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Cosmic rays, solar particles and space research

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a cura di B. Peters
Direttore del Corso

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Prolusione al Corso.

B. PETERS

Direttore del Corso

It is a pleasure to thank the Mayor of Varenna for the hospitality extended to us. I would like to thank Professor POLVANI for his words of welcome and through him thank the Italian Physical Society for its generosity which makes it possible to hold Summer Courses in this most beautiful place.

I welcome all of you who have come to participate in this course and shall use this opportunity to say a few words about its origin and purpose.

Last Fall, here in the Villa Monastero, Professor POLVANI, Prof. HOUTERMANS and I discussed the possibility and usefulness of organizing a course on Cosmic Radiation, Solar Particles and Space Research. Let me briefly explain the reason for choosing this subject.

As you know, Cosmic Ray Physics became an extremely active field of research soon after the war. Earlier, it had been a specialized field of study, almost completely isolated from other sciences; but in the last 12 years it has branched out.

Through the discovery and the study of the complex nature of the primary cosmic radiation it has become an integral part of astrophysics.

Through the study of cosmic ray produced isotopes it has made valuable contributions to fields of science as far apart as oceanography, meteorology and archaeology, and has contributed to our knowledge of the origin of meteorites.

The analysis of collisions of cosmic ray particles in the atmosphere has made it possible for the first time to study nuclear and electromagnetic interactions at energies which are large compared to the rest mass of the particles involved. Cosmic ray physics, thereby, has given rise to a new and still very active branch of physics, the physics of elementary particles.

Cosmic ray physicists are responsible for the discovery of mesons and of almost all the so-called strange particles. The results which they have obtained led to the design of the powerful particle accelerators which are in operation or in the course of construction in many parts of the world.

Perhaps the most active period of cosmic ray physics and the period which produced the most far-reaching changes in our views on the properties of matter was the period between 1951 and 1953, when new mesons and hyperons were identified and when the processes of their production and decay were studied for the first time.

After 1953 large accelerators and bubble chambers started to operate; there began a less productive period for cosmic ray physics. The study of elementary particles and the study of many electromagnetic and nuclear phenomena at high energies reverted to the laboratory.

There remained many unsolved problems in the nature of the primary cosmic radiation, but they were difficult to handle with the available experimental and technical equipment, consisting mainly of stratosphere balloons, emulsions, cloud chambers, and counters. It became increasingly difficult to improve the resolution between the particles of various mass numbers which compose the primary radiation, to determine the abundance of the rare elements, and to obtain higher statistical accuracy in the energy spectrum of various components.

Also the study of time variations in cosmic ray intensity, which has become of great importance, progressed only slowly during that period, because one had to rely on large networks of co-operating ground stations or on the synchronization of balloon ascents at widely separated places. The most valuable data had to be obtained in the least accessible places, (*i.e.*, the stratosphere in the polar regions) so that every new experiment involved a major expedition.

Recently, during the last three or four years, the rate of progress in cosmic ray physics has again accelerated. New avenues of research have been opened by the techniques of space research. New discoveries on the corpuscular radiation from the galaxy and the sun have been made and more important ones are in the offing. They will be made in the U.S.A. and in the U.S.S.R. but, for the time being not here in Europe, since European cosmic ray physicists have neither satellites nor space probes. If they do not want to continue working with outdated techniques, they have only the choice between switching their field of research and emigration.

About two years ago, Professor AMALDI wrote a memorandum on Europe and space research, which circulated mainly among scientists connected with CERN. In this memorandum Professor AMALDI emphasized that the investigation of space is giving rise to new and important technological developments and that, if Europe made no effort to participate in space research, it may within a period of 20 or 30 years lose its high technological standing and become one of the underdeveloped regions of the world.

About a year ago, the first serious steps were undertaken by individual scientists to explore the possibility of developing space research as a co-operative European effort. The brilliant success of CERN has greatly encouraged this approach of close co-operation between various nations. If such an enterprise was to succeed, it seemed important to counteract the drifting away of European cosmic ray physicists to other research fields and to other countries. A discussion of the present state of the science with particular emphasis on the problems which have become accessible to investigation by the advent of space vehicles seemed to be a useful step in that direction.

