COSMIC RAYS
An Introduction

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A BRIEF HISTORY

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The discovery

At the end of the XIX\textsuperscript{e} century, scientists were puzzled by the spontaneous discharge of their electroscopes which suggested the presence of an ionizing radiation. In 1909, Wulf noted that the rate of the discharge was decreasing with altitude (Eiffel tower). Between 1911 and 1913 the Austrian physicist Viktor Hess established the existence of an unknown penetrating radiation coming from above and most probably of extraterrestrial origin with balloon measurements reaching up to five kilometers in altitude. He shared the 1936 Nobel Prize with Carl Anderson.
In the following years cosmic rays became the subject of intense research, in particular with Millikan (who coined the name in 1925) and Anderson at Pikes peak. In 1927 the dependence on latitude and east-west asymmetry established unambiguously that cosmic rays were charged particles, not photons. In 1938, Pierre Auger, using counters in coincidence, discovered extensive air showers and understood that they were produced by very high energy (up to $10^{15}\text{eV}$) primaries interacting with the Earth atmosphere.
Robert Millikan at Pikes Peak and Pierre Auger at the Jungfrau Joch
Using cosmic rays

In the thirties and fourties, when accelerators were not yet dominating the scene, cosmic rays became the laboratory for the study of particle physics. Anderson discovered the positron in 1932 and the muon in 1938. Powell and Occhialini discovered the pion in 1947. Then came strange particles, kaons, hyperons and many others. In the fifties, accelerators took over and cosmic rays got studied for their own sake.
For many years following, major effort was devoted to the study of cosmic rays, trying to understand their origin. Ground detectors, large arrays and fluorescence telescopes, reached very high energies (John Linsley at Volcano Ranch: first $10^{20}$ eV shower in 1962).

Space astronomy has been a breakthrough for the study of low energy cosmic rays, in particular solar energetic particles (SEP).
John Linsley at Volcano Ranch (New Mexico) checking for rattle snakes in a stack of hay
Casa in Utah
COS-B, a pioneer in space
A recent example of space measurements in solar astronomy:

NASA's Advanced Composition Explorer ACE was launched from Cape Canaveral in 1997 to the Lagrange point between Sun and Earth.
In the past 20 years, spectacular progress in astrophysics and long time scales implied in the construction of very high energy accelerators have caused a burst of interest in cosmic ray physics under the name of astroparticle physics. In particular TeV gamma ray detectors have been constructed and operated. Their main asset is that they can point to the sources without suffering deflections from magnetic fields.
To study cosmic rays, a new generation of ground detectors was born. In particular, the Pierre Auger Observatory is a huge and hybrid detector covering 1500 km²; Showers are detected from the fluorescence they produce in atmosphere and by their impact on a ground detector array. Plans to use the whole Earth atmosphere as a radiator observed from space are being implemented. Neutrino astronomy is currently being pioneered.
1600 Cherenkov counters on ground measure the shower transverse profile and 4×6 fluorescence telescopes measure the longitudinal profile with a 10% duty cycle (clear moonless nights)
In both cases timing gives the direction (1°) and intensity gives the energy (10%)
Four stations of six eyes each, each eye covering a field of view of $30^\circ \times 28^\circ$ with a mirror focusing on an array of $22 \times 20$ pixels (photomultiplier tubes), each having $1.5^\circ$ aperture. They measure the induced fluorescence of nitrogen molecules (near UV).
The first four-fold event
May 2007, $\sim 10^{19}$ eV
Data are transferred by radio to an acquisition centre which filters them and sends them to the laboratories associated with this research.

While the ground array is not yet fully complete, the Observatory already reported two important results:

It has given evidence for the interaction of ultra high energy cosmic rays (UHECR) with the cosmic microwave background (CMB).

It has shown that at least part, if not all, UHECRs originate in regions which are rich in AGNs.
Looking into the future:

The EUSO project
EUSO concept: a space TPC

Focal surface
≈ 2 • 10^5 pixels

Double side Fresnel lenses

UHECR

30°
0.1°

Fluorescence

Cherenkov

Atmosphere + EUSO = Calorimeter
Contained EAS

Energy
Fluorescence + Cerenkov
Position
X, Y, Z (t): 0.3 - 1 km
Direction
Multi-hits tracks
\( \sigma_\theta \sim 0.3^\circ (h) - 3^\circ (v) \)
A compact instrument for the observation of EECRs and Neutrinos

France
(IN2P3/CNES)

Italy:
(INFN/ASI)

Portugal:
(ICCT/FCT)

