Open Problems in High Energy Astrophysics

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CRIS 2010
Catania 13th September 2010
1. DARK MATTER

2. The sources of COSMIC RAYS
Mysteries of the DARK UNIVERSE

DARK ENERGY:
Drives apart galaxies and other large scale structures
[The energy of vacuum itself ?]

DARK MATTER:
Holds together galaxies and other large scale structures
[A new elementary particle ?]

Exist at different scales:
Entire Universe
Clusters of Galaxies
Galaxy

See M. Roncadelli
Determination of the density and "equation of state" of the Universe.

1. SN1a (standard candle) luminosity – redshift relation
   \[ a(t) \leftrightarrow \ell(z) \]

2. Cosmic Microwave Background Radiation Anisotropies

3. Galaxy Distributions
Nucleosynthesis constraints on ordinary ("baryonic") matter

DARK MATTER is NON BARYONIC
COMA Galaxy Cluster

Optical
Fritz Zwicky 1933
First argument for Dark Matter

X-ray
[hot gas confined by deep gravitational well]
Bullet CLUSTER (2 colliding clusters)
MASS DISTRIBUTION
(from gravitational lensing)
X-RAY Emission
(gas of ordinary matter)

DARK MATTER exists!
[and is NOT one of the known constituents of the Standard Model]
DARK matter halos of spiral Galaxies

![Graph showing velocity curve for NGC 6503 with contributions from halo, disk, and gas.]
\[ \rho_\odot \simeq 0.3 \ \text{GeV/cm}^3 \]
DARK MATTER: we know a lot:

It exists (Serious difficulties for “modified gravity”)

Good estimate of the cosmological average (22%)

Most of it is non baryonic

Most of it is “cold”

It cannot be explained by the Standard Model in Particle Physics!!
What is the Dark Matter?

Possible theoretical ideas

- Thermal Relic
- Axion
- Super-massive particles

[perhaps the best motivated]
[Offers the best chances of discovery]
The "relic density" of a particle is determined by its annihilation cross section.

(some complications are possible)

\[ \Omega_j^0 \approx 0.3 \left[ \frac{3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}}{\langle \sigma v \rangle} \right] \]

\[ \sigma(\chi\chi \rightarrow \text{anything}) \approx 10^{-36} \text{ cm}^2 \]

\[ \sigma \approx \frac{\alpha^2}{M^2} \left( \frac{\hbar}{c} \right)^2 \]

\[ M \approx 200 \text{ GeV} \]
Dark Matter can be explained
With the existence of a stable “thermal relic”
Requirement on its annihilation cross sections.

Weakly (in the “technical” sense)
Interacting
Massive
Particle

the WIMP's “miracle”

“Killing two birds with a single stone”
PHYSICS beyond the STANDARD MODEL is **REQUIRED** to explain Dark Matter!!

Extension of the Standard Model are **EXPECTED** at the electroweak mass scale

These extensions can “naturally” result in the existence of Dark Matter!

**LHC/Dark Matter connection!!**

Problems with a different status:
DM problem: direct observational puzzle.
New physics at EW scale: theoretically motivated prediction
Standard Model fields

fermions
quarks
leptons
neutrinos

bosons
photon
$W$
$Z$
gluons
Higgs
$H$
$h$

2 Higgs

Super-symmetric extension

Squarks
Sleptons
Sneutrinos

New bosons (scalar)
photino
Wino
Zino
gluinos
Higgsino
$\tilde{H}$
$\tilde{h}$

New fermions
spin 0
spin 1/2
Stable supersymmetric particle

\[ |\chi\rangle = c_1 \ |\tilde{\gamma}\rangle + c_2 \ |\tilde{z}\rangle + c_3 \ |\tilde{H}\rangle + c_4 \ |\tilde{h}\rangle \]

“Neutralino”

Note: the concept of Dark Matter as a thermal relic is more general than the "Minimal super-symmetric Model"
3 Roads for WIMP discovery

Efficient annihilation now (Indirect detection)

Efficient scattering now (Direct detection)

Efficient production now (Particle colliders)
Overall view of the LHC experiments.

1st Road: Creation in an accelerator
"Direct" Search for Dark Matter

2\textsuperscript{nd} Road: Elastic Scattering in underground experiment

Elastic scattering

\[ \chi + A \rightarrow \chi + A \]

[Rita Bernabei
Gabriella Sartorelli
tuesday afternoon]
Predicted velocity distribution of DM particles
In the “Halo Frame”
Maxwellian form \( \left\langle v_{\text{wimp}} \right\rangle \approx 250 \text{ km/sec} \)

\[ v^{\odot}_{\text{rotation}} \approx 200 \text{ Km/sec} \]
\[ \vec{w}_\oplus(t) = \vec{w}_\odot + \vec{v}_{\text{orbit}}(t) \]

\[ w_\oplus(t) \simeq w_\odot + \sin \gamma \ v_{\text{orbit}} \ \cos[\omega(t - t_0)] \]

“Halo rest frame”

Velocity of Earth in the Halo rest frame

[Co-rotation ?]
Velocity distribution in the Earth Frame: 

- 2nd June
- 2nd December
Expected flux of Dark Matter particles (here !):

\[ \phi_\chi = \frac{\rho_\chi}{m_\chi} \langle v_\chi \rangle \]

\[ \approx 1000 \left[ \frac{100 \text{ GeV}}{m_\chi} \right] (\text{cm}^2 \text{ s})^{-1} \]
“Direct” Search for Dark Matter

