Chapter 1

Introduction to Cosmic Rays

1.1 Milestones of cosmic ray research

The study of cosmic rays has a long story. This year we celebrate the centenary of the first experimental discovery of cosmic rays.

By measuring the acummulated static charge, **C.T.R. WILSON** discovered in *1900* the continuous atmospheric ionisation. It was believed to be due to the natural radioactivity of the Earth.

In order to check that, **Victor HESS** (Nobel Prize 1936) from the University of Vienna launched in *1912* an electrometer aboard a balloon to the altitude of 5 km (Fig. 1.1).

He discovered that the ionization rate first decreased up to about 700 m as expected, but then increased with altitude showing thus an outer space origin for ionisation. During subsequent experiments, Hess showed that the ionising radiation was not of solar origin since it was similar for day and night time. The term cosmic radiation became common. First it was believed that the radiation consists of γ-rays . The topic was very intensively discussed, and in *1925* **Robert Millikan** (Caltech) introduced the term "cosmic rays".

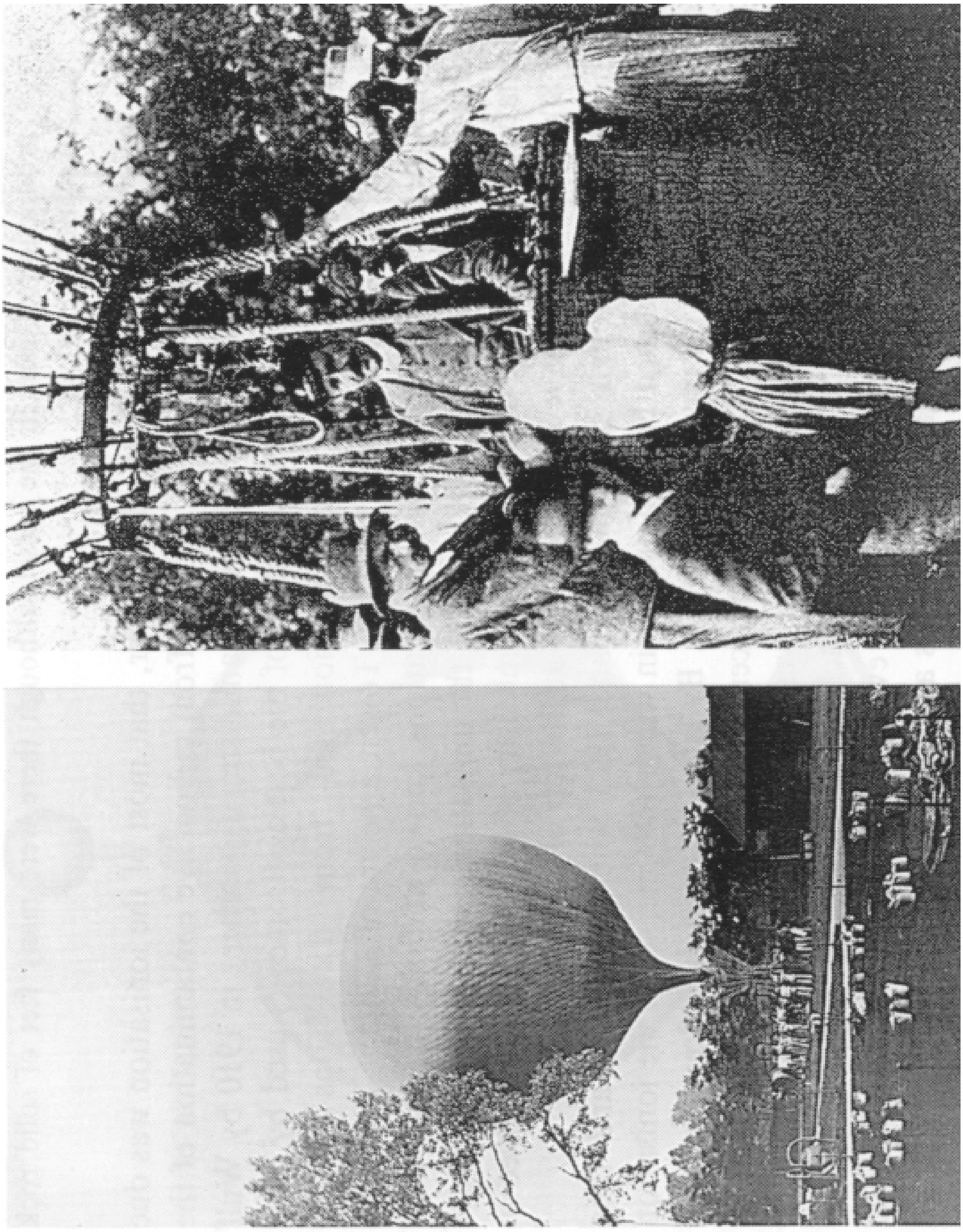

Figure 1.1: Victor Hess launching the balloon (1912).

