Part C Major Option Astrophysics

High-Energy Astrophysics

Michaelmas 2006

Lecture 11

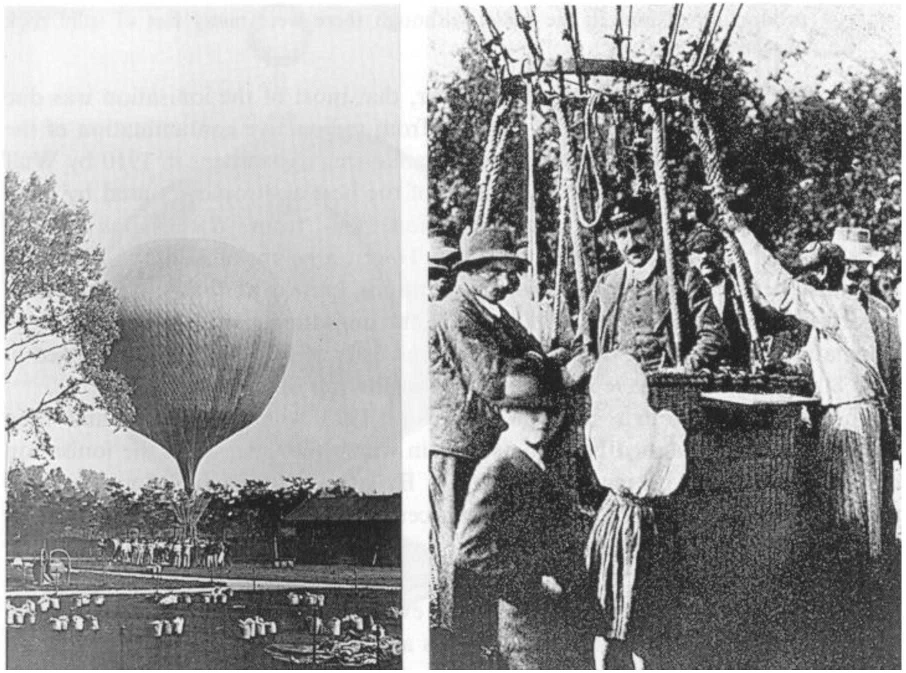
Today’s lecture

- Cosmic rays.
- Interactions in the atmosphere; air showers.
- Cerenkov radiation.
- Sources of cosmic rays.

Cosmic rays

The earth is hit by elementary particles and atomic nuclei of very large energies. Most of them are protons (hydrogen nuclei) and all sorts of nuclei up to uranium (although anything heavier than nickel is very, very rare). Other energetic particles are mainly electrons and positrons, as well as gamma-rays and neutrinos.

Cosmic rays discovered in 1912 by Hess



Cosmic rays were discovered in 1912 by Victor Hess, when he found that an electroscope discharged more rapidly as he ascended in a balloon. He attributed this to a source of radiation entering the atmosphere from above, and in 1936 was awarded the Nobel prize for his discovery.