Non relativistic WIMP

\[ E_{\text{wimp}} \sim M_\chi + \frac{1}{2} M_\chi v^2 \]

\[ E_{\text{nucleus}} = M_A + \left[ \frac{1}{2} M_\chi v^2 \right] \frac{4 M_A M_\chi}{(M_A + M_\chi)^2} \left( \frac{1 - \cos \theta^*}{2} \right) \]

\[ \chi + A \rightarrow \chi + A \]
\[ E_{\text{nucleus}} = M_A + \left[ \frac{1}{2} M_\chi \nu^2 \right] \frac{4 M_A M_\chi}{(M_A + M_\chi)^2} \left( \frac{1 - \cos \theta^*}{2} \right) \]

\[ 0 \leq E_{\text{recoil}} \leq \left[ \frac{1}{2} M_\chi \nu^2 \right] \frac{4 M_A M_\chi}{(M_A + M_\chi)^2} \]

\[ E_{\text{recoil}} \simeq 39 \text{ KeV} \quad \left[ \frac{M_\chi}{100 \text{ GeV}} \right] \left[ \frac{\nu_0}{220 \text{ km s}^{-1}} \right]^2 r \]

Kinematical factor \( r \)

\[ r = \frac{4 M_A M_\chi}{(M_A + M_\chi)^2} \]
\( \sigma_{\chi A} = \sigma_{\text{spin independent}} + \sigma_{\text{spin dependent}} \)

Target not point-like:
Form Factor

\[ Q^2 = 2 M_A E_{\text{recoil}} \]

\[
\frac{d\sigma_p}{d \cos \theta^*} = \frac{\sigma_p}{2} \ F_p(Q^2) \quad \sigma_p \propto \left( \frac{M_\chi M_p}{M_\chi + M_p} \right)^2
\]

\[
\frac{d\sigma_A}{d \cos \theta^*} = \frac{\sigma_A}{2} \ F_A(Q^2) \quad \sigma_A \propto \left( \frac{M_\chi M_A}{M_\chi + M_A} \right)^2
\]
Spin independent: coherent scattering + kinematics

\[ \sigma_A = \sigma_p A^2 \left( \frac{M_X M_p}{M_X + M_p} \right)^{-2} \left( \frac{M_X M_A}{M_X + M_A} \right)^2 \]

\[ M_A \simeq A M_p \]

\[ \sigma_A = \sigma_p A^4 \left( \frac{M_X + M_p}{M_X + A M_p} \right)^2 \]

Strong dependence on mass number A
\[ K \equiv E^*_{\text{recoil}} \]

\[ K^* = \frac{1}{2} M_\chi v_0^2 \frac{4 M_\chi M_A}{(M_\chi + M_A)^2} \]

\[ \frac{dR_A}{dK} = \left[ \frac{\rho_\chi}{M_\chi M_A} \right] v_0 \sigma_A \left[ F_A^2(2 M_A K) \right] \left\{ \frac{1}{K^*} F \left( \frac{K}{K^*}, t \right) \right\} \]

**Prefactor**

\[ \frac{9.3}{A} \text{ (Kg day)}^{-1} \left[ \frac{50 \text{ GeV}}{M_\chi} \right] \left[ \frac{\sigma}{10^{-36} \text{ cm}^2} \right] \left[ \frac{v_0}{220 \text{ km/s}} \right] \]

**Nuclear Form Factor**

**Universal (A independent) function**

**Velocity Distribution**
Quasi exponential distribution

\[ A = 127 \text{ (Iodium)} \]
\[ M_{\text{wimp}} = 50 \text{ GeV} \]

2\text{nd june}
2\text{nd december}
Directional Response

\[ K = 0.5, 1, 2, 3, 4, 5, 6 \text{ KeV} \]

\[ M_\chi = 11.6 \text{ GeV} \]

\[ A = 127 \]
\[
\frac{dR}{dE_{\text{recoil}}} (E_{\text{recoil}}, t) = R_0 (E_{\text{recoil}}) + A (E_{\text{recoil}}) \, f(t)
\]

\[
f(t) \approx \cos \left[ \frac{2 \pi}{T_0} (t - t_0) \right]
\]

\[
A(K) = \left[ \frac{\rho_\chi}{M_\chi M_A} \sigma_A \right] \left[ \sin \gamma \, v_{\text{orbit}} \right] \frac{F_A^2 (2 M_A K)}{K^*} \left\{ \frac{1}{K^*} G \left( \frac{K}{K^*} \right) \right\}
\]

\[
G(x) = v_0 \left. \frac{d}{dw} F(x, w) \right|_{w = w_\odot}
\]
$A = 127$ (Iodium)
$M_{\text{wimp}} = 50$ GeV
DAMA-LIBRA (Gran Sasso underground Laboratory)

250 Kg NaI scintillator.

Observation of sinusoidal time-modulation of the Energy Deposition Rate

(controversial) claim of evidence of detection of Galactic Dark Matter

1.17 ton \times yr
Dama average Counting Rate

\[ 1 \text{ KeV}_{ee} \approx 11 \text{ KeV}_{\text{recoil}} \]
Robust evidence for the existence of a Sinusoidal time modulation of single hits signals:

<table>
<thead>
<tr>
<th>Energy interval (keV)</th>
<th>DAMA/LIBRA (6 annual cycles)</th>
<th>DAMA/Nal &amp; DAMA/LIBRA (7+6 annual cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-4</td>
<td>$\chi^2$/d.o.f. = 90.0/43</td>
<td>$\chi^2$/d.o.f. = 147.4/80</td>
</tr>
<tr>
<td></td>
<td>$P = 3.6 \times 10^{-5}$</td>
<td>$P = 6.8 \times 10^{-6}$</td>
</tr>
<tr>
<td>2-5</td>
<td>$\chi^2$/d.o.f. = 82.1/43</td>
<td>$\chi^2$/d.o.f. = 135.2/80</td>
</tr>
<tr>
<td></td>
<td>$P = 3.1 \times 10^{-4}$</td>
<td>$P = 1.1 \times 10^{-4}$</td>
</tr>
<tr>
<td>2-6</td>
<td>$\chi^2$/d.o.f. = 68.9/43</td>
<td>$\chi^2$/d.o.f. = 139.5/80</td>
</tr>
<tr>
<td></td>
<td>$P = 7.4 \times 10^{-3}$</td>
<td>$P = 4.3 \times 10^{-5}$</td>
</tr>
</tbody>
</table>
Period one year.
(... well obvious...)