D/UK/CH

Europe
ESA

Japon
RIKEN
NASDA

USA
OWL
NASA
THE MAIN FEATURES

Introduction

Showers

Knee, ankle, GZK
Elemental abundances

While hydrogen and helium are essentially primordial the heavier elements have been produced in stars and supernova explosions. Even-even nuclei are naturally favored and the iron region which corresponds to the strongest nuclear binding is enhanced.
Cosmic rays show similar abundances suggesting that they have been accelerated from interstellar matter. However, the valleys are filled by spallation reactions on matter in the interstellar medium ($\sim 7 \text{ gcm}^{-2}$).
Cosmic rays are ionized nuclei that travel in space up to extremely high energies, \( \sim 10^{20} \text{ eV} = 16 \text{ Joules!} \)

There are very few of them but they carry as much energy as the CMB or the visible light or the magnetic fields \( \sim 1\text{eV/cm}^3 \)

They have a power law spectrum over 32 decades (12 decades in energy), \( \sim E^{-2.7} \).
Energetics of cosmic rays

Energy density
\[ r_E \sim 10^{-12} \text{ erg/cm}^3 \]

Galactic escape time
\[ \sim 3 \times 10^6 \text{ y} \]

Power
\[ \sim 10^{-26} \text{ erg/cm}^3 \text{s} \]

SN power
\[ 10^{51} \text{ erg/SN} \]

\~ 3 SN per century in the disk
\[ \sim 10^{-25} \text{ erg/cm}^3 \text{s} \]

\~ 10% efficiency

Spectral Energy Distribution
(linear inset \( \rightarrow \) most \( E < 100 \text{ GeV} \))

Kinetic energy per nucleus
Energy of extragalactic component

Energy density
\[ \rho_{\text{CR}} > 2 \times 10^{-19} \text{erg/cm}^3 \]

Estimate requires low energy extrapolation

Power needed \( > \rho_{\text{CR}}/10^{10} \) y \( \sim 1.3 \times 10^{37} \) erg/Mpc\(^3\)/s

\( 10^{-7} \) AGN/Mpc\(^3\) need \( > 10^{44} \) erg/s/AGN

1000 GRB/y Need \( > 3 \times 10^{52} \) erg/GRB
Electron and photon showers

Ionization losses: Bethe Bloch
\(~2 \text{ MeV/g/cm}^2\) at minimum.

Exponential radiation losses:
Bremsstrahlung, radiation length in air 37g/cm\(^2\)

Pair creation probability:
7/9 per radiation length

Transverse extension:
Moliere radius is
21 MeV/ critical energy
\(=\frac{1}{4} \text{ rad. l.} = 100 \text{ m}\)
Hadronic showers

Total cross section
Int. length ~ 70 g/cm²

Leading proton (1 - \eta) × energy
\eta = inelasticity ~ 0.9
Rapidity ~ ln tan θ/2

Meson density
\sim log E

Transverse momentum
dN/dp_⊥^2
\langle p_⊥ \rangle \sim 200 \text{ MeV}

\pi^0 \rightarrow \gamma \gamma
\pi^± \rightarrow \text{interacts or decays} \rightarrow \mu

Electron-photon dominated
High energy showers are electron/photon dominated because $\pi^0$s decay immediately ($\gamma\gamma$) while $\pi^\pm$ may either interact again or decay ($\mu\nu$). A nucleus of energy $E$ and atomic number $A$ behaves as $A$ nucleons of energy $E/A$. Heavier nucleus implies smaller $x_0$. 

- $S_{\text{max}} \sim E$
- $X_{\text{max}} \sim \ln E$
- $x_0$ 
- Rise time
- Muons first
- $p$
- $\text{Fe}$

Shower development
A developing shower
Measuring the shower energy

Ground array: Transverse
- Well-defined acceptance
- Indirect measurement: needs simulation and/or hybrid calibration

Fluorescence: Longitudinal
- Track-length integral gives calorimetric measure of energy
  \[ X_{\text{max}} \text{ sensitive to primary mass: } X_{\text{max}} \sim L \ln(E_0/A) \]
- Delicate systematics
The pixel pattern defines the shower detector plane (accurately), the time distribution along the track locates the shower within this plane (not accurately)
Fluorescence:

A single eye alone is insufficient for an accurate location of the shower in the plane. Binocular detection or hybrid detection (FD and SD) are necessary. Both are available in Auger.
**SHOWER RECONSTRUCTION**

4 unknowns: event time $t_0$, shower front curvature $C$, shower axis direction cosines $u$

For each detector hit:

$$\sigma = u \cdot a$$

$$t = t_0 + \sigma - C[t^2 + a^2 - 2\sigma t]$$

The figure is drawn in the shower detector plane when the shower front hits the detector.
ENERGY MEASUREMENT IN THE GROUND ARRAY

The energy measurement obtained from the surface detector relies on the dependence of the measured signals on the distance to the shower axis (so-called lateral distribution function, LDF).
Calibration using hybrid events