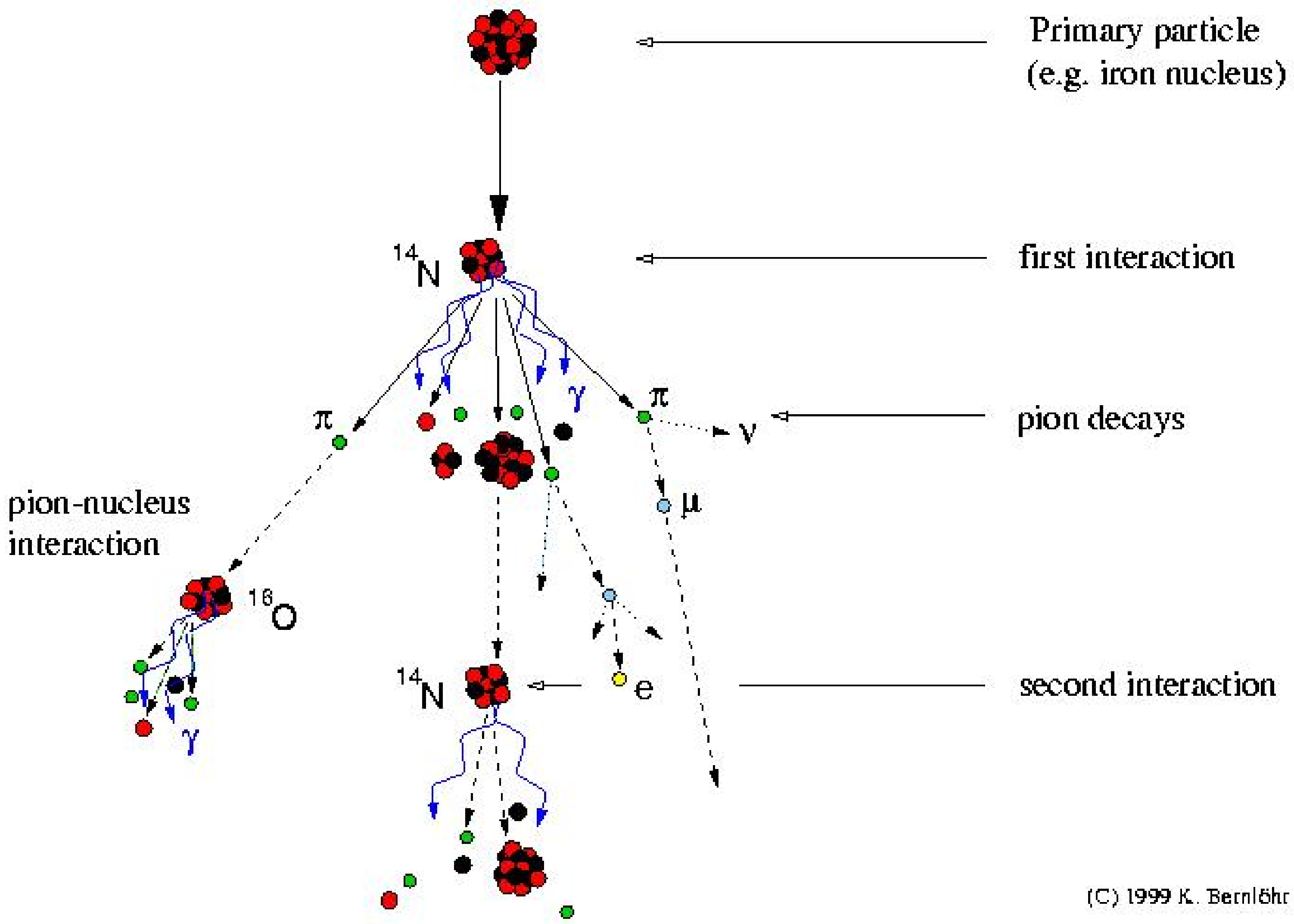
Air showers

The incident particles invariably interact with nuclei in the atmosphere, usually several ten of kilometres up, and produce a cascade or shower of secondary particles.