These then were the main considerations governing the choice of subject matter for this course. The scientific programme has been arranged accordingly; it consists of a number of review lectures, each one dealing with a different aspect of solar and galactic particles. These lectures take up about half of the available time. The rest will be devoted to discussions and to shorter contributions from an audience which consists almost entirely of people coming from laboratories which are engaged in one or another aspect of cosmic ray research. I invite all of you who can contribute to the subject matter treated in this course to inform me within the next few days.

On the 1st of December 1960, at Meyrin, the site of CERN, an agreement was signed between representatives of 11 nations (Belgium, Denmark, France, Holland, Italy, Norway, Spain, Switzerland, Sweden, United Kingdom and West Germany) to set up a committee to investigate the possibilities of space research in Europe, and to prepare an international treaty for a European Space Research Organization (ESRO). This committee whose name, « COPERS », derives from the words « Commission Preparatoire Européenne pour la Recherche Spatiale », has held many meetings and is approaching the stage where it can make concrete proposals to the participating governments. It seems likely that these efforts will lead to the setting up of European Space Research laboratories and to the recruiting of staff for these laboratories in the early part of 1962. In anticipation of such an agreement, many countries, now engaged in rocket and upper atmosphere research, have declared their willingness to accept engineers and scientists from other countries for training purposes. Those who are interested in availing themselves of such opportunities should write to Professor P. AUGER, Secretary of COPERS (36 Rue La Perouse, Paris XVI).

If then it seems likely that Europe will actively carry out space research in the coming years, it becomes important to keep well informed on the development of space research abroad. I am therefore particularly happy that among the participants in our course are two representatives of NASA (National Aeronautic and Space Administration of the U.S.), Dr. LUDWIG and Dr. OGILVIE, who have been active in the most recent work on the properties of cosmic radiation in space.

It is a loss to this course that Professor GINZBURG of the Lebedev Institute in Moscow who, as you know, is one of the authors of a detailed and very successful theory on the origin of cosmic radiation, has been unable to accept uur invitation.

I also regret to report that Professor DENISSE of the Observatoire de Paris at Meudon has fallen ill. He had planned to give an introductory lecture on the sun from the point of view of an astrophysicist. I am very grateful to Professor HACK of the Merate Observatory who, on rather short notice, has agreed to give this introductory lecture.

Before closing let me say a few words about nomenclature. « Cosmic rays » is not a fortunate designation for the mixture of high energy nuclei which originate and are accelerated in our galaxy. « Galactic high energy particles » would be a more appropriate term to distinguish these particles from other forms of radiation which reach us either from our galaxy or from the more distant places of the cosmos. But the name « cosmic rays » has been used for so long that it seems impractical to change it at this late date. This is no reason, however, why we should admit such illogical terms as « solar cosmic radiation » into our vocabulary, in order to designate particles accelerated on or near the sun. This designation has already made its appearance in the literature, but its spread can still be arrested; it should, I feel, be replaced by a less ambiguous term such as « solar corpuscular radiation » or « solar particles » as we have done in the title of this course.

I have the honour of opening now the scientific part of the 1961 programme of the « Enrico Fermi » Summer School.

INDICE

Relazioni tra Sole e Terra.

Problemi galattici.

Storia ed origine dei raggi cosmici.

Strumenti e programmi di ricerca.

The Surface of the Sun.

M. HACK
Osservatorio di Merate

1. – Introduction.

Most of the disturbances occurring in the solar atmosphere, which are strictly connected with emission of X-rays and corpuscular radiation from the sun probably find their initial cause in the convective zone underlying the photosphere. For this reason, before starting to speak about the solar atmosphere and its disturbances we must give a brief account of the main properties of the solar surface, where evidence of the convective zone is apparent.