Later, it has been shown that cosmic rays (CR) consist of CHARGED PARTICLES:

1928: **J. Clay** discovered that the ionisation rate increased with latitude thus showing that the sources of ionisation were charged particles deflected by geomagnetic field;

1929: Using a newly invented cloud chamber, **Dimitry Skobelzyn** observed the first ghostly tracks left by cosmic rays.

1929: **Bothe and Kolhorster** verified experimentally that CR are charged particles. At that time it was assumed that CR consist of electrons only.

1937: **Seth Neddermeyer and Carl Anderson** discovered muons in cosmic rays. Particle physicists used cosmic rays for their research until the advent of particle accelerators in the 1950's.

1938: **T.H. Johnson et al.** discovered that the ionisation rate is increased from east to west viewing angle, indicating that the ionisation was due to positively charged particles (correctly assumed to be PROTONS).

1938: **Pierre Auger**, who had positioned particle detectors high in the Alps, noticed that two detectors located many meters apart both detected the arrival of particles exactly at the same time. Auger had discovered "extensive air showers", showers of secondary nuclei produced by the collision of primary high-energy particles with air molecules (Fig. 1.2). In this way, cahnging the distance between detectors, he could observe CR with energies of 10^{15} eV - ten million times higher than reached so far.

28 Feb. 1942: First detection of solar cosmic rays.

1948: **Phyllis Frier et al.** discovered He and heavier elements in CR.

May 11, 1950: U.S. Naval Research Lab fired the *Viking* research rocket at the intersection of the geographic and geomagnetic equators, to