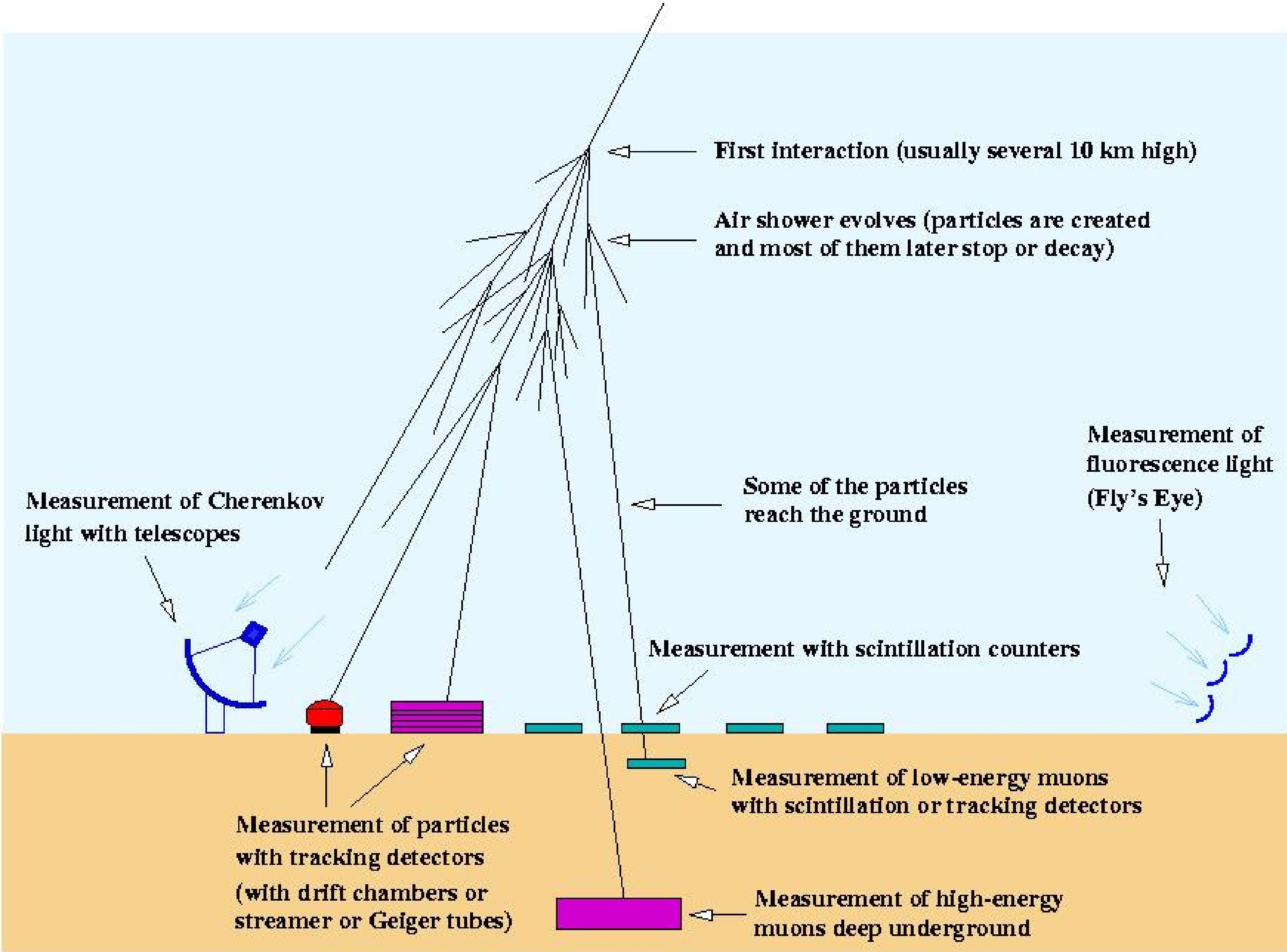
Most of the new particles are π-mesons of all charges (+,-,neutral). Neutral pions very quickly decay, usually into two gamma-rays. Charged pions also decay but after a longer time. Therefore, some of the pions may collide with yet another nucleus of the air before decaying, which would be into a muon and a neutrino. The fragments of the incoming nucleus also interact again, also producing new particles.

The γ-rays from the neutral pions may also create e^+/e^- pairs and these pairs in turn may produce further γ-rays by inverse-Compton scattering and bremsstrahlung.

