Propagations of Cosmic Rays. II

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stanford/kipac
Outline

First lecture
- General information
- Transport equation
- Propagation near the CR sources
- Propagation in the ISM. I. Components of the ISM

Second lecture
- Propagation in the ISM. II. Cosmic Rays
  - Isotopic composition
  - Determination of the Propagation parameters
  - K-capture isotopes
  - Diffuse gamma rays
  - Extragalactic diffuse emission
- CR propagation in the heliosphere
  - Transport equation
  - Heliospheric modulation
  - IC scattering on solar photons
  - gamma-ray albedo of small solar system bodies
- CRs in the other normal galaxies
  - EGRET observations
  - Magellanic clouds and Andromeda galaxy
  - Estimates of gamma-ray fluxes
- Exotic Physics
  - Dark matter
  - Dark matter signatures in CRs and diffuse gamma rays
  - 511 keV line from the Galactic center
Propagation in the interstellar medium

II. Cosmic rays
CR Isotopic Abundances vs SS Abundances

Very detailed low-energy data exist!

ACE: 100-200 MeV/nucleon

Wiedenbeck+2001

ACE data
Solar System

Radio decay product

20, 21, 22

53, 54, 55

Relative Abundance (28Si=1000)

He, Be, B, C, O, Ne, Mg, Si, S, Ar, Ca, Ti, V, Cr, Fe, Ni, Zn

Propagation of cosmic rays/IVM 4
SLAC Summer Institute/Aug 2008
How It Works: Fixing Propagation Parameters

Using secondary/primary nuclei ratio & flux:
- Diffusion coefficient and its index
- Propagation mode and its parameters (e.g., reacceleration $V_A$, convection $V_z$)
- Propagation params are model-dependent
- Make sure that the spectrum is fitted as well

Parameters (model dependent):
- $D \sim 10^{28} \left( \rho / 1 \text{ GV} \right)^\alpha \text{cm}^2/\text{s}$
- $\alpha \approx 0.3-0.6$
- $Z_h \sim 4-6 \text{kpc}$
- $V_A \sim 30 \text{ km/s}$

Radioactive isotopes:
- Galactic halo size $Z_h$

Diffusion coefficient

Self-consistent

B/C

$E_k$, MeV/nucleon

$E_{\text{kin}}, \text{GeV/nucleon}$

Data:
- Voyager
- Ulysses
- ACF
- HEAO-3

Interstellar

Diffusive halo model

Leaky box model

$Z_h$ increase

$D \sim 10^{28} \left( \rho / 1 \text{ GV} \right)^{\alpha}$ cm$^2$/s
$\alpha \approx 0.3-0.6$
$Z_h \sim 4-6 \text{kpc}$
$V_A \sim 30 \text{ km/s}$
CR anisotropy

\[ \delta = -\left[ 3D \nabla f + u_p (\partial f / \partial p) \right] / v f \]

- \( f \) - phase space density
- \( u \) - convection velocity
- \( v \) - plain diffusion

Strong+’07
Discrimination of the propagation models

- Different propagation models are tuned to fit the low energy part of sec./prim. ratio where the accurate data exist.
- However, the differ at high energies which will allow to discriminate between them when more accurate data will be available.
- The sharp peak at ~1 GeV/nucleon seems to be confirmed by Pamela! (Vannuccini talk)

The data were taken at different times (1980-now) in different energy ranges and by different instruments, so the probability of systematic errors is high.
Secondary/primary: \((\text{Sc+Ti+V})/\text{Fe}\)

Similar shape, but the data are not that accurate

Jones+'01
**C & O spectra from CREAM**

Wakely et al, OG1.3 oral; Zei et al. OG1.1 oral; Ahn et al. OG1.1 oral (30th ICRC)

- **CREAM results span ~ 4 decades in energy: ~ 10 GeV to ~ 100 TeV**
- **Different techniques give consistent spectra**