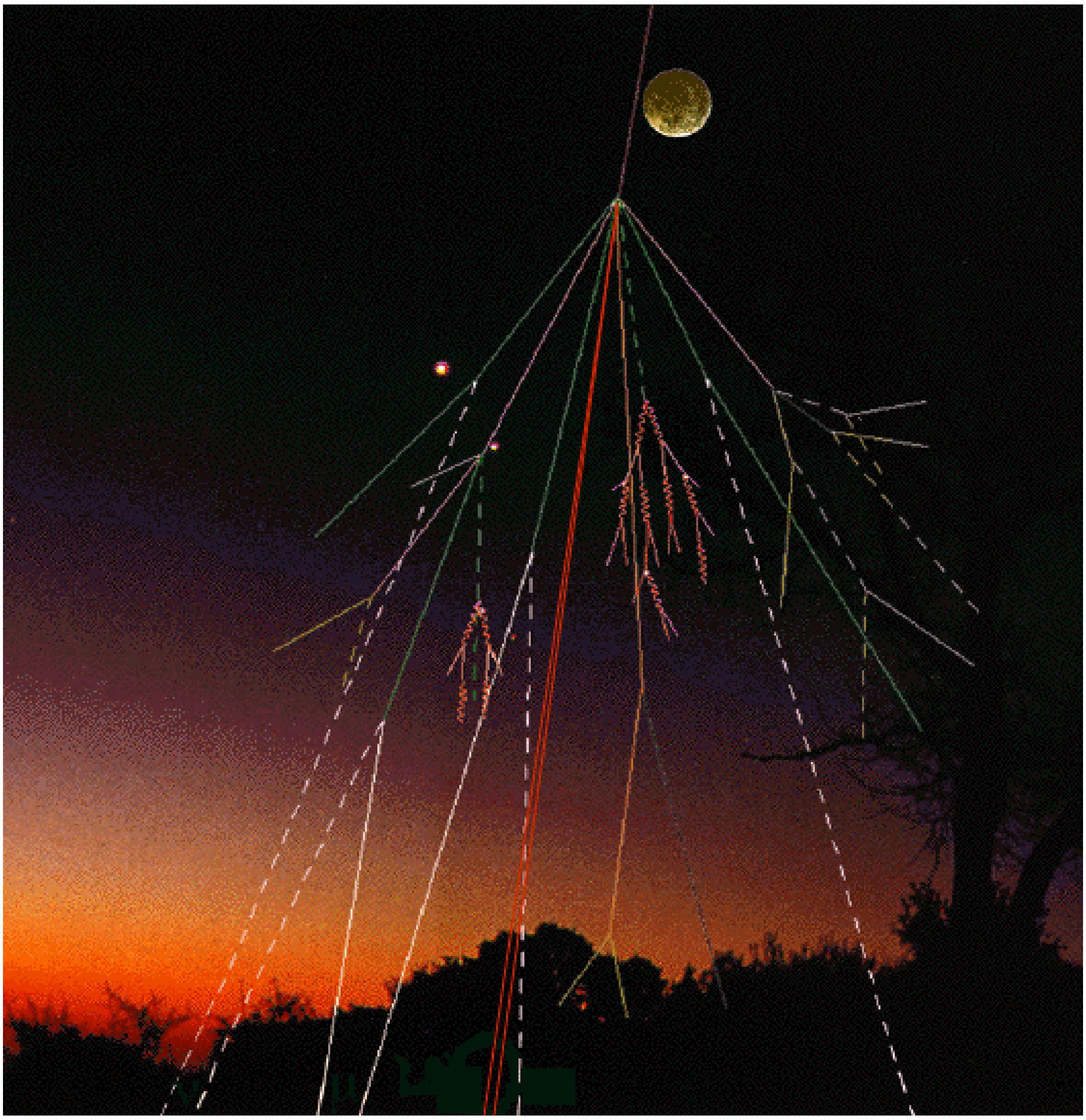

Figure 1.2: An artistic view of atmospheric shower.

collect cosmic ray and pressure and temperature data.

1959: Konstantin Gringauz (USSR) flew "ion traps" on the Soviet *Luna* 2 and 3 missions. *Explorer VII* was launched into Earth orbit with a particle detector.

1977: The *Voyager* 1 and 2 spacecrafts were launched to an interstellar mission.

1977-1982: **Bogomolov et al.** in a series of balloon experiments found antiprotons in CR.

1990: The *Ulysses* mission was launched for the first time out of the ecliptic plane and passed through the solar poles to study the 3D picture of solar wind and cosmic rays.

The study of cosmic rays provides unique opportunities to study nuclear and particle physics in the energy range hardly reachable in laboratories. It is hard to overestimate the contribution of cosmic ray studies (including neutrino and γ-ray observations) ito nuclear and particle physics. However, what is more important for us here is the astrophysical aspect of cosmic rays. The study of CR pushed forward such theoretical investigations as the theory of nova and supernova, MHD and plasma theory in astrophysics. In these areas, the following milestones can be noted.

1934: **W. Baade and F. Zwicky** suggested that supernova explosions (Fig. 1.3) are the sources of cosmic rays.

1949: **Enrico Fermi** suggested that the cosmic rays are accelerated in the interactions of CR with magnetic field irregularities.

1977: **Ian Axford et al.** suggested that the cosmic rays are Fermi accelerated by supernova shocks in a hot interstellar medium.

Besides, works of such famous scientists as **Alfvén, Ginsburg, Parker, Zeldovich** and many others should be acknowledged in the development of CR physics.