The sun is a gaseous sphere mainly composed of hydrogen (H is 85 % in number of atoms, He 15 %, for the other atoms we have H/metals $\simeq 10^4$); its radius is equal to 700 000 km and its mass is $2 \cdot 10^{33}$ g. Temperature, density and pressure steadily decrease from the centre to the surface. This sphere is in hydrostatic equilibrium under its own gravitation; this means that the pressure exerted by a column of gas lying below any layer is counter-balanced by the weight of the column of gas above the layer. The energy distribution of the continuous spectrum of the sun is very similar to that of a black body at the temperature of 5 700 °K. From the whole surface of the sun $4 \cdot 10^{33}$ erg s^{-1} are emitted. The luminosity of the sun is maintained by production of energy by means of nuclear reactions occuring in the core. At the temperature and density of the solar core ($T_c = 15 \cdot 10^6$ °K, $\varrho_c = 90$ g cm^{-3}) the main nuclear reaction chain is the proton-proton cycle.

We must explain what we mean by solar surface, since this gaseous sphere does not have a well defined boundary.

We call the surface, or the photosphere, a layer dense enough to emit continuous radiation and to show a considerable brightness, but still sufficiently transparent to allow a direct investigation of the same layer. In other words the surface is the whole of layers from which we receive an appreciable percentage of radiation; its depth is about 300 km; radiation from layers deeper than 300 km is almost completely absorbed by the overlying layers. The opacity of the photosphere is mainly due to the absorption of negative hydrogen H^-, and also to bound-free and free-free transitions of electrons moving in the fields of ions. The small depth of the photosphere, which is less than 1/2 000 of the solar radius, and which is seen from the earth under an angle of 0.5″ explains why looking at the sun we have the impression of seeing a solid well bounded surface.

A direct proof of the semitransparency of the photosphere is given by the existence of limb darkening. The decrease of brightness from the centre to the limb of the solar disk is due to the inward temperature increase of the photospheric layers. When we look at the centre of the disk our line of sight enters normally to the surface of the sun: so we receive radiation from the layers on the average deeper and hotter. When we observe the limb our line of sight enters tangentially to the surface and we receive radiation only from the cooler layers of the top. The limb darkening is a function of the wave length, and is more apparent in the violet than in the red.

The photosphere is not homogeneous. Pictures of the sun in white light show a granular structure, which consists of bright blobs on a dark background. The sizes of the granules vary from 0.3″ to 2.5″ with a mean value of 1.0″, corresponding to 700 km. The best photographs of granulation are those obtained by SCHWARZSCHILD, ROGERSON and EVANS from a balloon at an altitude of 25 km, to reduce the disturbing effect due to the turbulence of our atmosphere. The intensity difference between granules and dark background corresponds to an average difference in temperature of between 120° and 230°. These temperature differences refer to the mean level from which the continuous radiation emerges, *i.e.* from an optical depth of ~ 1 (which corresponds to a depth of ~ 280 km). The zig-zag structure of the absorption lines of the solar spectrum is also a proof of this lack of homogeneity of the photosphere, at the higher layers where the absorption lines originate ($\tau \simeq 0.1$ corresponding to a depth of ~ 190 km). This zig-zag structure is an evidence that the spectra of the individual granules are slightly shifted with respect to each other because of Doppler effects (radial velocity difference ~ 0.4 to $1.5\ \text{km s}^{-1}$). The granulation is the evidence of the existence in the upper parts of the sun of a zone where convective currents are present. Theory also requests that in those parts of a star where the gas is partially neutral and partially ionized convective currents must develop.

