

Extraction of Antiparticles Concentrated in Planetary Magnetic Fields

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Personnel Involved

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- Special Thanks
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 - Anatoly Gusev, PhD (Space Research Institute, Moscow, Russia)
 - Richard Selesnick, PhD (The Aerospace Corporation)
 - John West (Draper Laboratory)
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 - Shari Bickford

Motivation



- **Applications for Antimatter**

- Aggressive high ΔV space exploration
 - High energy density fuel (10 orders of magnitude better than the best chemical propellant)
 - Catalyst for nuclear reactions (nanogram range)
- Medicine
 - Tumor treatment, medical diagnostics
- Homeland Security
- Basic Science

- **Conventional Production**

- Limited to high energy particle accelerators
 - CERN, Fermilab
- Inefficient and energy intensive
 - \$160 trillion/gram collected (Lapointe, 2001)
- Limited production capability
 - Dedicated accelerator production rate currently in the ~nanogram/year range (Schmidt, 1999)

- **Antimatter Storage**

- Very limited quantities stored for ~days.
 - Vacuum limits (annihilation losses)
- Current technology $\sim 10^{10}$ kg/ $\mu\text{g}_{\text{stored}}$



Traditional Manned Mars Mission
(Draper/MIT CE&R concept)

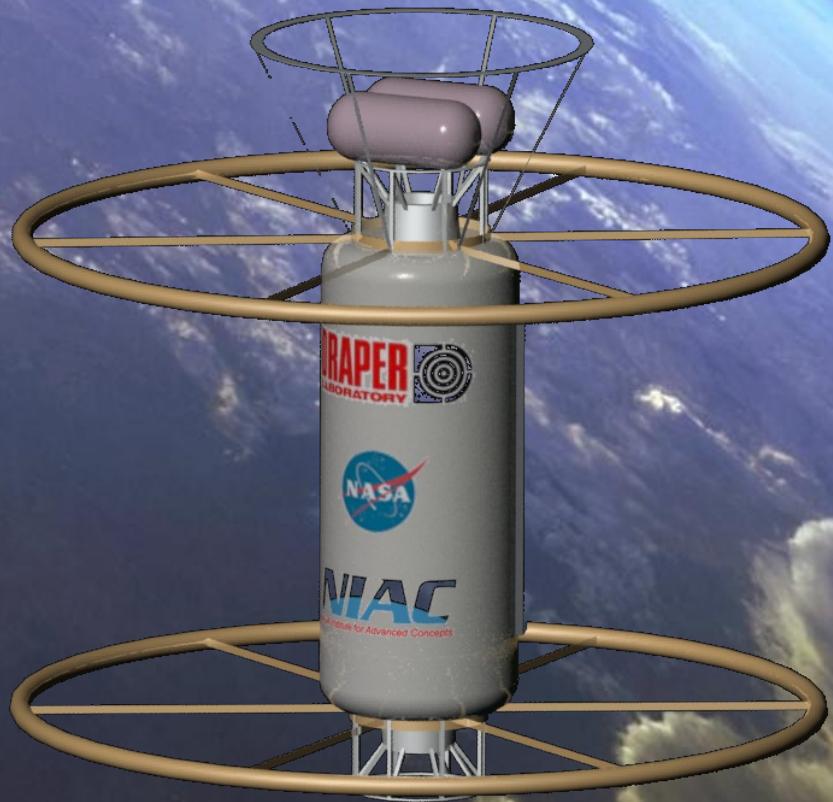
Fuel	Energy Density (J/kg)	Notes
Battery	7.2×10^5	Lithium Ion
Chemical	1.4×10^7	LO_2/LH_2
Fission	8.2×10^{13}	U^{235}
Fusion	3.4×10^{14}	DT
Antimatter	9.0×10^{16}	$E=mc^2$

Overview

- **Antiproton Sources**
 - Cosmic Ray Albedo Antineutron Decay (**CRANbarD**)
 - $p + p \rightarrow n\bar{n} + n + p + p \rightarrow p\bar{p} + e^+ + \text{positron} + \nu + p + p$
 - Pair production and trapping in the exosphere
 - $p + p \rightarrow p\bar{p} + p + p + p$
 - Transient galactic cosmic rays (GCR) background
 - Artificial Augmentation
- **Positron Sources**
- **Loss Mechanisms / Replenishment Rates**



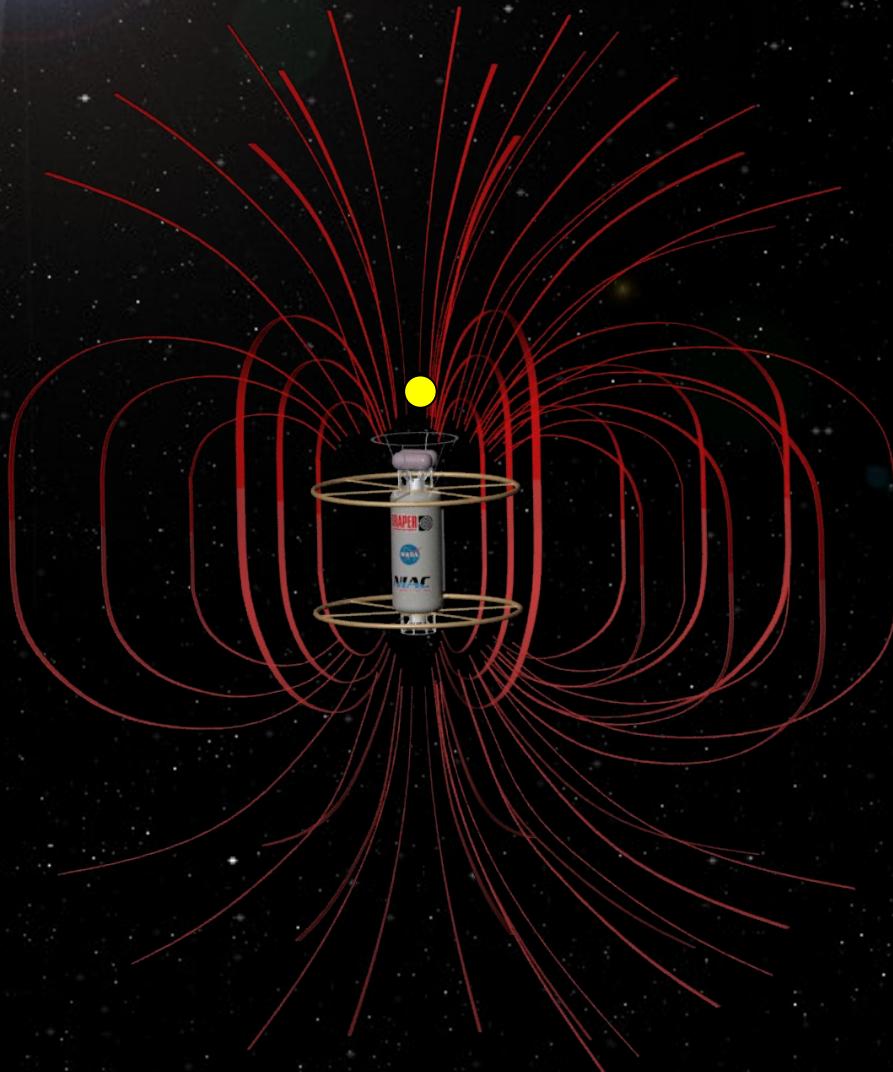
Overview



- **Orbital Collector**
 - Efficiency
 - Rate



Concept Vision

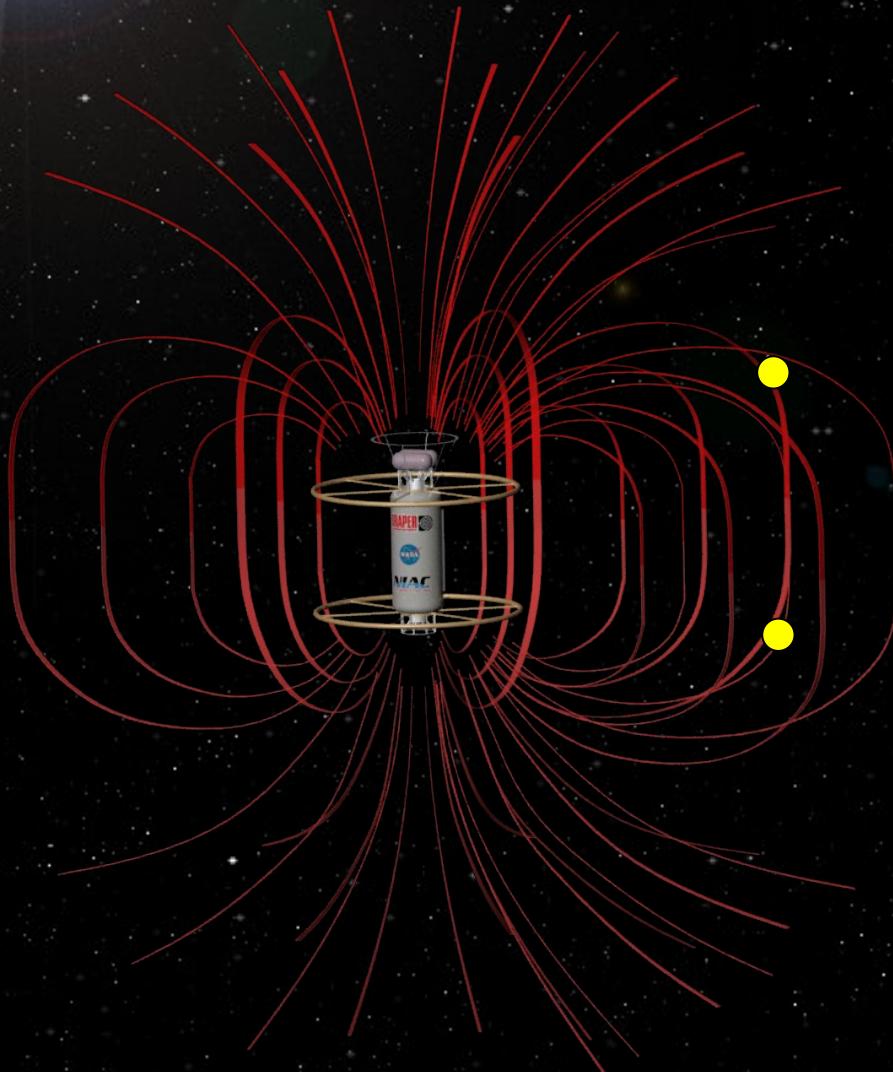


Magnetic Field

- Antimatter Collection
 - Magnetic scoop collects charged particles over large expanses of space.



Concept Vision

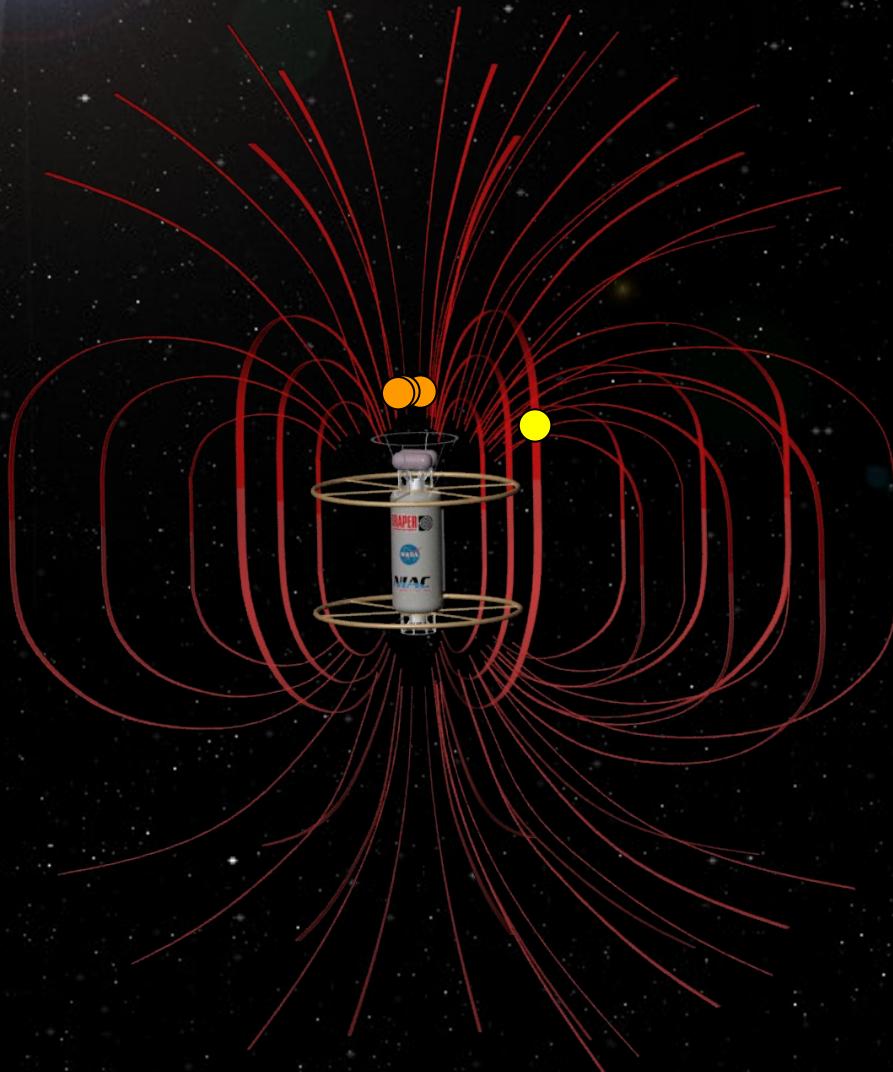


Magnetic Field

- Antimatter Collection
 - Positively and negatively charged particles held in mini-magnetosphere.
 - Leverages the large scale vacuum provided by the natural space environment.
 - Particles and their antiparticles can coexist in the field due to the very low annihilation rates at high energy and low density.