$S_{38}^{(1000)}$ vs. $E_{FD}$

Nagano et al., FY used

387 hybrid events

$4 \times 10^{19} \text{eV}$
$X_{\text{max}}$ vs energy

Protons penetrate deeper into atmosphere, heavy nuclei develop higher up
Shower to shower fluctuations should give additional information
Knee of spectrum

Differential spectral index changes at $\sim 3 \times 10^{15}$ eV

$a = 2.7 \rightarrow a = 3.0$

Continues to $3 \times 10^{18}$ eV

Expect $\exp\{-E / Z E_{\text{max}}\}$ cutoff for each $Z$

Fine-tuning problem: to match smoothly a new source with a steeper spectrum
Energy spectrum of CRs

Dip scenario

\[ J_{\log \varepsilon} \sim \varepsilon^{-2.7} \]

CR spectrum, produced in SNRs

CR spectrum from extragalactic sources

\[ J_{E_G} \sim \varepsilon^{-2.7} \]

Dip scenario

\[ p + \gamma \rightarrow p + e^+ + e^- \]

GZK cutoff

\[ p + \gamma \rightarrow N + \pi \]

Experiment:
Akeno-AGASA
(Takeda et al. 2003)
HiRes
(Abbasi et al. 2005)
Yakutsk
(Egorova et al. 2004)
Interaction with the CMB

The photoproduction of pions is expected to occur above a threshold of some $10^{20}\text{eV}$

$$p + \gamma \rightarrow p + \pi$$

$$M^2(p+\pi) = M_p^2 + 2(E_p + P_p)E_\gamma$$

$$\approx M_p^2 + 2M_pM_\pi$$

$$M_pM_\pi \approx 2E_pE_\gamma$$

$$E_\gamma = 2.7K = 3.10^{-4}\text{eV}$$

$$E_p = \frac{1}{2} 0.14 \times 10^{18} \times 10^4/3 = 2 \times 10^{20}\text{eV}$$
Greisen Zatsepin Kuzmin (GZK)

With a typical interaction length in the few 10 Mpc scale: cosmic rays coming from larger distances will not make it to the Earth without interacting, and therefore loosing energy: their flux will be significantly damped.
Earlier data: AGASA vs HiRes

Exposures \((10^3 \text{ km}^2 \text{ yr sr})\)
- AGASA: 1.3
- HiRes (mono): 2.2

Number of events \(>10^{20}\)
- AGASA: 10 (+2?)
- HiRes (mono): 2?

Both detectors have (different) energy-dependent acceptances

HiRes stereo data
Favored GZK cutoff
While earlier results were inconclusive the Auger results have now sufficient statistics to establish unambiguously the existence of the GZK cutoff
As a consequence, only nearby (<100 Mpc) sources can contribute to the UHECR spectrum.

Mean energy of protons as a function of propagation distance through the CMB. Curves are for energy at the source of 10^{22} eV, 10^{21} eV, and 10^{20} eV. (from J W Cronin)
Georgi Zatsepin (Pamir, 1946)
THE SOURCES

Solar energetic particles (SEP)
Gamma ray astronomy and Supernova remnants (SNR)
Ultra high energy cosmic rays (UHECR)
Particles coming from the Sun reach 100 MeV and are mostly associated with solar activity and flares (magnetic field lines recombination and field inversion with a 11 yr cycle). Coronal Mass Ejections and interplanetary shocks (most are caused by CME) are similarly correlated. On the contrary, galactic cosmic rays are anticorrelated with the solar activity increasing the magnetic field which acts as a shield.
SUN:ACE
Energetic particle fluences
Gamma ray astronomy as a tracer of cosmic ray sources

Contrary to cosmic rays, gamma rays travel straight in the universe and point back to the sources. They are good at detecting the high energy decay photons coming from neutral pions produced in the interaction of very high energy cosmic rays with interstellar matter.
The High Energy Stereoscopic System (HESS, Namibia): four telescopes at the corners of a 120×120 m² square, operating above 100 GeV. Its field of view is 5° and its resolution a few arc minutes. It takes only 30 seconds to take a picture of the Crab.
Gamma ray astronomy has established that most galactic cosmic rays originate from Supernova remnants (SNRs) by comparing their X-ray and γ-ray images.
Main sources of photons are bremsstrahlung (synchrotron radiation) at low energies and at high energies $\pi^0$ decays (hadrons) or inverse Compton on CMB (electrons).
HESS TeV Observations have revealed numerous shell-type SNRs