Observations of KIEPENHEUER [1] suggest that the granules have a magnetic field of the order of 400 G. This kind of observation is very difficult because of the small dimensions of the granuli. The existence of a magnetic field of this order of magnitude is supported by theoretical arguments: in a turbulent plasma, electric currents are generated between regions of different electron densities and temperatures; these produce weak magnetic fields. These fields can be increased in intensity by the so-called « spaghetti process ». Since the electrical conductivity of the ionized gas is very high the lines of force are « frozen » in the gas. The turbulent motions tangle the magnetic lines of force. The continual twisting of the lines of forces serves to increase the number of lines through unit cross-sectional area, and hence the intensity of the magnetic field. This process will continue until equipartition between the turbulent and the magnetic energy density is reached: $H^2/8\pi = \frac{1}{2}\varrho v^2$. From the solar models the density at the top of the granulation zone is about $3\cdot10^{-7}$ g cm^{-3}. The curve of growth gives for the turbulence $v \sim 1.5$ km s^{-1}. It follows that $H = 290$ G, a value in good agreement with the observation.

2. – Phenomena of solar activity on the solar surface.

The appearance of spots, changing in number and shape with time on the bright surface of the sun, is a well known phenomenon since the time of Galileo, who first observed it. Spots appear generally between $|5°|$ and $|40°|$ of latitude. None has been observed at latitudes higher than $|50°|$. They appear either isolated or, more often, in groups. A typical spot consists of a dark umbra (temperature of 4000 °K, to be compared with the 6000 °K of the surrounding photosphere) surrounded by a penumbra. Zeeman splitting of the absorption lines is evident in the spectra of the spots. It is found that the magnetic field of the spots is mostly perpendicular to the surface, and the intensity is of the order of some hundred to some thousand gauss. There is a strict correlation between the spot and the intensity of the magnetic field, which can be represented by the formula [2]

$$H = 3\,700[A/(A+66)]\ \text{G}\,,$$

where A is the area of the spot, in 10^{-6} of the visible hemisphere (so for A included between 10 to 400 we have H between 480 and 3200 G). Observation of Doppler shift of the lines in the spot spectra shows that gas of deeper layers of the photosphere is streaming out of the spot, while gas of high atmospherical layers is streaming into the spot (Evershed effect).

Spot groups or single spots always appear in a facula.

Faculae are bright structures, similar to clouds, slightly brighter than the surrounding photosphere. If there are no spots without faculae, the reverse is not true, and often small faculae appear without spots. Faculae have weak magnetic fields, of the order of a fraction of a gauss to several gauss.

Theory must try to explain the diverse features of the solar activity at the surface: appearance of spots and faculae, low temperature of the spots and high temperature of the faculae, magnetic fields which are so strong in the spots, the often observed bipolarity of the spot groups, the 11 year cycle and the inversion of polarity which happens at each cycle so that the full solar cycle is in fact 22 years.

No completely satisfactory theory has been proposed until now. On this subject I will point out only this: until 20 years ago it was thought that the spots were places of large convection, where the low temperature follows from the adiabatic expansion of the ascending gas. Now we know that the strong magnetic fields supress convective motions and tend to bind together neighbouring masses of gas inhibiting flow across the magnetic lines of force. A rising gas cannot therefore flow horizontally and descend again to complete the convections cycle. So spots are region of calm in a turbulent atmosphere.

Since convection is lacking, energy flow occurs only by radiation; hence is suggested that spots are cooler because convective energy transport is less in the presence of magnetism.

In the regions just outside the spots convection must be greater to make up the diminished heat flow over the spot areas. This could explain the brightness of the faculae which surround the spots.

We can compute that no convection will occur above the depth where magnetic energy density is of the same order as the energy of turbulent motions. For the high values of the density which we find in the interior of the sun, the field H becomes less than $v\sqrt{4\pi\varrho}$ so that in the deep layers convection will not be prevented. Apparently, by local violent convection, some of these field lines of the interior are brought to the surface, forming a spot or a group of spots.

3. – The solar atmosphere.

It is difficult to give a very short account of all the complex properties of the solar atmosphere. I will try to say briefly:

a) What we mean by chromosphere and corona.

b) Their main aspects derived by optical observations.

c) A very short account of the theories explaining the support and the heating of the solar atmosphere.

d) What are the components of radio emission of the quiet sun.

e) What are the components of radio emission of the active sun and their correlation with optical disturbances.