- The same slope (~2.70, from the plots) for C and O, consistent with HEAO-3 at lower energies
- The Boron spectrum if measured can tell us about the rigidity dependence of the diffusion coefficient

Credit P.Blasi/Rapporteur talk
Preliminary Results from PAMELA

- PAMELA data are tremendously accurate, but currently only the "arb.units"
- Interestingly, the same slope for H and He and very close to C and O from CREAM
- Protons are flatter than BESS and AMS data
K-capture isotopes

Electron attachment & stripping

$^{51}\text{Cr}$ (τ~28 d)

$^{51}\text{V} / ^{51}\text{Cr} \equiv \text{daughter/parent}$

Stable in CRs (bare nuclei); in the medium decay via electron capture

Solar modulation effect

$^{51}\text{V} / ^{51}\text{Cr}$

ISM

$^{51}\text{Cr}$

EC decay

Electron attachment & stripping

$^{51}\text{Cr}$

$\eta_H=0.34/\text{cm}^3$

Other losses

$^{51}\text{V} / ^{51}\text{Cr}$

$\Phi = 500 \text{ MV}$

Disk-Halo Diffusion

Reacceleration

Without K-capture

Ek, MeV/nucleon

K-capture & reacceleration

Ek, MeV/nucleon

Stable in CRs (bare nuclei); in the medium decay via electron capture

Ek, MeV/nucleon

Ek, MeV/nucleon

Jones et al. 2001

Niebur et al. 2003

$^{51}\text{Cr}$ ($\tau \sim 28$ d)

$^{51}\text{V} / ^{51}\text{Cr} \equiv \text{daughter/parent}$

Electron attachment & stripping

$^{51}\text{Cr}$

$\eta_H=0.34/\text{cm}^3$

Other losses

$^{51}\text{V} / ^{51}\text{Cr}$

$\Phi = 500 \text{ MV}$

Disk-Halo Diffusion

Reacceleration

Without K-capture

Jones et al. 2001

Niebur et al. 2003

Ek, MeV/nucleon
CR source abundances

Determination of the CR source isotopic abundances is a non-trivial task, but if determined, it can give us a clue of the origin of CRs

Two key measurements (ACE/CRIS):
• $^{59}$Ni and $^{59}$Co abundances in CRs (Wiedenbeck+'99) indicate $>10^5$ years delay between nucleosynthesis and CR acceleration
• $^{22}$Ne/$^{20}$Ne and $^{58}$Fe/$^{56}$Fe ratios show consistency with a strong Wolf-Rayet star ejecta component in the GCRs (Binns+'05)

CR source material:
80% ISM + 20% ejecta from Wolf-Rayet and massive OB stars
CR source isotopic abundances

- Two K-capture isotopes are present in the sources! –
  $^{41}\text{Ca}^*$ ($\tau \sim 10^5\text{yr}$), $^{53}\text{Mn}^*$ ($\tau \sim 4 \times 10^6\text{yr}$)
- Could tell us about the origin of CRs -- supports “volatility” hypothesis, but needs more analysis

- Good
- Xsections
- Well-known
- Differences in models

The first time that a realistic propagation model has been used to derive isotopic source abundances!
Wherever you look, the GeV $\gamma$-ray excess is there!

EGRET data

- Instrumental artefact?
- Physical phenomena?

GLAST will answer...

Strong+00,04
Optimized model

- CR spectra are not the same everywhere in the Galaxy
- It is possible to tune proton and electron spectra to make a fit to diffuse gamma rays
Diffuse emission model vs. EGRET data

Longitude profiles |b|<5°
Diffuse emission from the Galactic center

Intrinsic connection between the diffuse Galactic γ-ray emission in different energy ranges:

- **100 keV - few MeV**: IC emission by CR electrons and positrons on optical & IR radiation (primary + secondary electrons and positrons)
- **100 MeV - 10 GeV**: produced by protons via $\pi^0$-decay; these protons also produce secondary positrons and electrons
- **10 GeV-10 TeV**: Produced via IC scattering of primary electrons on the same optical & IR photons