Largest TeV source known: RX J0852.0-4622
RX J1713

ROSAT 1996
Mostly non-thermal X-rays
D ~ 1 kpc

H.E.S.S. 2004
4-telescope 33 h live-time
Shell resolved
X-Ray observations locate the shock accurately.
80% correlation between TeV $\gamma$-rays and X-rays (HESS and ASCA)
Auger data show a clear correlation of UHECR (>6 $10^{19}$ eV) with nearby (<75 Mpc) galaxies. There is an even better correlation with nearby AGNs. Correlation disappears when including lower energy cosmic rays (pointing accuracy) or farther away galaxies (GZK).
Our environment (100 Mpc radius) is extremely inhomogeneous.
Circles of 3.1° on 27 UHECR detected by Auger
Red crosses are 472 AGN (318 in field of view) having z<0.018 (D<75Mpc)
Solid line shows field of view (zenith angle < 60°)
Color tells exposure
Dashed line is super galactic plane
The UHECR detected by the PAO are able to point to sources in the sky (typically within $1^\circ$). It was not a priori so obvious because of uncertainties in magnetic fields met by UHECR during their journey to the Earth (typically $3\mu G$ in the disk mean $6 \times 10^{17}$ eV).

A new page of astronomy has been opened, until now only photons could be used. It remains to be understood why such and such a galaxy, AGN or else, is a source while such and such another is not. Neutrinos are next to come
Not many celestial objects have large enough Magnetic field $\times$ volume to be candidates for UHECR acceleration (Hillas plot). Apart from magnetars which would suffer of excessive synchrotron losses, the only possible candidates are GRBs or active galaxies.
$E_{\text{max}}$ ZBL (Fermi)
$E_{\text{max}}$ ZBL $\Gamma$ (Ultra-relativistic shocks–GRB)
SUMMARY OF THE FIRST LECTURE

Cosmic rays are accelerated atomic nuclei with elemental abundances as prevails in the Universe (apart from spallation reactions) but uncertainties subsist at UH energies; CR have a power law spectrum with index ~2.7 cutoff at ~$10^{20}$eV by interactions with the CMB; they contribute ~$1\text{eVcm}^{-3}$ to the energy density of the Universe, as much as visible light, CMB or magnetic fields; they play an important role in the ISM dynamic. The Sun, wind and shocks, contributes to low energies. Most cosmic rays are of galactic origin and accelerated in the shells of young SNRs. Most UHECR have their sources in AGN rich regions. Recent progress in $\gamma$ ray and UHECR astronomies have made cosmic ray physics a field of astrophysics in its own right.
ACCELERATION IN SHOCKS

Introduction
ISM and magnetic fields
Generalities on SNRs
Generalities on shocks
Magnetic field amplification
Larger scale shocks
Diffusive shock acceleration: an introduction

As in a cyclotron the particle is accelerated locally on traversing the shock (equivalent of the gap between the dees) and is guided by magnetic fields on either side in such a way as to come back to the shock (equivalent of the dipole guide field).
However both the acceleration and guiding processes are very different from the cyclotron case. **Guiding** is provided by stochastic collisionless scattering on magnetic turbulences. **Acceleration** is best described in the shock frame where both upstream and downstream media move toward each other with large relative velocity $\beta$. 
Hence the energy $E + \Delta E$ of the cosmic ray (mass $M$) after having traversed the shock is given as a function of its energy $E$ before having traversed the shock as

$$E + \Delta E = \gamma \beta E + \gamma p$$

with $\gamma^2 = \gamma^2 \beta^2 + 1$ and $E^2 + p^2 = M^2$

$\beta \ll 1 \rightarrow \gamma \sim 1$

For relativistic cosmic rays, $p = E$ and

$$\Delta E = \beta E + O(\beta^2)$$
$\Delta E/E = \beta$ implies

$E_n = E_0(1+\beta)^n$ after $n$ shock traversals

One speaks of first order Fermi acceleration

A stochastic succession of such processes nearly cancels: second order Fermi acceleration has negligible effects
Inter Stellar Medium (ISM)
Not static but alive, continuously recycled through star collapses, made of three basic constituents: matter, magnetic fields and cosmic rays
Amounts to 10-15% of the MW disk mass, half of it in clouds occupying 1-2% of the ISM volume, mostly very cold dark molecular peaking at R=5±2 kpc and cold diffuse atomic extending from 0 up to 20 kpc
Elemental abundances close to solar system, 91% H
About 0.5-1% in mass in the form of dust
OB associations and SNs affect ISM through winds, radiation, heating, ionization, explosions
ISM density is so small that collisions can be neglected: momenta (not energy!) change exclusively via the action of magnetic fields.

