Dark matter searches by charged cosmic rays detection in space

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**SIGNALS from RELIC WIMPs**

**Direct searches:** elastic scattering of a WIMP off detector nuclei
Measure of the recoil energy

**Indirect detection:** in cosmic radiation
- signals due to annihilation of accumulated $\chi\chi$ in the centre of celestial bodies (Earth and Sun)
  $\rightarrow$ neutrino flux

- signals due to $\chi\chi$ annihilation in the galactic halo
  $\rightarrow$ neutrinos
  $\rightarrow$ gamma-rays
  $\rightarrow$ antiprotons, positrons, antideuterons

\(\nu\) and \(\gamma\) keep directionality

- can be detected only if emitted from high \(\chi\) density regions

Charged particles diffuse in the galactic halo

- antimatter searched as rare components in cosmic rays (CRs)

For a review, see i.e. Bergstrom hep-ph/0002126
The presence of neutralino annihilation will distort the positron, antiproton and gamma energy spectrum from purely secondary production.
Antideuterons

- Pair annihilating WIMPS produce:
  \[ \gamma, \nu, e^+ \ldots \bar{p} \ldots \]

Dark Matter Hadronization Model  Coalescence Monte Carlo Model


Cosmic antideuterons represent a near “smoking gun” signature of dark matter
Stratospheric balloons
The antimatter balloon flights: overview

Aim of the activity is the detection of antimatter and dark matter signals in CR nei RC (antiprotons, positrons, antinuclei) for energies from hundreds of MeV to about 30 GeV, and measurements of primary CR from hundreds of MeV to about 300 GeV.

6 flights from the WIZARD collaboration: MASS89, MASS91, TRAMP-SI, CAPRICE 94, 97, 08. The flights started from New Mexico or Canada, with different geomagnetic cut-offs to optimize the investigation of different energy regions. The flights lasted about 20 hours.

4 flights from the HEAT collaboration: 2 HEAT-e+, in 1994 and 1995, and 2 HEAT-pbar flights, in 2000 and 2002
- Charge sign and momentum determination;
- Beta selection
- Z selection
- hadron – electron discrimination
Results from MASS/TrampSI/CAPRICE/HEAT:
Positrons & antiprotons

Highest energetic points available from balloons
Protons and heliums
The BESS program

- The BESS program had 11 successful flight campaigns since 1993 up to 2008.

- A modification of the BESS instrument, BESS-Polar, is similar in design to previous BESS instruments, but is completely new with an ultra-thin magnet and configured to minimize the amount of material in the cosmic ray beam, so as to allow the lowest energy measurements of antiprotons.

- BESS-Polar has the largest geometry factor of any balloon-borne magnet spectrometer currently flying (0.3 m²-sr).
BESS Collaboration

High Energy Accelerator Research Organization (KEK)
The University of Tokyo
Kobe University

BESS Collaboration

National Aeronautical and Space Administration Goddard Space Flight Center
University of Maryland
University of Denver (Since June 2005)

Institute of Space and Astronautical Science/JAXA
Rigidity measurement

**SC Solenoid (L=1m, B=1T)**
- Min. material (4.7g/cm$^2$)
- Uniform field
- Large acceptance

**Central tracker**
- Drift chambers (Jet/IDC)
  - $\delta \sim 200$ $\mu$m

$Z, m$ measurement

$R, \beta \rightarrow m = Z e R \frac{1}{\beta^2 - 1}$

$dE/dx \rightarrow Z$
BESS-Polar I and II

Long duration flights of total 38 days with two circles around the Pole
Results: antiproton/proton ratio

BESS-Polar II: with ¼ statistics
Limits on antimatter (antiHe and antiD)

100 times improvement
CREAM – Overview

• Aim is the study of CR from $10^{12}$ to $5 \times 10^{14}$ eV, from proton to Iron, by means of a series of Ultra Long Duration Balloon (ULDB) flights from Antarctica.


The instrument is composed by a sampling tungsten/scintillating fibers calorimeter (20 r.l.), preceded by a graphite target with layers of scintillating fibers for trigger and track reconstruction, a TRD for heavy nuclei, and a timing-based segmented charge device.