Concept Vision

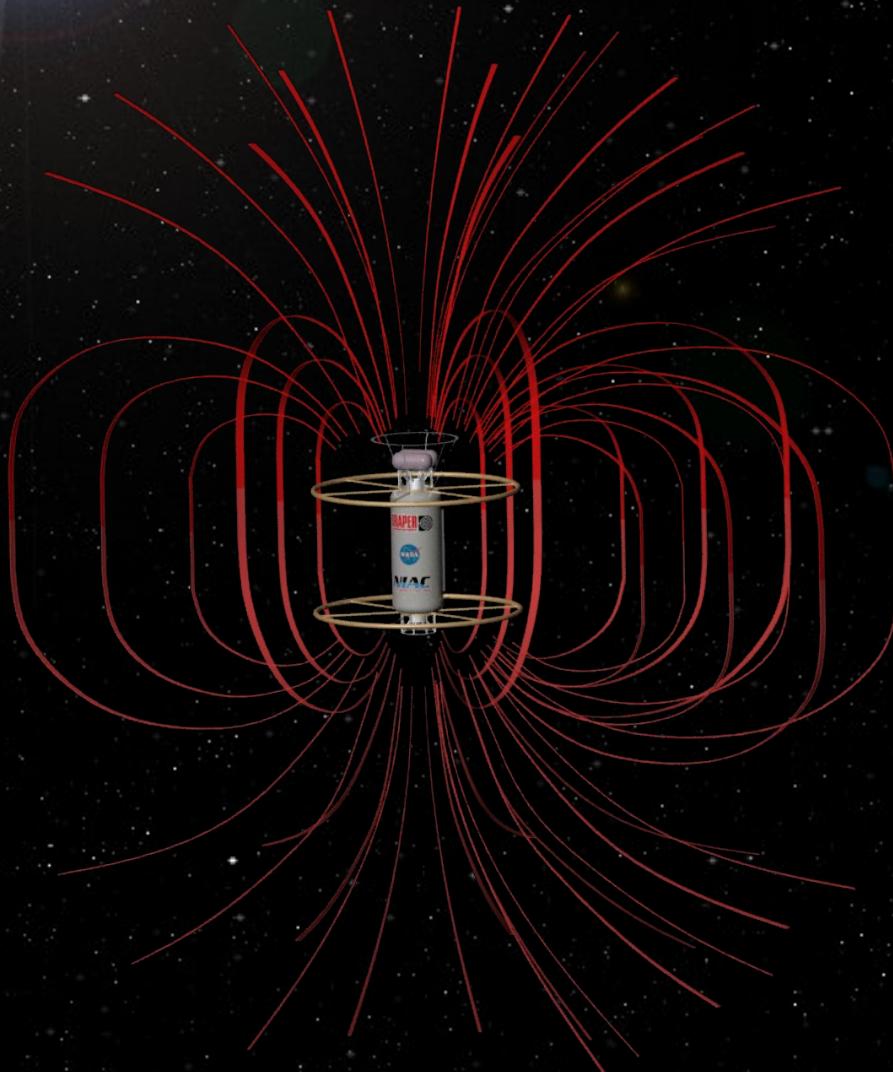


Magnetic Field

- Antimatter Collection
- Antimatter Storage
- Propulsion System
 - Directs ejecta from catalyzed nuclear reactions
 - Differential extraction of kinetic energy?



Concept Vision



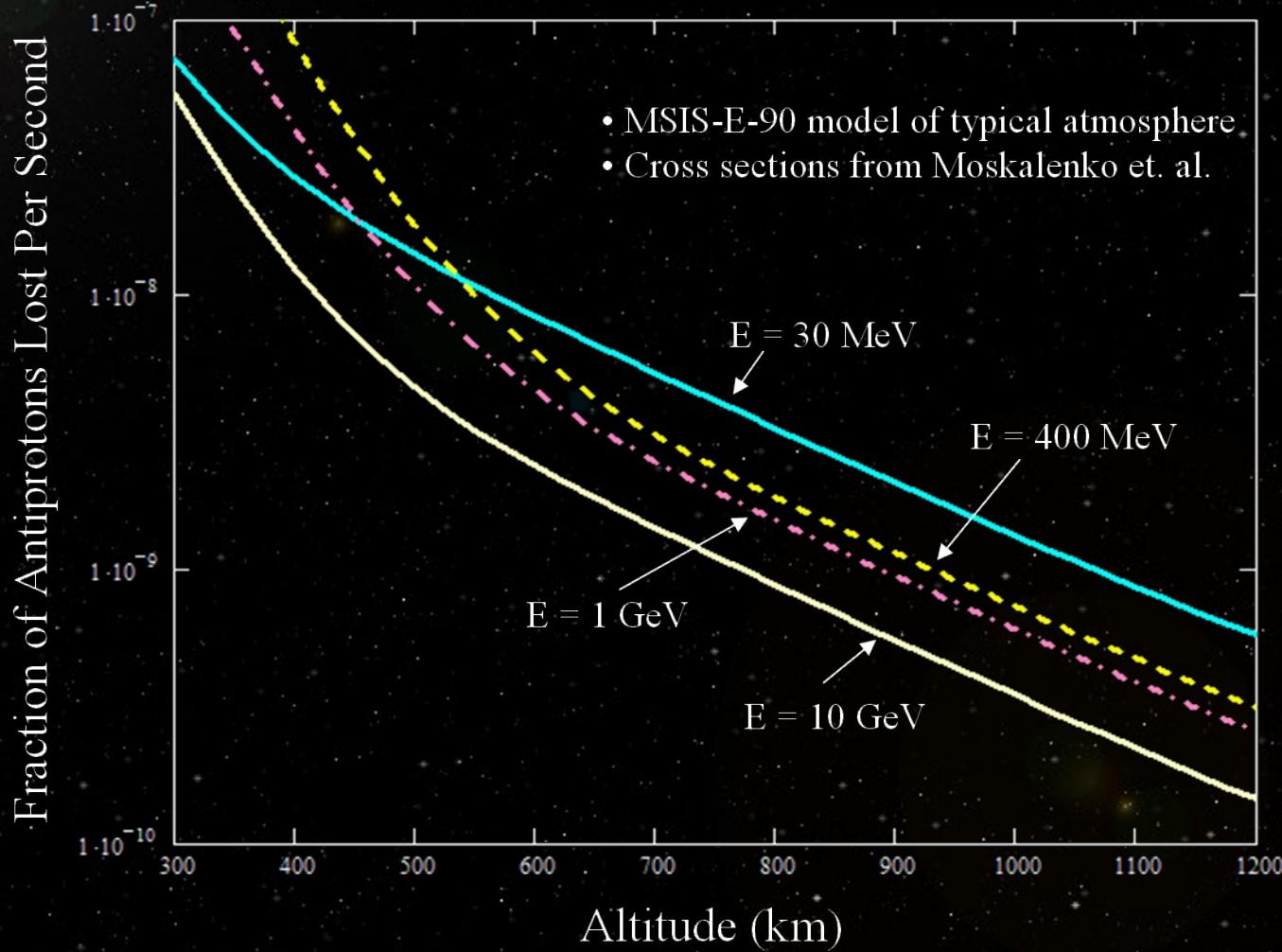
Magnetic Field

- Antimatter Collection
- Antimatter Storage
- Propulsion System
- Radiation Shield
 - Intrinsic protection against charged particles.

Atmospheric Annihilation



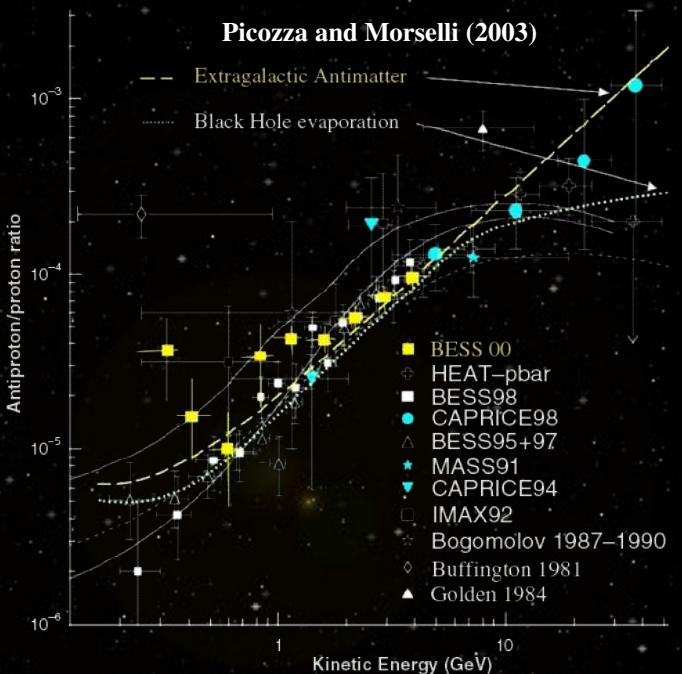
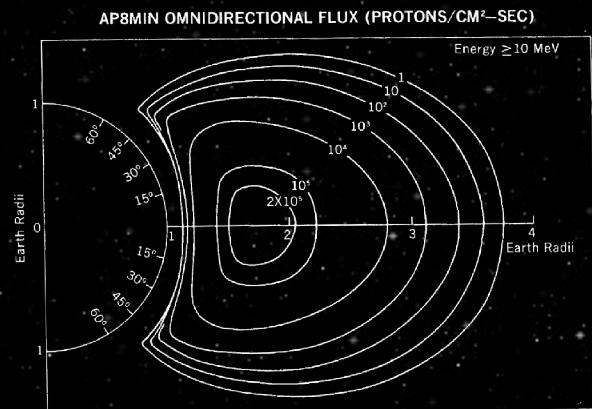
The first question I always get – why don't the antiparticles just annihilate with the atmosphere?



Initial View (Empirical Data)



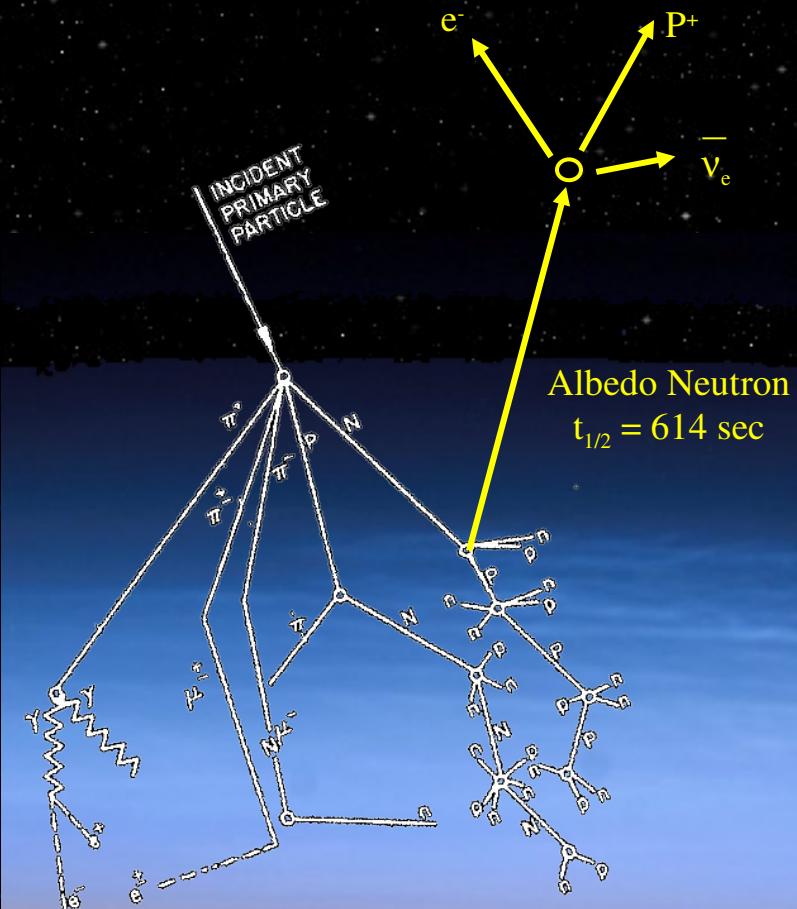
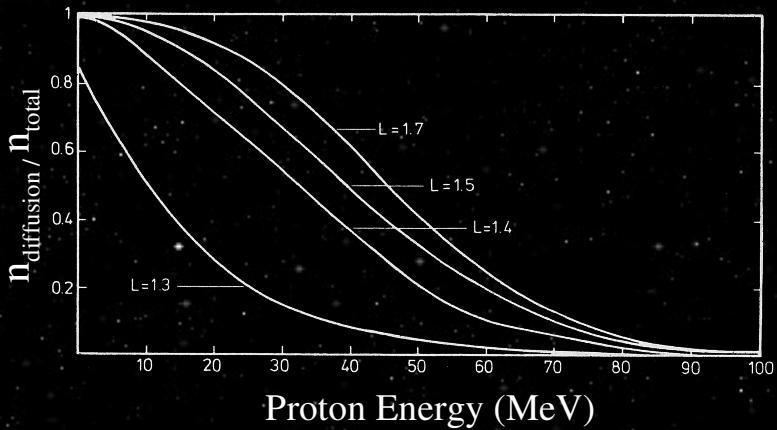
- Total Belt Mass Content
 - Integration of AP8/AE8 radiation models.
 - Protons : ~ 2.5 kg ($E > 1$ MeV)
 - Electrons : ~ 8.5 g ($E > 100$ keV)
- Empirical satellite/balloon data
 - Antiparticle formation from pair production from GCR passing through 5-7 gm/cm² of interstellar material.
 - Total pbar/p ratio : $\sim 10^{-4}$
 - Total e⁺/e⁻ : ~ 0.1
 - Belts and GCR antiproton flux both formed from nuclear interactions with GCR protons.
 - Implied vast trapped antiparticle reserves
 - True?
 - Focus of this study.



