CURRENT STATUS OF ASTROPHYSICS OF COSMIC RAYS

IGOR V MOSKALENKO – STANFORD
There is nothing new to be discovered in physics now. All that remains is more and more precise measurement

— Lord Kelvin, 1900
Timeline of $\gamma$-ray, CR, and particle experiments

- 2005: Milagro, TRACER, BESS-Polar
- 2010: Fermi, AGILE, CREAM, PAMELA, Voyager 1, 2, ACE
- 2015: HESS, MAGIC, VERITAS, HAWC, LHC, NUCLEON-Resourse, ISS-CREAM
- 2020: CTA, CALET, AMS-02
PAMELA discovery: Rising positron fraction

- TS93 (Golden+’96): flat positron fraction 0.078±0.016 in the range 5-60 GeV (US)
- HEAT-94,95,00 (Beatty+’04): “a small positron flux of nonstandard origin”
- PAMELA team reported a clear and very significant rise in the positron fraction compared to the “standard” model predictions
- “Standard” model:
  - Secondary production in the ISM
  - Steady state
  - Smooth CR source distribution
AMS-02: measurement of the positron fraction

- Confirmed and extended earlier PAMELA and Fermi-LAT measurements
- Keen to see the behavior >400 GeV!

Asymptotically approaches a constant ~0.15 or drops?

Fermi (East-West effect)

Aguilar+’13, Accardo+’14
The impact (NASA’s ADS)

- An anomalous positron abundance in cosmic rays with energies 1.5-100 GeV, Nature 2009, 458, 607 (PAMELA) – 1600 citations
- First Result from the Alpha Magnetic Spectrometer on the International Space Station: Precision Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5-350 GeV, PRL 2013, 110, 141102 (AMS-02) – 470 citations
- New Measurement of the Antiproton-to-Proton Flux Ratio up to 100 GeV in the Cosmic Radiation, PRL 2009, 102, 051101 (PAMELA) – 470 citations
- Measurement of the Cosmic Ray $e^+e^-$ Spectrum from 20 GeV to 1 TeV with the Fermi Large Area Telescope, PRL 2009, 102, 18110 (Fermi-LAT) – 810 citations (cf. 1000 for 2FGL and 710 for 1FGL)
- PAMELA Results on the Cosmic-Ray Antiproton Flux from 60 MeV to 180 GeV in Kinetic Energy, PRL 2010, 105, 121101 (PAMELA) – 380 citations
- PAMELA Measurements of Cosmic-Ray Proton and Helium Spectra, Science 2011, 332, 69 (PAMELA) – 320 citations
Other recent most remarkable results

✧ Observation of the \(^{60}\text{Fe}\) nucleosynthesis-clock isotope in galactic cosmic rays, Science 352 (2016) 677
✧ Precision Measurement of the Boron to Carbon Flux Ratio in Cosmic Rays from 1.9 GV to 2.6 TV with the Alpha Magnetic Spectrometer on the International Space Station, PRL 2016, 117, 231102
✧ Antiproton Flux, Antiproton-to-Proton Flux Ratio, and Properties of Elementary Particle Fluxes in Primary Cosmic Rays Measured with the Alpha Magnetic Spectrometer on the International Space Station, PRL 2016, 117, 091103
✧ Precision Measurement of the Helium Flux in Primary Cosmic Rays of Rigidities 1.9 GV to 3 TV with the Alpha Magnetic Spectrometer on the International Space Station, PRL 2015, 115, 211101
✧ Precision Measurement of the Proton Flux in Primary Cosmic Rays from Rigidity 1 GV to 1.8 TV with the Alpha Magnetic Spectrometer on the International Space Station, PRL 2015, 114, 171103
✧ Precision Measurement of the \((\text{e}^+ + \text{e}^-)\) Flux in Primary Cosmic Rays from 0.5 GeV to 1 TeV with the Alpha Magnetic Spectrometer on the International Space Station, PRL 2014, 113, 221102
✧ Electron and Positron Fluxes in Primary Cosmic RaysMeasured with the Alpha Magnetic Spectrometer on the International Space Station, PRL 2014, 113, 121102
✧ High Statistics Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5-500 GeV with the Alpha Magnetic Spectrometer on the International Space Station, PRL 2013, 110, 141102
Positron anomaly: Astrophysical papers (~200)

- Blasi 2009 “Origin of the positron excess in cosmic rays”
- Blasi & Serpico 2009 “High-energy antiprotons from old supernova remnants”
- Mertsch & Sarkar 2009 “Testing astrophysical models for the PAMELA positron excess with cosmic ray nuclei”
- Shaviv+ 2009 “Inhomogeneity in cosmic ray sources as the origin of the electron spectrum and the PAMELA anomaly”
- Delahaye+2010 “Galactic electrons and positrons at the Earth: new estimate of the primary and secondary fluxes”
- Stawarz+2010 “on the energy spectra of GeV/TeV cosmic ray leptons”
- Lee+ 2011 “Explaining the cosmic ray e⁺/(e⁻+e⁺) and pbar/p ratios using a steady-state injection model”
- Kachelriess+2011 “Antimatter production in supernova remnants”
- Kachelriess & Ostapchenko 2013 “B/C ratio and the PAMELA positron excess”
- Blum+ 2013 “AMS-02 results support the secondary origin of cosmic ray positrons”
- Cholis & Hooper 2013 “Dark matter and pulsar origin of the rising cosmic ray positron fraction in light of new data from the AMS”
- Erlykin & Wolfendale 2013 “Cosmic ray positrons from a local, middle-aged supernova remnant”
- Berezhko & Ksenofontov 2013 “Energy spectra of electrons and positrons produced in supernova remnants”
- Berezhko & Ksenofontov 2013 “Antiprotons produced in supernova remnants”
- Cholis & Hooper 2014 “Constraining the origin of the rising cosmic ray positron fraction with the boron-to-carbon ratio”
- Di Mauro+2014 “Interpretation of AMS-02 electrons and positrons data”
- Mertsch & Sarkar 2014 “AMS-02 data confronts acceleration of cosmic ray secondaries in nearby sources”
- Cowsik+2014 “The origin of the spectral intensities of cosmic ray positrons”
- ...
- ✨ + Dark Matter papers >1300
All-electron spectrum