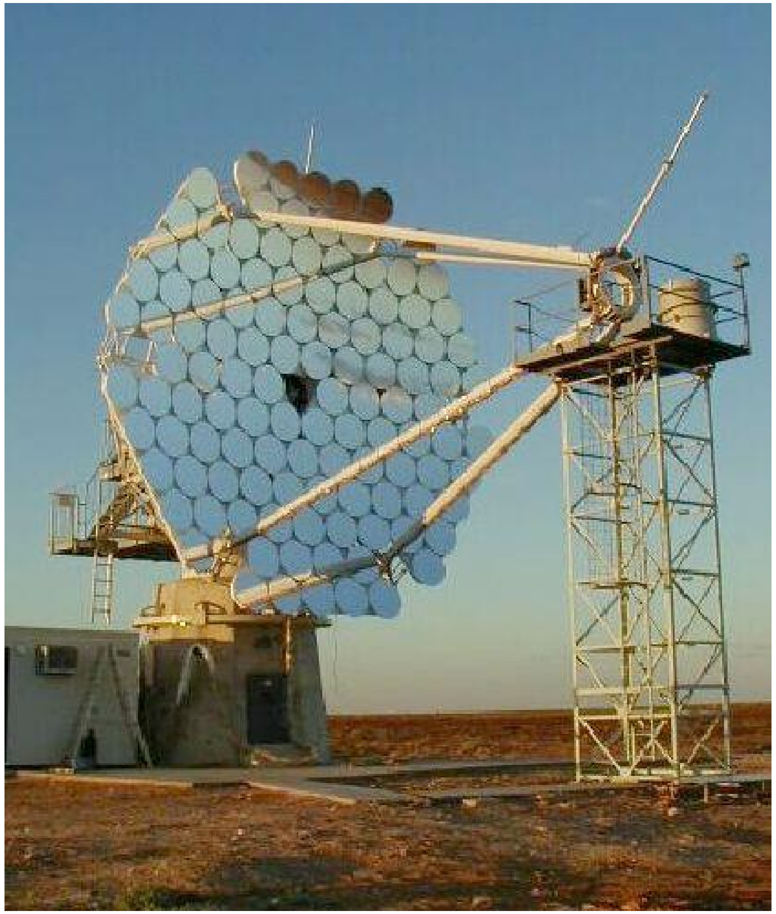
Development of cosmic-ray air showers



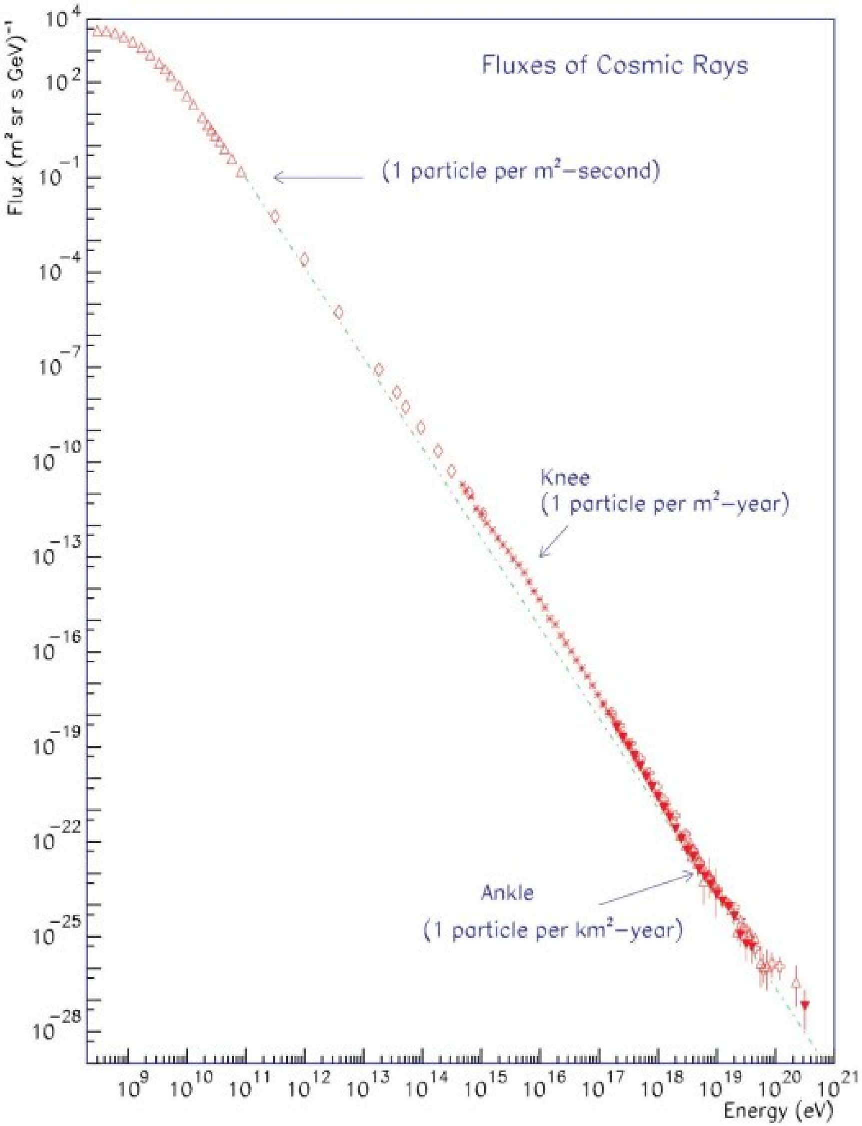
Measuring cosmic-ray and gamma-ray air showers