Proton Belt Source



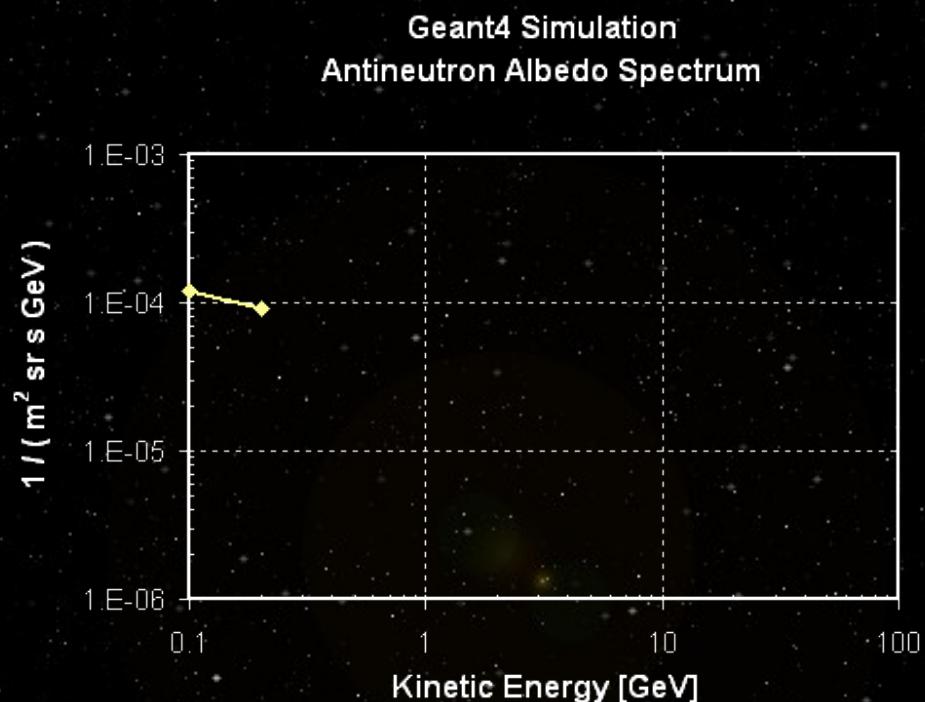
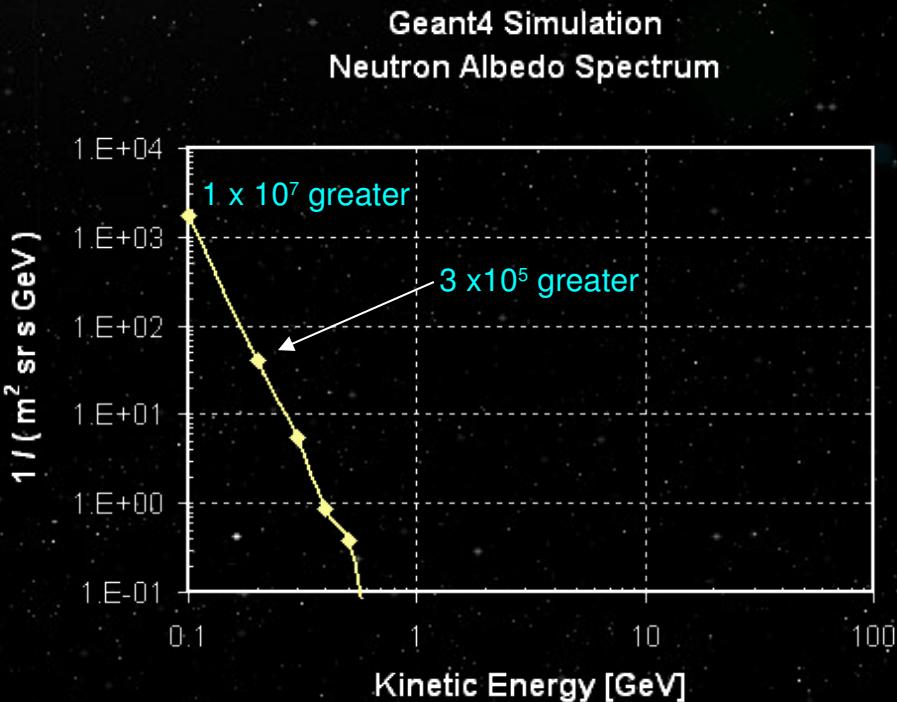
- Cosmic Ray Albedo Neutron Decay (CRAND)
 - Albedo neutrons decay within trapping region to populate the belts.
 - Primary generation source for high energy inner belt protons ($E > 30$ MeV).
- Diffusion of Solar Protons
 - Magnetic fluctuations allow low energy solar protons to diffuse inward
 - Relative contribution given by Jentsch model (1981)





Albedo Spectrum

- Preliminary Geant4 simulations predict an antineutron albedo flux about 7 orders of magnitude lower than the corresponding albedo neutron flux.

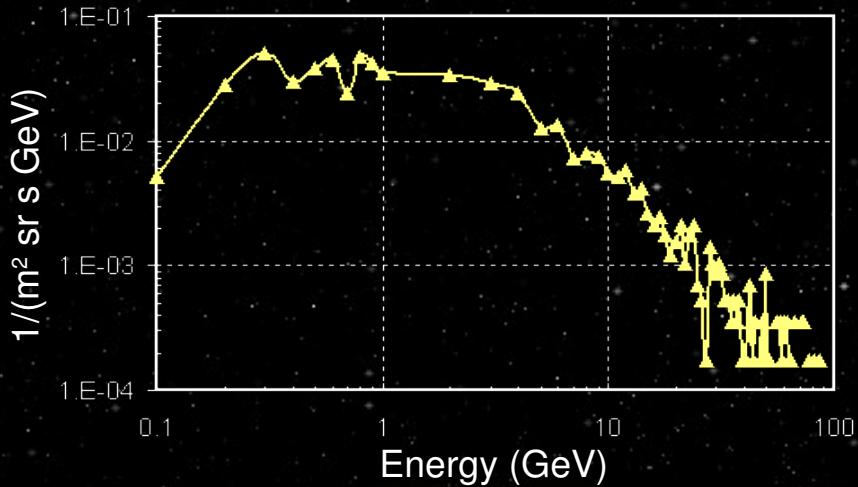


Albedo Antineutrons

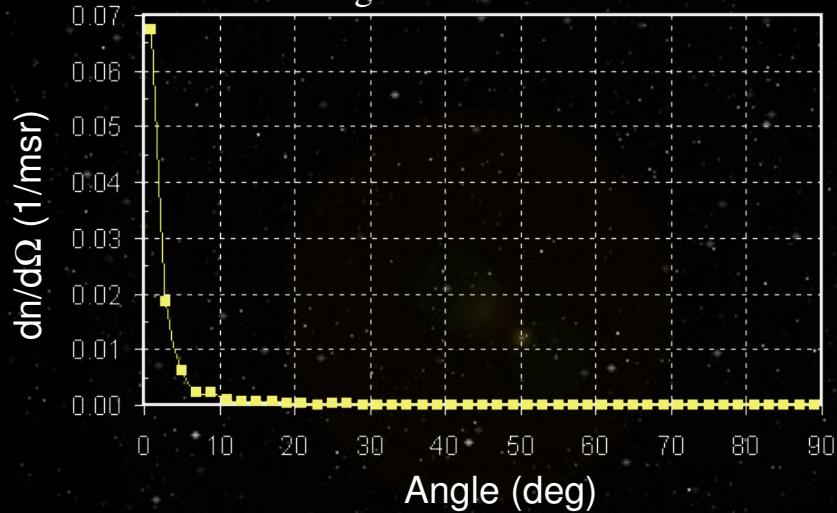


- Narrow downward angular distribution of GCR pair produced antineutrons produces limited numbers of albedo anti-neutrons.
- Significant loss in efficiency relative to neutron backscatter
 - Preliminary Geant4 simulations show the ratio is about 1 albedo anti-neutron for every 10^5 - 10^9 albedo neutrons.
 - Pugacheva et al. (2003) provided a similar estimate at 100 MeV.
 - Antiproton flux reduced by this fractional efficiency
- Proton flux provided by AP8
- Contribution of solar protons provided by Jentsch model.
- Effective fluxes calculated by combining the above empirically derived models.

Antineutron Atmospheric Production Spectrum



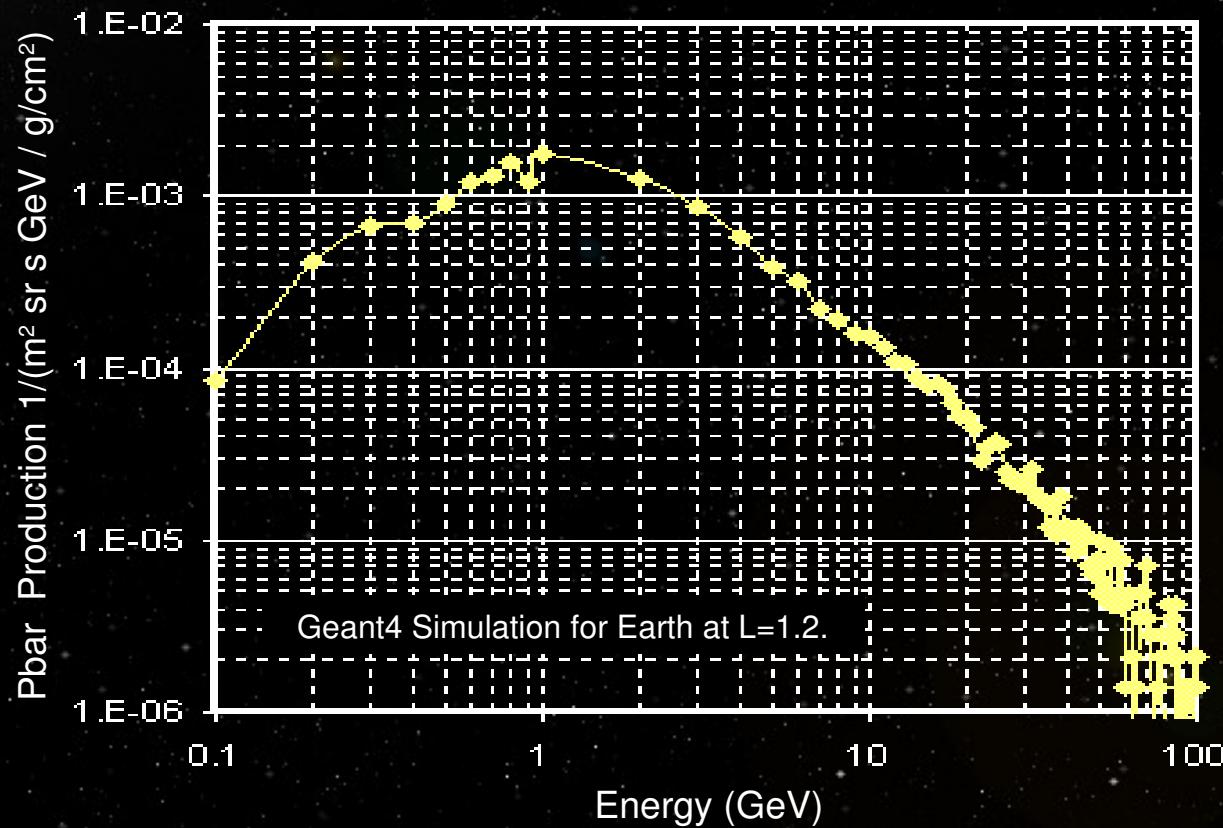
Angular Distribution





Pbar Source Function

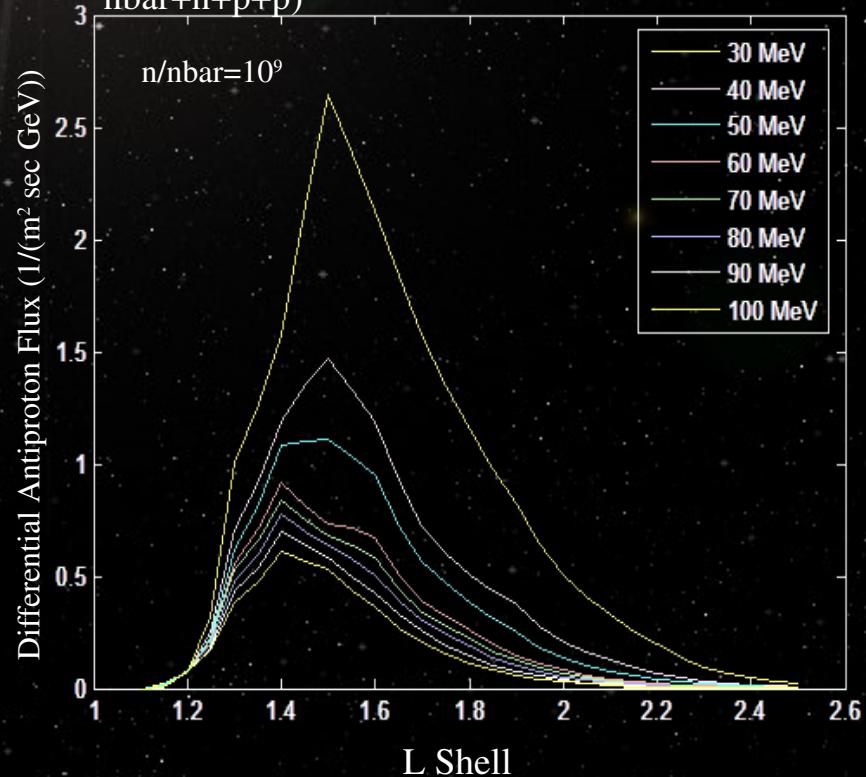
- Antiprotons also produced directly via pair production in the residual atmosphere.
 - Particles generated with trajectories outside the loss cone will be trapped.
 - Balance between sufficient density to produce antiprotons, and loss rates due to annihilation with the upper atmosphere.