"Phase"
Is centered
At the "right" value (!!)

Maximum
The 2\textsuperscript{nd} june
day: \((146 \pm 7)\)

Fundamental discovery ?!

Unknown background
(with coincident phase) ?
Energy dependence of the Modulation amplitude

The graph shows the energy dependence of the modulation amplitude, $S_m$, in units of cpd/kg/keV as a function of energy in keV. The data points indicate a nearly flat trend across the energy range from 0 to 20 keV.
Gaussian with detector resolution
Relation between Light collected by PMT and $E_{\text{recoil}}$

$E(\text{recoil}) = 11.0 \times E(\text{electron-equivalent})$

In presence of “channeling”
Scattering in certain directions

$E(\text{recoil}) = 1.0 \times E(\text{electron-equivalent})$

Important Ambiguity
In the interpretation
Of the energy scale
WIMPs
Neutrons
Scatter on
Target nuclei

Most background
From photons and
electrons
Scattering on
Atomic nuclei

light  charge  heat
CDMS II ZIP Detectors

- Surface rejection from pulse shapes
- 30 detectors stacked into 5 towers of 6 detectors

E_{phonon}

E_{charge}

ER background

NR signal

1 \mu m tungsten

380 \mu m x 60 \mu m aluminum fins

Jodi Cooley - Stanford University
CDMS II Results

NO EVENTS OBSERVED!

PRL 102, 011301 (2009)
XENON100: The TPC Assembly

- Electrical Connections (outside Bell)
- Electrical Connections (inside Bell)
- Chamber Flange
- Cover of Vessel
- Top Shield
- Side Shield
- Bell
- Top Array (98 PMT)
- Anode and Grids (Prop. Scintillation)
- PTFE Panels with Field Shaping
- Bottom Array (80 PMT)
- Bottom Shield
- Side Shield

170 kg LXe
(70 kg target)
The XENON two-phase TPC

- Single electron and single photon measurement sensitivity
- > 99.5% ER rejection via Ionization/Scintillation ratio (S2/S1)
Xenon-100 (liters) results

40 Kg of fiducial mass
11.17 days of data taking  [1/1000 the DAMA exposure]
0 candidates
4 “allowed regions for DAMA” [Dominant Na, I] * [“channelling”]

WARNING !! Spin independent cross section + A number of assumptions enter in this exclusion plot

[computed by Gelmini et al.]
Intense controversy around these results and their interpretation.

Is it possible that DAMA is detecting a time dependent background that by “coincidence” has the “right” features that mimic Dark Matter?
[Crucial test: repeat in different environment (south hemisphere?)]

If DAMA does see a DM signal:
why the other detector do not see a signal?
  Experimental problems?!
  Unexpected properties of DM particles?!

Several other experiments are taking data
What should they see?
Indirect searches for DARK MATTER

3rd Road
To WIMP's Discovery
Power injection for Dark Matter annihilation

\[ L(\vec{x}) = \frac{\rho(\vec{x})^2}{M_\chi^2} \langle \sigma \nu \rangle M_\chi \]

\[ \chi + \chi \rightarrow \gamma \quad e^+ \quad \bar{p} \quad \nu_\alpha \]

Injection of energy because of DM annihilation in our own galaxy.
Astrophysical information

Dark Matter in the Milky Way

\[ \rho_{dm}(\vec{x}) \]

Dark Matter density distribution

\[ f_{dm}(\vec{v}, \vec{x}) \]

Velocity distribution

[consistency requirement]
Astrophysical information

Dark Matter in the Milky Way

\[ \rho_{dm}(\vec{x}) \]

Dark Matter density distribution

\[ f_{dm}(\vec{v}, \vec{x}) \]

Velocity distribution

[consistency requirement]

Problems:

- “The CUSP”
- “Granularity” [“the BOOST factor”]
\[ L(\vec{x}) = \frac{\rho(\vec{x})^2}{M_\chi} \langle \sigma \, v \rangle \, M_\chi \]

- \[ L_{\text{DM}} \propto \frac{1}{M_\chi} \]
- \[ \langle \rho(\vec{x})^2 \rangle \geq \langle \rho(\vec{x}) \rangle^2 \]
  "Granularity" boosts the power output.
- The "WIMP miracle"  \[ \langle \sigma \, v \rangle \simeq 3 \times 10^{-26} \, \text{cm}^3 \, \text{s}^{-1} \]
  \[ v_{\text{freeze out}} \simeq 0.2 \div 0.3 \]
  \[ v_{\text{Galaxy}} \simeq 10^{-3} \]
First possibility: Sommerfeld effect

Different possibilities for extrapolating the cross section from the early Universe:

DM is charged under a (new) gauge force, mediated by a “light” boson: this sets a non-perturbative long-range interaction, analogously to Coulomb interaction for positronium:

\[ V(r) = -\frac{\alpha}{r} \]

gives the enhancement in the cross section:

\[ S = \left| \frac{\psi(\infty)}{\psi(0)} \right|^2 = \frac{\pi \alpha/v}{1 - e^{-\pi \alpha/v}} \quad v \ll \alpha \to \frac{\pi \alpha}{v} \]

The same \( v/v \) enhancement is obtained for a Yukawa potential. In a DM context, first studied in the MSSM for pure very massive Winos or Higgsinos and weak interaction as gauge force (light W boson).
Annihilation cross section

\[ \sigma(\chi + \bar{\chi} \rightarrow \text{anything}, \nu_{\text{rel}}) \]

\[ \frac{dn}{dE} \bigg|_{(\chi + \chi \rightarrow \gamma)} \]

\[ \frac{dn}{dE} \bigg|_{(\chi + \chi \rightarrow \gamma, e^+, \bar{p}, \nu_\alpha)} \]