Porter+’08
Anisotropic Inverse Compton Scattering

- Electrons in the halo see anisotropic radiation
- Observer sees mostly head-on collisions

Important @ high latitudes!
Effect of anisotropic ICS

- The anisotropic IC scattering plays important role in modeling the Galactic diffuse emission
- Affects estimates of isotropic extragalactic background

![Graph showing the ratio of anisoIC to isoIC against Galactic latitude, degrees. The graph highlights intermediate latitudes and poles with red arrows.](image)
Extragalactic Gamma-Ray Background

Predicted vs. observed

\[ E^2 \times F \]

\[ E, \text{ MeV} \]

Sreekumar et al. 1998
Strong et al. 2004

- Blazars
- Cosmological neutralinos

EGRB in different directions

\[ \chi^2 = 1.05 \]
\[ m_\chi = 520 \text{ GeV} \]

\[ \langle v\nu \rangle = 3.1 \times 10^{-26} \text{ cm}^3/\text{s} \]
Contributions to the extragalactic background

\[ \sum + \text{relic neutralinos} > 100\%! \]
Cosmic rays in the heliosphere

More on Voyagers - lecture by Stone
Interplanetary B-field & solar wind

Parker spiral

Propagating cosmic rays
Modulation models are based on the numerical solution of the CR transport equation (Parker 1965):

$$\frac{\partial f(r, \rho, t)}{\partial t} = -(V + \langle v_D \rangle) \cdot \nabla f + \nabla \cdot (K_S \cdot \nabla f)$$

$$+ \frac{1}{3} (\nabla \cdot V) \frac{\partial f}{\partial \ln \rho},$$

\( f \) - CR distribution function
\( V \) - solar wind velocity
\( \langle v_D \rangle = \nabla \times K_A \vec{B}/B \)
\( K_A \) - antisymmetric part of the diffusion tensor
\( K_S \) - symmetric part of the diffusion tensor
\( \rho \) - rigidity

- Not all factors are well known
- Local interstellar spectrum of CRs is unknown (exception pbars)
Heliospheric current sheet

A surface where the polarity of the solar magnetic field changes

Maximum Inclination of the Current Sheet (N-S Mean): 1976-2008

A>0 A<0

Hoeksema model
Variations over the solar cycle (pbars, p)

Propagation of cosmic rays/IVM  26 SLAC Summer Institute/Aug 2008

Modulation increases

A>0

antiprotons

protons

A<0

antiprotons

protons
Charge Sign Effect

The Unv. of New Hampshire Neutron Monitors
Cosmic Ray Intensity (daily solar-rotation averages through SR 2500):
- < 500 MeV
- > 500 MeV

Predictions for $A < 0$

Ekin, GeV
• Direct CR measurements on spacecraft are possible in a few locations at different heliospheric distances
• A sensitive gamma-ray telescope (e.g., GLAST) is able to constantly monitor the CR fluxes in a considerable part of the heliosphere

How?
The heliosphere is filled with Galactic CR electrons and solar photons

- electrons are isotropic
- photons have a radial angular distribution
Anisotropic effect on solar photons

Target photons:
\[ \rho = 0.25 n_{bb}(R./r)^2 \]
\[ T_* = 6000 \text{ K} \]

Following collision:
\[ E_{\gamma_o} \sim (1/\gamma_o)^{\frac{1}{2}} M_* \]
\[ \sim M_* \]

10 GeV e's $\bullet$ 100 MeV $\gamma_o$'s

IVM, Porter, Digel'06, Orlando & Strong'07

Propagation of cosmic rays/IVM 30

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Flux_{IC} \sim 1/r

\begin{align*}
r_1 (AU) &= \sin \theta, \quad \theta < 90^\circ \\
r_1 (AU) &= 1, \quad \theta > 90^\circ \\
r_2 &= 10r_1
\end{align*}