<table>
<thead>
<tr>
<th>Component</th>
<th>T(K)</th>
<th>Observed</th>
<th>N(cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular</td>
<td>10-20</td>
<td>2.6mm CO</td>
<td>$10^2$-$10^6$</td>
</tr>
<tr>
<td>Cold atomic</td>
<td>50-100</td>
<td>21cm H$_I$</td>
<td>20-50</td>
</tr>
<tr>
<td>Warm atomic</td>
<td>6000-10000</td>
<td>21cm H$_I$</td>
<td>0.2-0.5</td>
</tr>
<tr>
<td>Warm ionized</td>
<td>~8000</td>
<td>Dispersion pulsar signals</td>
<td>0.2-0.5</td>
</tr>
<tr>
<td>Hot ionized</td>
<td>~$10^6$</td>
<td>UV abs lines X soft emission</td>
<td>A few $10^{-3}$</td>
</tr>
</tbody>
</table>
Reflexion from a moving magnetic wall

![Diagram of reflexion](image)

\[ \Delta E/E \sim -2\beta v \cos \theta \]

\( V < 0 \rightarrow \Delta E > 0 \)

The induced electric field is \(-\beta B\) along \(x\)

Integrating over the arc gives the same result.

A similar result would apply for a magnetic bottle, indeed for any moving magnetic field.

\[ E_{in} = \gamma E - \gamma \beta p_z \]

\[ p_{zin} = \gamma \beta E - \gamma p_z \]

\[ E' = \gamma E_{in} + \gamma \beta p_{zin} \]

\[ P'_z = \gamma \beta E_{in} + \gamma p_{zin} \]

\[ E' = \gamma^2 (1 + \beta^2) E - 2\gamma^2 \beta p_z \]

\[ p_z = pc \cos \theta = vE \cos \theta \]

\[ E' = \gamma^2 (1 + \beta^2 - 2\beta v \cos \theta) E \]

\[ \Delta E/E \sim -2\beta v \cos \theta \]

for \(|v| >> \beta\)
Typical ISM magnetic fields are at μG scale

Star light polarisation due to spinning dust grains aligned on B: local field parallel to galactic plane and tangential Zeeman splitting (21cm H$_1$ line) shows ISM field in the few μG region with little dependence on density

Faraday rotation of the plane of linear polarization of pulsars gives the B component along the line of sight in the warm ionized medium: uniform and random components, μG scale

Synchrotron radiation of all sky radio continuum due to cosmic rays suggests again a few μG scale.
GENERALITIES ON SNRs
Supernovae and SNRs

Type Ia: a white dwarf, member of a binary, accreting from its companion until reaching Chandrasekhar mass of 1.4 solar masses: the core is fully burned, the SNR shell is empty

Type II: a massive star collapsing into a neutron star that remains in the center, possibly detected as a pulsar (Crab) the wind of which gives energy to the remnant (plerion)
Shell SNRs and plerions

Cassiopeia A (Chandra)  
Crab Nebula (Chandra)
X ray images allow for very high resolutions

Kepler SNR 1604
Tycho SNR 1572
N 49
Dominated by thermal emission at ~1keV
Optically thin plasma means strong atomic lines (C to Fe),
stronger in young SNRs (enriched ejecta)
Type Ia progenitors yield more Si/S/Ar/Fe
than Type II
**Type Ia:**
Complete burning of C-O white dwarf produces mostly Fe-peak nuclei (Ni, Fe, Co) with some intermediate mass (O, Si, S, Ar...): very low O/Fe ratio

**Core Collapse:**
Explosive nucleosynthesis builds up light elements: very high O/Fe ratio

O, Ne, Mg, Fe very sensitive to progenitor mass
SN 1006
Type Ia
Age = $10^3$ yr
Ang. Diam. $0.5^\circ$
Distance =2 kpc

X-ray emission:
thermal in faint areas
synchrotron in bright rims

Interior shows thermal ejecta
XMM-Newton

2 – 4.5 keV
non-thermal

Oxygen band
(0.5 – 0.8 keV)
thermal

Radio

SN 1006
Profile shows magnetic field normal to bright limbs (polar caps)
DEM L71
Type Ia
~5000 y old

LMC SNR
LMC-like abundances
Central emission evident at E>0.7 keV
Fe/O > 5 × solar
typical of Type Ia
Reverse shock has heated all ejecta
SNR shell structures

Expansion blast wave sweeps up ISM in forward shock. As mass is swept up, forward shock decelerates and ejecta (abundances as in progenitor) catch up. Reverse shock heats ejecta. Nuclear reactions produce new heavy elements. Once enough mass has been swept up (> 1-5 $M_{ej}$) SNR enters so called Sedov phase.
Particle distributions in SNRs

Thermal particles and magnetic field are concentrated in the shell
Relativistic particles extend to much larger distances
Synchrotron emission is confined to magnetic field region
The shock structure depends on the SNR age: distinguish between young and old SNRs.
Pulsar wind sweeps up ejecta; termination shock decelerates flow; PWN forms; Supernova Remnant sweeps up ISM; reverse shock heats ejecta; ultimately compresses PWN;
GENERALITIES ON SHOCKS
**Ideal shocks** (no magnetic field)