Inclusive spectra

\[ B(\chi + \bar{\chi} \rightarrow F) \]

Branching Ratios in different final states F

In most models DM particle = Majorana particle
Photon emission from DM annihilation

\[ J(\Omega) = \frac{1}{R_{\odot}} \int d\ell \, \frac{\rho^2(\ell, \Omega)}{\rho_{\odot}^2} \]
Photons from Dark Matter

\[ \phi_\gamma(\Omega) = K_\gamma \ J(\Omega) \left. \frac{dn}{dE} (E) \right|_{\chi\chi \rightarrow \gamma} \]

\[ K_\gamma = \frac{1}{4\pi} \ \frac{1}{2} \ \frac{\langle \sigma v \rangle}{M_\chi^2} \ \frac{\langle \rho_\odot \rangle^2}{R_\odot} \]

\[ K_\gamma \approx 3.7 \times 10^{-10} \ \left[ \frac{\langle \sigma v \rangle}{3 \times 10^{-6} \text{ cm}^3 \text{ s}^{-1}} \right] \ \left[ \frac{100 \text{ GeV}}{M_\chi} \right]^2 \]

\[ J(\Omega) = \frac{1}{R_\odot} \int d\ell \ \frac{\rho^2(\ell, \Omega)}{\rho^2_\odot} \]

Adimensional Angular factor
$E_\gamma > 100 \text{ MeV}$
$J(\Omega)$

The graph shows the function $J(\Omega)$ plotted against $\theta_{GC}$ (degrees). The y-axis is on a logarithmic scale, with values ranging from $10^{-5}$ to $10^5$. The x-axis represents $\theta_{GC}$ in degrees, ranging from 0.1 to 100.
Galactic Cosmic Ray Halo

Smaller CR density in the LMC and SMC
Charged Particles: magnetic confinement

Escape
SOURCE(s) + Propagation  $\rightarrow$ Observable Cosmic Rays
\[ p + p_{\text{ISM}} \rightarrow e^+ \ldots \]
\[ p + p_{\text{ISM}} \rightarrow \pi^+ \ldots \]
\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]
\[ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \]

\[ \chi + \chi \rightarrow e^+ + \ldots \]

Possible positron accelerators
PAMELA detector

Launch
15th June 2006
(4 years ago)

The “positron excess”: Evidence for DM ?? or astrophysical effect?
Crucial ingredient: the MAGNET!

Flight data:
- 0.171 GV positron
- 0.169 GV electron
Antiproton result

Agreement
With standard production mechanism
An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV
An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV

High energy: ratio $e^+ / e^-$ grow with $E$!!

$$\frac{\phi_{e^+}}{\phi_{e^-}} \propto E^{0.52}$$

Very unexpected result!
ATIC

Balloon experiment (electron + positron)

KK dark matter with $m \sim 600$ GeV

"Shoulder" [??!]

Nature: October 2008
Annihilation of 2 Dark-Matter Particles. Produce particles with energy spectrum that extends to $E = m$

$\chi + \chi \rightarrow e^+ + e^-$

Injection spectrum

Observable Flux

(after propagation + energy losses)
FERMI: electron + positron flux
FERMI: electron + positron flux

"Excess" [??] of electrons + positrons

..., Possible...

\[ J_{\text{extra}}(E) \propto E^{-\gamma_e} \exp\left\{-E/E_{\text{cut}}\right\} \]

but certainly not necessary
From: Cirelli

Results

Which DM spectra can fit the data?

E.g. a DM with: - mass $M_{DM} = 150$ GeV
- annihilation $\text{DM DM} \rightarrow W^+W^-$
  (a possible SuperSymmetric candidate: wino)

Positrons:

Anti-protons:

Yes!

NO!
Results

Which DM spectra can fit the data?

E.g. a DM with: -mass $M_{DM} = 10 \text{ TeV}$
-annihilation $\text{DM DM} \rightarrow W^+W^-$

but...: -boost $B = 2 \cdot 10^4$

No...

Positrons:

Anti-protons:

PAMELA 08

Yes!

background?

boost $\approx 20000$

$0.3\%$

$1\%$

$3\%$

$10\%$

$30\%$

Positron fraction

Positron energy in GeV

$10^{-5}$

$10^{-4}$

$10^{-3}$

$10^{-2}$

$\bar{p}/p$

$\bar{p}$ kinetic energy in GeV

PAMELA 08

background?

boost $\approx 20000$
Dark Matter explanation of the “Pamela positron excess” in terms of the “WIMP” model is possible, but not in its Simplest, most natural version.

[1.] The DM annihilation does not produce antiprotons “Leptophilic” Dark Matter [?]
(no convincing dynamical explanation)

[2.] Include a large “Boost factor” to increase the rate of the DM annihilations. Very “clumpy” dark matter.
(very lucky in being close to a big DM clump) “winning the jackpot” [?]
Dark Matter explanation of the “Pamela positron excess” in terms of the “WIMP” model is possible, but not in its simplest, most natural version.

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to increase the rate of the DM annihilations.
Very “clumpy” dark matter.
(very lucky in being close to a big clump)
“winning the jackpot” [?]

Is this “adding epicycles” to the wrong theory?