Looking in different directions one can probe the e-spectrum at different distances from the sun!
The ecliptic

Averaged over one year, the ecliptic will be seen as a bright stripe on the sky, but the emission comes from all directions.
IC spectrum <1 GeV shows strong dependence on the modulation level

* variations of γ-ray flux over the solar cycle

**Table 1. All-sky average integral flux**

<table>
<thead>
<tr>
<th>$E$</th>
<th>$\Phi_0 = 0$</th>
<th>500 MV</th>
<th>1000 MV</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;10 MeV</td>
<td>5.6</td>
<td>3.4</td>
<td>2.4</td>
</tr>
<tr>
<td>&gt;100 MeV</td>
<td>0.69</td>
<td>0.56</td>
<td>0.47</td>
</tr>
<tr>
<td>&gt;1 GeV</td>
<td>0.05</td>
<td>0.04</td>
<td>0.04</td>
</tr>
</tbody>
</table>

**Note.** — Flux units $10^{-6}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$. 

**IC integral flux**

$F(>100$ MeV, $\theta<2.5^\circ)$~$2 \times 10^{-7}$ cm$^{-2}$ s$^{-1}$

**EGRET upper limit** $=2 \times 10^{-7}$ cm$^{-2}$ s$^{-1}$
Thompson+ 1997:
Upper limit (>100 MeV): $2 \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$

Reanalysis by Orlando+’07:

Discovery of both solar disk pion-decay emission and extended inverse Compton-scattered radiation in combined analysis of EGRET data from June 1991!!
Gammas & neutrinos from the quiet sun

Solar “albedo” due to the interactions of CR particles with solar atmosphere: CRs produce cascades in the solar atmosphere

- Gamma rays can be observed (GLAST)
- Neutrinos propagate through the sun and also can be observed (IceCube)

Can be used to probe the solar atmosphere and the matter distribution in the solar core

IVM+’91, Seckel+’91
The moon is brighter in gamma rays than the sun!

Kinematics of the interaction:
- The cascade goes through to the depth where gamma-rays cannot come out
- Splash pions are low-energy and decay at "rest"

Simulation of the GLAST observations

IVM, Porter'07
(earlier work: Morris'84)
A Zoo of Small Solar System Bodies

- Jovian Trojans
- Neptunian Trojans
- Centaurs
- Main Belt
- Comets

- Kuiper belt:
  - Classical Disk
  - Scattered Disk
  - Plutinos

- Oort cloud

<table>
<thead>
<tr>
<th>Table 1 The primary cometary reservoirs of the Solar System</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Kuiper belt</strong></td>
</tr>
<tr>
<td>Shape</td>
</tr>
<tr>
<td>Distance range</td>
</tr>
<tr>
<td>Comet population</td>
</tr>
<tr>
<td>Estimated mass (including smaller debris)</td>
</tr>
<tr>
<td>Ambient surface temperatures</td>
</tr>
<tr>
<td>Origin</td>
</tr>
<tr>
<td>Return mechanism from the reservoir</td>
</tr>
</tbody>
</table>

Stern 03
Hot Topics

• Formation and evolution of the planetary system and exo-solar planetary systems
  - 1992 (Jewitt & Luu) - first object beyond Neptune since Pluto
  - 2004, 2005 (Sheppard & Trujillo) - discovery of Neptunian Trojans (L4); L5 is currently in the direction of the GC
  - Ejection of material into distant eccentric orbits (Oort cloud)
  - Orbital precession (expansion/contraction) of the giant planets and SSSB families (Neptune: 20 AU -> 30 AU; Kuiper belt)

• The number of small solar system bodies in different dynamic families and their size distribution
  - Formation of planetesimals
  - Pristine material
  - “Freeze-in” capture (Trojans)

