Lecture8

CH \2: Cosmic Rays:

Ref. :1- Atomic and nuclear physics
2nd Ed. Talittlefield

1\ Discovery

As long ago as 1900, Wilson and others found that the charge on an electroscope always 'leaked' away in time, and this could never be prevented, no matter how good the insulation. When the properties of radioactive radiations were better known Rutherford showed that the rate of leakage was considerably reduced by shielding the electroscope with thick slabs of lead, but there was always a residual leakage of charge which could not be eliminated. It was thought therefore that the initial conduction in the enclosed gas was probably due to ionizing radiations from radioactive minerals in the ground. When it was shown that over the sea, where mineral radioactive effects are negligible, the rate of leakage was still pronounced, and was only partially diminished by shielding, it was concluded that the ionizing radiations were descending as well as ascending.

In 1912 Hess sent up an ionization chamber in a balloon and found that the - intensity of ionization actually increased up to a height of 5000 m and then decreased again, showed beyond doubt that these ionizing radiations travel down to earth through the air. A further observation showed that the intensities were the same for night or day, indicating that the origin of these radiations was not solar.

- Hess suggested therefore that these rays were of cosmic origin, and they were finally called 'cosmic rays' by Millikan in 1925.

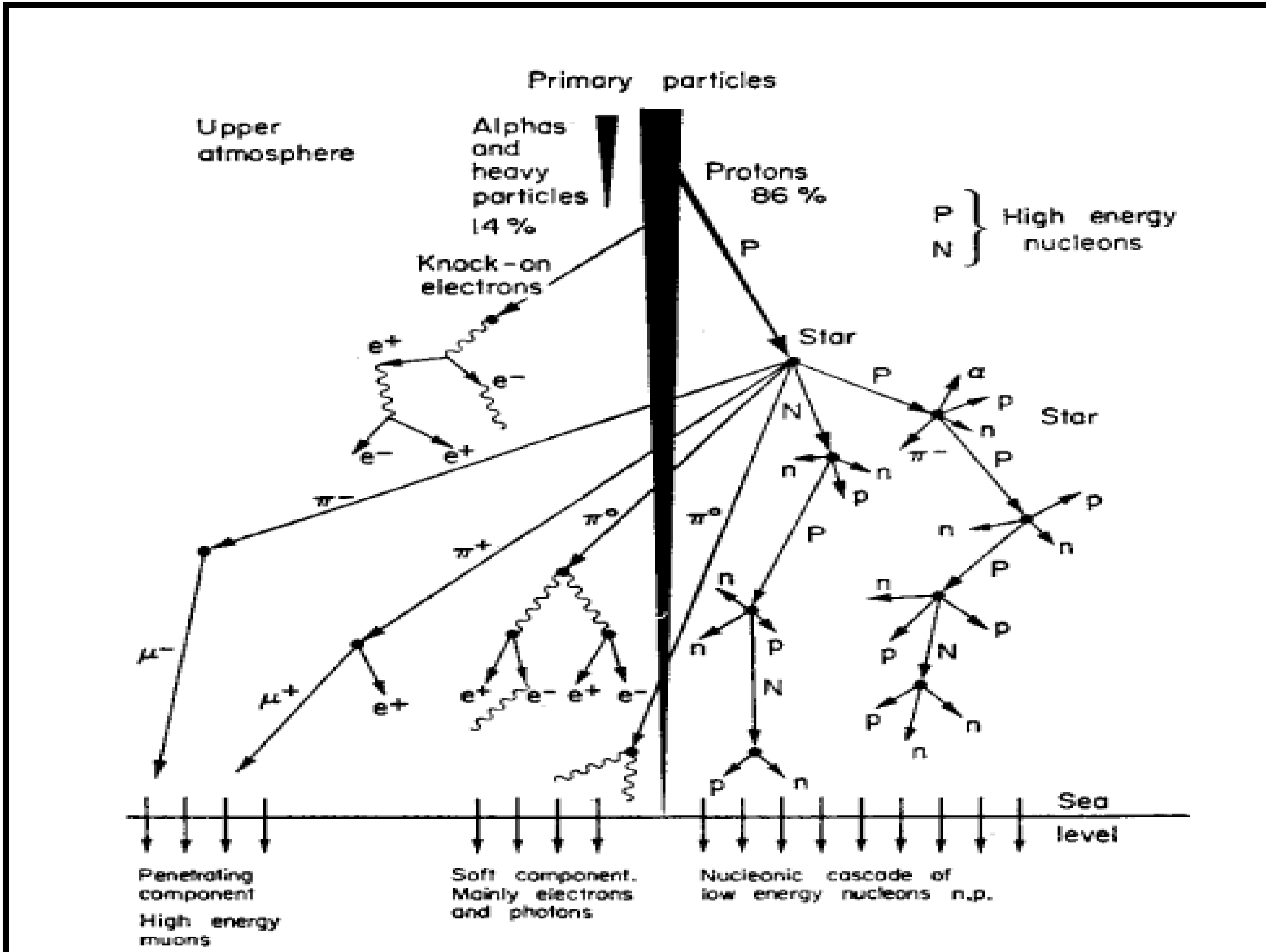
Millikan and others conducted some early researches on cosmic rays and found that there were two components, soft and hard, and that the hard, or very penetrating component, was not fully absorbed by many feet of lead or even at the bottom of lakes as deep as 500 m. This showed that the energy of cosmic rays was many times that of any other natural or artificial radiation known at that time.