Are there other possible interpretations for this result.
Proton and electron + Positron energy spectra

Use: $e^+/e^-$ ratio from Pamela fit of $e=(e^++e^-)$ data to estimate $e^+$ flux

$E^{-2.70}$

$E^{-3.04}$
Proton and electron + Positron energy spectra

Use: $e^+/e^-$ ratio from Pamela fit of $e=(e^++e^-)$ data to estimate $e^+$ flux
Spectra of approximately form:

<table>
<thead>
<tr>
<th>Species</th>
<th>Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>protons</td>
<td>$E^{-2.70}$</td>
</tr>
<tr>
<td>electrons</td>
<td>$E^{-3.04}$</td>
</tr>
<tr>
<td>positrons</td>
<td>$E^{-2.5}$</td>
</tr>
</tbody>
</table>

Completely unexpected result

Rough expectation
For the positron slope SOFTER than electrons
**PULSARS**

Proposed as possible Accelerators of $e^+ e^-$

---

**CRAB Nebula**

$P_{\text{Crab}} = 0.0334 \text{ s}$

$\dot{P}_{\text{Crab}} = 4.2 \times 10^{-13} \text{ s}$

$(\Delta P_{\text{Crab}})_{\text{year}} = 13.2 \times 10^{-6} \text{ s}$

---

*[Fig 15.14, H.S. Longair, "High Energy Astrophysics"]*
Fermi Pulsar detection

Fermi Pulsar Detections

- New pulsars discovered in a blind search
- Millisecond radio pulsars
- Young radio pulsars
- Confirmed pulsars seen by Compton Observatory EGRET instrument

Pulses at 1/10th true rate
Contribution from all Pulsars

\[
\frac{dN_e}{dE_e} \approx 8.6 \times 10^{38} \dot{N}_{100} \left(\frac{E_e}{\text{GeV}}\right)^{-1.6} \exp\left(-\frac{E_e}{80 \text{ GeV}}\right) \text{ GeV}^{-1} \text{ s}^{-1}
\]
NEW Mechanism
In a standard source [SNR]

\[ \left( \frac{E}{E_{\text{injection}}} \right)^{-\alpha} \]

Pasquale Blasi
Astro-ph/0903.2794
Injection of relativistic e+e- in SNR

\[ E^{-(\alpha-\delta)} \]
Importance of AMS mission.

scheduled: February 26th 2011
Below the "Knee" Cosmic Rays

Several interesting problems:

- Detailed shape of the spectra
  (slope breaks indicated by CREAM)

- Anisotropies ("Milagro hot spots")

- Study of the confinement time.
TeV spectra are harder than spectra < 200 GeV/n

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

Flux $\times E^{2.75}$ (m$^2$ s sr$^{-1}$) (GeV)$^{1.75}$

AMS
$\gamma_p = 2.78 \pm 0.009$
$\gamma_{He} = 2.74 \pm 0.01$

CREAM-1
$\gamma_p = 2.66 \pm 0.02$
$\gamma_{He} = 2.58 \pm 0.02$

Energy (GeV)
Cosmic Ray Nuclear Composition

Overabundance of Li, Be, B

Sub-iron elements

Spallation effect:

Column density

Confinement time

Figure 1. The relative abundance distribution of the elements in the cosmic radiation and in the solar system (normalized to Si = 100) from He to Ni (solid circles, 70–280 MeV per nucleon; open circles, 1000–2000 MeV per nucleon; open diamonds, solar system abundance distribution). [Reproduced with permission from J. A. Simpson (1983). Ann. Rev. Nucl. Part. Sci. 33 by Annual Reviews, Inc.]
From CREAM

\[ \tau(E) \sim E^{-0.6} \]
Injection from a thin plane:

\[ n_e(E, 0) = \frac{1}{4\sqrt{\pi}} \frac{q_0}{\sqrt{D_0 b}} C(\alpha, \delta) E^{-(\alpha+1/2+\delta/2)} \]

\[ n_e(E) \sim q_e(E) \frac{\tau_{\text{loss}}(E)}{R_{\text{diff}}(E)} \]

\[ \alpha_e = \alpha_0 + \frac{\delta}{2} + \frac{1}{2} \]
Injection from a plane

\[ \alpha_p = \alpha_0 + \delta \approx 2.70 \]

\[ \alpha_e = \alpha_0 + \frac{\delta}{2} + \frac{1}{2} \approx 3.04 \]

\[ \alpha_0 \approx 2.38 \]

\[ \delta \approx 0.32 \]

Homogeneous injection

\[ \alpha_p = \alpha_0 + \delta \approx 2.70 \]

\[ \alpha_e = \alpha_0 + 1 \approx 3.04 \]

\[ \alpha_0 \approx 2.04 \]

\[ \delta \approx 0.66 \]
Milagro collaboration

Discovery of Localized Regions of Excess 10-TeV Cosmic Rays

ARGO

VERNETTO et al. SKY MONITORING WITH ARGO-YBJ
High Energy Astrophysical Source:

Object (or an “event”) that produces (and for some time contains) relativistic particles

Escaping particles: CR

Unavoidable Photon+ neutrino emission!
$p + \text{target} \rightarrow \text{many particles}$

$\rightarrow p(n) + \pi^+ + \pi^- + \pi^0$

$\mu^+ + \nu_\mu \rightarrow \gamma + \gamma$

$e^+ + \nu_e + \bar{\nu}_\mu$

“Hadronic Emission”

$e^\mp + B \rightarrow e^\mp + \gamma_{\text{synchrotron}}$

“Leptonic Emission”

$e^\mp + \gamma_{\text{soft}} \rightarrow e^\mp + \gamma_{\text{Inverse Compton}}$
Accelerators associated with acceleration of astronomical masses.

Emission of Gravitational Waves

Multi-messenger Astrophysics

COSMIC RAY physics

GAMMA Astronomy

NEUTRINO Astronomy
"A golden age For Gamma Astronomy"
Cherenkov Imaging Telescopes

MAGIC
HESS
VERITAS
MAGIC $2 \times 236 \text{ m}^2$

2\textsuperscript{nd} telescope: April 2009
HESS Telescope (Namibia)
The “RICHNESS of GAMMA ASTRONOMY”

The TeV sky is approaching 100 sources belonging to several different classes:
Launch of “GLAST”  
28th August satellite renamed FERMI
The “Richness of the High-Energy Sky”

Several astrophysical objects are capable of accelerating charged particles to relativistic energy.