In the shock frame **Mass** \( \rho_1 v_1 = \rho_2 v_2 \)

**Momentum** \( \rho_1 v_1^2 + p_1 = \rho_2 v_2^2 + p_2 \)

**Energy** \( \rho_1 v_1 (\frac{1}{2}v_1^2 + \gamma p_1 / \rho_1 [\gamma - 1]) = \rho_2 v_2 (\frac{1}{2}v_2^2 + \gamma p_2 / \rho_2 [\gamma - 1]) \)

\( \gamma = C_p / C_v = (3 + 2n) / (1 + 2n) \) (n atoms/molecule)

\( v_s = \sqrt{\gamma p / \rho} \) is the sound velocity

\( M = v / v_s \) is the Mach number

\( v_1 - v_2 = 2v_1 (1 - M_1^{-2}) / (\gamma + 1) \)

\( \rightarrow 2v_1 / (\gamma + 1) = 3v_1 / 4 \) for large \( M \)

and monoatomic gas

Compression ratio \( r = \frac{\rho_2}{\rho_1} = \frac{v_1}{v_2} = (\gamma + 1) / (\gamma - 1) = 4 \)
As the shock progresses into the unperturbed ISM the density increases suddenly by a typical factor of 4 and the temperature increases by a factor $\sim \frac{1}{3} M_1^2$.

On either side of the shock one sees the other medium approach at a velocity $v_1 - v_2$ and a relativistic cosmic ray crossing the shock at an angle $\theta$ gets always a first order Fermi acceleration

$$\frac{\Delta E}{E} \sim 2(v_1 - v_2) \cos \theta$$

Writing $(v_1 - v_2) = \frac{3v_1}{4}$ and $\cos \theta \sim 2/3$

$$\frac{\Delta E}{E} \sim \frac{V_{\text{shock}}}{c}$$
It is important to be conscious that there is no collision in the process, but magnetic field volumes acting as scattering centres and aiming at each other on either side of the shock at relative velocity $v_1 - v_2$. The above calculation serves only as an illustration but is not really what we need: we need a model of these scattering centres and an understanding of how they evolve on crossing the shock.
The conservation relations that have been written on either side of the shock must of course include the magnetic pressure and energy density. But this is not enough, one needs to understand in detail the nature of the magnetic scattering centres and how they meet at the shock: this is not well understood but only crudely modelled.
Energy spectrum

The rate of acceleration is given by the ratio of the relative energy gain when crossing the shock back and forth, \( \Delta E/E \sim V_{\text{shock}} \), to the time \( \Delta t \) it takes. In the relativistic limit and in the approximation where the distribution of the scattering centres is irrelevant, the length of the trajectories scales with energy, \( \Delta t = kE \).
Once in region 1, the particle will always be caught by the shock, which is aiming toward it. However, once in region 2, it may escape the shock region for ever with a probability $P_{\text{esc}}$. In this region, the scattering centres move away from the shock at velocity $v_2 \sim \frac{1}{4}v_{\text{shock}}$ while the particle moves at light velocity at varying angles to the shock. Integrating over these angles, $P_{\text{esc}} = \beta_{\text{shock}}$. 
\[ \Delta E/E \sim \beta_{\text{shock}} \quad \Delta t = kE \quad P_{\text{esc}} = \beta_{\text{shock}} \]

After n cycles across the shock,
\[ E_n = E_0 (1 + \beta_{\text{shock}})^n \]
At each cycle only a fraction
\[ (1 - P_{\text{esc}}) = (1 - \beta_{\text{shock}}) \]
survives
Hence after n cycles one has
\[ N = N_0 (1 - \beta_{\text{shock}})^n \] particles
having energy
\[ E = E_0 (1 + \beta_{\text{shock}})^n \]
\[ \ln(N/N_0)/\ln(E/E_0) = \ln(1 - \beta_{\text{shock}})/\ln(1 + \beta_{\text{shock}}) = -1 \]
\[ N = N_0 (E/E_0)^{-1} \]
and \[ dN/dE \approx E^{-2} \]
In general, for a compression ratio $r$, 
\[ \frac{dN}{dE} \approx E^{-\alpha} \text{ with } \alpha = \frac{(r+2)}{(r-1)} \]

Diffusive shock acceleration results in a universal power law energy distribution
TURBULENCES AND MAGNETIC FIELD AMPLIFICATION
There exists copious evidence in favor of strong magnetic turbulences and magnetic field amplification in the shock region of young SNRs.