A fundamental aspect of the instrument is the capability to obtain simultaneous measurements of energy and charge for a sub-sample of nuclei by calorimeter and TRD, thus allowing an inter-calibration in flight of the energy.
The CREAM instrument

- Transition Radiation Detector (TRD) and Tungsten Scintillating Fiber Calorimeter
  - In-flight cross-calibration of energy scales for Z > He
- Complementary Charge Measurements
  - Timing-Based Charge Detector
  - Cherenkov Counter
  - Pixelated Silicon Charge Detector

- CREAM uses two designs
  - With and without the TRD
- This exploded view shows the “With TRD” design
- The “Without TRD” design uses Cherenkov Camera

Collecting power: 300 m²-sr-day for proton and helium, 600 m²-sr-day nuclei
Protons and heliums

Ahn et al. (CREAM collaboration), ApJ 714, L89, 2010

Our fluxes are significantly higher than the extrapolation of a single-power law fit to the low energy spectra

Different types of sources or acceleration mechanisms? (e.g., Biermann, P. L. A&A 271, 649, 1993)

\[ \text{Flux} \times E^{2.75} \left( \text{m}^2 \text{s}^{-1} \text{sr}^{-1} \right) \]

\[ \gamma_P = 2.66 \pm 0.02 \]

\[ \gamma_{\text{He}} = 2.58 \pm 0.02 \]
Heavier elements: hardening
Advanced Thin Ionization Calorimeter (ATIC)

ATIC COLLABORATION:
Institute for Physical Science and Technology, University of Maryland, College Park, MD, USA
Marshall Space Flight Center, Huntsville, AL, USA
Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow, Russia
Purple Mountain Observatory, Chinese Academy of Sciences, China
Max Planck Institute for Solar System Research, Katlenburg-Lindau, Germany
Department of Physics, Southern University, Baton Rouge, LA, USA
Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA, USA
Department of Physics, University of Maryland, College Park, MD, USA

The ATIC balloon flight program measures the cosmic ray spectra of nuclei: $1 < Z < 26$ between $10^{11} \text{ eV}$ and $10^{14} \text{ eV}$.

ATIC has had two successful long-duration balloon (LDB) flights launched from McMurdo Station, Antarctica in 2000 and 2002.
ATIC Instrument Details

Antarctic Flights:

- 12/28/00 - 1/13/01
- 12/29/02 – 1/18-03
- 12/27/07 – 1/15/08
Protons and heliums
The ATIC “bump” in the all-electron spectrum

“Source on/source off” significance of bump for ATIC1+2 is about 3.8 sigma

ATIC-4 with 10 BGO layers has improved e, p separation.

“Bump” is seen in all three flights.

Significance for ATIC1+2+4 is 5.1 sigma
FERMI does not confirm the ATIC bump but finds an excess wrt conventional diffusive models
Satellite flights
PAMELA
Payload for Matter/antimatter Exploration and Light-nuclei Astrophysics

- **Direct** detection of CRs in space
- Main focus on **antiparticles** (antiprotons and positrons)

- PAMELA on board of Russian satellite **Resurs DK1**
- Orbital parameters:
  - inclination \(~70^\circ\) (⇒ low energy)
  - altitude \(~360-600\) km (elliptical)
  - active life \(>3\) years (⇒ high statistics)

→ **Launched on 15th June 2006**
→ **PAMELA in continuous data-taking mode since then!**
PAMELA detectors

Main requirements:
- high-sensitivity antiparticle identification
- precise momentum measurement

**Time-Of-Flight**
plastic scintillators + PMT:
- Trigger
- Albedo rejection;
- Mass identification up to 1 GeV;
- Charge identification from dE/dX.