- Pulsars
- SuperNova Remnants
- MicroQuasars
- Active Galactic Nuclei
- Gamma Ray Bursts.

........
The “Richness of the High-Energy Sky”

Several astrophysical objects are capable of accelerating charged particles to relativistic energy.

- Pulsars
- SuperNova Remnants
- MicroQuasars
- Active Galactic Nuclei
- Gamma Ray Bursts.

Most of the observed relativistic particles are leptons.

Open Question: Where are the observed CR accelerated?
ACTIVE GALACTIC NUCLEI

3C219

Optical

Radio
Geometry of the emission of the two jets

Intense radiation field
Of the companion star
Absorbs TeV photons [?]
GAMMA RAY BURSTS (GRB's)

Proposed source Of the CR
Extraordinary Large (beamed) Energy Output
GRB: associated with a subset of SN Stellar Gravitational Collapse
The SuperNova “Paradigm” for CR acceleration

CAS A
(1667)

Powering the galactic Cosmic Rays

\[ L_{\text{cr}}(\text{Milky Way}) \approx \frac{\rho_{\text{cr}} V_{\text{conf}}}{T_{\text{conf}}} \]

\[ \approx 2 \times 10^{41} \left( \frac{\text{erg}}{\text{s}} \right) \]

\[ \approx 5 \times 10^{7} L_{\odot} \]

- ENERGETICS
- DYNAMICS [Diffusive Shock acceleration]
Power Provided by SN is sufficient with a conversion efficiency of 15-20% in relativistic particles.

\[ L_{\text{Milky Way kinetic}} \approx E_{\text{SN}} f_{\text{SN}} \]

\[ L_{\text{SN kinetic}} \approx \left[ 1.6 \times 10^{51} \text{ erg} \right] \left[ \frac{3}{\text{century}} \right] \]

\[ M = 5 M_\odot \]

\[ v \approx 5000 \text{ Km/s} \]

\[ L_{\text{Milky Way kinetic}} \approx 1.5 \times 10^{42} \frac{\text{erg}}{\text{s}} \]
Comparison with ROSAT observation

HESS Telescope

Observations with TeV photons

SuperNova RX J1713.7-3946
Have we proved that SNR are the source of the bulk of the Galactic Cosmic Rays?
Have we proved that SNR are the source of the bulk of the Galactic Cosmic Rays?

The evidence is accumulating. Fermi, Hess results

Detection of Star-Burst Galaxies....

Perhaps case not closed...
[different opinions]
What about:

NEUTRINO

ASTRONOMY
The idea to observe the Universe using Neutrinos is profoundly fascinating.

The insights about Nature that are possible using this: "New Way" to look at the Sky can be profound.

CATANIA (with Emilio Migneco and his collaborators) is one of the "capitals" of the efforts in this direction.

Tuesday morning session
Possible structure of a “KM3” detector in the Mediterranean Sea:

“tower” [6 PMT's]

127 towers (180 m)

Detection Unit layout.
Water Cerenkov in the Mediterranean (ANTARES)
80 + 6 strings (125 m)
60 PMT / strings (17 m)
2400 PMT + surface array

85 strings, 60 OMs/string
17 m between OMs, 125 m between strings
IceTop: 80 stations of 2 tanks with 2 modules

IceCube total strings 59
IceCube

80 + 6 strings (125 m)
60 PMT / strings (17 m)
2400 PMT + surface array

No SIGNAL (yet)

85 strings, 60 OMs/string
17 m between OMs, 125 m between strings
IceTop: 80 stations of 2 tanks with 2 modules
UHECR

1. Energy Spectrum
2. Anisotropy
3. Composition
1. Energy Spectrum

- Clear identification of a high energy suppression [the “END” (... well the “suppression”) of exotic/fundamental physics modeling for UHECR].

- Excellent agreement between experiments [“small” but important question about the energy scale].

- Physical interpretation strongly coupled to (2., 3.) (anisotropy + composition). [proton GZK ?]
Short distance structure of space time

\[ c(E) = c \times \left( 1 - \xi \frac{E}{M_{\text{Planck}}} + \ldots \right) \]

\[ \Delta t \simeq \xi \frac{E}{M_{\text{Planck}}} \frac{L}{c} \]

\[ \Delta t \simeq 0.06 \ E_{\text{GeV}} \ z \]

Delay of high energy photons
Markarian 501 (120 Mpc)

9 july 2005
2 minutes bins
Structure in the energy spectrum

- "Knee"
- "2nd Knee"
- "Ankle"

Log$_{10}$[\(\phi(E) E^3\) (eV$^2$/cm$^2$s sr)]

Log$_{10}$[E (eV)]

High Energy suppression


~50 years of UHECR

EXTREMELY ENERGETIC COSMIC-RAY EVENT

John Linsley, Livio Scarsi,† and Bruno Rossi

Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received April 12, 1961)

Hadronic interaction Modeling

Energy

it follows on any reasonable shower model that the energy of the primary particle was about $10^{19}$ ev. Taking the usual estimate $3 \times 10^{-6}$ gauss for the galactic magnetic field, one finds the radius of curvature of the path of a proton of such energy to be about $10^4$ light years. Since, according to current estimates, the radius of the galactic halo is only about five times this value, while the thickness of the galactic disk is about five or ten times smaller, it seems certain that the primary particle acquired its energy outside our galaxy.

An important question is whether the primary particle was a proton or a heavier nucleus.