Cerenkov telescope



Cosmic ray energy spectrum



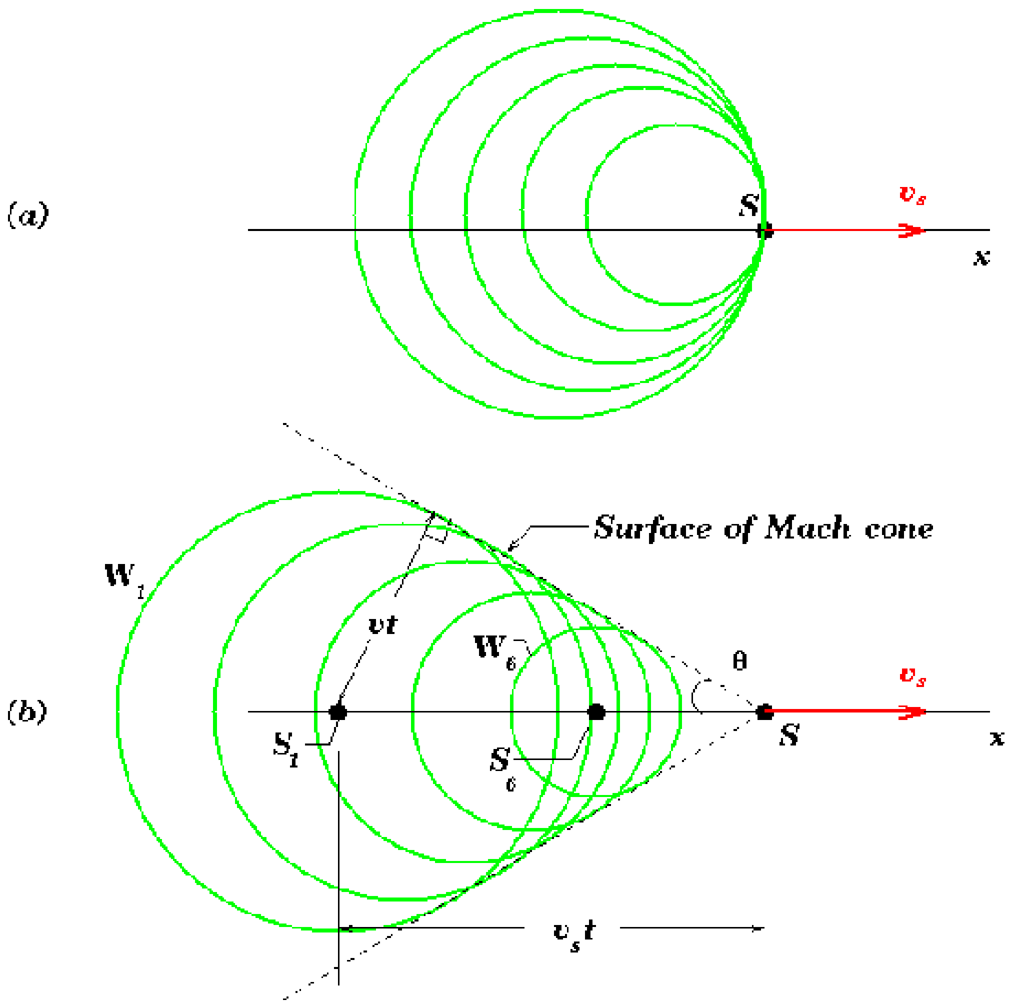
Fluxes of Cosmic Rays
Flux (m² sr s GeV)⁻¹
(1 particle per m²–second)
Knee
(1 particle per m²–year)
Ankle
(1 particle per km²–year)
Energy (eV)

Cosmic rays: observed properties

- Mostly nuclei; a couple of percent e^{+}/e^{-}
- About 80% of the nuclei are protons; 15% He nuclei.
- Energy distribution has power-law form similar to that inferred for shock acceleration. There are two breaks in the spectrum: at $\sim 10^{16}$ eV and at $\sim 10^{19}$ eV.