**Electromagnetic calorimeter**
W/Si sampling (16.3 X0, 0.6 λI)
- Discrimination e+ / p, anti-p / e-
  (shower topology)
- Direct E measurement for e-

**Neutron detector**
36 He³ counters:
- High-energy e/h discrimination

**Spectrometer**
microstrip silicon tracking system + permanent magnet
It provides:
- *Magnetic rigidity* \( R = \frac{p c}{Z e} \)
- *Charge sign*
- *Charge value from dE/dx*

GF: 21.5 cm² sr
Mass: 470 kg
Size: 130x70x70 cm³
Power Budget: 360W
H & He absolute fluxes

- First high-statistics and high-precision measurement over three decades in energy
- Dominated by systematics (~4% below 300 GV)

- Low energy → minimum solar activity ($\phi = 450 \div 550$ GV)
- High-energy → a complex structure of the spectra emerges...

Adriani et al., Science 332 (2011) 6025
P & He absolute fluxes @ high energy

Deviations from single power law (SPL):

- Spectra gradually soften in the range 30 ÷ 230 GV
- Abrupt spectral hardening @ ~235 GV

Eg: statistical analysis for protons

- SPL hp in the range 30 ÷ 230 GV rejected @ >95% CL
- SPL hp above 80 GV rejected @ >95% CL

Standard scenario of SN blast waves expanding in the ISM needs additional features
**H/He ratio vs R**

**Instrumental p.o.v.**
- Systematic uncertainties **partly cancel out** (livetime, spectrometer reconstruction, ...)

**Theoretical p.o.v.**
- Solar modulation negligible \(\rightarrow\) information about IS spectra down to GV region
- Propagation effects (diffusion and fragmentation) negligible above \(~100\text{GV}\) \(\rightarrow\) information about source spectra

(Putze et al. 2010)
First clear evidence of different H and He slopes above ~10GV

Ratio described by a single power law (in spite of the evident structures in the individual spectra)

\[ \alpha_{\text{He}} - \alpha_p = 0.078 \pm 0.008 \]
\[ \chi^2 \approx 1.3 \]
Electron energy measurements

Two independent ways to determine electron energy:

1. Spectrometer
   - Most precise
   - Non-negligible energy losses (bremsstrahlung) above the spectrometer → unfolding

2. Calorimeter
   - Gaussian resolution
   - No energy-loss correction required
   - Strong containment requirements → smaller statistical sample

Electron identification:
   - Negative curvature in the spectrometer
   - EM-like interaction pattern in the calorimeter

Adriani et al., PRL 106, 201101 (2011)
Electron absolute flux

- Largest energy range covered in any experiment hitherto with no atmospheric overburden

- Low energy
  - minimum solar activity ($\phi = 450 \div 550$ GV)

- High energy
  - No significant disagreement with recent ATIC and Fermi data
  - Softer spectrum consistent with both systematics and growing positron component

Adriani et al., PRL 106, 201101 (2011)

Spectrometric measurement

Calorimetric measurements
(e^+ + e^-) absolute flux

- Compatibility with FERMI (and ATIC) data
- Beware: positron flux not measured but extrapolated from PAMELA positron flux!
- Low energy discrepancies due to solar modulation
$(e^+ + e^-)$ absolute flux

- Compatibility with FERMI (and ATIC) data
- Beware: positron flux not measured but **extrapolated** from PAMELA positron flux!
- Low energy discrepancies due to solar modulation
Positron fraction

- **Low energy** → charge-dependent solar modulation (see later)

- **High energy** → (quite robust) evidence of positron excess above 10GeV

(Galprop code
  - Plain diffusion model
  - Interstellar spectra)
The Fermi-LAT has measured the cosmic-ray positron and electron spectra separately, between 20 – 130 GeV, using the Earth’s magnetic field as a charge discriminator.

The two independent methods of background subtraction, Fit-Based and MC-Based, produce consistent results.

