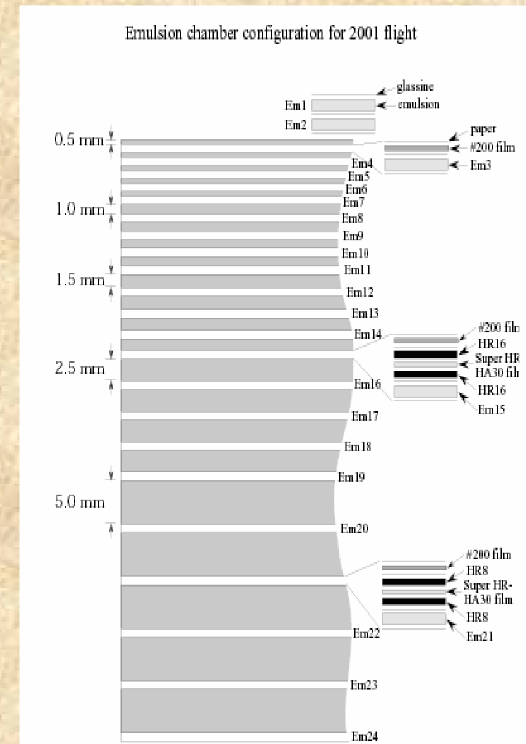
数100 GeV ～ 10 TeV の高エネルギー領域の電子スペクトルには、電子加速源と推定される超新星残骸のうち、地球近傍（1kpc以内）で年齢10万年以下の超新星残骸の影響が強く表れる。

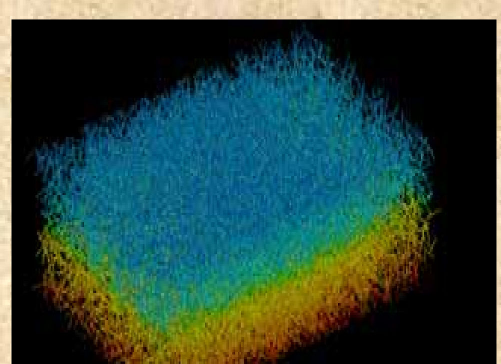


Micro Segment Chamber (MSC)

Automatic Tracing Tracks in each layer of ECC

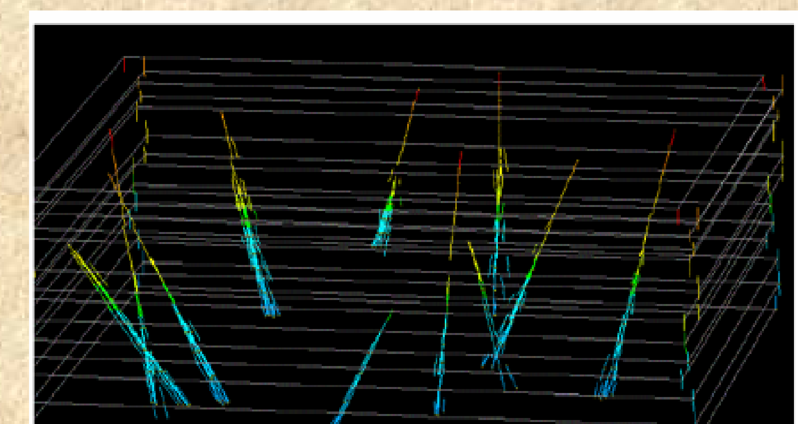
エマルションチェンバー



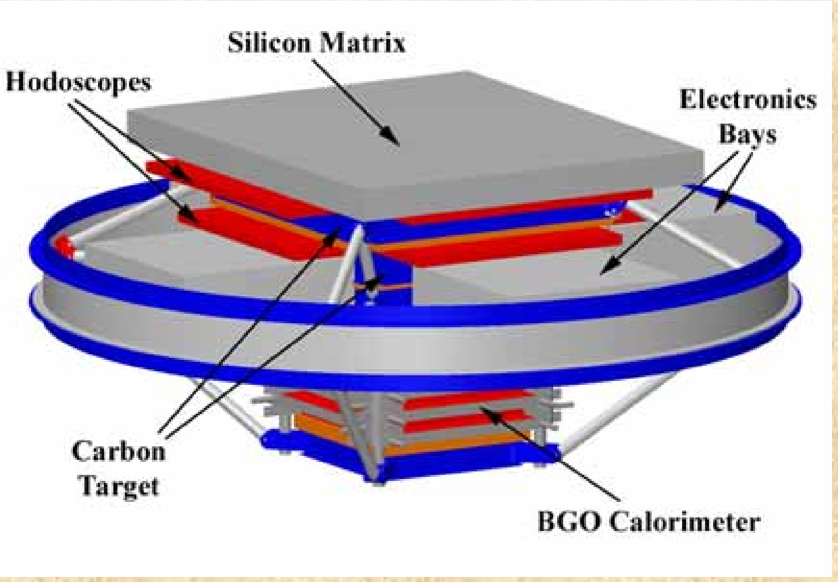


ECCの閾値を下げる
(～1０ GeV)

2cmx3cmx5Xo depth ~40hr
Exposure at Balloon Altitude



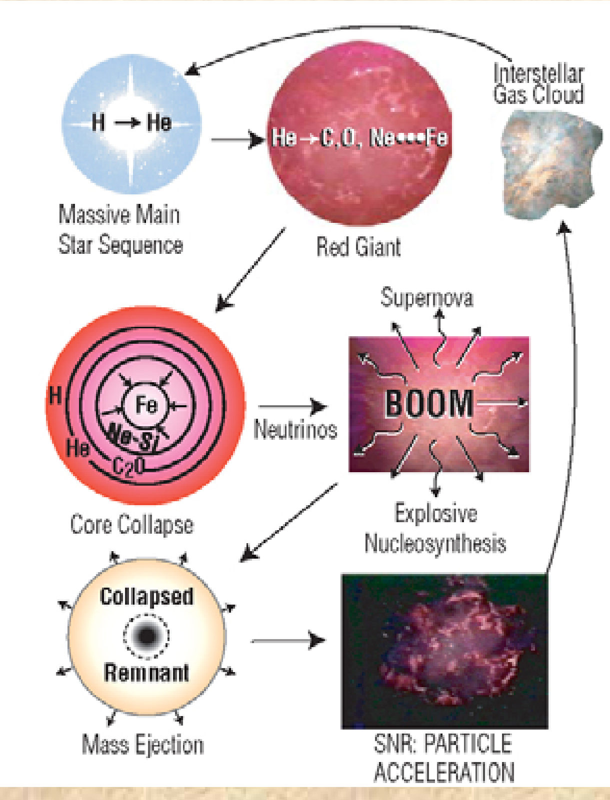
ATIC Instrument



Total weight：
　～1,500 kg (3,300 lbs),
Total power consumed：
　＜ 350 Watts (including power conversion efficiency)
Balloon Alititude:
　~36km
Geometrical factor：
　0.45 m^2 sr (calorimeter top) ～ 0.24 m^2 sr (calorimeter bottom).

Standard Model of Cosmic Ray Acceleration

- Supernova shock waves may accelerate cosmic rays via first order Fermi process
  - Model predicts an upper energy limit of E ~ Z x 10^{14} eV

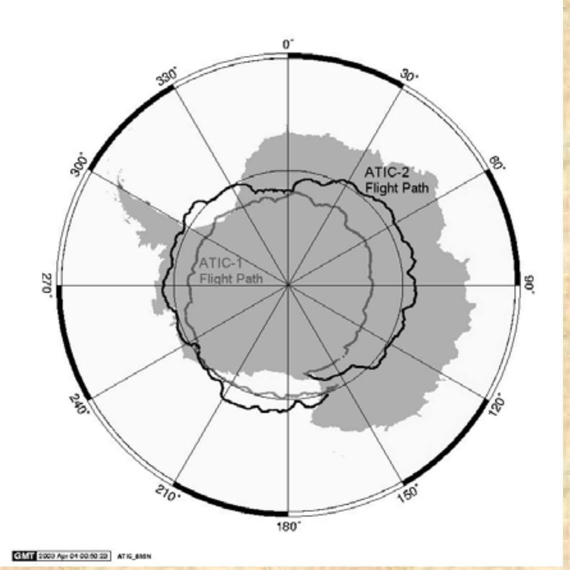


- Investigate relationship between Supernova Remnant (SNR) Shocks and high energy galactic cosmic rays (GCR)
  - Are SNR the "cosmic accelerators" for GCR
- Measure GCR Hydrogen to Nickel from 50 GeV to ~100 TeV total energy
  - Determine spectral differences between elements
- Flight test pixilated Silicon detector