Hydrodynamic instabilities: density map
HESS/Suzaku RX J1713
RX J1713: Chandra observes variable shock structure, suggestive of substantial magnetic field amplification.
Particle Acceleration in SN 1006

Chandra observations show distinct shock structure in shell.
Cassiopeia A, young core-collapse SNR

Complex ejecta distribution
Neutron star in centre
Nonthermal filaments:
cosmic-ray acceleration
Cas A: X-ray imaging of the blast wave

Continuum band (4 to 6 keV) Chandra (resolution <1") resolves the blast wave from the reverse shock. Sharp filaments are apparent at the blast wave all around.
EVIDENCE FOR MAGNETIC FIELD AMPLIFICATION

From the ratio of radio to TeV emission: a same distribution of electrons produces synchrotron (radio, X-ray) and TeV (IC) but synchrotron depends directly on field while IC and pion decays do not.

From sharp outer X-ray edges seen in several young SNRs (Kepler, Cas A, Tycho, SN1006). Shock front compression is a revelator of field amplification. X-ray synchrotron emission from TeV electrons enhanced by strong field implies short electron lifetime and short diffusion lengths → narrow X-ray structures.

Magnetic fields are enhanced by factors of hundred, much more than the factor of 4 associated with the compression factor of an ideal shock.
Projected X-ray brightness of Cassiopeia A
direct evidence for magnetic field amplification

Experiment confirms high internal magnetic field extracted from the fit of volume integrated synchrotron flux.
Radial X-ray profiles show very sharp (3 - 4") outer rim
Width is only 2% of the SNR radius
Mostly in continuum emission

Gotthelf et al. 2001 (Cas A)

Hwang et al. 2002, (Tycho)
Cosmic rays and the magnetized plasma carry similar energy densities: they do interact on each other.

Accelerated particles tend to stream ahead upstream, which causes the generation of streaming instabilities and makes the evolution non linear, resulting in a strong amplification of the mean field.

The structure of the shock is modified by cosmic ray retroaction
The higher field, in turn, depresses IC wrt synchrotron emission, implying faster scattering and increased maximum momentum.

Sharply peaked X-rays at forward shock are evidence that the field is large and increases sharply at the shock, and that diffusive shock acceleration is efficient and nonlinear at SNR outer blast wave shocks.

Older remnants do not show such field amplification: The excitation of turbulences decreases with shock velocity, while damping (by non-linear wave interactions and ion-neutral collisions) does not.
Contact discontinuity (green line) lies close to outer blast wave determined from 4-6keV (non thermal) X-rays

2-D hydro simulation Blondin/Ellison
No acceleration  Efficient acceleration
Tycho’s SNR 1572

Chandra found that the stellar debris are only half a light-year behind the outer shock instead of two expected, suggesting that a large fraction of the energy of the outward-moving shock wave is going into the acceleration of atomic nuclei (in addition to the electrons revealed by radio and X ray observations).

The energy contained in accelerated nuclei is about 100 times that in electrons.
Radio observations (images from interferometric arrays, global fluxes from single dish telescopes, mostly 6 to 90 cm) show limb brightening similar to X-rays, young remnants have steeper spectra than old remnants.

Observed polarization (a few %) is much smaller than for intrinsic synchrotron emission in an ordered field (~70%) because the field is turbulent.

In young remnants, the magnetic field direction tends to be radial (magnetic amplification at interface), in older remnants, it tends to be tangential (shock compression).
Successful modelling of emission over the whole frequency range

SN 1006

SNR J1713

Cas A
LARGE SCALE SHOCKS
Galaxy collisions

Recent observations and studies of colliding galaxies and merging galaxy clusters suggest that these were common phenomena in the early denser Universe. Such collisions are now believed to have played an important role in the process of galaxy formation. Galaxy collisions usually do not imply direct star collisions but the strongly increased gravity field enhances the collapse of hydrogen clouds and the formation of new stars, many of which very massive and therefore having a short life time.
A typical example is that of the Antennae galaxy, 20 or so Mpc away from us.

Left: ground telescope.
Right: zooming with HST.
Details reveal intense star formation activity
There now exist many documented examples, including collisions of >2 galaxies
Other examples of multiple collisions
The Cartwheel Galaxy, a collision between two galaxies
Abell 754 is made of the merging of two small clusters. NGC1700, 30 kpc in diameter, intense X-ray source (Chandra) likely to result from a collision between an elliptical and a spiral.
Colliding galaxies and merging galaxy clusters are sites of large scale shocks.

Radio emission: Remnant of large scale (>1 Mpc) particle acceleration site.

X-ray surface brightness.

Turbulent gas flow.

XMM temperature map (U.G. Briel et al).

Abell 3667.
AGN’s

Cyg A (radio)
Quasar 3C175
YLA 6cm image (c) NRAO 1996

Bridle et al. (1994)
Jets of Active Galactic Nuclei provide powerful large scale shocks

- Shear flow
- Effective frictional acceleration
- Diffusive shock acceleration
Image of the galaxy cluster Abell 400 (blue=X, pink=radio) showing jets from two merging AGNs.
Centaurus A (NGC1528) is the closest AGN, 33 Mpc away from us, result of a collision between a spiral and an elliptical. The Black hole has a mass of some 10 billion solar masses.
X-rays (Chandra) reveal two jets
M82 may have collided with M81 and produce NGC3077. It has an AGN in its centre.
Spectacular rings of stars are visible near the centres of active galaxies.