- In 1927 Clay found that the intensity of cosmic rays depended upon latitude, being a minimum at the equator and a maximum at the poles. This is a geomagnetic effect supporting the suggestion that cosmic rays, are charged particles entering the earth's magnetic field from a great distance. At this stage the really intensive study of the properties of cosmic rays and their uses in nuclear physics had begun.

- 2\ Nature of Cosmic Rays:
- Primary cosmic rays have their origin somewhere out in space. They travel with speeds almost as great as the speed of light and can be deflected by planetary or intergalactic magnetic fields. They are unique in that a single particle can have an energy as high as 10^{19}eV but the collective energy is only about $10\,\mu$Watt\ m^2 for cosmic rays entering the atmosphere, which is roughly equal to the energy of starlight. In starlight the energy of a single photon is only a few electron volts,compared with the average for cosmic rays of 6 GeV per particle.
- The composition of cosmic rays entering the earth's atmosphere is fairly well known from balloon experiments, and it is found that these primary cosmic rays consist mainly of fast protons.

- There are very few positrons, electrons or photons, and the 'particle' composition is mainly 92% protons, 7% $\alpha-$ particles and 1 % 'heavy' nuclei, carbon, nitrogen, oxygen, neon, magnesium, silicon, iron, cobalt and nickel stripped of their electrons. The average energy of the cosmic ray flux is 6 GeV, with a maximum of about 10^{10} GeV. (Compare this with 300 GeV, the max. energy of the artificially accelerated particles.) The radiation reaching the earth is almost completely isotropic.
- As soon as the primary rays enter the earth's atmosphere multiple collisions readily take place with atmospheric atoms, producing a large number of secondary particles in showers. Thus when a primary proton strikes an oxygen or nitrogen nucleus a nuclear cascade results.

- These secondary atmospheric radiations contain many new particles, neutral and ionized, as well as penetrating photons, but little if any of the primary radiation survives at sea-level. Secondary cosmic rays at sea-level consist of about 75% muons and about 25% electrons and positrons, although some α-particles, γ-photons and neutrons may be present in negligible quantities. The muon will be described later.
- The collision cross-sections for the primary component of cosmic rays are of the order of 10^{-1} barns and the mean free path for a collision process at the top of the atmosphere may be as high as several kilometres. The new particles produced after primary collisions give in their turn more secondary radiations by further collisions until a cascade of particles has developed, increasing in intensity towards the earth. This is shown in Fig.(1)



Primary particles
Upper atmosphere
Alphas and heavy particles 14 %
Protons 86 %
P
N
High energy nucleons
Knock-on electrons
Star
e+
e−
e−
e+
P
α
p
n
Star
π−
π−
N
n
n
p
P
p
n
n
π°
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N
N
p
n
n
p
n
Sea level
Penetrating component
High energy muons
Soft component. Mainly electrons and photons
Nucleonic cascade of low energy nucleons n,p.

The energy spectrum of the primary cosmic rays ranges from 10^9 eV to about 10^{19} eV and can be written:

$$\frac{dN}{dE}=K(E+m_oc^2)^{-\gamma}$$

where N is the number of nuclei with a kinetic energy per nucleon E (in GeV), m_oc^2 is the nucleonic rest energy and K & γ are constants for a given cosmic ray component. This is represented in Table(1).

Composition of Primary Cosmic Rays Entering Earth's Atmosphere

Nucleus	*% Composition*	*Energy range (GeV nucleon^{-1})*	*Flux, i.e. no. of particles m^{-2} s^{-1} sr^{-1}*
H	92	2–20	$4000\,E^{-8/7}$
He	7	1·5–8	$460\,E^{-7/4}$
Li Be B	0·18	–	$12\,E^{-7/4}$
C N O F	0·36	3–8	$24\,E^{-7/4}$
Ne and beyond	0·15	3–8	$16\,E^{-2}$

E is the total energy per nucleon in GeV.

3\ The Origin of Cosmic Rays:

- An early observation on cosmic ray intensities showed that the sun itself must actually be the source of at least some of the low-energy primaries, since at times of solar flares the cosmic ray intensity increased. However, this can only account for a small fraction of the total, and since cosmic rays are nearly isotropic around the earth their origin in such a 'point source' as the sun is precluded and we must look much further into the depths of space.