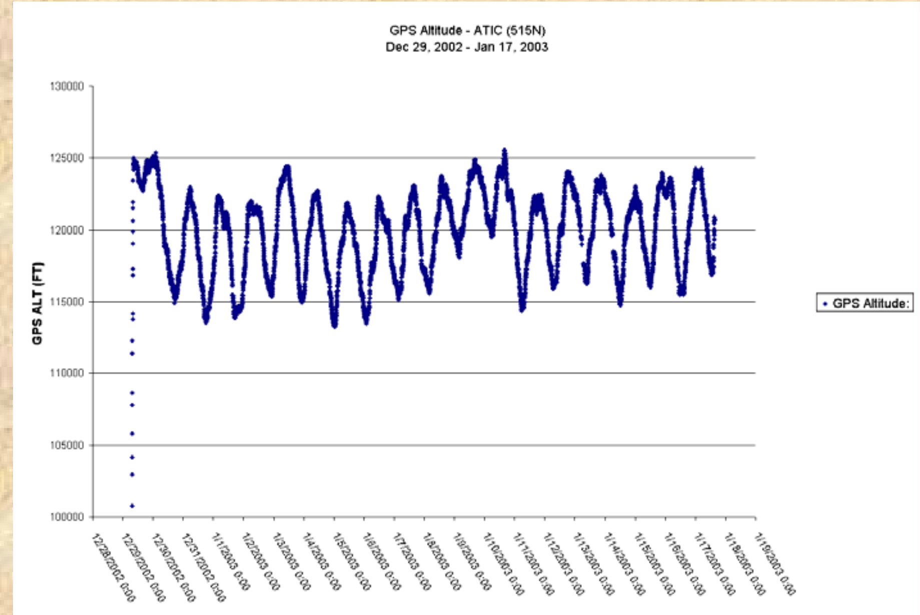
ATIC Observations

Multiple flights needed to obtain necessary exposure
- ATIC-1 during 2000-2001 – 14 days exposure
- ATIC-2 during 2002-2003 – 17 days exposure
- ATIC-3 anticipated for 2004 or 2005

Flight path for ATIC-1 (2000) and ATIC-2 (2002)



ATIC-2 Flight Curve

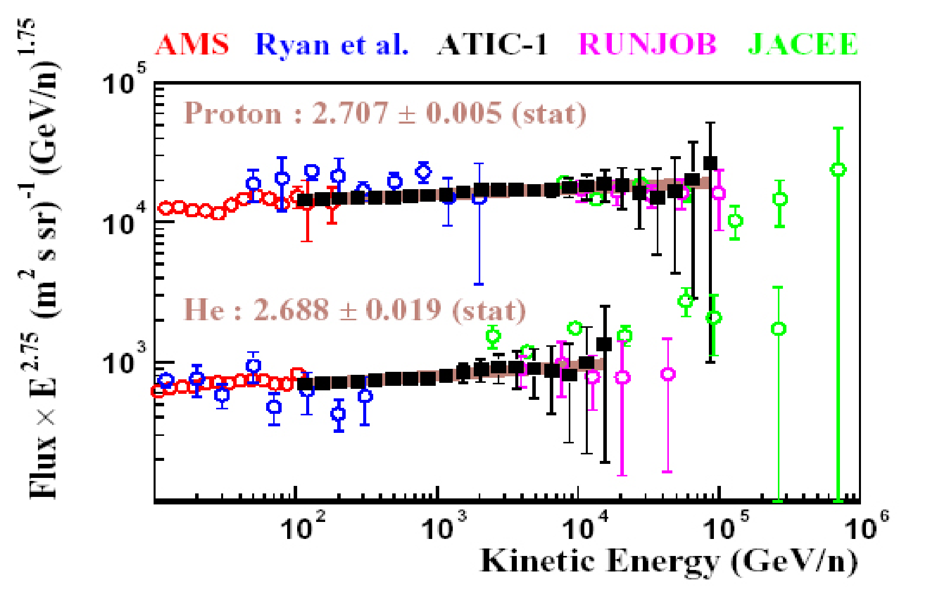


Flight and Recovery

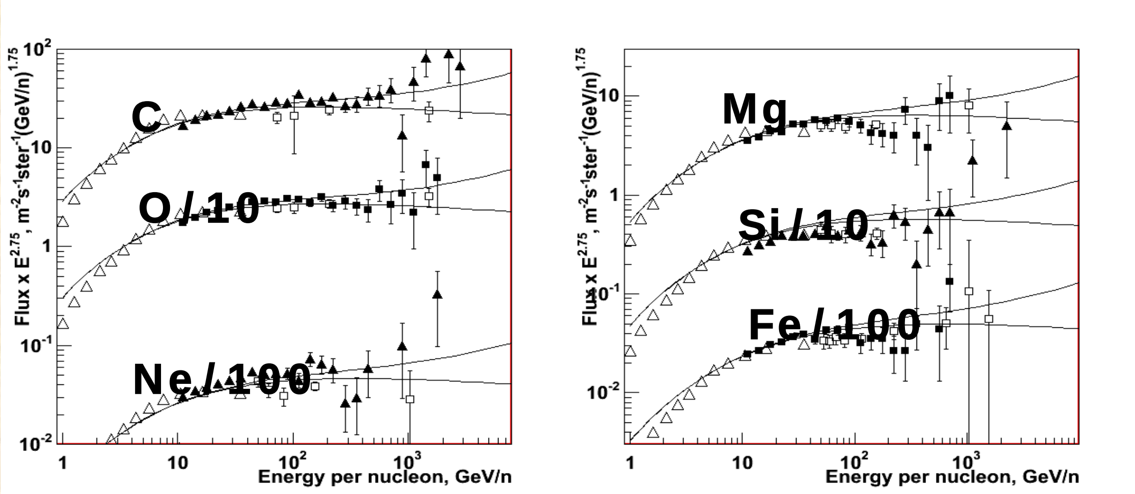
Flight

The good ATIC-1 landing on 1/13/01 (left) and the not so good landing of ATIC-2 on 1/18/03 (right)

ATIC Results



P, He

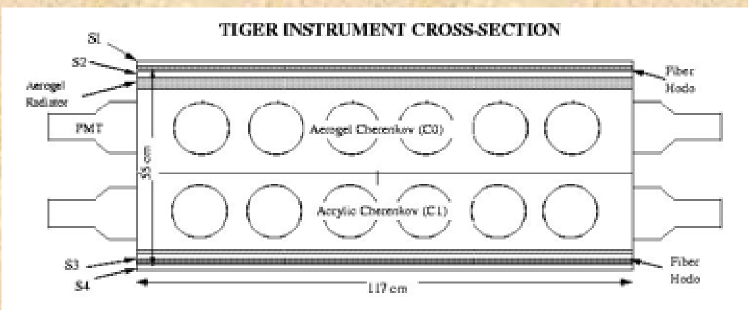


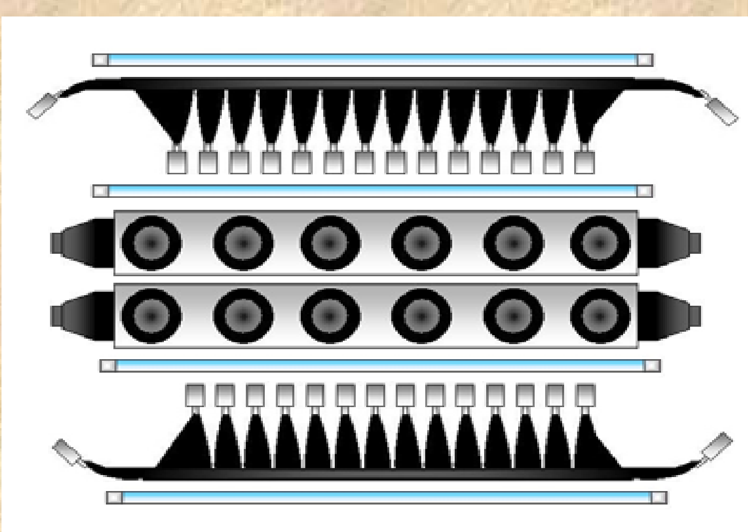
△ HEAO-3-C2 ▲■ ATIC-2 □ CRN

Heavy Nuclei

衛星実験に
匹敵するデータ

TIGER Instrument

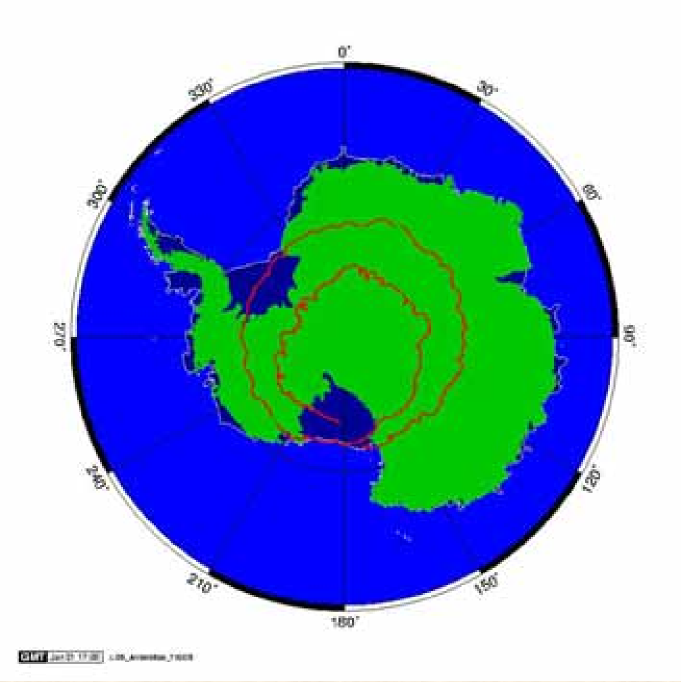




- Experiment Weight : ~1050kg
- Balloon Altitude: > 35.5 km
- Measurement of the elemental abundances of nuclei with 26 < Z < 40
- Energy measurement in 0.3-10 GeV/n.