• Probe of interstellar spectrum of CR protons + He
2. SMALL SOLAR SYSTEM BODIES

The asteroid mass and size distributions are thought to be governed by collisional evolution and accretion. Collisions between asteroids give rise to a cascade of fragments, shifting mass toward smaller sizes, while a small body impact with a much larger asteroid leads to the growth of the latter. The first comprehensive analytical description of such a collisional cascade is given by Dohnanyi (1969). Under the assumptions of scaling of the collisional response parameters and an upper cutoff in mass, the relaxed size and mass distributions approach power-laws:

\[ dN = am^{-k} \, dm \]  \hspace{1cm} (1)
\[ dN = br^{-n} \, dr \]  \hspace{1cm} (2)

where \( m \) is the asteroid mass, \( r \) is the asteroid radius, and \( a, b, k, n \) are constants. These equilibrium distributions extend over all size and mass ranges of the population except near its high-mass end. The constants in eqs. (1), (2):

- **Collisional evolution & accretion**
- **Relaxed size distribution n=3.5** (assuming scaling of collisional response parameters)
- **Scaling breaks...**
SSSB Albedo and the Ecliptic

- The ecliptic crosses the Galactic equator near the Galactic center and anti-center with inclination ~86.5°
- Galactic center is crowded with sources and harbors the enigmatic source of the 511 keV positron annihilation line
- Passes through high Galactic latitudes - extragalactic emission
- The orbits of the Moon and the Sun
Gamma-Ray Albedo Flux Estimates (Moon flux units)

- **MBAs (sum over ecliptic latitude and longitude)**
  \[ F_{\text{tot}} / F_{\text{moon}} \approx 0.06, 0.67, 10 \quad (n = 2.5, 3.0, 3.5) \]
  Changes by \( \times 5 \) with solar elongation angle (from 1.7 AU to 3.7 AU)

- **Jovian Trojans (assuming the same size distr. as MBAs)**
  \[ F_{\text{tot}} / F_{\text{moon}} \approx 0.009, 0.07, 0.77 \quad (n = 2.5, 3.0, 3.5) \text{ -average} \]
  \[ F_{\text{tot}} / F_{\text{moon}} \approx 0.01, 0.1, 1.1 \quad (n = 2.5, 3.0, 3.5) \text{ -max} \]
  \[ F_{\text{tot}} / F_{\text{moon}} \approx 0.006, 0.05, 0.5 \quad (n = 2.5, 3.0, 3.5) \text{ -min} \]
  Concentrated in small bunches, positions are well known – relative to Jupiter

- **KBOs (probe of the local interstellar CR spectrum!)**
  \[ F_{\text{tot}} / F_{\text{moon}} \approx 0.2, 34, 1168 \quad (n = 3.0, 3.5, 3.9) \]
  Does not vary with solar elongation angle

*cf. EGRET upper limit \( \approx 12 \, F_{\text{Moon}} \)*
CRs in Other Normal Galaxies
Local Group Galaxies
Cosmic Rays – galactic or universal?

- Milky Way and M31 are the dominant galaxies in the group.
- Many others are irregular or dwarf spheroidal.
- Additional members are still being discovered.

What’s here?
Summary: EGRET Observations

- LMC detection: CR density is similar to MW
- SMC non-detection: CR density is smaller than in the MW (otherwise it would be $\sim 2.4 \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$)
- First direct evidence: CRs are galactic and not universal!
- M31 non-detection: has to have smaller CR density than the MW (size M31 > MW!)