- An interesting feature of the composition of the primary rays is the existence of heavy nuclides up to relative atomic masses of about 60, and the fact that the distribution of the elements in cosmic rays shows a similar trend to that in the sun, stars, nebulae and in the non-volatile parts of meteorites, although the primary cosmic radiations are significantly richer in heavy nuclei compared with the general matter of the universe. This seems to indicate a cosmic ray origin in which matter is present and where the conditions are of relatively low energy (compared with cosmic ray energies), possibly in supernovae explosions.

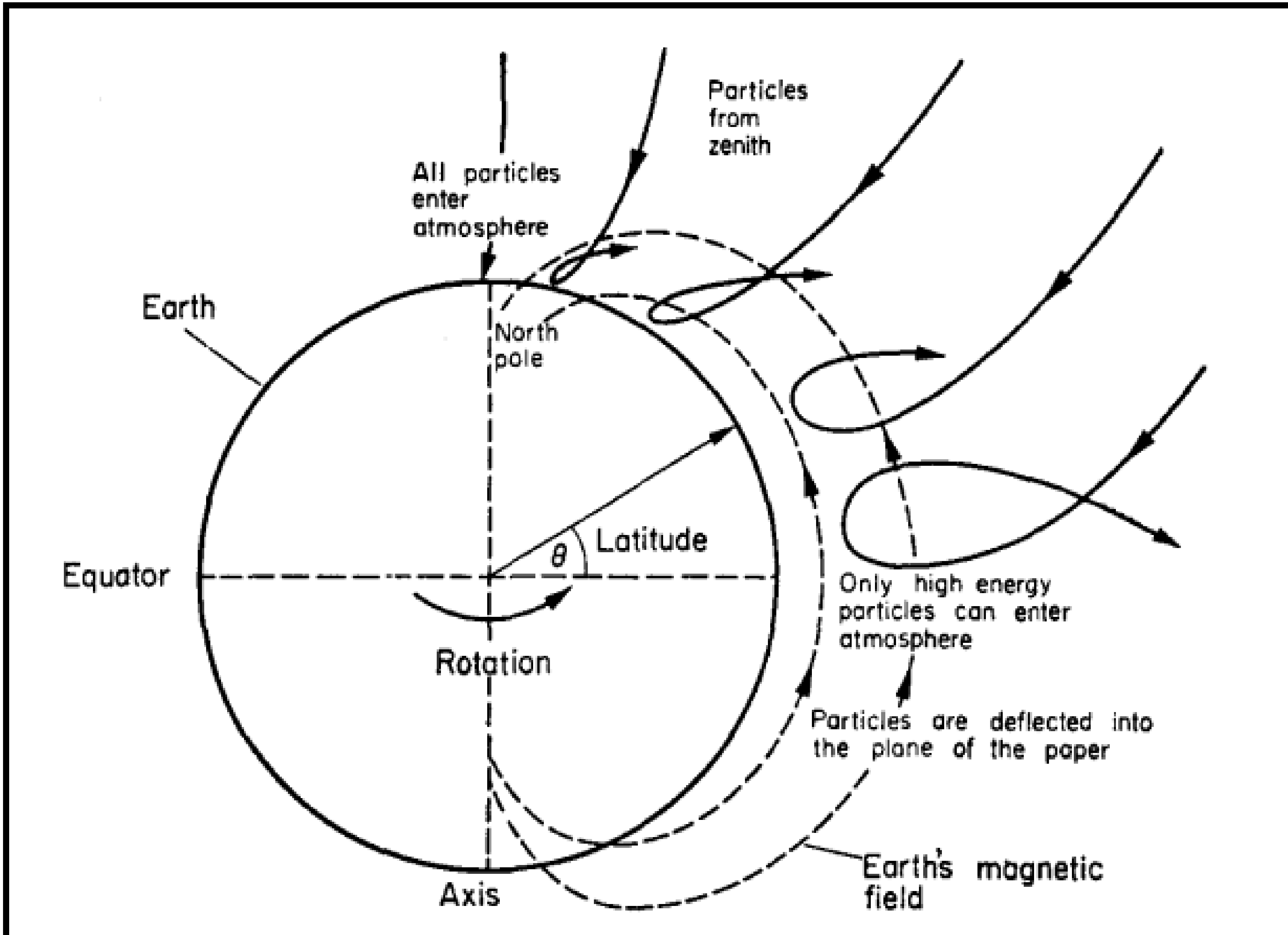
- **Fermi suggested** that the cosmic rays have their origin in interstellar space and are accelerated to high energies, as they stream through the arms of a galaxy, by the associated galactic magnetic field which is about 10^{-9} T or 1 nT. The cosmic ray particle is injected into the galactic magnetic field from the surface of a star with an appreciable initial energy and is caused to spiral in this field. It will eventually 'collide' with another region of high magnetic field which is approaching it with a high velocity. The cosmic ray particle is reflected or repelled with increased energy since the magnetic field is moving towards it. When a cosmic ray particle is trapped between two such fields it gains energy by multiple repulsions and the more energetic particles of the distribution finally escape into space with a high velocity of projection.