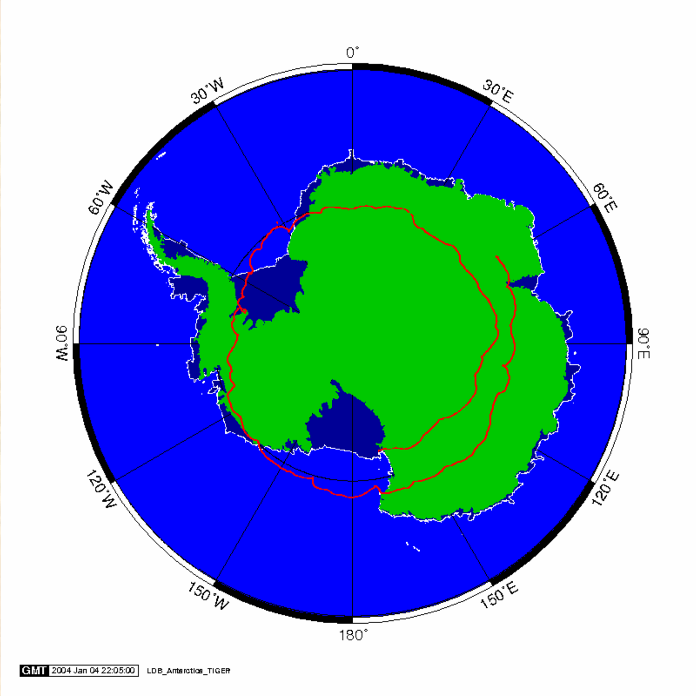
Flight Path for TIGER

2001-2002



31 days 21.5 hours
> 33 km

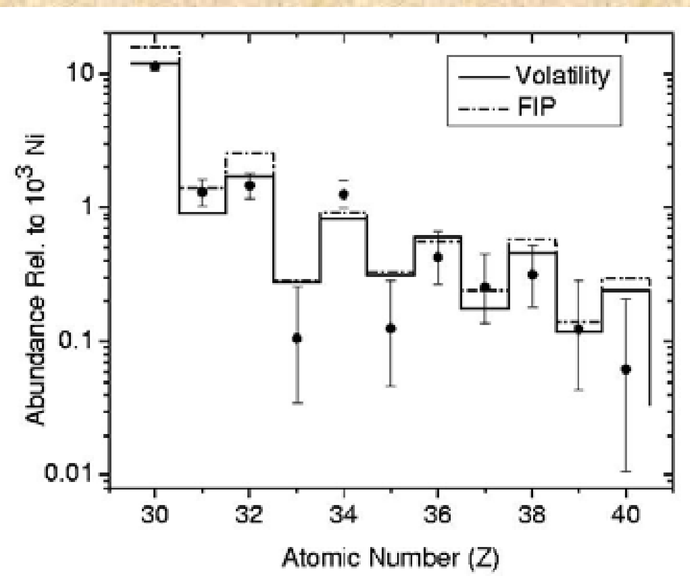
2003-2004



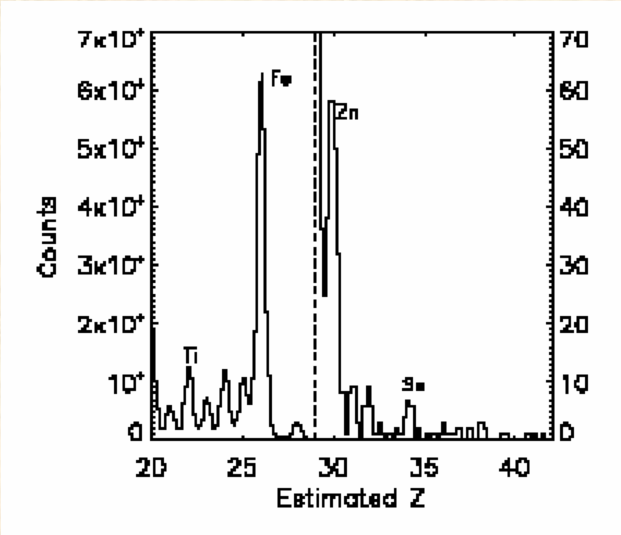
18 days
~38 km

TIGER Results

ICRC2003 2001-2002 data



360,000 Iron
300 Nuclei Z=30~40

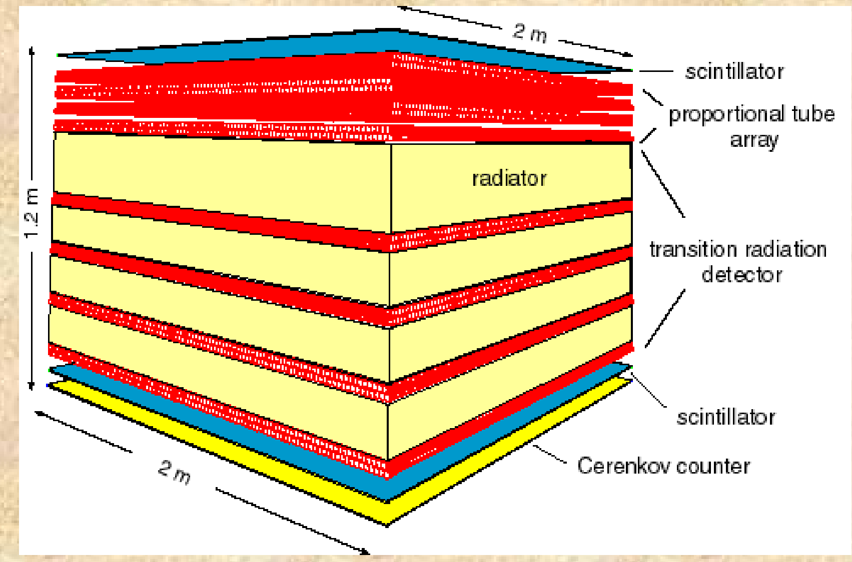


Z=30,32はVolatilityにはよく合うが
Z=31はFTPによく合う (Volatility
からのズレは～1.5σ)。
全体的にはVolatilityの方に近い。
ー＞　さらに統計が必要。

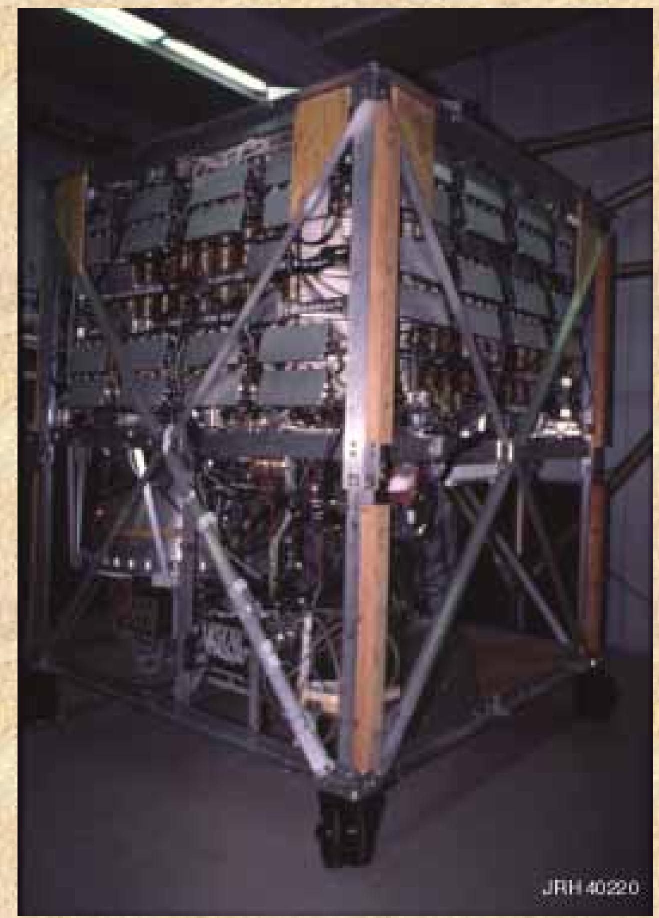
Cosmic Ray Source

- FIP or Volatility
- r-process, s-process ?

TRACER Instrument



The whole detector is mounted inside a 2.5 x 2.5 x 3 m^3 aluminum structure without a surrounding pressurized shell.