Mass A

Measure a single slice of the shower at the ground

MUONS

(shielded)

3.8

3

3

4

7

11

7

17

19

17

14

30

54

74

45

236

536

241

1.8 km
Observed Light \rightarrow \text{Emitted Photons} \rightarrow \text{Shower Size}

\[ L(\Omega) \rightarrow F_{\gamma}(X) \rightarrow N_{e^\pm}(X) \]
Area \propto \text{Energy}

\[ E_{\text{tot}} = E_{\text{ionization}} + E_\nu + E_\mu + E_{\text{ground}} \]

Small model dependence

Shape depends on:
- Primary Identity
- Interaction Model
$E \approx 10^{20}$ eV

NOT an IRON nucleus

IF model is approximately correct
Proton showers: Deeper, larger fluctuations
UHECR

1. Energy Spectrum

2. Anisotropy

3. Composition

- Significant Experimental Discrepancies
- Auger/Hires
- Confusing situation.
1. Energy Spectrum
2. Anisotropy
3. Composition

Consistent interpretation of AUGER results is problematic.

“CRISIS” (?)
Piece of extragalactic space: Non MilkyWay-like sources
UHECR

Crucial Problem:

Galactic Extragalactic Transition

1. Maximum Energy of Milky Way sources
2. Power of Extragalactic CR sources
3. Shape of injection spectrum of extragalactic CR

Energy Spectrum "feature"
Composition change
Isotropy effect
UHECR

Crucial Problem:

Galactic Extragalactic Transition

1. Maximum Energy of Milky Way sources
2. Power of Extragalactic CR sources
3. Shape of injection spectrum of extragalactic CR

Energy Spectrum “feature”
Composition change
Isotropy effect
Not detected
Poorly predicted
MW large scale field
"Ankle like" transition

"Knee like" transition
Structure in the energy spectrum

"Knee"

"2nd Knee"

"Ankle"

High Energy suppression

$\log_{10}[E(eV)]$ vs $\log_{10}[\phi(E)E^3]$ (eV$^2$/cm$^2$/s sr)
Power Law Injection (No Cosmic Evolution)

Remarkable “coincidence” (?!)

Berezinski et al. “DIP Model”
Power Density Requirements to Generate the Extra-Galactic Cosmic Rays:

$\alpha = 2.0$

\[ \mathcal{L} \approx 1.1 \times 10^{37} \left[ 1 - \ln \left( \frac{E_{\text{min}}}{10^{18} \text{ eV}} \right) \right] \frac{\text{erg}}{\text{s Mpc}^3} \]

3000 Solar luminosities

$\alpha = 2.7$

\[ \mathcal{L} \approx 3.4 \times 10^{37} \left( \frac{E_{\text{min}}}{10^{18} \text{ eV}} \right)^{-0.7} \frac{\text{erg}}{\text{s Mpc}^3} \]

9000 Solar luminosities
“Average Power Density”
needed to produce the Extra-Galactic Cosmic Rays

\[
\mathcal{L}_{\text{ExtraGalactic}}^{\text{cr}} \sim \left(10^3 \div 10^5\right) \frac{L_\odot}{\text{Mpc}^3}
\]

\[
\mathcal{L}_{\text{stars}} \sim 10^9 \frac{L_\odot}{\text{Mpc}^3}
\]

\[
\mathcal{L}_{\text{SN}}^{\text{Kinetic}} \sim 4 \times 10^6 \frac{L_\odot}{\text{Mpc}^3}
\]

\[
\mathcal{L}_{\text{AGN}}^{\text{bolometric}} \sim 2 \times 10^7 \frac{L_\odot}{\text{Mpc}^3}
\]

Possible Sources
Galaxies with Redshift $z < 0.018$

Matter distribution of the "near universe"
COSMIC Ray ASTRONOMY [?!] (imaging of the sources)

almost nothing

very poor

poor

excellent
AUGER result on Correlations with the VCV AGN catalogue November 2008.

Select highest energy Showers.

- $6 \times 10^{19}$ eV
- 75 Mpc
- 3.1°

- 14 ev.
- 8 coincid. (2.9)
- 13 ev.
- 9 coincid. (2.7)
AUGER result on Correlations with the VCV AGN catalogue

$6 \times 10^{19}$ eV
75 Mpc
3.1°

Significant dilution [but not disappearance] of the statistical significance

14 ev. 8 coincid. (2.9)
13 ev. 9 coincid. (2.7)
42 ev. 12 coincid. (8.8)
Discussion on CEN A
The AGN closest to us.

3 events within 3 degrees
8 events within 18 degrees

November 2008
3, 20 degrees circles
Discussion on **CEN A**  
The AGN closest to us.

3 events within 3 degrees  +0  events within 3 degrees  
8 events within 18 degrees  +5  events within 18 degrees

---

November 2008 (13 + 14 events)  
Update  September 2010 (+42 events)
\[\delta \theta = (\delta \theta)_{\text{Milky Way}} + (\delta \theta)_{\text{Intergalactic}} + (\delta \theta)_{\text{Source Envelope}}\]

Deviation in GALACTIC Magnetic Field

\[\delta \approx 2.7^\circ \frac{60 \text{ EeV}}{E/Z} \left| \int_0^D \left( \frac{dx}{kpc} \times \frac{B}{3 \mu G} \right) \right|\]

Deviation in EXTRA-GLACTIC Magnetic Field

\[\delta_{rms} \approx 4^\circ \frac{60 \text{ EeV}}{E/Z} \frac{B_{rms}}{10^{-9} \text{G}} \sqrt{\frac{D}{100 \text{ Mpc}}} \sqrt{\frac{L_c}{1 \text{ Mpc}}}\]
Faraday Rotation of the polarization of pulsars
Field COUNTERCLOCKWISE in arm regions (clockwise in interarm regions)

Regular Magnetic Field in the plane of the Milky Way

\[ \langle B, L(\Omega) \rangle_{\text{Milky Way}} \sim 1 \mu \text{Gauss Kpc} \]
Mass Composition becoming heavy? at very high energy?