The observed positron fraction is consistent with the one measured by PAMELA.
Antiproton flux

- Largest energy range covered hiterto
- Overall agreement with pure secondary calculation
- Experimental uncertainty (stat\(\oplus\)sys) smaller than spread in theoretical curves → constraints on propagation parameters

(Donato et al. 2001)
- Diffusion model with convection and reacceleration
- Uncertainties on propagation param. and c.s.
- Solar modulation: spherical model (\(\phi=500\text{MV}\))

(Ptuskin et al. 2006) GALPROP code
- Plain diffusion model
- Solar modulation: spherical model (\(\phi=550\text{MV}\))
Antiproton-to-proton ratio

- Overall agreement with pure secondary calculation

Adriani et al. - PRL 105 (2010) 121101
A challenging puzzle for CR physicists

**Antiprotons**
→ Consistent with pure secondary production

**Positrons**
→ Evidence for an excess
**Positron-excess interpretations**

**Dark matter**
- boost factor required
- lepton vs hadron yield must be consistent with p-bar observation

**Astrophysical processes**
- known processes
- large uncertainties on environmental parameters

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(Blasi 2009) e+ (and e-) produced as **secondaries** in the CR acceleration sites (e.g. SNR)

(Hooper, Blasi and Serpico, 2009) contribution from diffuse mature & nearby young pulsars.
Positrons vs electrons

- Fit of electron flux

Two scenarios:
1. **standard** (primary+secondary components)
2. **additional primary** $e^-$ (and $e^+$) component

Electron data are not inconsistent with standard scenario, but...

...an additional component better reproduces positron data

GALPROP calculation
diffusion + reacceleration (Ptuskin et al. 2006)
H and He primary spectra from best fit of propagated spectra to PAMELA results

Adriani et al. – PRL 106, 201101 (2011)

$p$-law fit $\gamma \sim 3.18$

Primary $e^- + secondary (e^++e^-)$
(best fit $\rightarrow$ s.index 2.66 @ SNR source)

With additional $(e^++e^-)$ primary component
(best fit $\rightarrow$ s.indexes 2.69 SNR and 2.08 @ exo source)
Orbiting Space Station
Search for primordial anti-matter
Indirect search of dark matter
High precision measurement of the energetic spectra and composition of CR from GeV to TeV

AMS-01: 1998 (10 days) - PRECURSOR FLIGHT ON THE SHUTTLE

AMS-02: Since May 19th, 2011, safely on the ISS. Four days after the Endeavour launch, that took place on Monday May 16th, the experiment has been installed on the ISS and then activated. COMPLETE CONFIGURATION FOR >10 YEARS LIFETIME ON THE ISS
AMS-02: the collaboration

500 physicists, 16 countries, 56 Institutes
AMS-02 goals and capabilities

Cosmic rays spectra and chemical composition up to 1 TeV

Search for Antimatter in Space

Search for Dark Matter

Gamma Rays

AMS will identify and measure the fluxes for:
- $p$ for $E < 1$ TeV with unprecedented precision
- $e^+$ for $E < 300$ GeV and $e^-$ for $E < 1$ TeV (unprecedented precision)
- Light Isotopes for $E < 10$ GeV/n
- Individual elements up to $Z = 26$ for $E < 1$ TeV/n

Absolute fluxes and spectrum shapes of protons and helium are important for calculation of atmospheric neutrino fluxes
Composition and spectra are important to constraint propagation, confinement, ISM density
The AMS-02 detector
AMS positron fraction

AMS-02 Antihelium Limits

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(a)Buffington et al. 1981
(b)Golden et al. 1997
(c)Badhwar et al. 1978
(d)Alcaraz et al. 1998
(e)Sasaki et al. 2001
AMS first events

42 GeV Carbon nucleus
CALorimetric Electron Telescope (CALET)

- **Instrument:**
  High Energy Electron and Gamma-Ray Telescope

- **Carrier:**
  HTV: H-IIA Transfer Vehicle

- **Attach Point on the JEM-EF:** #9
  for heavy (≤ 2000 kg) payloads

- **Nominal Orbit:**
  407 km, 51.6° inclination

- **Launch plan:**
  FY 2013

- **Life Time:**
  ≥ 5 years

1 GeV ~ 20 TeV for electrons
20 MeV ~ TeV for gamma-rays
Weight: 500 kg
GF (fiducial volume): ~ 0.12 m²sr
Power Consumption: 640 W
Data Rate: 300 kbps
**CALET Overview**