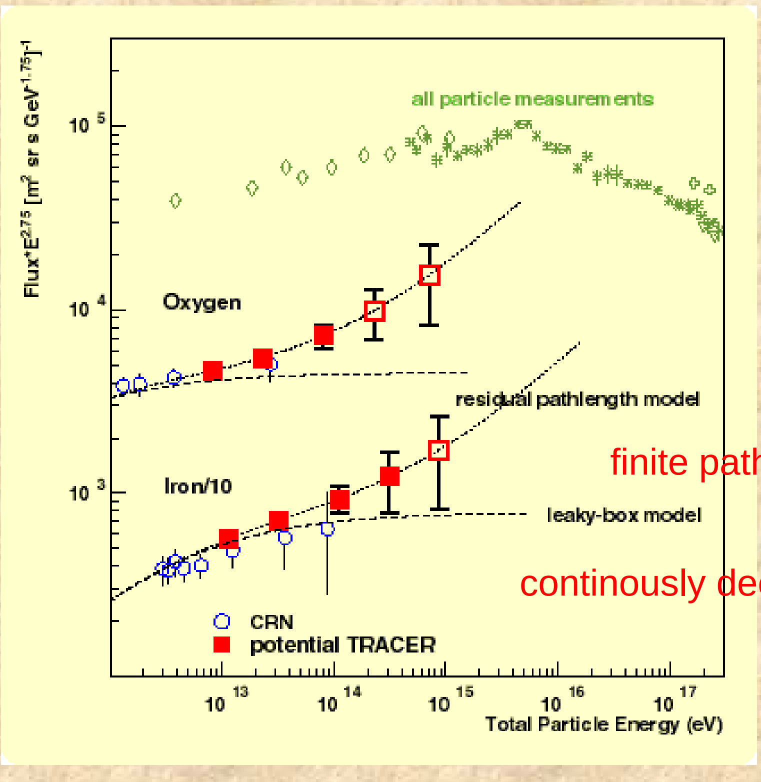


- Detector:
  Two layers of plastic scintillators (2 x 2 m^2),
  One Cerenkov counter (2 x 2 m^2)
  Transition radiation detector system which determines the Lorentz factor.
- Oxygen to iron in 10^{13} to several 10^{14} eV per nucleus
- 60 m^2 sr days for 12 days flight
- Altitude 37.5 km

TRACER Flight

2003.12 14days

TRACER Expectation



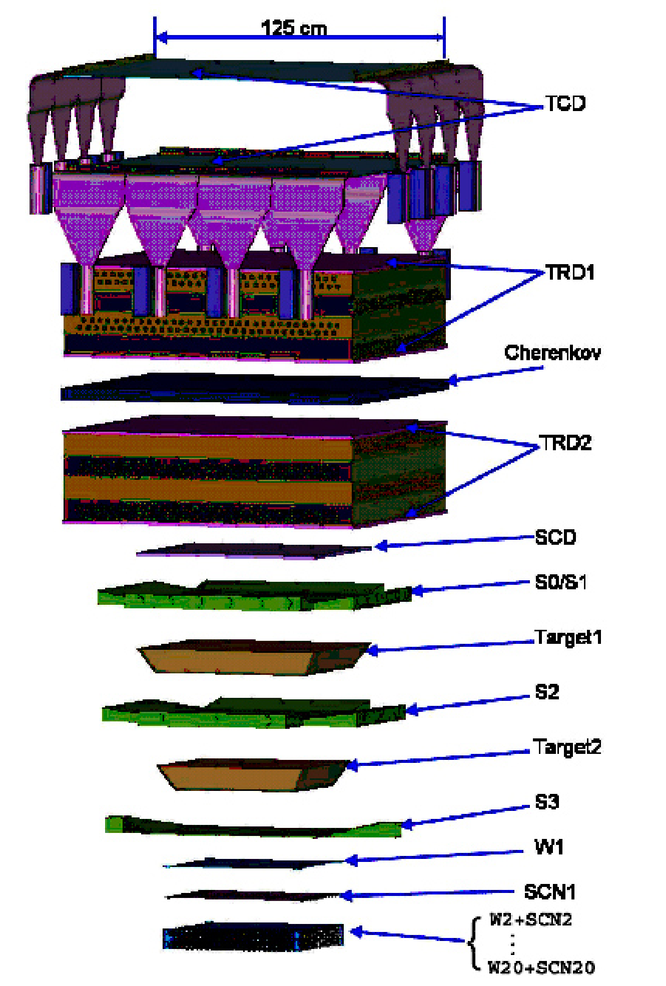
over 50 Million heavy Cosmic Rays (Carbon through Iron).

finite pathlength of 0.013 g/cm^2.

continously decreasing pathlength proportional to $E^{-0.6}$

Simulated data for oxygen and iron, indicating the statistical quality of data from TRACER for a 12 day flight.

CREAM Instrument

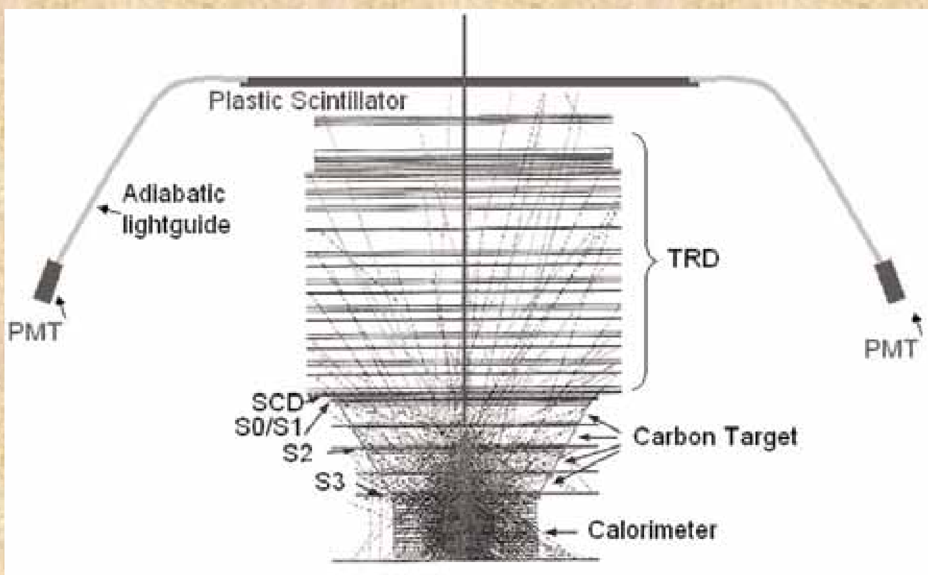


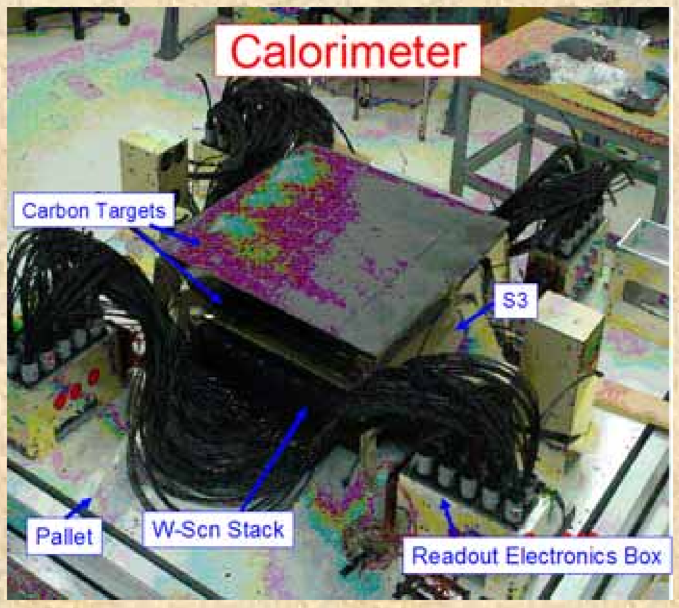
A key feature of the instrument: Simultaneous measurements of the energy and charge of a subset of nuclei by the complementary calorimeter and TRD techniques, thereby allowing in-flight inter-calibration of their energy scales.

Timing-Based Charge Detector
- Identify incoming particle
- Penn State U

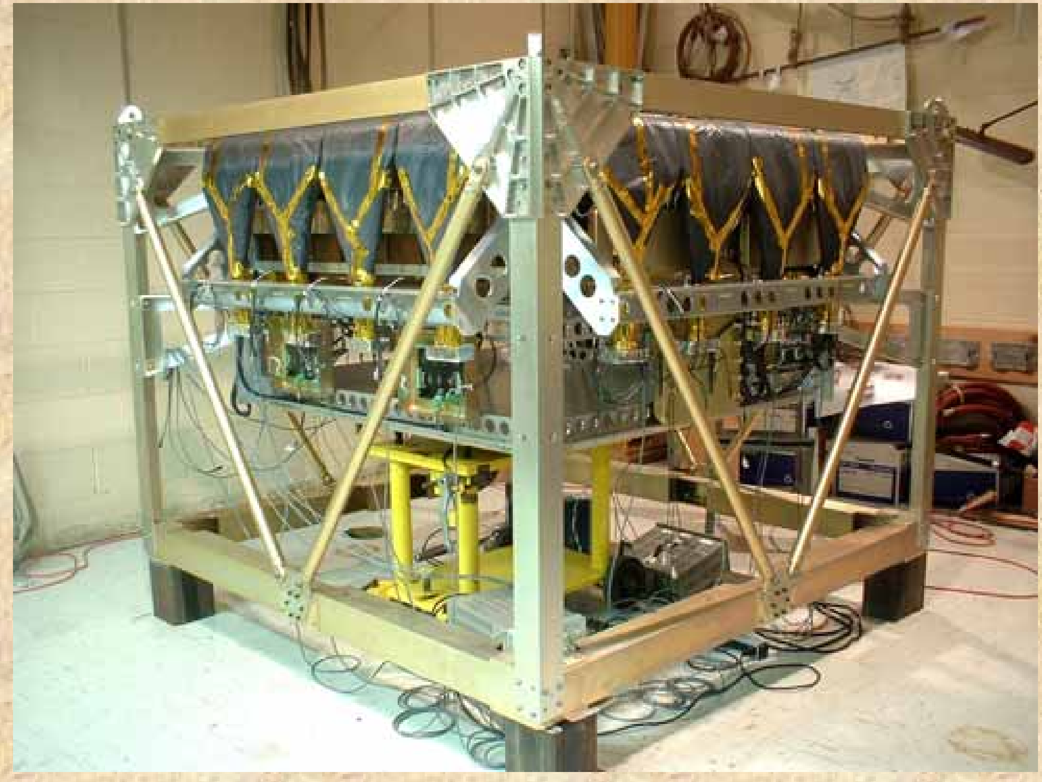
Transition Radiation Detector
- Measure velocity for Z ≥ 3
- U of Chicago