- Fermi-LAT and PAMELA data agree well
- Shows some structure
- Flatter than extrapolated from low energies
- Sharp cutoff at 1 TeV (HESS), as expected

- Cannot be reproduced with a single power-law injection spectrum
- Origin
  - Local sources?
  - needs a component with hard spectrum (positrons?)
- CALET was launched to the ISS in 2015 to find out!
AMS-02 All Electron Spectrum

◊ A dedicated experiment AMS-02 has improved a measurement of the all-electron spectrum
◊ Still show a puzzlingly flat spectrum with no breaks from 10 GeV to ~1 TeV
◊ Note the linear scale in intensity!
◊ No effect of energy losses at HE or an additional (local) component?
◊ Local source of HE electrons?
More on electrons and positrons

✧ Looks like the individual spectra of $e^-$ and $e^+$ are disconnected
✧ But indices (different in absolute value!) behave similarly. Why?

![Graph showing spectral index vs. energy for positrons and electrons]

Different behavior of $e^-$ and $e^+$ at HE

$\sim 0.4$
Breaks in p and He spectra

✧ First noticed in ATIC and CREAM data, hints were present in earlier data
✧ Spectrum of He is flatter than spectrum of protons
✧ Perhaps similar breaks exist in spectra of heavier nuclei
PAMELA: first definitive evidence of the breaks

◊ Breaks are at the same rigidity pointing to the same origin of the breaks
AMS-02 study of the break structure

- Breaks are smooth at the same rigidity
- $p/He$ ratio shows no structure, why?
- Diff. in indices $p$, He: $\Delta \delta \sim 0.1$, why?
Most puzzling!

- If excess positrons are produced in pulsars or DM why the $p/e^+$ ratio is flat?
- Is there a break in the $p/e^+$ ratio (and $e^+$)?

✧ The flat ratios of $\bar{p}/p$, $p/e^+$, and $\bar{p}/e^+$ indicate a common origin of $p$, $\bar{p}$, $e^+$!
Yet more puzzling!

✧ Boron and pbars both are secondary, but why pbar/p is flat when B/C ratio is falling?
✧ Same break in Carbon and Boron spectra?
✧ “Standard picture” is wrong?
CRs in the interstellar medium

Gamma rays:
- Trace whole Galaxy
- Line of sight integration
- Only major species (p, He, e)

CR measurements:
- Detailed information on all species
- Only one location
- Solar modulation

Modeling is a must!
And yet even more puzzling!

✧ Observed Fermi-LAT counts in the energy range 200 MeV to 100 GeV

✧ Gamma rays are tracing the whole Galaxy!

✧ Predictions are made on the basis of conventional propagation model (GALPROP reacceleration model tuned to local CR observations)

✧ Remarkable agreement: residuals (Obs-Pred)/Obs ~ % level, ~10% in some places

✧ So, the “standard picture” is correct?
Fermi Bubbles

- Artist’s concept of Fermi Bubbles
- Puzzles:
  - The spectrum is “flat” (ongoing acceleration!)
  - The spectrum is uniform over these huge structures! (what is the mechanism?)
What the heck does this all mean?
— An anonymous astrophysicist, ca. 2017
ACCURACY is now the next frontier!

✧ Last decade has clearly demonstrated that the ACCURACY is the key in discovering new phenomena in CR
✧ To understand what is going on, we have to extend the coverage of CR measurements beyond the current limits
✧ Increase statistics and energy resolution
✧ Some directions to extend:
  ✧ P, He, Z>2 spectra >0.5 TeV/n
  ✧ Isotopic spectra/abundances >0.5 GeV/n & esp. radioactives
  ✧ Heavy nuclei Z>28 - all energies
  ✧ Search for fine structure in e± spectra at all energies, and esp. >1 TeV
  ✧ Antiproton measurements
Next steps?

✧ However, we do not have any new NASA’s major mission
  ✧ PAMELA was an Italian-Russian mission
  ✧ AMS-02 is a DoE mission which primary goal is the dark matter
  ✧ CALET is a Japanese mission
  ✧ Voyager 1,2 were launched in 1977
  ✧ ACE was launched in 1990’s with a 5-year goal
  ✧ FERMI is a gamma-ray mission (not cosmic ray)
  ✧ ISS-CREAM is sitting on the ground since 2015

✧ The US cosmic ray community has a number of bright and crazy ideas on what to do and which missions to launch to address the current challenges

✧ Bright and crazy enough to make them successful!
Without a clear path to the next NASA mission the US cosmic ray community is losing a life-time opportunity to lead the discovery crew!