The layers overlying the photosphere are called the solar atmosphere. They include the chromosphere, or low-atmosphere, extending from the photosphere to 6 000 km of height, and the corona, a very rarefied envelope of ionized gas extending probably as far as the earth or further.

A model for the chromosphere and the corona has been computed by

WOOLLEY and ALLEN; it explains fairly well the optical and radio spectrum of the chromosphere and corona, in absence of perturbation (see Table I).

TABLE I. – *Models of Woolley and Allen.*

h (10^3 km)	T (°K)	log N_e (cm^{-3})
4	5 040	9,4
6	6 300	10,4
6,001	14 500	10,2
6,01	36 000	9,8
6,1	91 000	9,4
7	230 000	9,0
10	400 000	8,8
20	660 000	8,6
30	800 000	8,5
40	950 000	8,4
70	—	8,25
700	—	6,50

4. – The chromosphere.

The chromosphere has a spicular compositon. Each spicule has a thickness of about **500 km**; they are more or less perpendicular to the solar limb, and grow above the general level up 10 000 to 20 000 km and disappear in the course of some minutes.

The spectrum of these spicules show that they have temperatures of 10 000 to 20 000 °K; they are hence cold elements in a hot corona, having a temperature of about 500 000 °K.

The density in the spiculae is about 1000 times higher than in the surrounding corona.

5. – Prominences.

Prominences are visible as bright structure extending beyond the sun's limb, in the corona. When viewed on the disk they take the name of filaments. Typical dimensions are 200 000 km in length, 50 000 km in height, and 10 000 km in thickness. They are probably supported by magnetic fields; when an ionized cloud of gas falls in such a field the turbulent motions are stopped. The support is stable at these points where the magnetic field is horizontal. A quiescent prominence may become active, activation may be due to flares. The equilibrium is perturbed, and the prominence moves along the magnetic lines of force and may disappear suddenly.

6. – Flares.

Flares are sudden brightenings of the faculae fields. They are mostly observed in monochromatic light (H_α); often they are observed several times in a day.

Only 17 cases are recorded to have been observed in white light. Their areas are included between 100 and 1200 in units of 10^{-6} of the visible hemisphere.

They originate near quickly developing spots. Observations of limb flares show that they reach heights of 7 000 to 16 000 km on the surface.

Often the flare is surmounted by an ascending eruptive prominence (surge). Several concomitant phenomena occur together with a flare *i.e.* radiobursts and emissions of cosmic rays and X-radiation.

Flares are classified according to their area. They are classified in three classes of increasing importance: 1, 2 and 3. Subdivisions are 1^- and 3^+ (those having area respectively less than 100 and larger than 1200. The area is expressed in 10^{-6} of the visible hemisphere). The light curve of the flares is steeper in the ascending part that in the descending part. Flares are probably regions where the temperature is the same as in the surrounding parts, but the electron density becomes 10^3 to 10^5 higher than in the surrounding parts of the chromosphere and the corona. (N_e flare $\sim 10^{13}$ cm^{-3}, N_e chr. $\sim 10^{10}$, N_e cor $\sim 10^{8}$).

7. – The corona.

The corona is so faint compared with the brightness of the sky and with the solar light scattered by the optical parts of a telescope that it is impossible to observe it except during an eclipse. Only the coronographic equipment allows the study of the brightest parts of the corona outside an eclipse. The shape of the corona is a function of the 11 year cycle. Typical features are the streamers and the polar plumes.

The spectrum of the corona is composed: *a*) of a continuous spectrum due to solar light scattered by the coronal electrons (corona K); this fraction of coronal light is polarized; *b*) of a continuous spectrum due to solar light scattered by dust in interplanetary space (corona F). This light is probably unpolarized; *c*) monochromatic emission by Ca, Fe, Ni, A ions, 9 to 14 times ionized. The ionization is due to collisions. The electron temperature of the corona in the regions where the yellow line of Ca XV at 5694 Å ($I \cdot P = 814$ eV) appears may reach $5 \cdot 10^6$ °K.

8. – Support and heating of the chromosphere and corona.