<table>
<thead>
<tr>
<th>Source</th>
<th>$F(&gt;100 \text{ MeV}), \text{ cm}^{-2} \text{ s}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LMC</td>
<td>$(1.9 \pm 0.4) \times 10^{-7}$</td>
</tr>
<tr>
<td>SMC</td>
<td>$&lt; 0.5 \times 10^{-7}$</td>
</tr>
<tr>
<td>M31</td>
<td>$&lt; 0.8 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

Sreekumar et al. (1992-94)

$L_{\text{MW}}(>100 \text{ MeV}) \sim 5.4 \times 10^{39} \text{ erg/s (SMR00)}$

$\sim 3 \times 10^{43} \text{ phot/s}$

$F_{\text{MW}}(@\text{M31 distance}) \sim 4.4 \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$
Magellanic Clouds

**Type:** Irr/SB(s)m  
**Magnitude:** 0.9  
**Size:** $\sim$10° $\times$ 10° $\sim$ few kpc  
**Distance:** $\sim$50 kpc

**Type:** Im IV-V  
**Magnitude:** 2.3  
**Size:** 280 $\times$ 160 arcmin $\sim$kpc  
**Distance:** $\sim$60 kpc
Parkes HI survey: LMC & SMC

Brüns et al. (2005)

HI \((x10^8 \, M_\odot)\)

LMC \((4.41\pm0.09)\times[d/50\,kpc]^2\)

SMC \((4.02\pm0.08)\times[d/60\,kpc]^2\)

Bridge \(1.84\times[d/55\,kpc]^2\)

Interface \(1.49\times[d/55\,kpc]^2\)
Andromeda Galaxy: M31

**Type:** SA(s)b I-II
(Hubble: ordinary spiral s-shaped with well defined arms)

**Magnitude:** 3.4

**Size:** 185.0 x 75.0 arcmin
>50 kpc

**Distance:** 725 kpc

Larger than the Milky Way!
Radiation Field in M31

Gordon et al. 2006 (MIPS)

$L_{IR} \sim 1.7 \times 10^{43}$ erg/s
Star form. rate:
$\sim 0.75 \, M_{\odot}/yr$
(cf. MW $\sim 3 M_{\odot}/yr$)
Some Math (Pavlidou & Fields 2001)

Transport equation for CR number density (steady-state leaky-box):

\[
\frac{\partial N_i(T, t)}{\partial t} = Q_i(T, t) + \frac{\partial}{\partial T} \left[ b_i(T) N_i(T, t) \right] - \frac{1}{\tau_{esc}} N_i(T, t)
\]

Trivial solution:

\[
0 = Q_p(T) - \frac{1}{\tau_{esc}} N_p(T)
\]

In terms of CR flux:

\[
\phi_p(T) = l_{esc} Q_p(T)
\]

\[
l_{esc} = \tau_{esc} v
\]

\[
l_{esc}(G) \sim l_{esc}(MW)
\]

Assuming CR injection rate proportional to SN rate:

\[
Q_p^G \propto R_G
\]

CR flux in a galaxy G:

\[
\frac{\phi_p^G}{\phi_p^{MW}} = \frac{R_G}{R_{MW}} = f_G
\]
γ-ray flux from a galaxy:

\[ F^G_\gamma = \frac{1}{4\pi d^2} \frac{M_{\text{gas}}}{m_p} q^G_\gamma \]

\[ q^G_\gamma(>100 \text{ MeV}) = 2.36 \times 10^{-25} f_G \text{ photons s}^{-1} \text{ (H atom)}^{-1} \]

Emissivity calcs \(q(>100 \text{ MeV})\): pp→ \(\pi^0 \times 1.55\) (bremss) \(\times 1.5\) (A>1 nuclei)

Combined:

\[ F^G_\gamma(>100 \text{ MeV}) = 2.34 \times 10^{-8} f_G \frac{M_{\text{gas}}}{10^8 M_\odot} \]

\[ \times \left( \frac{d}{100 \text{kpc}} \right)^{-2} \text{ photons cm}^{-2} \text{ s}^{-1} \]
### Properties of the LG galaxies & γ-ray flux