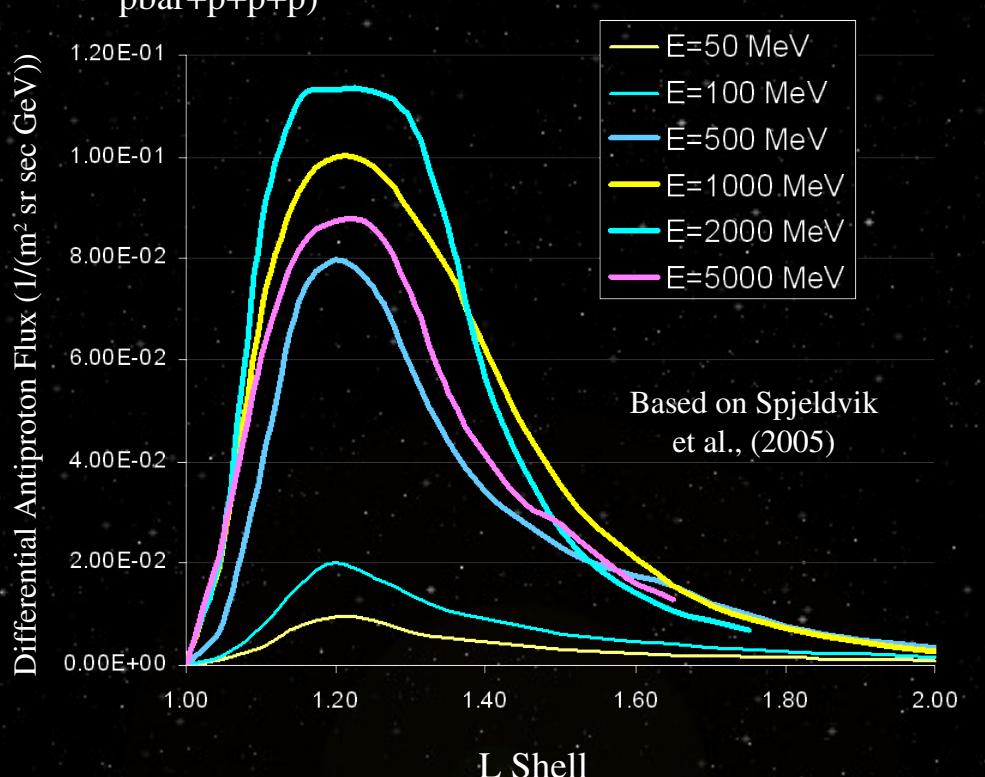
Internal Antiproton Fluxes



CRANbarD Induced Fluxes ($p+p \rightarrow n\bar{n} + n+p+p$)

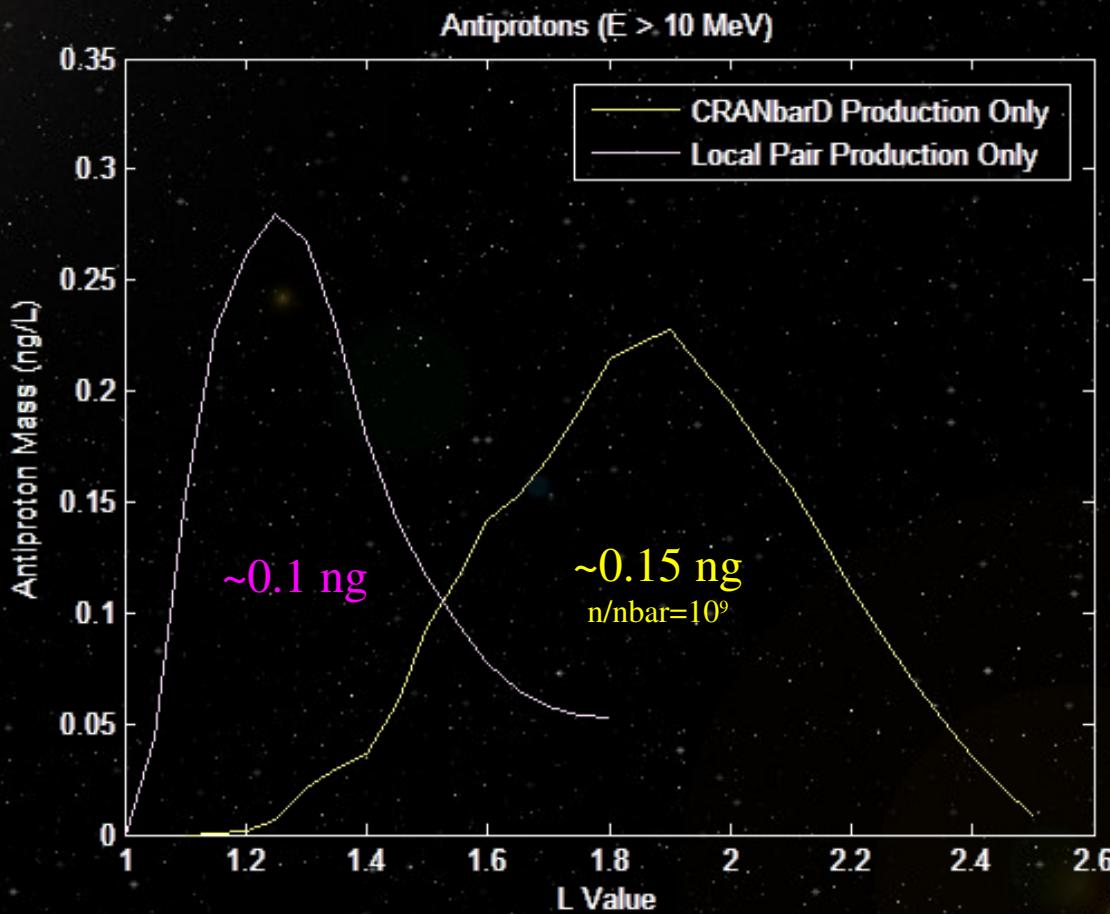


Direct Internal Source Fluxes ($p+p \rightarrow p\bar{p} + p+p$)



Calculated inner belt antiproton fluxes can exceed the GCR fluxes by an order of magnitude or more depending upon energy. At the 2 GeV GCR peak, the internal source flux at Earth is about 5X higher than the interstellar one.

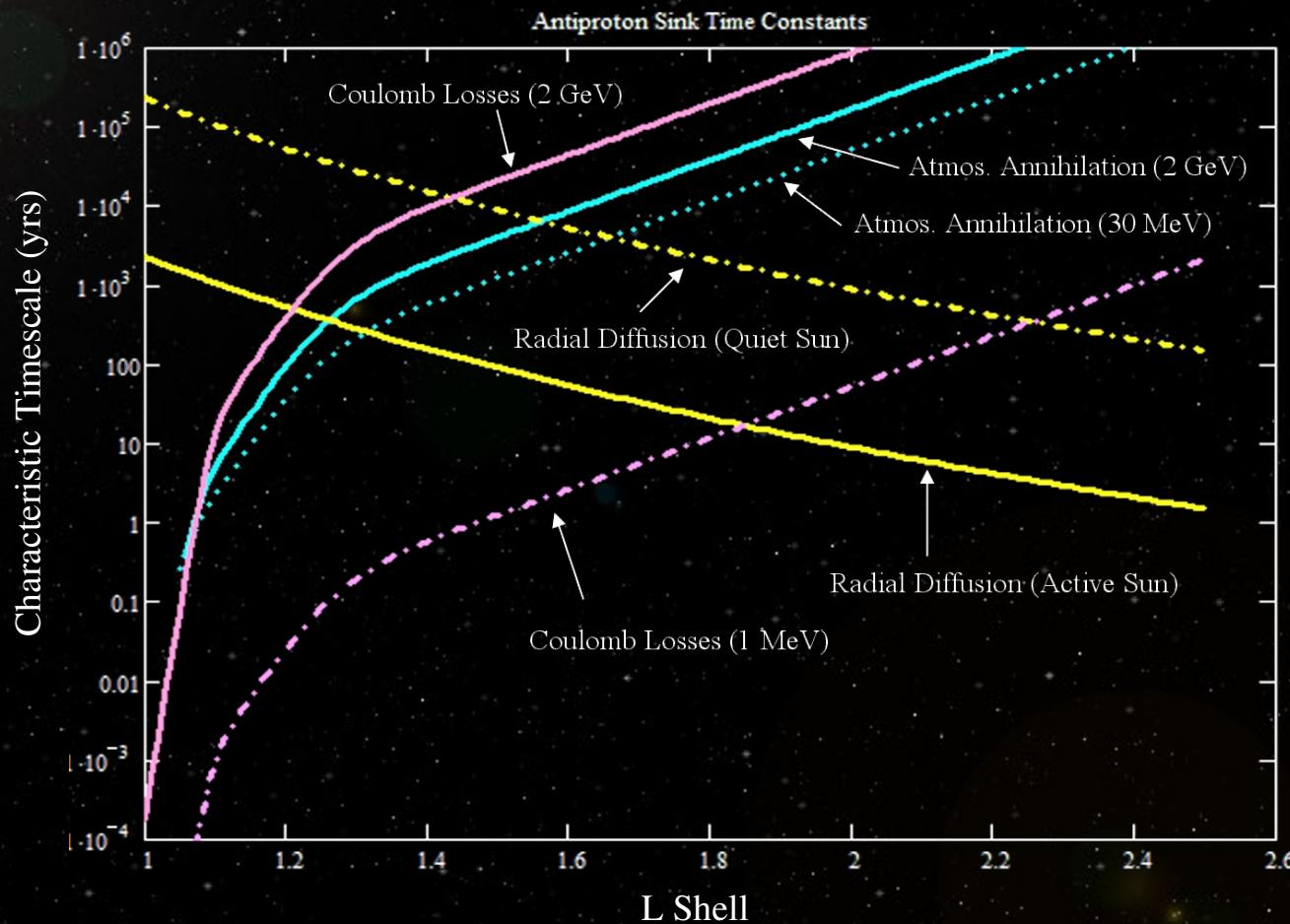
Trapped Inner Belt Mass



The estimated quasi-static antiproton belt mass is only about 0.25 nanograms around the Earth.



Antiproton Loss Timescales

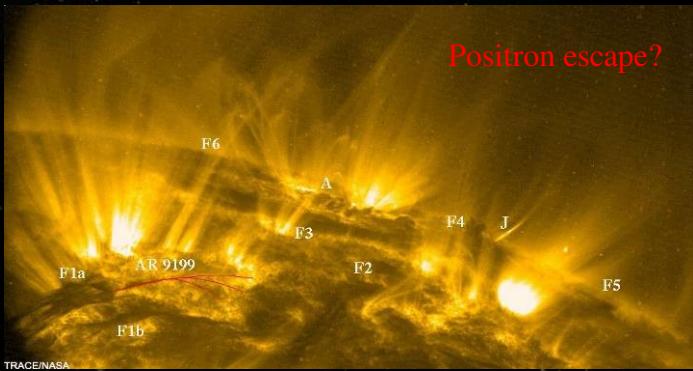


The antiproton radiation belt is replenished over the timescale of years ($<< 1 \text{ ng/yr}$). Given these rates, the trapped Earth supply does not represent a practical source of antiprotons for mining.