Significance would be very important!

Constraints on the structure and properties of the astrophysical sources.

Observational controversy NON confirmation of HiRes

Correlation with sources Small deviation in magnetic Fields (Z < 3?)
“If these trends persist to the highest energies there would appear to be a conflict between conclusions that can be drawn from the anisotropy and the conclusions drawn from the elongation rate measurement.”

“These results also demand a more careful review of what seemed to be an obvious conclusion that iron nuclei could not show an anisotropy because of galactic and perhaps extragalactic magnetic fields.”
HiRes 2009

\[
\langle X_{\text{max}} \rangle (\text{g/cm}^2)
\]

- **HiRes Data**
- QGSJET01
- QGSJET-II
- SIBYLL 2.1

\[
\log(E(\text{eV}))
\]

- **P**
  - 211
  - 226
  - 146
  - 107
  - 67
  - 40
  - 10
  - 8

- **Fe**
  - 660
  - 670
  - 700
  - 750
  - 800
  - 850
Overall comparison of $X_{\text{max}}$ data with QGSJET02 p and FE HIRES

Very important
To study the entire Distribution (not only the 1st two momenta)
HIRES 2009

Fluctuations on $X_{max}$

$\sigma_x (g/cm^2)$ vs. $\log(E(eV))$:
- **HiRes Stereo Data**
- **QGSJET-II Protons**
- **QGSJET-II Iron**
Comparison of the "Theory curves" (same model: Sibyll 2.1) for Auger (blue) HiRes (red)
Theoretical curves for Auger (Sibyll 2.1 model):
Theoretical curves for HiRes (Sibyll 2.1 model):

- Proton
- Iron
- Proton (E → E/56)
One proton Shower: $E_0 = 10^{19}$ eV

50 highest energy individual sub-showers
100 photons ~50% of energy
1000 photons ~70% of energy

Approximately 100 photons
In 30-40 interaction vertices
Control the structure of the Shower: $x \sim 0.1$
Average longitudinal development of a photon shower well understood

Photon showers

Theoretically
Well understood

$X_{\text{max}}(E) \simeq \lambda_{\text{rad}} \ln \left(\frac{E}{\varepsilon}\right)$

$N_{\text{max}}(E) \simeq \frac{E}{\varepsilon} \frac{1}{\sqrt{\ln(E/\varepsilon)}}$

Elongation Rate

85 (g/cm$^2$)/decade
Scaling model:
85 \text{(g/cm}^2\text{)/decade}

Increasing cross sections
Softer spectra

Elongation Rate
For protons
Shower fluctuations

Auger (PRL 2010)

RMS($X_{\text{max}}$) vs Energy [eV]

- Proton
- Iron

Model Predictions:
- Sibyll
- QGSJet
- QGSJetII
- EPOS
FLUCTUATIONS on $X_{\text{max}}$

\[ X_{\text{max}} = X_{1st} + Y_{\text{max}} \]

\[ \sigma^2_{X_{\text{max}}} = \sigma^2_{X_{1st}} + \sigma^2_{Y_{\text{max}}} \]

\[ \left( \frac{\sigma_{\text{proton}}}{\langle X_{\text{max}} \rangle} \right)^2 \sim \lambda^2_p + \sigma^2_{Y_{\text{max}}} \]
\[ \left( \sigma_{\text{proton}, \langle X_{\text{max}} \rangle} \right)^2 \approx \lambda_p^2 + \sigma_{Y_{\text{max}}}^2 \]

\[ \left( \sigma_{\langle X_{\text{max}} \rangle}^{A} \right)^2 \approx \frac{f(A)}{A} \lambda_p^2 + \frac{\sigma_{Y_{\text{max}}}^2}{A} \]

\[ A = 56 \]

\[ \frac{1}{\sqrt{A}} = 0.13 \]

\[ \sqrt{f(A)} \approx 0.4 \]

Nuclear interaction.
Several Nucleons
Interact at same point.
$^{56}$Fe interactions. $E_{\text{tot}} = 10^{19}$ eV

$\lambda_p = 48.5 \text{ g cm}^{-2}$

$\sigma\langle X_{1st} \rangle \approx \frac{\lambda_p}{\sqrt{A}} \approx 6.5 \text{ g cm}^{-2}$

$\sigma\langle X_{1st} \rangle \approx 20.5 \text{ g cm}^{-2}$
2 component model: Proton + Iron

\[
\langle X_{\text{max}} \rangle_{\text{obs}} \simeq \langle X_p \rangle - D_p \langle \log A \rangle
\]
\[ \sigma^2_X = f_p \sigma_p^2 + (1 - f_p) \sigma_{Fe}^2 + f_p(1 - f_p) \left( \langle X_p \rangle - \langle X_{Fe} \rangle \right)^2 \]

\[ f_{iron} = 1 - f_{proton} \]
\[ \sigma_X^2 = \sum_j f_j \sigma_{A_j}^2 + \sum_j f_j \langle X_{A_j} \rangle^2 - \left( \sum_j f_j \langle X_{A_j} \rangle \right)^2 \]

\[ \sigma_X^2 = \langle \sigma_A^2 \rangle + D_p \left[ \langle (\log A)^2 \rangle - \langle \log A \rangle^2 \right] \]

\[ \sigma_X^2 \sim \langle \sigma_A^2 \rangle + D_p \sigma_{\log A}^2 \]
Mass Composition becoming heavy? at very high energy?

Significance would be very important!
Constraints on the structure and properties of the astrophysical sources.

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Conclusions

1. Very exciting time for Cosmic Ray science and High Energy Astrophysics

2. Crucial moment for Particle Physics and accelerators. [Important connections with Astro-Particle Physics: Dark Matter, Hadronic interactions]

3. Many important open questions. [....which make life interesting....]