**Observed Properties of Selected Local Group Galaxies**

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>SN Rate (century⁻¹)</th>
<th>Adopted f</th>
<th>HI (× 10⁶ Mₜₜ kpc⁻²)</th>
<th>M₂ (× 10⁶ Mₜₜ kpc⁻²)</th>
<th>H₂ (× 10⁶ Mₜₜ kpc⁻²)</th>
<th>Mₜₜ (total) (× 10⁶ Mₜₜ kpc⁻²)</th>
<th>M₂ (total)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LMC 50 kpc</td>
<td>0.1⁹, 0.23ˢ, 0.49ᵉ</td>
<td>0.14</td>
<td>22 ± 6¹, eṣ, g</td>
<td>5.5×10⁸</td>
<td>4.6³</td>
<td>1.2×10⁸</td>
<td>26.6</td>
</tr>
<tr>
<td>SMC 60 kpc</td>
<td>0.06⁵, 0.12ᵉ</td>
<td>0.04</td>
<td>17 ± 4², h</td>
<td>6.1×10⁸</td>
<td>0.7⁶</td>
<td>0.3×10⁸</td>
<td>17.8</td>
</tr>
<tr>
<td>M31 725 kpc</td>
<td>0.9¹, 1.2¹, 1.25ʲ</td>
<td>0.45</td>
<td>0.9 ± 0.2⁴, k</td>
<td>4.7×10⁹</td>
<td>0.06⁴</td>
<td>0.3×10⁹</td>
<td>0.92</td>
</tr>
<tr>
<td>M33 795 kpc</td>
<td>0.28ᵐ, 0.35¹, 0.68ᵉ</td>
<td>0.17</td>
<td>0.26 ± 0.05ᵈ</td>
<td>1.6×10⁹</td>
<td>0.00⁴</td>
<td>0.3×10⁹</td>
<td>0.26⁴</td>
</tr>
<tr>
<td>NGC 6822...</td>
<td>0.04⁶</td>
<td>0.02</td>
<td>0.05 ± 0.02ᵈ</td>
<td>0.00⁶</td>
<td>0.056</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IC 10.......</td>
<td>0.082–0.11⁴</td>
<td>0.04</td>
<td>0.016 ± 0.003³</td>
<td></td>
<td></td>
<td>≳10⁻⁵ˢ</td>
<td>0.016</td>
</tr>
</tbody>
</table>

**MW ~2.5**

**HI ~ H₂**

(2-6)×10⁹

**Predicted Gamma-Ray Flux and GLAST Requirements for Selected Local Group Galaxies**

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Flux &gt; 100 MeV</th>
<th>GLAST Significance</th>
<th>GLAST On-Target 5 σ Exposure Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Prediction (photons cm⁻² s⁻¹)</td>
<td>EGRET Value/Limit (photons cm⁻² s⁻¹)</td>
<td>2 yr (σ)</td>
</tr>
<tr>
<td>LMC ..........</td>
<td>11×10⁻⁸</td>
<td>(14.4 ± 4.7)×10⁻⁸</td>
<td>42</td>
</tr>
<tr>
<td>SMC ..........</td>
<td>1.7×10⁻⁸</td>
<td>&lt;4×10⁻⁸</td>
<td>19</td>
</tr>
<tr>
<td>M31 ..........</td>
<td>1.0×10⁻⁸</td>
<td>&lt;1.6×10⁻⁸</td>
<td>13</td>
</tr>
<tr>
<td>M33 ..........</td>
<td>0.11×10⁻⁸</td>
<td>...</td>
<td>1.9</td>
</tr>
<tr>
<td>NGC 6822....</td>
<td>2.6×10⁻¹¹</td>
<td>...</td>
<td>0.04</td>
</tr>
<tr>
<td>IC 10.........</td>
<td>2.1×10⁻¹¹</td>
<td>...</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Matter, Dark Matter, Dark Energy...

\[ \Omega \equiv \frac{\rho}{\rho_{\text{crit}}} \]

\[ \Omega_{\text{tot}} = 1.02 \pm 0.02 \]

\[ \Omega_{\text{Matter}} = 4.4\% \pm 0.4\% \]

\[ \Omega_{\text{DM}} = 23\% \pm 4\% \]

\[ \Omega_{\text{Vacuum}} = 73\% \pm 4\% \]

SUSY DM candidate has also other reasons to exist - particle physics...