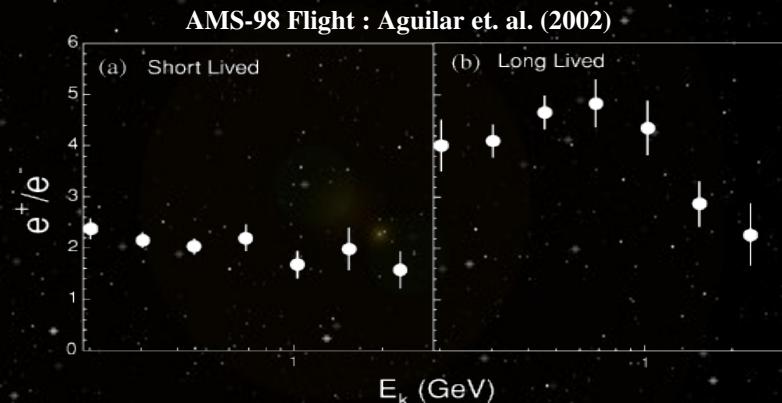
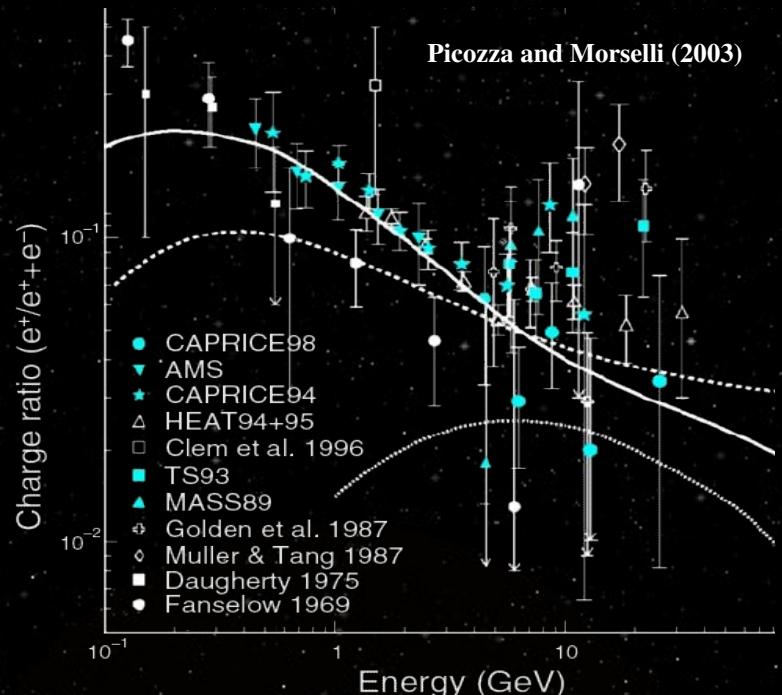


Positron Estimates

- Interesting positron measurements
 - Measured GCR $e^+/e^- \approx 0.1$
 - AMS-98 measured an excess of positrons around $L=1.05$ ($e^+/e^- \approx 4$)
 - Explained by Gusev et al. (2000) as the result of trapping pion decay products produced during high energy proton interactions with the atmosphere.
 - RHESSI measured positron annihilation lines in the Sun following a solar flare (Share et. al., 2003)



- Analysis Cases
 - Local production only?
 - $e^+/e^- = 4$ ($1.05 < L < 1.2$) ?
 - Total : $11 \mu\text{g}$ ($E > 100 \text{ keV}$)
 - Total : 45 ng ($E > 1 \text{ MeV}$)
 - Inward diffusion from external source
 - $e^+/e^- = 0.1$ ($1.2 < L < 6$) ??? - unlikely
 - Total : 840 mg

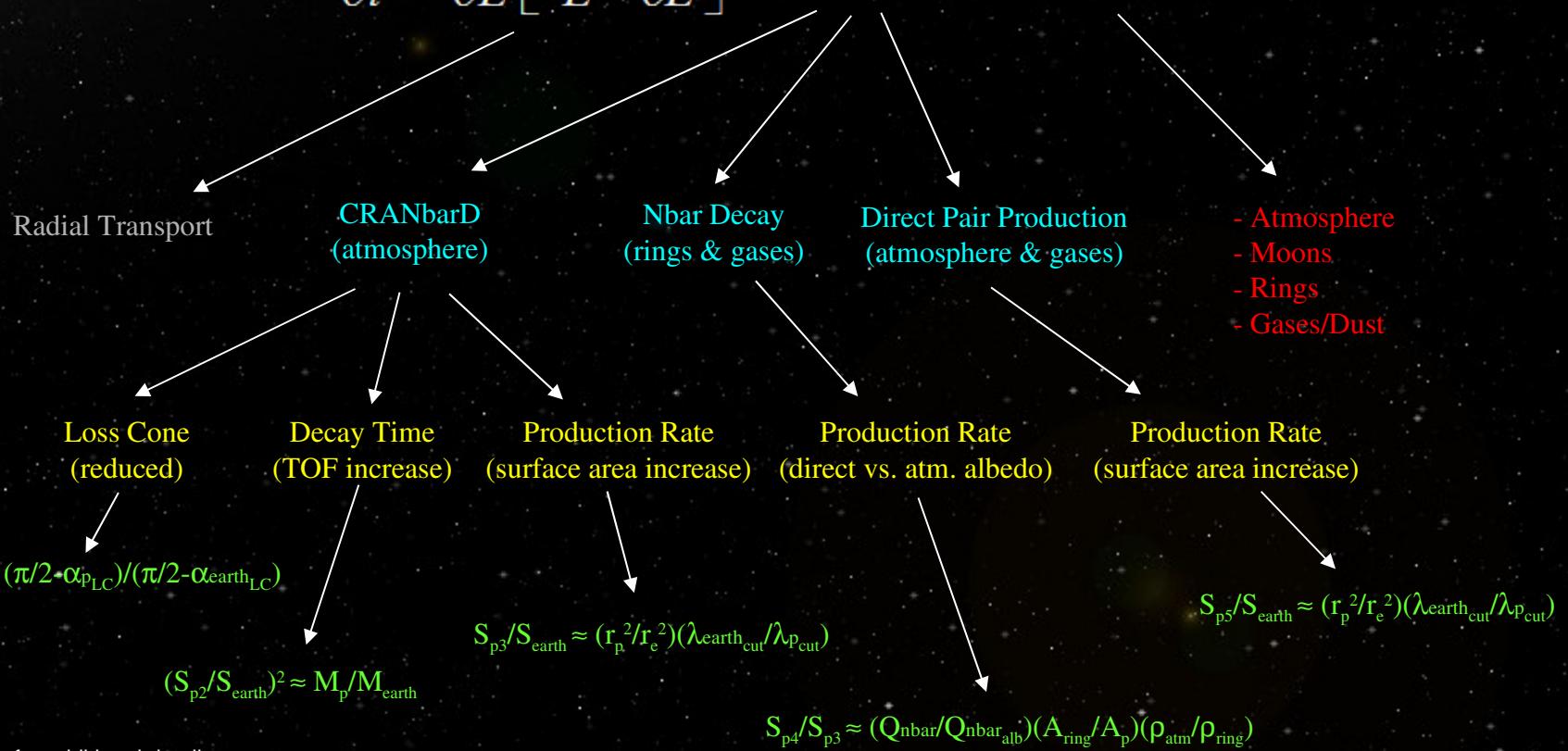


Antiproton Scaling Relationships



Jovian to Earth Radiation Belt Scaling

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial L} \left[\frac{D_{LL}}{L^2} \frac{\partial f}{\partial L} \right] + Sources - Losses$$

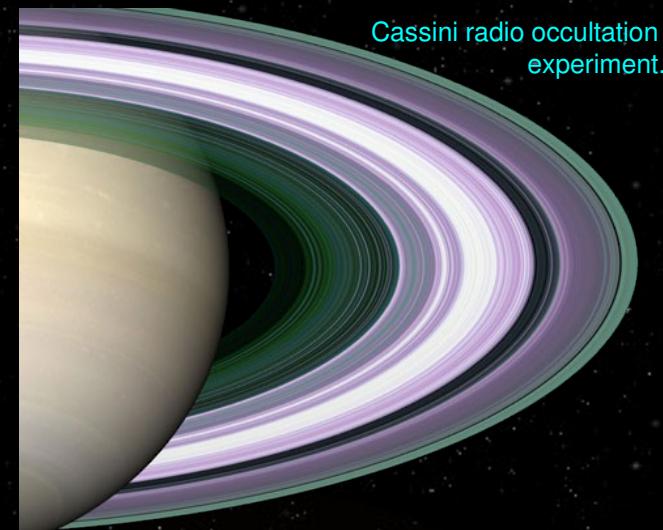


See backup slides for additional detail...



Jovian Estimates

- Dominant Antiproton Source
 - Fraction of antineutrons which decay in Jovian magnetospheres.
- Jupiter
 - Smaller supply than originally anticipated due to the cutoff of the GCR production spectrum by its large magnetic field.
 - Approximately 1 μgm spread throughout its magnetosphere.
- Saturn
 - Rings are the largest source of locally generated antiprotons in the solar system. Nearly a half milligram of antiprotons are trapped.
 - Primarily formed by the decay of ring produced antineutrons in the magnetosphere. Antineutrons generated in the A&B rings (20-100 gm/cm^2 , Nicholson and Dones, 1991) do not have to be backscattered for trapping which drastically increases the efficiency.
 - Rings are also a significant source of antiprotons which are directly produced but which are reabsorbed by the rings after one or more bounce periods.



$$(S_p/S_{\text{earth}}) \approx (S_{p1}/S_{\text{earth}1}) (S_{p2}/S_{\text{earth}1}) (S_{p3}/S_{\text{earth}1}) + (S_{p4}/S_{\text{earth}1-3}) + (S_{p5}/S_{\text{earth}5})$$

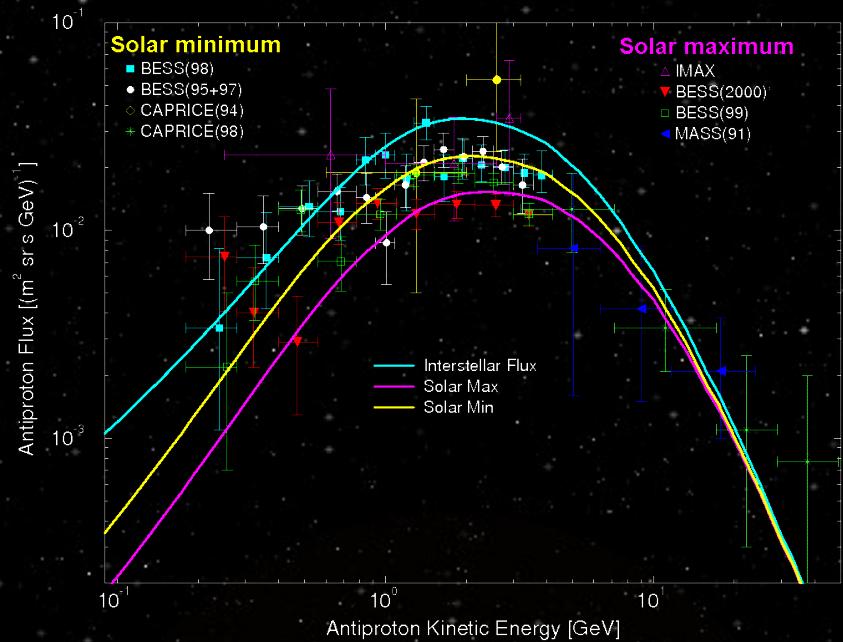
	S_{1-3}/S_{earth}	S_1/S_{earth}	S_2/S_{earth}	S_3/S_{earth}	S_4/S_{1-3}	S_5/S_{earth}	Mass
	<i>Nbar Related</i>	<i>Loss Cone</i>	<i>Decay Time</i>	<i>Production Area</i>	<i>Rings (Nbar)</i>	<i>Direct Pbar</i>	<i>Trapped Pbar</i>
Earth	1	1	1	1	0	1	$\sim 0.25 \text{ ng}$
Jupiter	$> 6 \times 10^3$	< 1.2	~ 140	~ 45	~ 0	~ 45	$\sim 1 \mu\text{gm}$
Saturn	$> 3 \times 10^3$	< 1.2	~ 25	~ 90	$10^3 (?)$	~ 90	$\sim 400 \mu\text{gm}$
Uranus	> 110	< 1.2	~ 7	~ 15	~ 0	~ 15	$\sim 18 \text{ ng}$
Neptune	> 75	< 1.2	~ 5	~ 15	~ 0	~ 15	$\sim 13 \text{ ng}$

Note : Values shown are very coarse engineering estimates based on extrapolations only.

Transient GCR Antiprotons



- GCR Antiproton Content Impinging on Planetary Magnetospheres
 - Created from GCR passing through 5-7 gm/cm² of matter in the galaxy.
 - Can planetary magnetospheres help concentrate the GCR flux to assist in collection?