Tungsten-SCN Calorimeter
- Measure energy for Z ≥ 1
- U of Maryland




Calorimeter
Carbon Targets
S3
Pallet
W-Scn Stack
Readout Electronics Box

CREAM TCD



CREAM Performance

Instrument Weight ~1100 kg

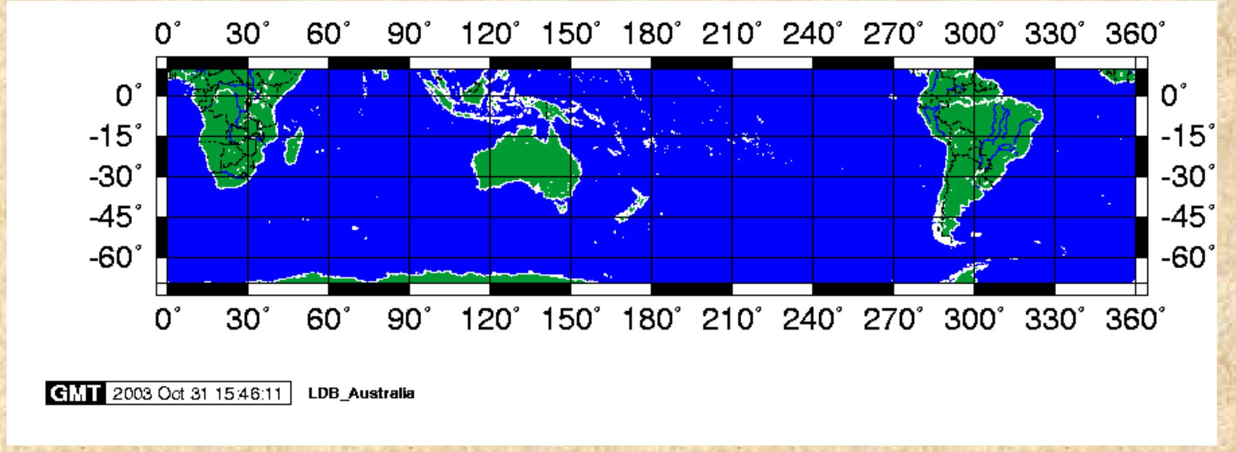
10^{12} to > 5 x 10^{14} eV by 3 flights of ULDB ⟶ 100 m^2sr day for P & He

• Element Coverage:	H to Ni (Z = 1 through Z = 28)
– Calorimeter	Z ≥ 1
– TRD	Z ≥ 3
• Charge Resolution:	Individual elements Z < 15
	Individual or element groups Z ≥ 15
• Energy Calibration:	Better than 10%
• Energy Resolution:	Better than 50%

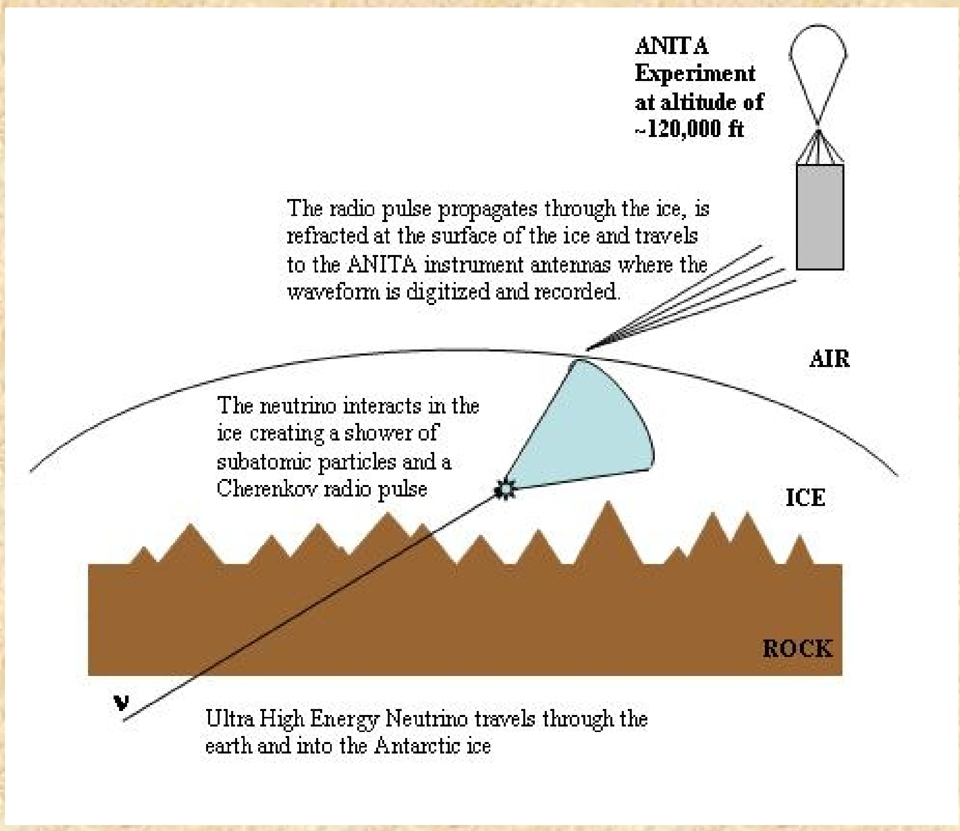
- Collecting Power:
  - 0.3 m^2sr for Z = 1 & 2 (considering interaction fractions)
    1.3 m^2sr for Z ≥ 3 (efficiency not included)

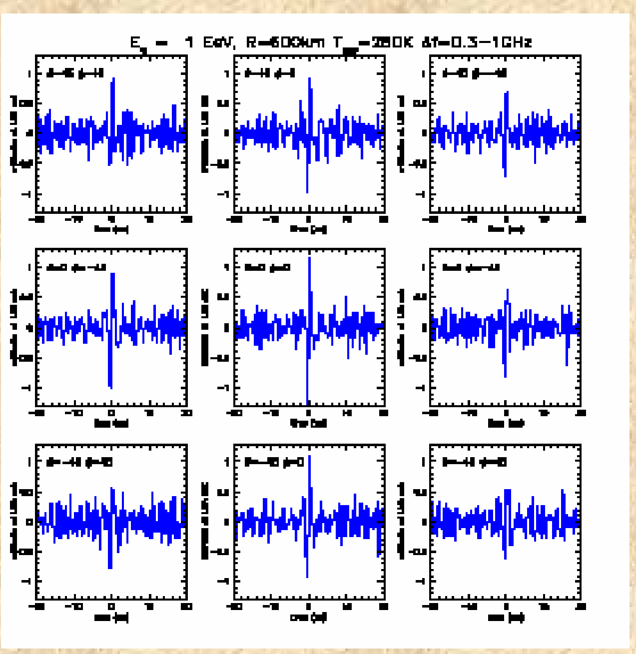
スーパプレッシャー気球

テストペイロード



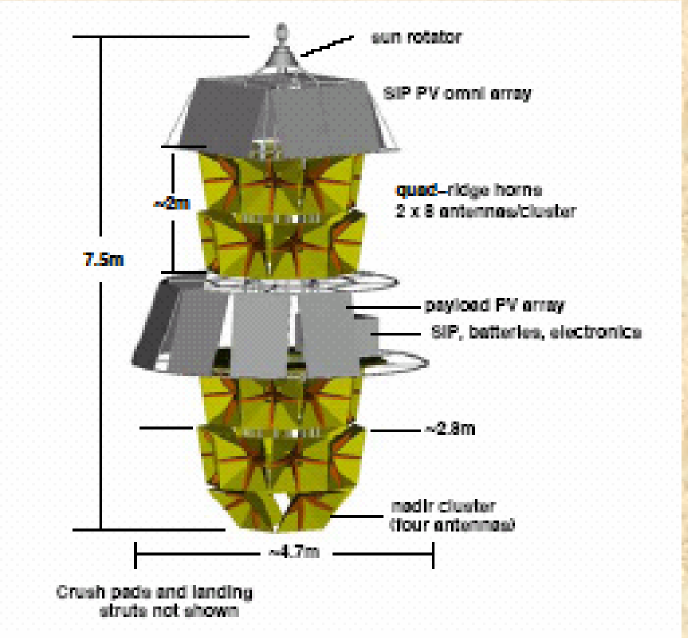
ANITALite　(Prototype of ANITA、SMEX Mission)





The ANITA instrument is designed to fly over the continent of Antarctica which is the location of some of the most pure ice in the world as well as one of the most radio quiet spots on earth. Flying at 120,000 ft (~ 37 km) the instrument can observe ~1.5 million square kilometers of ice. A simple pictorial explanation of ANITA's detection of neutrinos follows below