**Supersymmetry** is a mathematically beautiful theory, and would give rise to a very predictive scenario, if it is not broken in an unknown way which unfortunately introduces a large number of unknown parameters...

Lars Bergström (2000)
Where is the DM ?!

Flavors:
- Neutrinos ~ visible matter
- Super-heavy relics: “wimpzillas”
- Axions
- Topological objects “Q-balls”
- Neutralino-like, KK-like

Places:
- Galactic halo, Galactic center
- The sun and the Earth

Tools:
- Direct searches
  - low-background experiments (DAMA, EDELWEISS)
  - Accelerators (LHC)
- Indirect searches
  - neutrino detectors (AMANDA, IceCUBE)
  - CR, γ’s (PAMELA, GLAST, BESS)
DM signal analysis chain

**Annihilation into secondary particles**

- WIMP Dark Matter Particles $E_{CM} \sim 100$ GeV
- $\chi \rightarrow W^+/Z/q$
- $W^+/Z/q \rightarrow \pi^0, \gamma$
- $\pi^0 \rightarrow \gamma, \gamma$
- $\gamma \rightarrow e^+, \mu^+$
- $\mu^+ \rightarrow \nu_\mu, \nu_\mu$
- $\nu_\mu \rightarrow \nu_\mu$
- $\nu_e \rightarrow \bar{\nu}_e$
- Neutrinos
- $+ \text{a few } p/\bar{p}, d/\bar{d}$
- Anti-matter

**Direct annihilation into 2γ**

- WIMP Dark Matter Particles $E_{CM} \sim 100$ GeV
- $\chi \rightarrow \gamma, \gamma$
- Analysis Chain

-- Dark Matter Density e.g. N-body Simulation
-- New Particle Theory e.g. SUSY, Extra-dim
-- Final State Hadronization e.g. PYTHIA Simulation
-- Cosmic Ray Propagation and Galactic Interaction i.e. GALPROP
-- Detector Simulation i.e. GEANT4

Baltz+08
Examples of Dark Matter Signatures in CR

Diffuse gammas

Antiprotons

Look for a consistent signal in diffuse gamma rays, and CRs (antiprotons, antideuterons, positrons)
Positrons

Positron flux is consistent with predictions, but the error bars are large.
Simulated DM skymap

Dark matter
- Galactic center
- Galactic halo
- Minihalos

Credit E. Bloom
Clueless:

- Annihilation rate $\sim 10^{43}$ positrons/s
- The distribution of the 511 keV line is "Galactocentric" and does not much a distribution of any potential positron source (SNRs, pulsars,...)
- Dark Matter?
- Recent data indicate a disk/bulge ratio 1:3
Galactic positron factory: low mass X-ray binaries?

511 keV skymap

Low mass X-ray binaries

Weidenspointner+’08
The “haze” at the Galactic Center (WMAP)

Synchrotron emission from leptons produced in WIMP annihilations?

Dark Matter in the WMAP Sky

- In 2004, Doug Finkbeiner suggested that the WMAP Haze could be synchrotron from electrons/positrons produced in dark matter annihilations in the inner galaxy (astro-ph/0409027)

- In particular, he noted that:
  1) Assuming an NFW profile, a WIMP mass of 100 GeV and an annihilation cross section of $3 \times 10^{-26}$ cm$^3$/s, the total power in dark matter annihilations in the inner 3 kpc of the Milky Way is approximately $1.2 \times 10^{39}$ GeV/sec

  2) The total power of the WMAP Haze is between $0.7 \times 10^{39}$ and $3 \times 10^{39}$ GeV/sec

Coincidence?

Dan Hooper: Dark Matter Annihilations in the WMAP Sky
Conclusion

Astrophysics of cosmic rays and related topics is a very dynamic field: expect many breakthroughs and discoveries soon!