Planet	Standoff Distance ($2\rho v^2 = B^2/2\mu_0$)	Antiproton Rate ($1 \text{ GeV} < E < 10 \text{ GeV}$)	Yearly Antiproton Impingement (~inner magnetosphere)
Earth	$11 R_{\text{earth}}$	$0.13 \mu\text{g/sec}$	0.004 kg
Jupiter	$45 R_{\text{jupiter}}$	$287 \mu\text{g/sec}$	9.1 kg
Saturn	$20 R_{\text{saturn}}$	$41 \mu\text{g/sec}$	1.3 kg
Uranus	$26 R_{\text{uranus}}$	$12 \mu\text{g/sec}$	0.39 kg
Neptune	$25 R_{\text{neptune}}$	$10 \mu\text{g/sec}$	0.33 kg

GCR Simulation

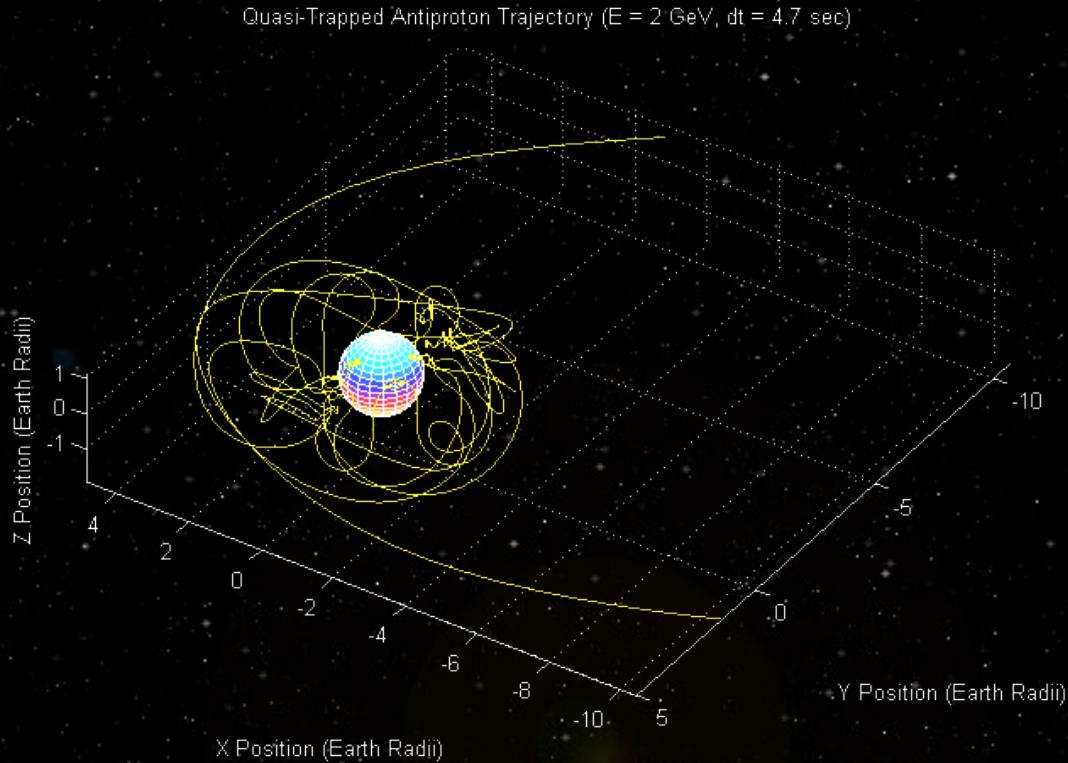


- Variable time step explicit Runge-Kutta ODE solver used to propagate high energy charged particles through the inner magnetosphere

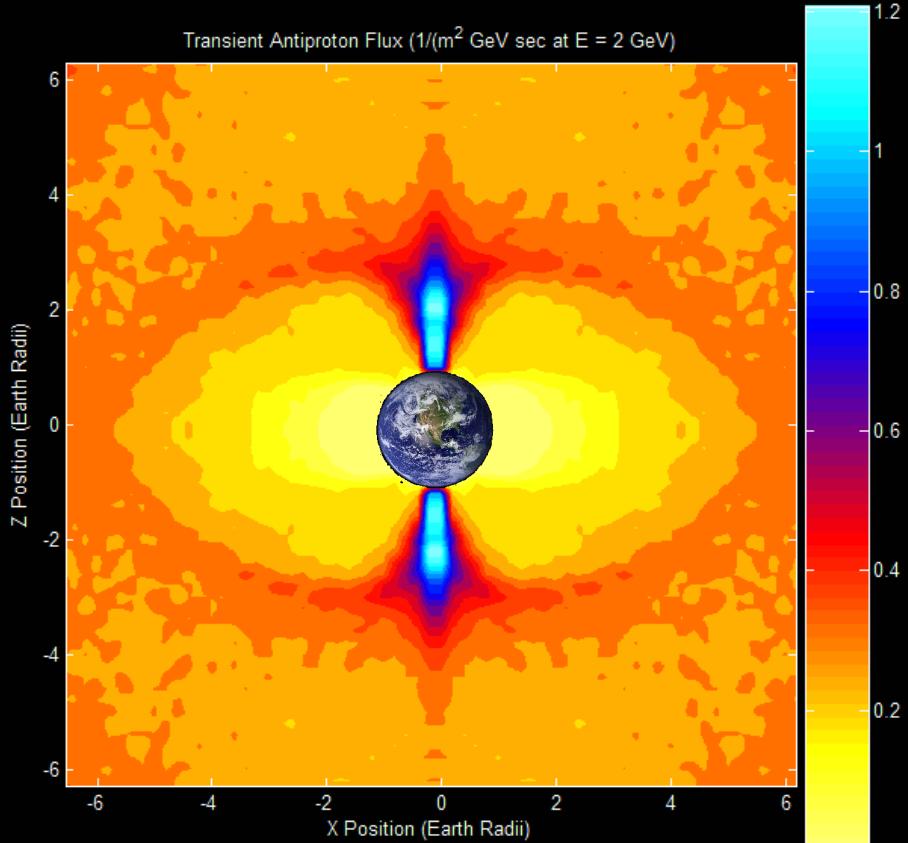
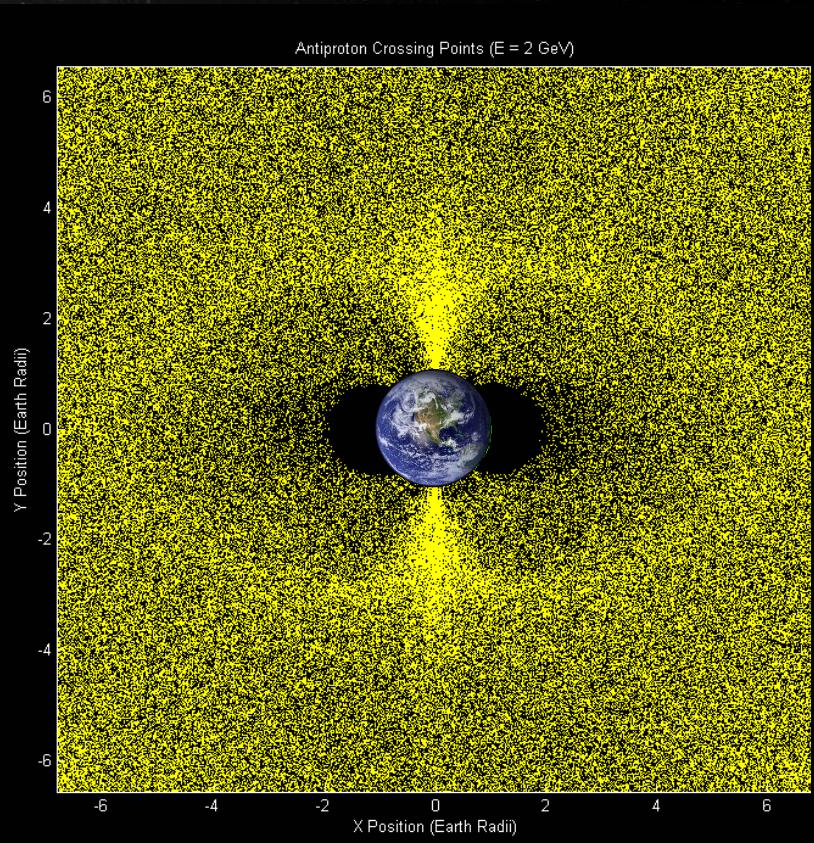
- Integration of Lorentz equation

$$\frac{d\vec{p}}{dt} = q(\vec{V} \times \vec{B} + \vec{E})$$

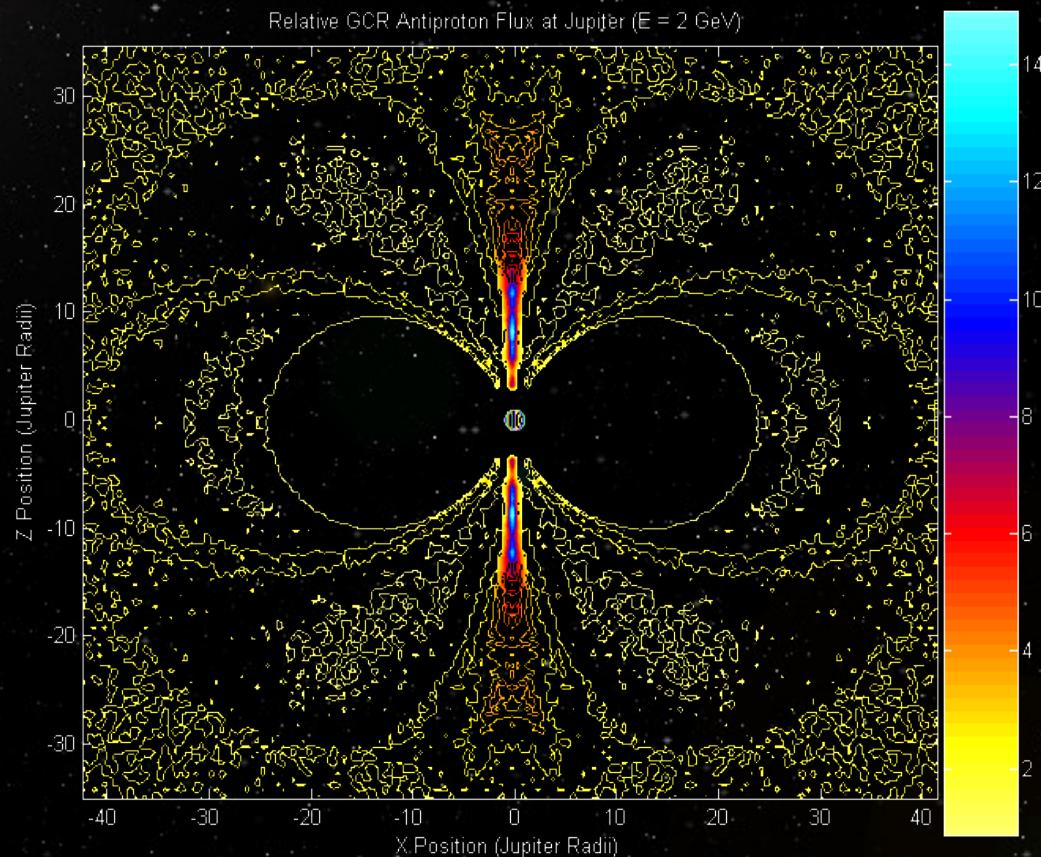
- System of first order ODEs
 - Static inner field dipole model of Earth and Jupiter simulated.
 - E=0
- Ability to expand on work first performed by Carl Stormer.
 - Modern desktop computers can duplicate 18000 hours (9 years) of graduate student work in about 3 seconds.



Transient GCR Antiproton Flux



Jupiter GCR Flux Concentration

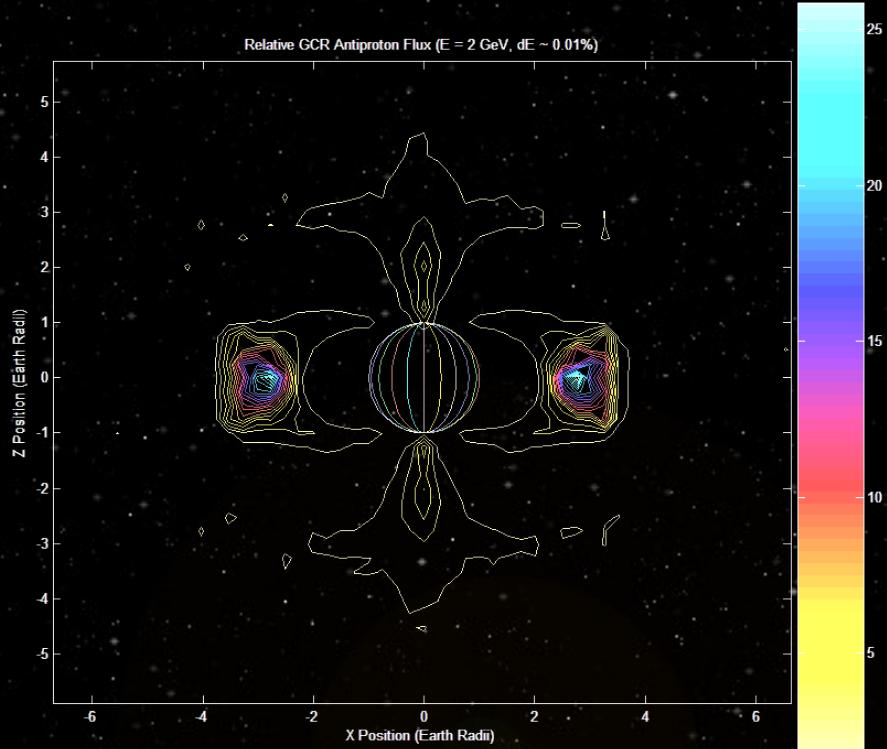


- High concentration factors near poles.
- Jupiter's forbidden region extensive relative to Earth due to strong magnetic field.

GCR Flux Augmentation



- Observed quasi-trapped GCR flux due to erroneous simulation where the particle energy was allowed to vary by about 0.01%
 - Induced flux was about 25X greater than GCR background around $L=2.75$ at 2 GeV.
- Artificial Augmentation
 - This could be artificially induced (and possibly increased) by artificial means.
 - RF source from surface
 - Electric fields in orbit
 - However, inducing these effects over such a large area does not seem practical.
 - Possibility of natural mechanism but unlikely to induce meaningful fluxes.



Local Production Augmentation



- Optimization of the production process has been proposed numerous times before.
 - About four orders of magnitude improvement in energy efficiency appears feasible.
- Space based production
 - First proposed in 1987 by Haloulakos and Ayotte.
 - Offers certain intrinsic advantages for space propulsion, namely that the antiprotons do not have to be stored and transported from Earth.
- In Situ Trapping
 - Generator placed within magnetic bubble or magnetosphere will collect generated antiprotons with high efficiency.
 - Configuration enables wide angular distribution and energy ranges to be captured with minimal complexity.
 - Leverages high vacuum environment.