ANITA Instrument



Balloon Gondola / Launch vehicle

- Balloon gondola plus science payload mass = 1840 kg (4050 lbs). Dual gondolas planned for 1yr turnaround.
- Power requirements = 1 kW, solar photovoltaic panels
- Gondola is anti-rotation stabilized, sun-pointing
- Long-duration balloon launch from McMurdo Station, Antarctica
- No deployments or articulations necessary during flight

Schedule & Cost

Initial Flight	Dec. 2006 / Jan. 2007
2nd Flight	Dec. 2007 / Jan. 2008
3rd Flight	Dec. 2008 / Jan. 2009
Initial Data release	April 2009
Phase A/B	$7.1M
Phase C/D	$17.1M
Phase E	$3.4M
Balloon launch costs	$4.3M
Total (FY2003 $)	**$31.9M**

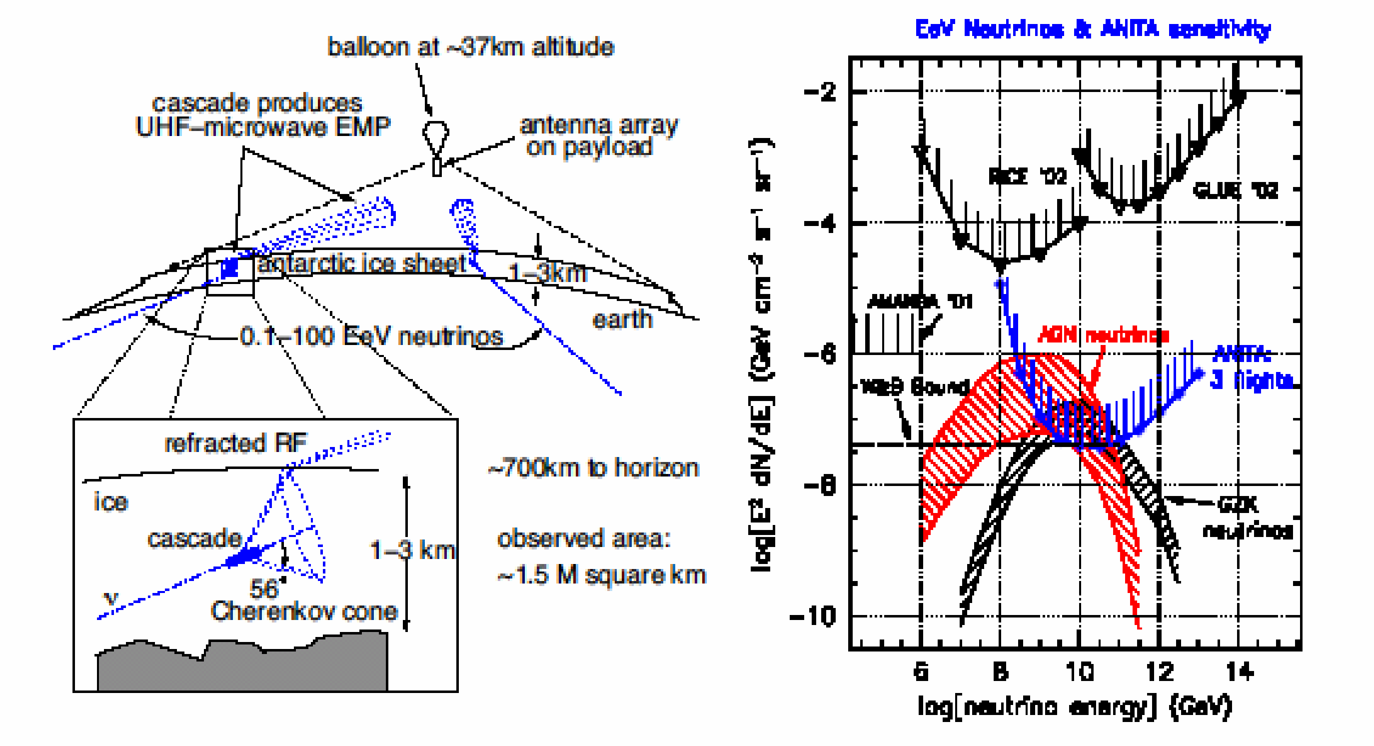
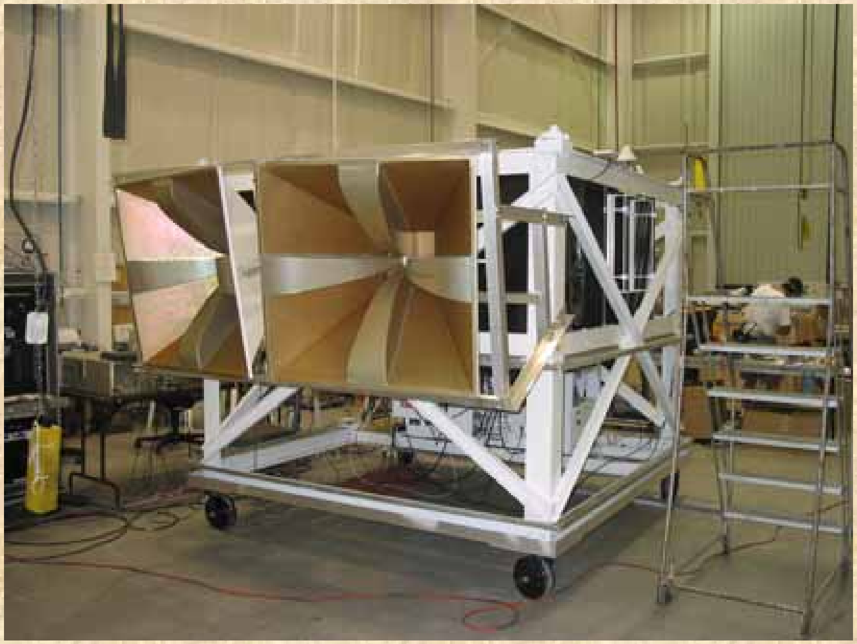


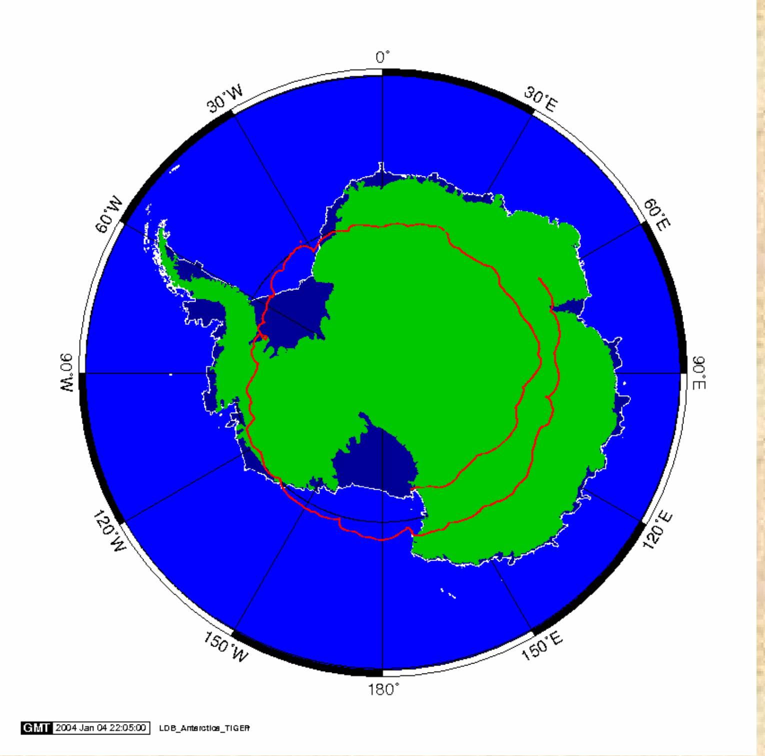
Figure 1: *Left: Schematic of the ANITA concept. Right:Neutrino models and limits along with estimated single-event sensitivity (SES) of ANITA for the baseline 45 day total exposure, assuming 75% observing efficiency. The AGN band is based on Mannheim [2] and covers a range from 0.1-1 of the nominal flux. The Waxman/Bahcall bound [3] is tied to the UHE cosmic ray flux and give a theoretical upper limit for optically thin sources, but does not apply for thick sources or top-down models. GZK neutrino flux range is given by ref. [7]. The GLUE and RICE limits are current experimental bounds on the neutrino fluxes.*