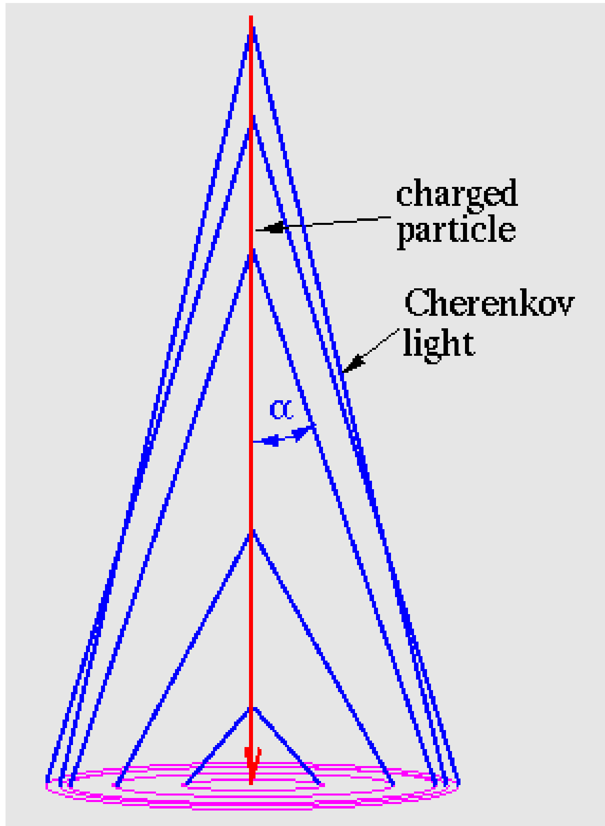
Cerenkov radiation

This is often qualitatively described as the “sonic boom” from a particle travelling faster than the speed of light in some medium.

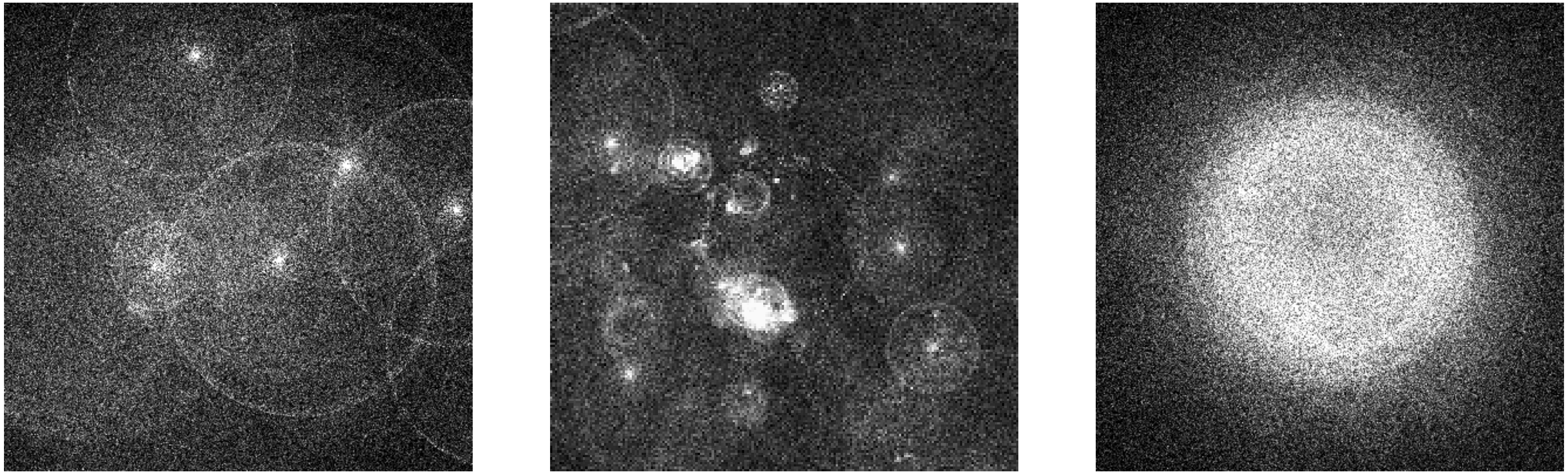

(a)
S
v_s
x
(b)
Surface of Mach cone
W_1
vt
W_6
θ
v_s
S
x
S_1
S_6
$v_s t$

Cerenkov radiation cont'd.