• This model is not unlike the 'mirror'machine. The trapping and ejecting mechanism can be repeated until the particle reaches the solar system where it is observed. It is concluded, therefore, that cosmic rays acquire their energies in the vicinity of magnetically active stars, especially supernovae. This is supported by the observations on radio stars which show intense radio *noise due to very fast electrons moving in magnetic fields, suggesting that cosmic rays may also be associated with stellar events of great violence.* Since the cosmic rays are pushed about in all directions by these great belts of stellar magnetic fields, in which they undergo multiple reflections and changes of direction, they surround the earth isotropically so that the earth can be regarded as a simple body in a whole sea of cosmic rays.

4\ Geomagnetic Effects:

- Compton and Millikan in 1935 carried out a world-wide survey of cosmic ray intensities and showed that the lines of equal cosmic ray intensity followed closely the earth's geomagnetic latitude indicating that some, at least, of the primaries must be charged particles affected by the variations in the geomagnetic field.

- The earth has a magnetic moment of about 10^{19} S.I. unit with a magnetic field of flux density 30 μT at the equator. As shown in Fig. (3), for the particles that enter the earth's atmosphere 'vertically' and parallel to the geomagnetic lines of force at the poles, there is little interaction between the magnetic field and the charged particles near the poles. However, **near the equator** the magnetic field is perpendicular to the direction of the cosmic rays and the interaction is therefore much greater so that the less energetic particles are deflected out of their original path. Only those exceeding a critical energy reach the earth's surface.


Particles
from
zenith
All particles
enter
atmosphere
Earth
North
pole
Latitude
θ
Equator
Rotation
Only high energy
particles can enter
atmosphere
Particles are deflected into
the plane of the paper
Axis
Earth's magnetic
field

- This critical energy is equivalent to a 'cut-off' in the energy spectrum,and depends on the latitude.
- The minimum particle momentum, corresponding to the cut-off energy, is given by:
- $P_{min} = 14{\cdot}85 \cos^4 \lambda$,
- where λ is the magnetic latitude and the unit of momentum is $\frac{GeV}{c}$,
- No particle below this limit can reach the earth at a given latitude λ and the max. value of P_{min} is 14.85 at the equator and about 0.9 at λ = 60°. It is probable that some of the low-energy components in the primary radiations are trapped in the earth's field at very high altitudes giving rise to the **Van Allen** radiation belts discovered in the American satellite experiments in 1958. These are toroid-shaped regions containing circulating particles of low energy but high intensity.

Problems

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- **Q\2*)** From the information given in Table (I) calculate the intensity of the various primary particles in microwatts\m^2 unit solid angle at 10 Ge V per nucleon. How would you expect this to vary with latitude? (Protons, 0·46 microwatt)
- **Q\3)** Discuss the fact that the primary cosmic rays do not contain appreciable numbers of electrons, positrons or photons.?
- **Q\4**) Write an essay on the origin of cosmic rays?
- **Q\6)** Estimate the dose rate at sea level at 45°N from cosmic ray secon-dary particles?
- **Q\7) In** a cloud chamber using a field of 2 T the radius of an electron track in a cosmic ray shower is 20 m. What is the energy of the electron?
- **Q\8)** Calculate the meson flux density at sea level if the ionization chamber used is a cylinder of 400 mm diameter and 400 mm long filled with air at 4 atm pressure, and gives a current of 56 fA.?
- 1 meson gives 70 ion pairs per centimetre path length in air at normal pressure.
- Assume the mesons enter the flat end only of the ionization chamber.
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Solution to Problem

- Q\2: Consider protons only.
- From Table (1) the flux is given by $\frac{4000}{E^{\frac{7}{8}}}$ particles\ m^2 s unit

solid angle, where E is in GeV.

- 4000
- ∴Flux = $\frac{4000}{10^{\frac{7}{8}}}$ = 290 particles\unit solid angle each with 10 GeV

energy.

- ∴ Energy intensity =290 x 10^4 x 1·6 X 10^{-13} J\ m^{-2} s unit solid

angle.

- = 0-46 microwatts\m ^{2} u.s.a.
-
- Q\6: P_{min} = 14·85 $\cos^4 \lambda$, where λ is the magnetic latitude and the unit of momentum is

$\frac{GeV}{c}$,

- =14.85 $\cos^4$ (45) =3.7$\frac{GeV}{c}$
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