How is the chromosphere supported? The great scale height is due to the intense turbulent motions having between 2 000 and 4 000 km an average value of 15 km/s.

Why has the chromosphere so high a temperature? The source of heating is probably the turbulence of the photosphere which in turn originates from the lower convective motions. The main part of the convective energy is dissipated in the convection zone but a small fraction of it moves upward in the form of travelling sound waves. The heating of the corona is explained in a similar way. The flow of mechanical energy coming from the photosphere, though dissipating part in the chromosphere, is still important when it arrives in the corona. We can compute that at a height of 6 000 km there is equality between dissipation of mechanical energy and radiation Higher up the temperature increases because the emission of radiation becomes relatively less important. The radiation of the corona is the order of $5 \cdot 10^3$ erg cm^{-2} s^{-1}, whereas the inflow of mechanical energy is about a factor of 10^2 greater.

This explains the sharp increase of temperature which is observed at 6 000 km above the photosphere.

A part of the mechanical energy absorbed by the corona is lost by « evaporation ». This evaporation must be important because the thermal velocity of the coronal gases is close to the velocity of escape. This proves that the hot coronal regions must necessarily be a source of particle emission.

Probably a mass of the same order as that evaporated is accreted from the interplanetary dust.

9. – Radio emissions from the sun.

Radio astronomical observations of the chromosphere and the corona give much information on the physical structure of these layers and their perturbations. In fact, as for all the ionized gas, they are optically thick for the radio waves, and hence good radio emitters, while in the optical dominion they are transparent and very poor emitters.

10. – Background radiation.

The solar radio emission is composed of a permanent part due to thermal radiation by the chromosphere and the corona; it is due to free-free transition of electrons in the field of ions, mainly protons. (The contribution of the photosphere is completely negligeable as a consequence of its low temperature).

It varies slowly in the course of the solar cycle.

This is called background radiation. Moreover we observe a transient component, presumably due to centres of activity, which consists of: slowly varying component, noise storms; and outbursts of several types.

The intensity of the quiet sun is obtained by eliminating the transient components. The computations of the emergent radiation for a chromospheric and coronal model offer no difficulties, and a comparison between observed and computed spectrum of the background radiation allows us to derive temperature and electron densities as a function of the height.

We remember that the refraction index μ of an ionized gas is equal to $\sqrt{1-(f_c/f)^2}$, where f_c in the mks-system is given by $f_c = 9\sqrt{N_e}$. For $f > f_c$ the radio waves propagation is normal. For $f < f_c$ μ is imaginary, the waves cannot propagate.

Going up in the corona, the electron density decreases, f_c decreases too, and the propagation of lower and lower frequency waves becomes possible. For example wave-lengths shorter than 3 cm can propagate for the whole chromosphere and corona, while waves longer than 10 m can propagate only in the high-corona. Hence 3 cm radiation comes from the whole atmosphere, but since the absorption coefficient of H II is given by $K \sim N_e/\mu f^2 T^{\frac{3}{2}}$ the chromosphere emission is more important then that of the corona. In fact observations show that the temperature of the disk at centimetric wave-lengths is that corresponding to the lower chromospheric layers, which are the main contributors of the emission; the temperature at metric wave-lengths is that corresponding to the coronal layers (for temperature we mean the equivalent temperature of the disk; *i.e.* the temperature of a black body of the same angular size of the sun which gives the same flux density which is observed for the sun). The angular size of the sun increases with the wave-length, and corresponds to the height of the different layers which are the main contributors to the emission.

11. – The slowly varying component.

The period of variation is about 27 days (which is the synodical rotation period). There is a strict correlation between sun spot area and flux density. The curve extrapolated to zero sunspot area gives the background radiation level. The origin of the slowly varying component is probably thermal. Since its spectrum extends only from 2 to 60 cm it is thought that the layers where this radiation arises are in the chromosphere and in the low corona.

It probably originates in the coronal condensations. These condensations are found in the region over a spot group; the electron density in the condensations is higher than in the near regions.