M94 (UV)  

centre of NGC4314
Galaxies having well defined AGNs in their centres
SUMMARY OF THE SECOND LECTURE

Spectacular progress in the understanding of the acceleration of galactic cosmic rays from SNR shocks suggest diffusive shock acceleration as a universal acceleration process. Magnetic turbulences and field amplification play an essential role.

It seems possible to accommodate UHECRs in such a scenario as evidence in favor of sufficiently large scale shocks is now growing. Such shocks may be found in colliding galaxies or galaxy clusters where active galaxies are numerous.

Yet, many unknowns subsist on the details and the relevant collisionless plasma physics which governs the shock region is still not well understood. The focus and emphasis placed in these lectures on diffusive shock acceleration should not make the student think that it must be the mechanism at play. It simply is the most likely scenario in the present state of knowledge.

The years to come, in particular with the PAO identifying numerous UHECR sources, will teach us a lot.
Thank you for your attention!
SPARES
Sky map (2) showing cosmic rays detected by the Pierre Auger Observatory. Low-energy cosmic rays appear to originate from evenly distributed sources (blue dots), but the origins of the highest-energy events (crosses) correlate with the distribution of local matter as represented by nearby active galactic nuclei (red stars). Thus, active galactic nuclei are a likely source of these rare high-energy cosmic rays.
The preceding example corresponds to what is called first order Fermi acceleration. Consider now a moving volume where exists a spatial distribution of magnetic fields (energy is conserved).

\[
E'_{\text{in}} = \gamma E_{\text{in}} (1 - \beta \cos \theta_{\text{in}}) \\
E_{\text{out}} = \gamma E'_{\text{out}} (1 + \beta \cos \theta_{\text{out}}) \\
E_{\text{out}} = \gamma^2 E_{\text{in}} (1 - \beta \cos \theta_{\text{in}})(1 + \beta \cos \theta_{\text{out}})
\]

For isotropic uncorrelated in and out distributions, \( \langle \cos \rangle = 0 \)

\[
\Delta E/E = \gamma^2 - 1 \sim \beta^2 > 0
\]

Assuming isotropization inside the volume but correcting for the fact that \( \theta_{\text{in}} \) is not isotropic (collision frequency depends on particle velocity wrt volume) one finds

\[
\Delta E/E \sim (4/3)\beta^2
\]

This is second order Fermi acceleration

\[\Delta E/E \approx \beta^2\]

Its effect is negligible.
maximum energy

condition of acceleration, critical Pecklet number (parameter of modulation)

\[
\frac{u_{sh} R_{sh}}{D(p)} \geq 10
\]

\[
\frac{W_{sn}}{n_0} = 10^{51}\text{erg}
\]

\[
D_{ism} \approx 6 \times 10^{28} \beta P_{GV}^{0.3} \text{ cm}^2 / \text{s}
\]

- maximum value

- typical in interstellar medium

diffusion should be anomalously slow near the shock (upstream and downstream)

cosmic ray streaming instability in shock precursor

Energy spectrum of CRs

Ankle scenario

Extragalactic (AGNs, GRBs...)

$J_{EG} \sim \varepsilon^{-2}$

Berezinsky et al. (2006)
Fig. 3. Spatially integrated spectral energy distribution of RX J1713.7-3946. The ATCA radio data (cf. Aharonian et al. 2005), ASCA X-ray data (cf. Aharonian et al. 2005), EGRET spectrum of 3EG J1714-3857 (Reimer & Pohl 2002), CANGAROO data (Enomoto et al. 2002), in red color) and H.E.S.S. data (Aharonian et al. 2005), in blue color) are shown. The EGRET upper limit for the RX J1713.7-3946 position (Aharonian et al. 2005) is shown as well (red colour). The solid curve at energies above $10^7$ eV corresponds to $\pi^0$-decay $\gamma$-ray emission, whereas the dashed and dash-dotted curves indicate the inverse Compton (IC) and Nonthermal Bremsstrahlung (NB) emissions, respectively.
• faint component (P2) is at the bulge center
• P2 is cuspy
• P2 has a compact blue component at its center (P3)
• bright component P1 is smooth
• total luminosity $6 \times 10^6 L_\odot (r \sim 0.5 \text{ pc})$ and is cuspy

Lauer et al. (1998)
M31

- the double nucleus is probably a thick eccentric disk of stars orbiting a black hole (Tremaine 1995)
- black hole is at P2; P1 is apocenter region of disk

Peiris & Tremaine (2003)