ANITALite FLIGHT with TIGER

2003-2004

Anita Tiger Track ~18 days

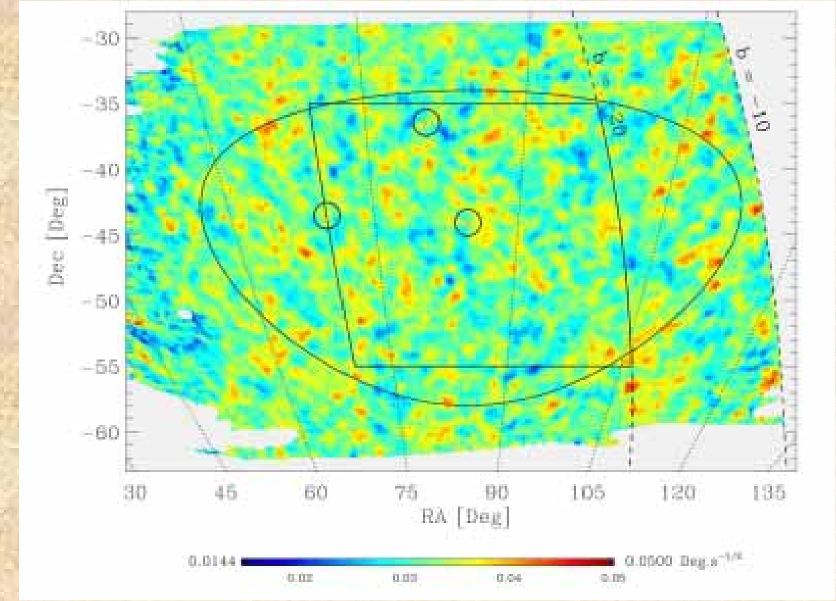




BOOMERANG Instrument and Result

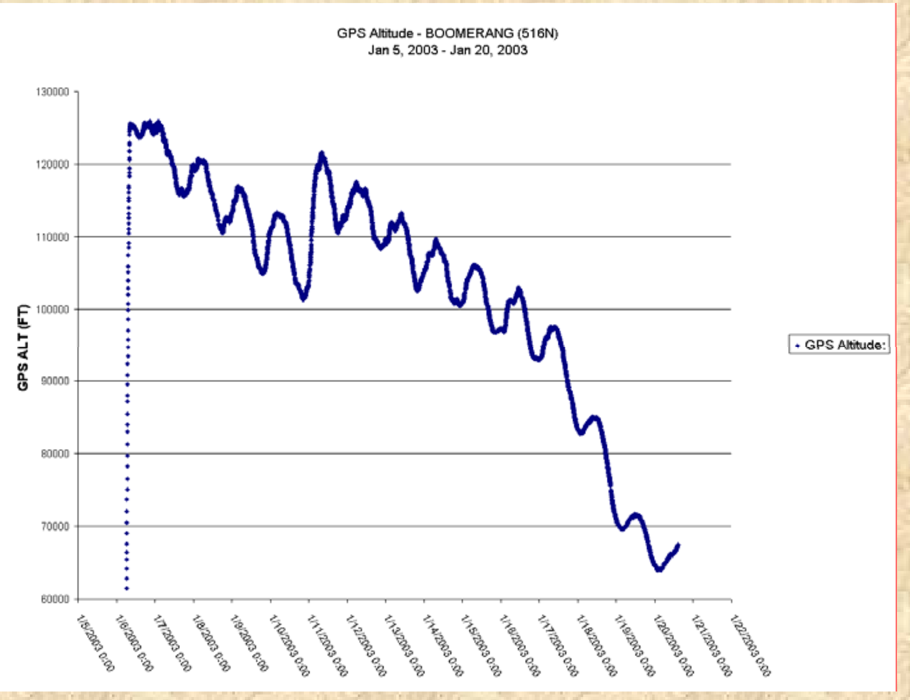
The 1998 LDB flight was 10.5 days long, more than 30 times longer than traditional flights flown from North America. The instrument measures the sky at four frequencies to help us separate faint galactic emissions from the CMB.

CMB Mapping

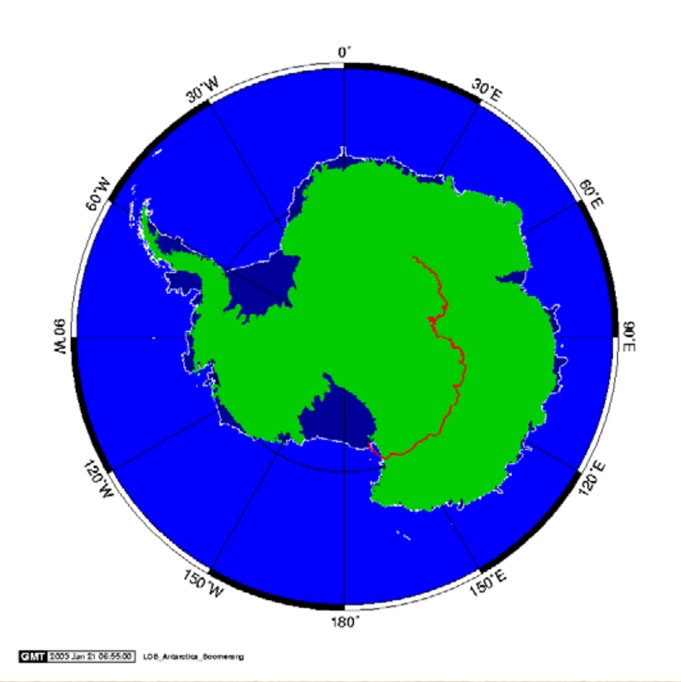


BOOMERANG Flight in 2003

Altitude



15 days flight in 2003.01



PPB-BETS Flight

- Launched at the Syowa Station, Antarctica
- Level Altitude ~34.6 km
- 13 days flight

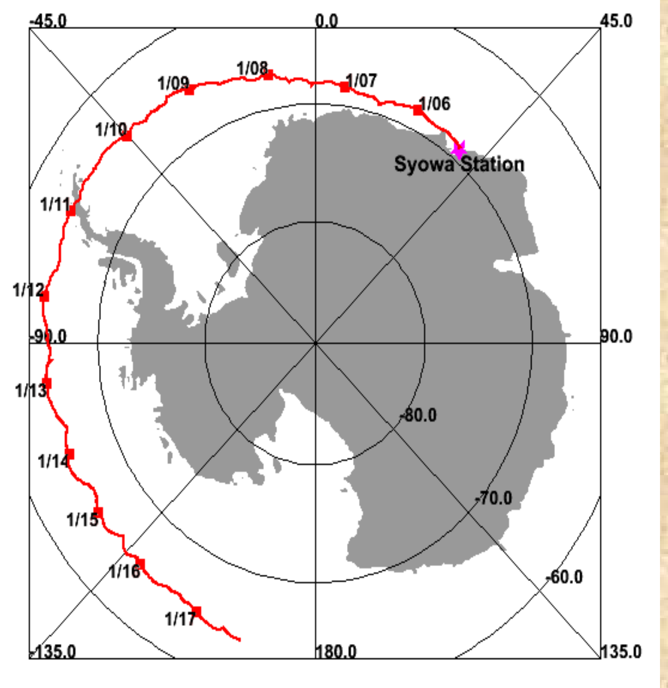
  (Jan. 4, 2004 to Jan. 17)

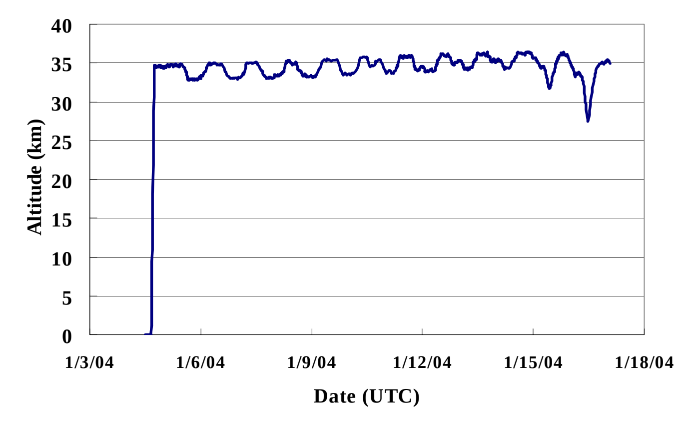
  HE (>100 GeV)

  〜5700 events, (0.02 Hz)

  LE(>10GeV)

  〜22000 events, (3 Hz)





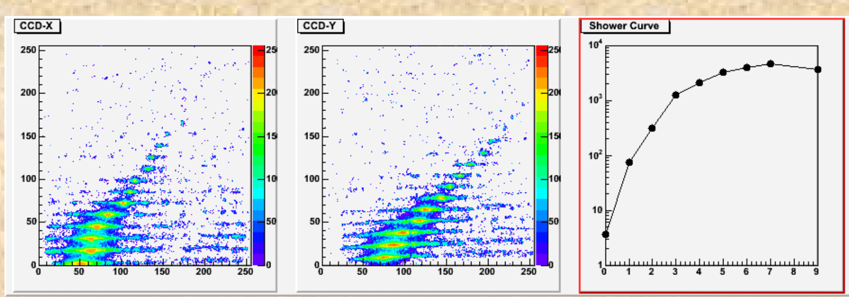
Basic Parameters of PPB-BETS

Detector Weight	200 kg	including un-pressurized gondola
(Total Weight including ballast for 30 days	500 kg)	
Power Consumption	70 W	supplied by solar batteries
Observation Altitude	~35 km	controlled by auto-level system
Data Transfer Rate	2.4 kbps	by the Iridium telephone line
	(64 kbps	by the telemetry to the stations)