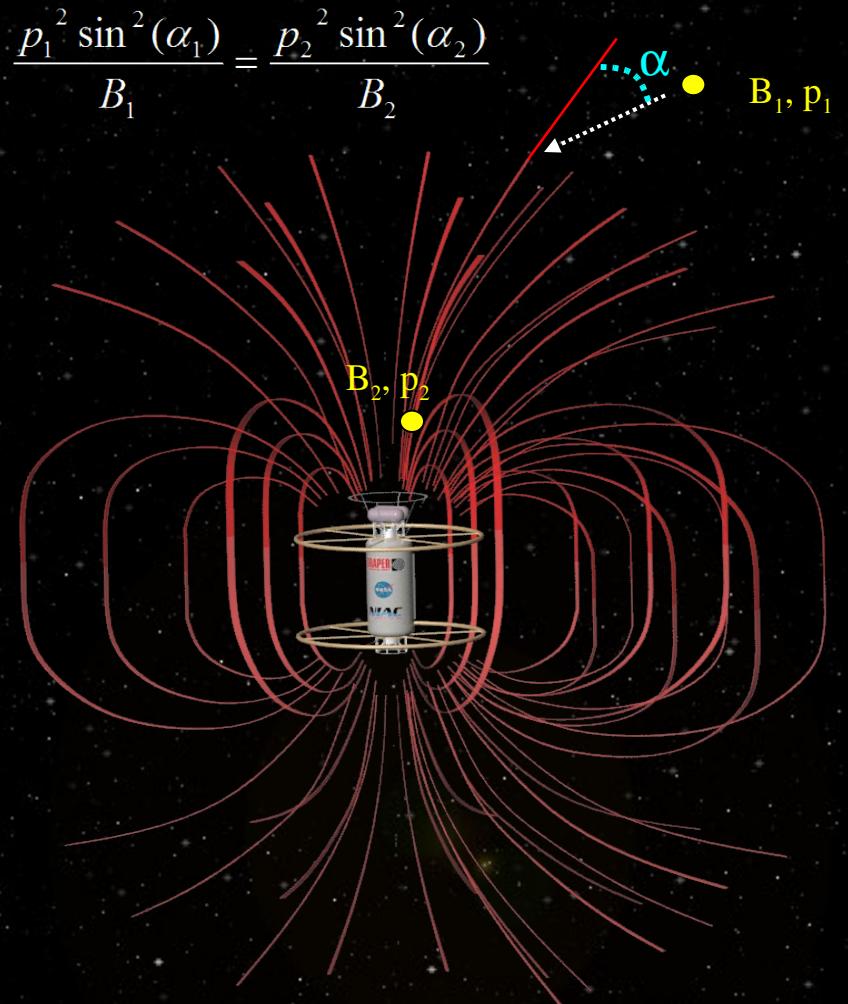
	CERN	Fermilab	In Situ
<i>Incident Proton Energy (GeV)</i>	26	120	200
<i>Generation Efficiency ($p\bar{p}/p$)</i>	0.4%	4.7 %	8.5%
<i>Angular Capture Efficiency</i>	20%	30%	100%
<i>Momentum Capture Efficiency</i>	1%	1.2%	85%
<i>Handling Efficiency</i>	5%	18%	80%
<i>Total Efficiency ($p\bar{p}/p$)</i>	4×10^{-7}	3×10^{-5}	0.058
<i>Overall Energy Efficiency</i>	1.4×10^{-9}	2.5×10^{-8}	2.7×10^{-4}
<i>Rate at 100 kWe (Prometheus)</i>			9.5 $\mu\text{g}/\text{yr}$
<i>Rate at 1 GWe</i>			95 mg/yr

Based on Forward (1985)



Antiproton Collection

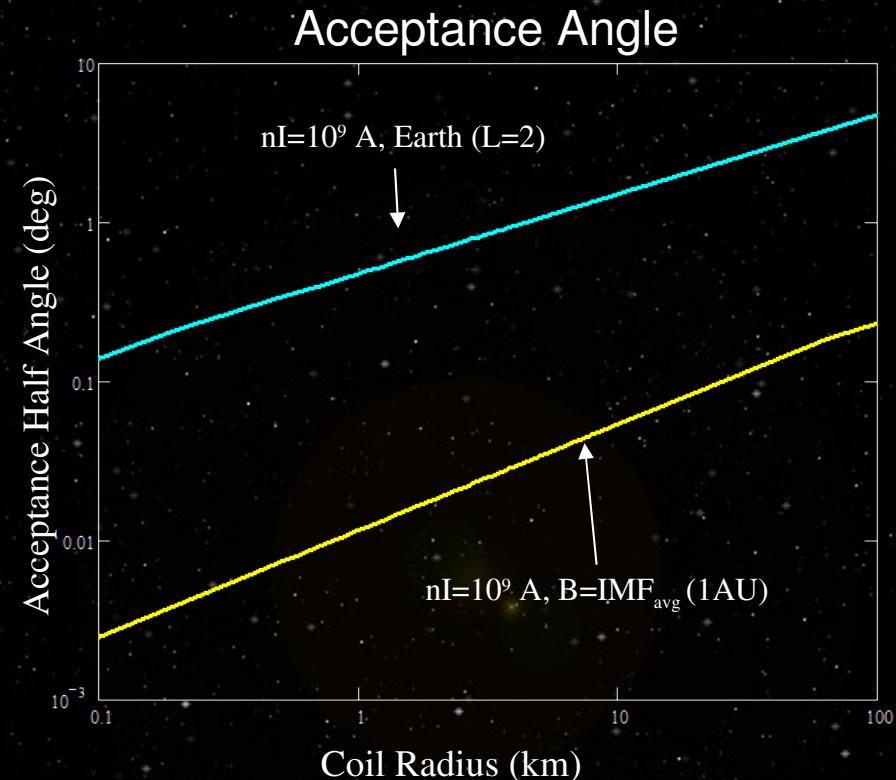
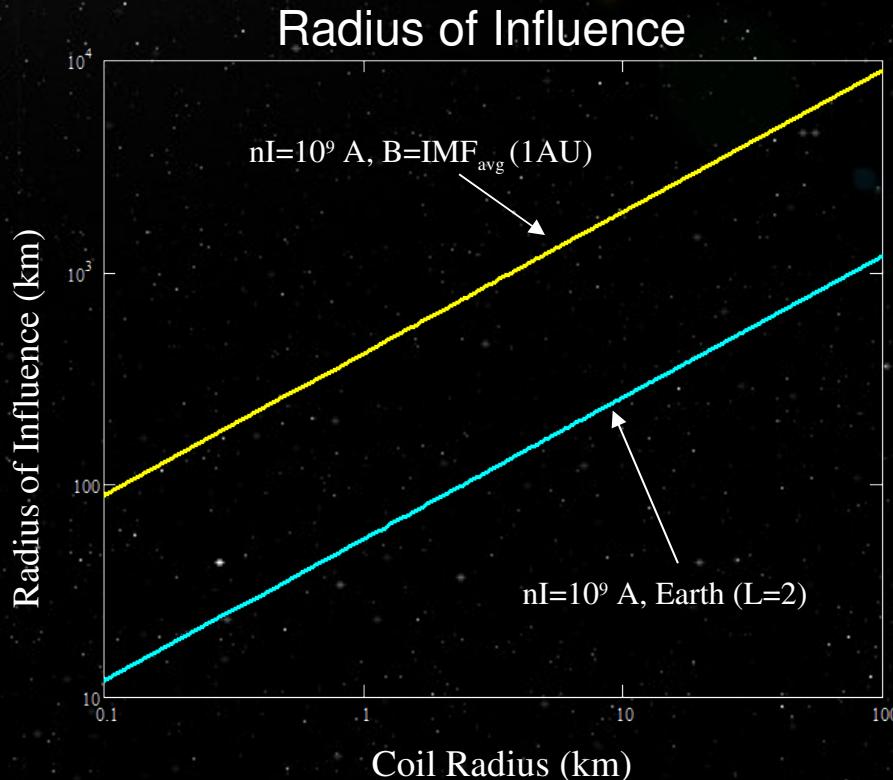
- Magnetic Scoop
 - Charged particles are concentrated as they follow magnetic field lines towards the dipole source.
- Scoop Efficiency
 - Limited by magnetic reflection & gyro radius limitations
 - Particles reflected when their pitch angle (α) reaches 90 deg
 - Gyro radius must be smaller than the radius of influence to ensure the particle does not spiral out of the field region before being trapped.
 - Related to relative magnetic field intensities and particle momentum.
 - Applied E and RF fields can be used to pull the particles towards the collector and extend the maximum obtainable acceptance angle.
- Collection
 - Particle can be collected (trapped in field) by degrading its energy and/or using a supplementary field (E-field easiest) to move the particle to a closed field line.
 - Restrictions on stable trapping based on particle momentum and field characteristics.





Collection Limits

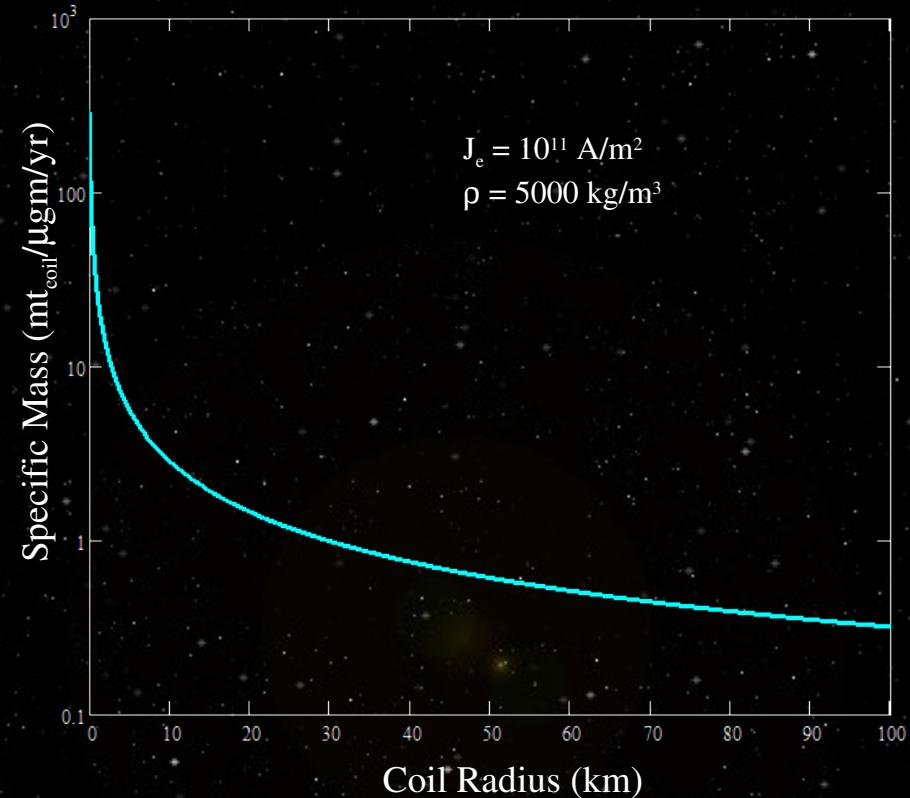
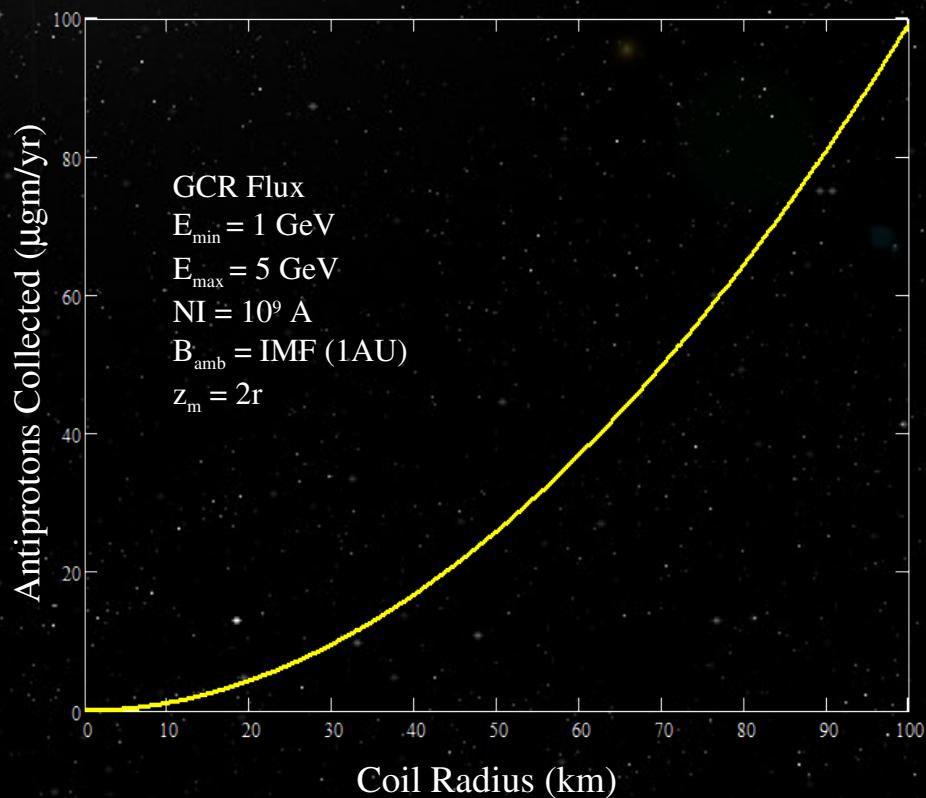
- Limit of magnetic influence restricts the potential antiproton collection region.
- Acceptance angle limits the collection efficiency
 - This can be improved by increasing the particle momentum
 - Apply E and/or RF fields
 - Efficiency scales linearly with final particle momentum (2X p gives 2X angle)
 - Feasible at lower energies but probably not at the GeV energy scale.