The light is emitted on a narrow cone around the direction of the particle. The opening angle alpha is a function of the density of the air and, thus, of the height of emission: it increases downwards but is always less than about 1.4 degrees. From each part of the particle track the Cerenkov light arrives on a ring on the ground.



Simulations of ideal Cerenkov shower patterns



Left: proton, energy 1 TeV. Centre: Fe nucleus, energy 5 TeV. Right: γ-ray, energy 300Gev.

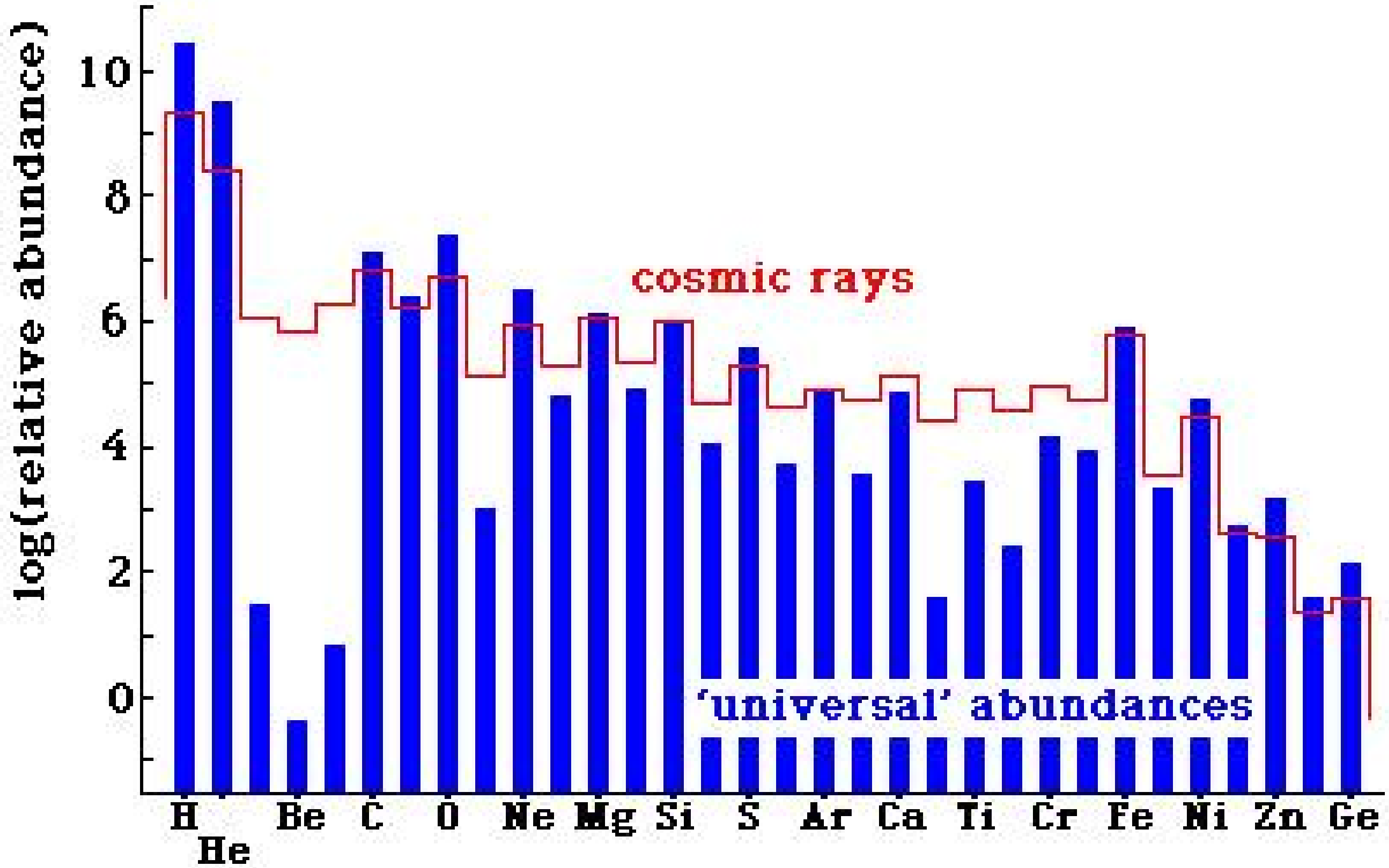
Origins of cosmic rays

- Correspondence of power-law energy distribution means that cosmic rays could in principle have galactic (supernovae) or extragalactic (AGN) origin.

- Some elements—e.g. Li, Be, B—are *overabundant* compared with the element abundances in the Solar System. This is believed to be because of *spallation* in interstellar space of C,O etc. The heavy nuclei break up by collision with protons in the interstellar medium.

- This evidence for spallation implies that the heavy nuclei are confined to the Galaxy.

Spallation


log(relative abundance)
10
8
6
4
2
0
cosmic rays
'universal' abundances
H
He
Be
C
O
Ne
Mg
Si
S
Ar
Ca
Ti
Cr
Fe
Ni
Zn
Ge

Confinement for protons/nuclei

- From the overabundance of elements which are the products of spallation, we can infer the column density of material they have passed through on their way to us: roughly 50 kg m^3.

- The density of the ISM in the Milky way is typically 10^6 particles m^{-3}

- So if the cosmic rays propagate at $\approx c$, they have a typical lifetime in the galaxy of 10^6 years.

- But the scale size of the Milky Way is only a few kpc: therefore the heavy cosmic ray particles must be largely *confined* in the Milky Way.

It is now felt that most of the cosmic ray particles below the “knee” at $10^15\ e$V are produced within in the Milky Way in SN shocks.

Ultra-high energy cosmic rays

However there is still some argument as to the origin of the highest-energy cosmic rays.

The arguments in favour of extragalactic origins are (in very broad terms!)