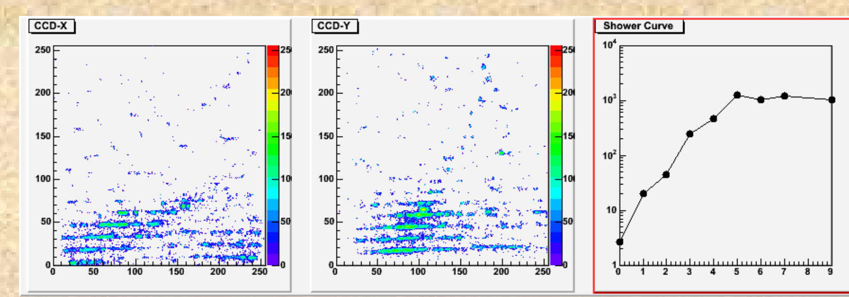
Energy Range	10 ~1000 GeV	by two modes of trigger
Geometrical Factor	550~600 $cm^2 sr$	by simulation (> 100 GeV)
Energy Resolution	12~ 16 %	by plastic scintillators
Angular Resolution	0.35~ 0.6 degrees	by shower image of SciFis

Examples of Observed Events

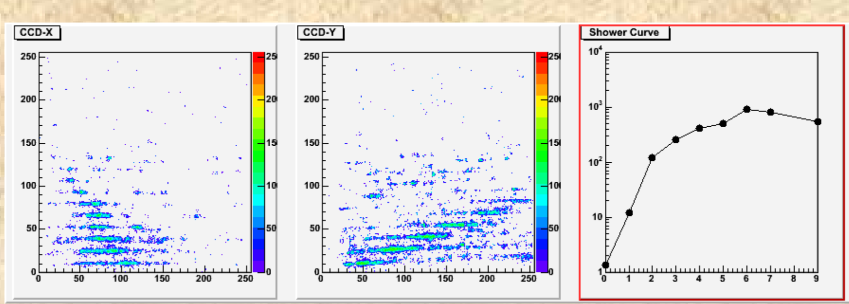
X,Y Image by CCD   Transition Curve



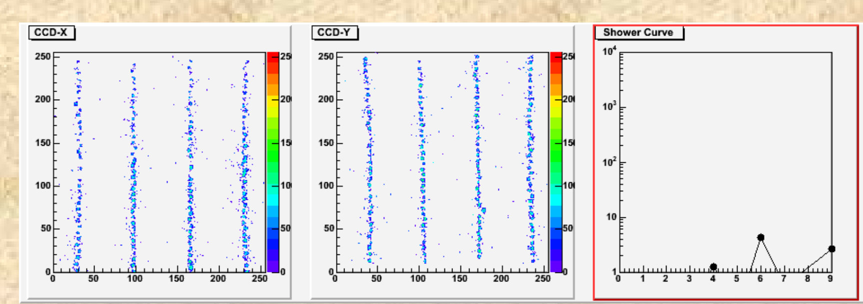
Electron-like Event



Proton-like Event



Proton –like Event



LED Calibration

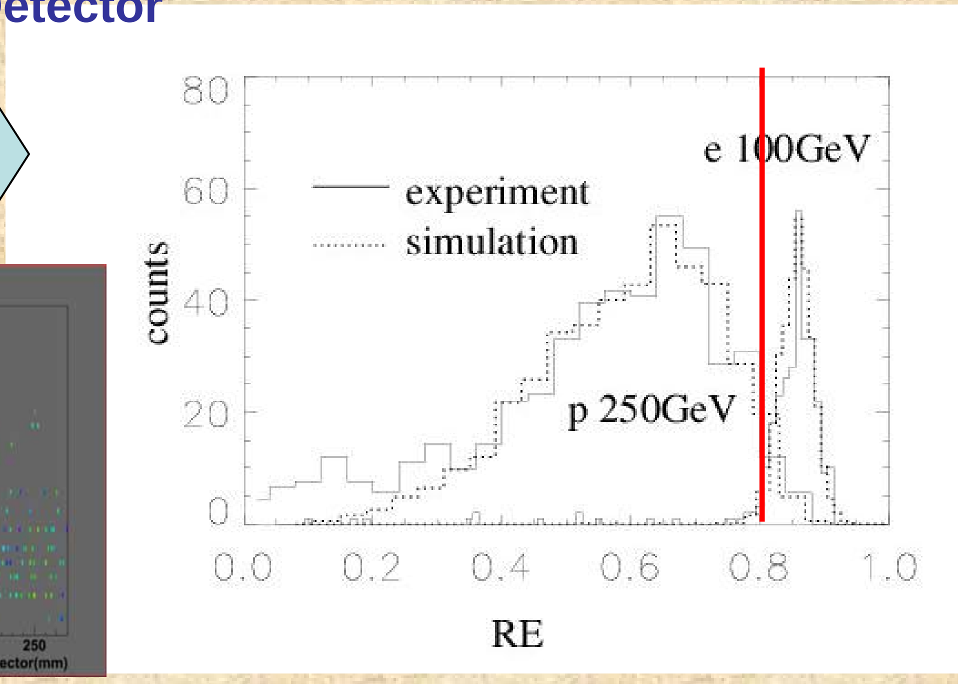
Selection of Electron Events

Reduction of proton backgrounds:

On-board Trigger by the 1st and 2nd levels
~ 95 %

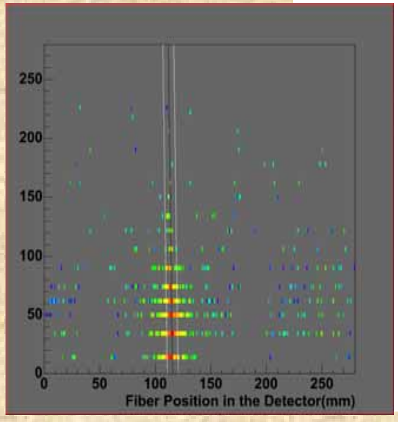
Selection of Contained Events in Detector
~ 90 %

Shower Image Analysis
~95 %



RE parameter:
Energy Concentration in Shower

$$RE = \frac{\text{within 5 mm from the axis}}{\text{Total}}$$

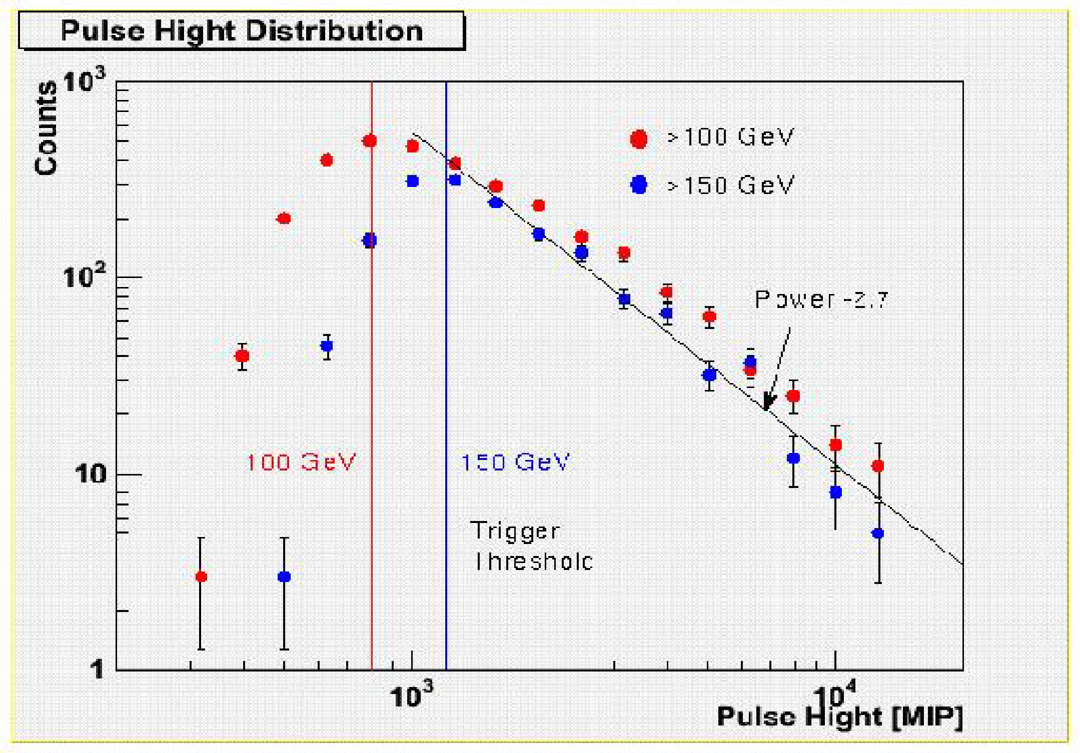


Total Rejection Power of Protons: 0.05 x 0.1 x 0.05 = 2.5x 10^{-4}

Preliminary Results of Data Analysis

Pulse Height Distribution @ 7 r.l.

●● : 2 sets of thresholds on HE trigger



Observed Number of Events

Trigger Mode >100 GeV
3066 events

Trigger Mode > 150 GeV
1637 events

Expected Number of Electrons over 100 GeV
~ 100 Events

More than one order of total number of BETS observation (4 events)

まとめ

１．２０００年以降になると、長期間気球による高精度装置を用いた宇宙線観測が実施されるようになった。

２．南極では、１５－３０日間の観測が可能であり、NASAでは装置の回収により、同じ装置による数回の観測が実施され、１００日に近い観測もある。

３．スーパープレッシャー気球を用いるとバラストが少量に押さえられるため、１００日間にわたる長期観測が可能となる。

４．国内でも、長期間気球（南極、南半球）の実現にむけて準備が進んでいる。

－＞新たな観測計画の提案