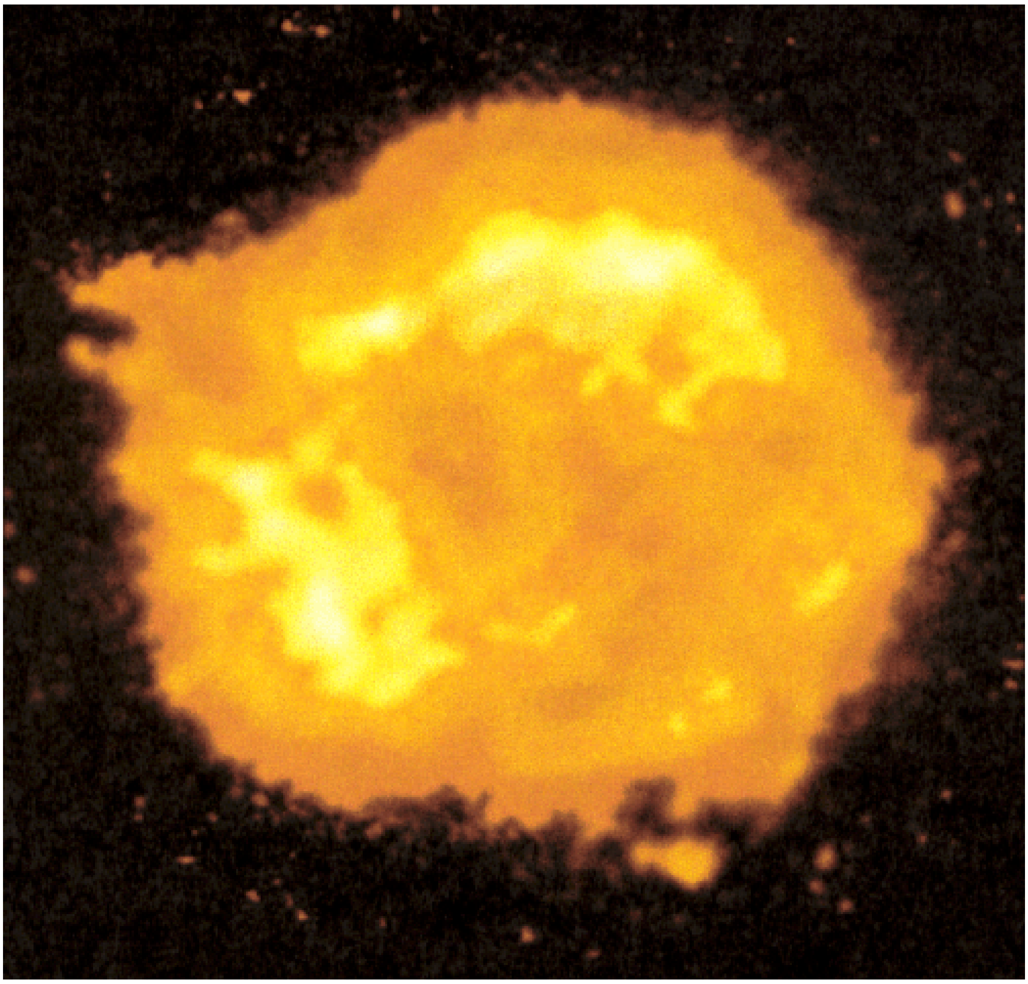

Figure 1.3: Signus loop supernova remnant. Image by ROSAT.

1.2 What is a Cosmic Ray?

A CR is not a ray, but is a **particle**. (Hard γ-quanta and neutrinos are beyond the scope of this course.) They include ionised atoms, ranging from a single proton, up to an iron nucleus and beyond. Cosmic rays originate from space, being produced by a number of different sources, such as the sun, other stars, and more exotic objects, such as supernova and their remnants, neutron stars and black holes, as well as active galactic nuclei and radio galaxies. Cosmic ray particles are travelling very close to the speed of light, and the most energetic particle ever observed had about 20 Joules of energy (equivalent to the kinetic energy of a fast shot base ball). The number density of CR integrated over energy ($>$ 100 MeV/nucleon) is about $N_{CR} \approx 10^{-10}\, cm^{-3}$ in the vicinity of the Earth. The total energy density of CR particles is $W_{CR} \approx 1\, eV\, cm^{-3}$.

The Earth's atmosphere protects us from being exposed to these particles. As a cosmic ray enters the atmosphere, it will collide with a particle in the atmosphere (usually a nitrogen or oxygen molecule).

It is common to separate three kinds of cosmic rays:

Galactic cosmic rays (GCR) originate far outside our solar system. They are most energetic with the energy extending up to 10^{20} eV. Composition is mostly protons with $\approx 7 - 10\%$ of He and $\approx 1\%$ of heavier elements. The source of very energetic GCR is not exactly known. GCR are the most typical cosmic rays, and their flux in the solar system is modulated by the solar activity: enhanced solar activity shields the system from these particles.

Solar cosmic rays (SCR) *aka* Solar Energetic Particles originating mostly from solar flares. Coronal mass ejections and shocks in the interplanetary medium can also produce energetic particles. SCR particles have energy of up to several handred MeV/nucleon (sometimes up to few GeV/nucleon). Composition is roughly similar to GCR: mostly protons, $\approx$ 10% of He, $<$ 1% - heavier elements. During strong solar flares (if optimally located on the Sun), the flux of CR at the Earth orbit can increase by some hundred percent during hours/days because of increase of SCR. This is called a Solar Particle Event.

Anomalous cosmic rays (ACR) originate from the interstellar space beyond the heliopause. We will discuss later the mechanism of ACR production. The composition of ACR is much different from GCR and SCR. They have more helium than protons, and much more oxygen than carbon.