Ring Radius Tradeoff



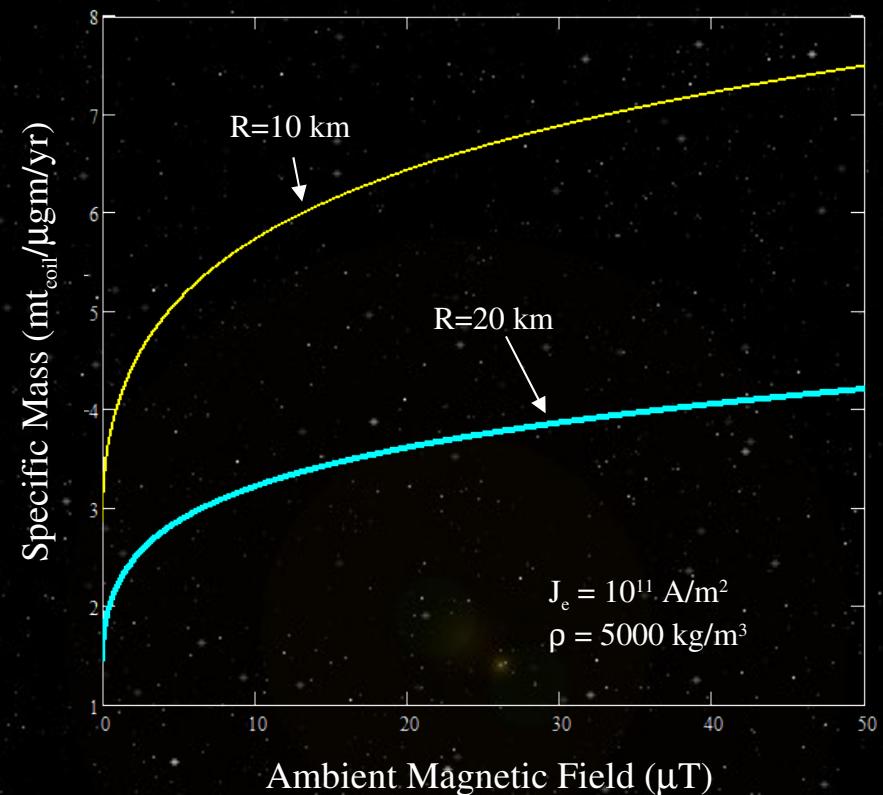
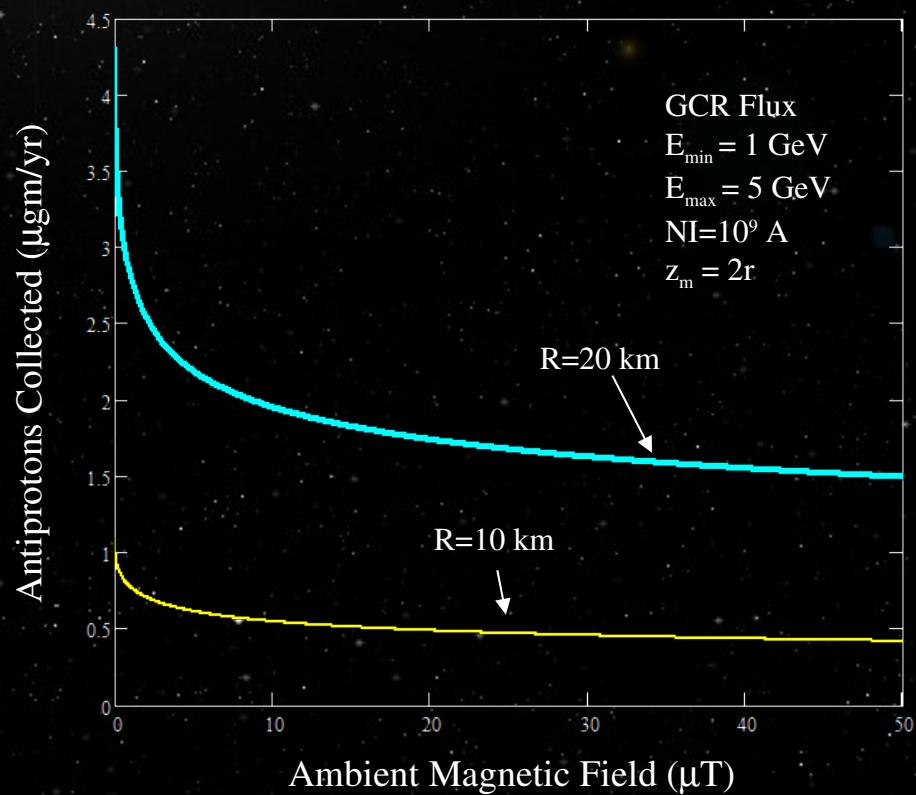
- Mass values assume no flux concentration from planetary phenomena.
 - Background GCR flux only.
 - Multiply by relative integral flux to obtain planetary collection rates.
- Collection rate and efficiency (collection rate versus ring mass) increase with loop diameter.



Ambient Field Tradeoff



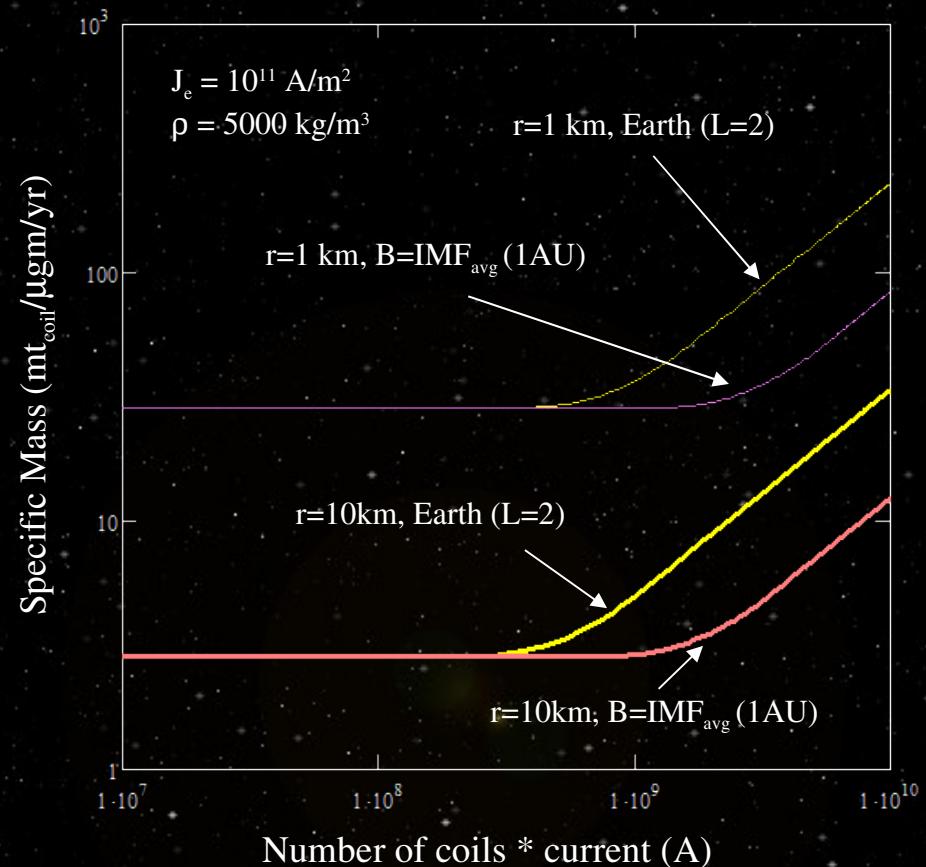
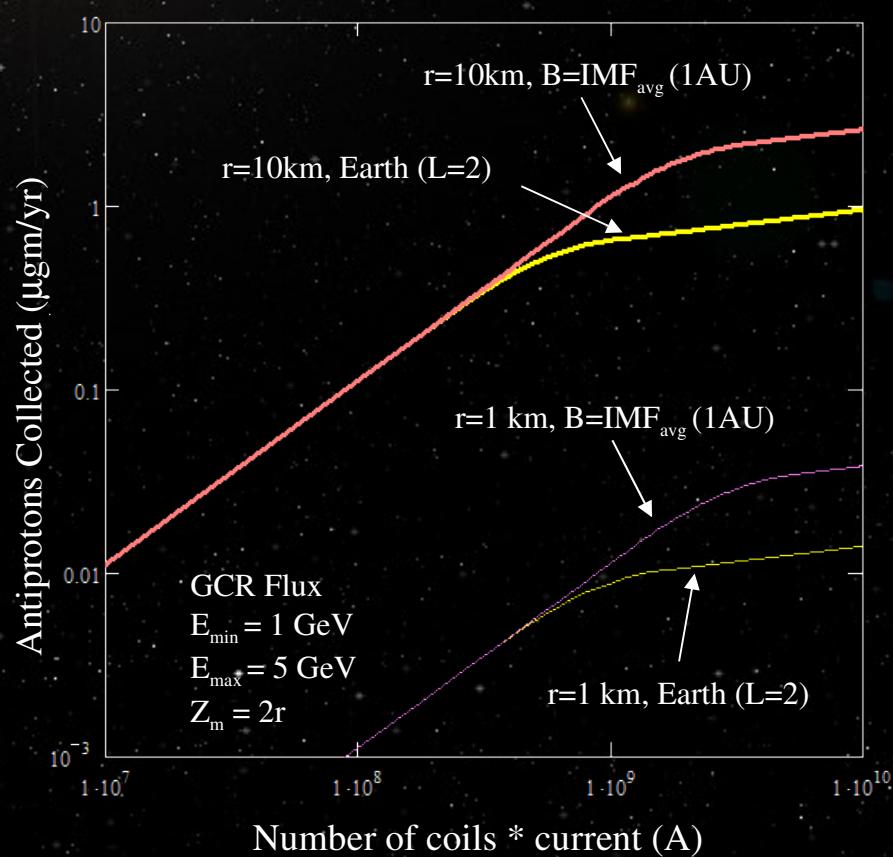
- Maximum collection rates and efficiency at low ambient field strengths



Ring Current Tradeoff



- Larmor radius limits collection when $NI < \sim 10^9$ A
- Magnetic reflection limits efficiency above $\sim 10^9$ A
- Best efficiency (coil mass relative to collection rate) in Larmor limited region.



Technology Development



- Technology Gap : Low mass, high strength, long strand, ultra-high current loops
 - Requirement : High temperature superconductors with $J_e > \sim 10^{10} \text{ A/m}^2$ at 90K and $L > 100\text{m}$.
 - Priority : Essential for collecting from natural low flux antiproton background, highly desirable for systems with artificial augmentation.
- Technology Gap : In-orbit power
 - Requirement : Space qualified nuclear reactor with $P \geq 100 \text{ kWe}$
 - Priority : Highly valuable though solar power is potentially another option.
- Technology Gap : High efficiency, orbital antiproton generator
 - Requirement : Orbital particle accelerator with beam power = 200 GeV.
 - Priority : Essential for artificial augmentation, not needed if natural antiproton sources are used.
- Technology Gap : Passive cooling systems
 - Requirement : Reduced mass multi-layer thermal blankets for passive temperature control of large structures with $T_{max} < 90\text{K}$ at 1 AU.
 - Priority : Improvements in reducing mass or operating temperature valuable; reduces requirements on HTS.
- Technology Gap : Affordable Lift
 - Requirement : Reduced cost to orbit. (\$/kg)
 - Priority : Not required, but helpful.



Summary (1 of 2)

- Earth has a minimal (< 1 ng) trapped supply of antiprotons. This is replenished over a period of several years. The low level is due to inefficiencies in backscattering albedo antineutrons from the atmosphere. Significant fluxes of positrons may exist, though the exact magnitude is still uncertain. A quasi-static supply < 1 μgm is most likely.
- Saturn has the largest trapped antiproton supply in the Solar System (estimated at ~400 μgm) due to high antineutron production from GCR interactions with its ring system. The flux of transient antiprotons produced in the ring system is also predicted to be significant. A refined radiation transport analysis should be completed.
- Jupiter has a lower than expected trapped antiproton supply since its magnetic field shields much of the atmosphere from the input production spectrum.
- High energy (GeV) antiprotons in the natural Galactic Cosmic Ray (GCR) background are very tenuous but are partially concentrated by planetary magnetic fields. Though not as desirable as collecting them from stable radiation belt supplies (MeV), extraction from the GCR background is also feasible.



Summary (2 of 2)

- Local transient antiproton fluxes from planetary rings (Saturn), comet tails, and other phenomena may significantly exceed background GCR fluxes.
- A magnetic funnel formed from passively cooled high temperature superconducting loops can be used to collect significant quantities of antiprotons from low GCR background levels or in regions of high intensity local production (Saturn). However, significant improvements in superconductor performance (A/m^2) will be required before this is practical at a large scale.
- A magnetic bottle formed from the same superconducting loops can be used to safely store antiprotons for long periods of time. Particles and antiparticles at various energies can coexist in the same device since the large trapped volume (km^3 or more) and natural vacuum afforded by the space environment minimizes losses.
- Artificially generating antiprotons in magnetospheres (natural or otherwise) would be very valuable and efficient. By effectively locating the particle accelerator within the magnetic ‘bubble’, the system can produce and trap antiparticles within high efficiency which can then be used for propulsion. Leveraging the development of a space qualified nuclear reactor (Project Prometheus) or 100 kWe solar array would enable $\sim 10+ \mu\text{gm}$ to be collected in orbit per year.