- The ultra-high energy cosmic rays seem to be isotropically distributed on the sky; they are not confined to the plane of the galaxy.

- For energies $> 10^15$ eV the gyro-radius of a proton in the equipartition field of a supernova remnant becomes comparable to the size of the remnant; hence these energies can't be obtained by SN shock acceleration in the Milky Way. The energies could however be obtained in stronger, AGN, shocks.

Ultra-high energy cosmic rays cont'd

The arguments against the highest-energy cosmic rays originating in AGN are:

- Protons of sufficiently high energy can interact with CMBR photons to produce pions, in reactions such as p $+ \gamma \rightarrow$ n $+ \pi^+$.
- The threshold proton energy for this reaction is $\approx 5 \times 10^{19}$ eV (when scattering against CMBR photons of typical energy $\sim 10^{-4}$ eV).
- Using the known density of CMBR photons in the local universe, we should therefore not expect cosmic rays of energy $> 10^{19}$ eV to propagate farther than 30 Mpc.
- But this distance is not far enough to get us to the large population of (isotropically distributed) AGNs.

Ultra-high energy cosmic rays cont'd

So we need sources of ultra-high energy cosmic rays which:

- Can accelerate the most energetic particles known.
- Do not suffer from the pion-production cutoff.
- Aren't associated with the small number of very nearby AGN, so as to produce an isotropic distribution on the sky.

The best candidate at the moment is the Gamma-ray-bursts, which, forty years after their initial discovery, are only just beginning to be studied in detail. The new models of gamma-ray bursts are that they are often caused by *hypernovae*: a star of sufficiently large mass and spin can form a relativistic jet in its final collapse. Thus we have a candidate mechanism for the production of some of the ultra-high energy cosmic rays in external galaxies, without having to rely on AGN at great distances. You will learn more about gamma-ray bursts in the Advanced Stellar Astrophysics course.