**Observation**
- **Electrons**: 1 GeV - 10 TeV
- **Gamma-rays**: 10 GeV-10 TeV (GRB > 1 GeV)
  - Gamma-ray Bursts: 7 keV-20 MeV
- **Protons, Heavy Nuclei**: several 10 GeV - 1000 TeV (per particle)
- **Solar Particles and Modulated Particles in Solar System**: 1 GeV-10 GeV (Electrons)

**Instrument**

**High Energy Electron and Gamma-Ray Telescope:**
- **CHarge Detector (CHD)**
  - (Charge Measurement in Z=1-40)
- **Imaging Calorimeter (IMC)**
  - (Particle ID, Direction)
  - Total Thickness of Tungsten (W): $3 X_0 \ 0.11 \lambda_1$
  - Layer Number of Scifi Belts: 8 Layers $\times \ 2 \(X,Y\)$
- **Total Absorption Calorimeter (TASC)**
  - (Energy Measurement, Particle ID)
  - PWO: $20\text{mm} \times 20\text{mm} \times 320\text{mm}$
  - Total Depth of PWO: $27 X_0 \ (24\text{cm}), 1.35 \lambda_1$

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**Cosmic Ray Sources**
- **SNIa**, **Supernova**, **Pulsar**, **AGN**, **International Space Station**

**Dark Matter**
- **Cosmic Ray Sources**
  - **SNIa**, **Supernova**, **Pulsar**, **AGN**, **International Space Station**

**Calorimetric Electron Telescope**
- A Dedicated Detector for Electron Observation in 1 GeV - 10,000 GeV

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**Diagram**
- **CHD**
- **IMC**
- **TASC**
- **IMC1+2**, **IMC3+4**, **IMC5+6**, **IMC7+8**

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- 4 -
The electron spectrum above 1 TeV

Is there a nearby (< 1 kpc) acceleration source?

- CALET will explore the spectral shape beyond 1 TeV with low background \((10^6\) rejection) and high energy resolution \((2 - 3\%)\)

- Anisotropy measurements to validate possible evidence of nearby source(s)

Nearby Pulsars or Dark Matter?

**Vela**
- 10,000 years
- 820 ly
- (by CHANDRA)

**Cygnus Loop**
- 20,000 years
- 2,500 ly
- (by ROSAT)

**Monogem**
- 86,000 years
- 1,000 ly

Candidate Nearby Sources
- \(T < 10^6\) years
- \(L < 1\) kpc
The electron spectrum above 1 TeV

- CALET will perform Anisotropy measurements to validate possible evidence of nearby source(s)

The electron spectrum below 1 TeV

Accurate spectral shape measurements in the region of the ‘ATIC anomaly’ and of the spectrum down to 1 GeV.

CALET expected in 5 y: KKDM hypothesis
The GAPS experiment

- A time of flight (TOF) system tags candidate events and records velocity
- The antiparticle slows down & stops in a target material, forming an excited exotic atom with near unity probability
- Deexcitation X-rays provide signature
- Pions and protons from annihilation provide added background suppression
Si(Li) Wafers will be hexagonally packed into detector planes & surrounded by segmented Plastic TOF

pGAPS Instrument for Taiki Launch 2011

Vessel for DAQ card cage

Vessel for GPS, PC/104 stack, TOF VME crate

Si(Li) detector

TOF plastic scintillator

~200 kg Si(Li) mass -
• GAPS will provide 2-3 orders of magnitude improvement on the antideuteron limit obtained with BESS-polar
• Payload design and hardware fabrication is underway for a prototype (pGAPS) experiment from Taiki, Japan in 2011
• GAPS Development Plan Culminates in a Long-Duration Balloon (LDB) Experiment from Antarctica with the bGAPS science experiment in late 2014-2015
Conclusions

- Indirect dark matter searches with charged CR are a tool to seek for dark matter, complementary to direct searches and collider experiments;
- Some interesting “signals” in the data created big excitement in the last 2 years, but no “smoking gun” yet;
- While searching for dark matter, new “astrophysics” has been found, which points towards new mechanisms of production and/or acceleration of charged CR.
- New experiments ready to provide data soon!

PS: I apologize for the experiments I did not have time to mention ...