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mc crystal transducer which was coupled to the test specimen with a light grease. Special calibration test blocks were made from the same material as the tubing being tested. Thickness tests were made on the tubing using the test blocks for reference.

CONCLUSION

The ultrasonic test results were confirmed by physical measurements and found to be accurate to .0005 inch for .4500 inch of specimen wall thickness. Thus the difficult operation of determining the inner to outer diameter concentricity relationship of a long hollow cylindrical shape was easily and accurately accomplished with ultrasonic resonant gauging.

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Solar Protons and Their Geophysical Effects

S. M. KRIMIGIS[1]

Abstract. In this paper, a review of the present state of knowledge of solar particle emission is given, and the effect of this emission in geophysical phenomena is analyzed. It is pointed out that the particle emission can be categorized into (a) continuous plasma emission and (b) occasional emission of solar cosmic rays. The plasma emission mainly determines the shape of the magnetospheric boundary, whereas the cosmic ray emission accounts for the geomagnetic storms, intense aurorae, ionization of the upper atmosphere, and Forbush decreases in the primary cosmic radiation. In addition, some of the remaining fundamental questions to be investigated in the future are pointed out.

We shall begin by quoting a passage from "Stars and Atoms" of the famous British physicist, Sir Arthur Eddington. "In ancient days two aviators procured to themselves wings. Daedalus flew safely through the middle air and was duly honoured on his landing. Icarus soared upwards to the sun till the wax melted which bound his wings and his flight ended in fiasco . . . The classical authorities tell us, of course, that he was only 'doing a stunt'; but I prefer to think of him as the man who brought to light a serious constructional defect in the flying machines of his day.

"So, too, in science. Cautious Daedalus will apply his theories where he feels confident they will safely go; but by his excess of

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caution their hidden weaknesses remain undiscovered. Icarus will strain his theories to the breaking point till the weak joints gape. For the mere adventure? Perhaps partly, that is human nature. But if he is destined not yet to reach the sun and solve finally the riddle of its constitution, we may at least hope to learn from his journey some hints to build a better machine".

It appears to me that the space scientist of today is just like Icarus of the legend. He continuously strains his theories to the breaking point at an ever accelerating pace, hoping to learn from his journey, about the earth, the sun, the solar system, the galaxy. One of the main problems in space physics today is the understanding of the sun and the way it affects the earth and the planets. We shall try to give a qualitative review of what is presently known about this problem.

Solar particle emission can in general be divided into two broad categories, with the particle energy used as the main criterion for the distinction. These categories are: (a) Solar plasma emission and (b) Solar cosmic ray emission. The solar plasma emission or "solar wind" as it is usually called, consists of protons and possibly other ions in the energy range of tens to thousands of electron volts. The solar cosmic rays are arbitrarily taken to be protons in the energy range of 100 keV to a few BeV. A more definite and less arbitrary distinction between the two emissions can probably be given by considering the mode of production and the acceleration mechanism in the chromosphere of the sun; however, this is not possible at the present time.

In the following, we shall briefly review the experimental results obtained so far in measurements of the solar wind, and then turn our attention to the more well-known phenomena of solar cosmic rays.

Solar Plasmas And The Solar Wind

The fact that streams of plasma flow continuously away from the sun in an approximately radial direction is supported by a good amount of indirect evidence. The original suggestion of this so called "solar wind" came from Lindermann, who suggested that the geomagnetic storms and aurorae were due to the interaction of these ionized gases with the earth's magnetic field. The presence of approximate 27-day variations in the occurence of magnetic fluctuations and aurorae near the poles seems to support and expand the original hypothesis, and in addition to suggest that not all portions of the sun emit plasma at the same rate.

The first somewhat direct evidence of the existence of the solar wind came from Bierman's analysis of Type I comet tails.

These comet tails consist of ions, and accelerate away from the sun in a radial direction. Bierman[1] suggested that the acceleration of such tails as well as their ionization and excitation could be accounted for only in terms of a solar corpuscular emission. For the quiet sun, Bierman arrived at the conclusion that the density of the plasma is about 100 protons and electrons per cm^3, and its velocity is in the neighborhood of 500 km/sec. Later work reduced these numbers to 10 cm^{-3} and 300 km/sec; these values may be considered as typical average values.

Measurements of the plasma density were first made by Luniks II and III and gave an approximate flux of 2 x $10^8 cm^{-2} sec^{-1}$. Additional information with simultaneous measurements of the magnetic field was obtained by means of Explorer X.(5) The plasma probe of this satellite recorded a flux of protons of the order of 4×10^8 particles cm^{-2} sec^{-1} with an energy spectrum peaked at about 500 eV. They apeared to come from the direction of the sun with a possible angular spread not greater than ±25°. The velocity of the plasma stream was about 300 km/sec, in agreement with previous indirect observations. The necessity of making simultaneous measurements of both the plasma and the interplanetary magnetic field should be emphasized. The high electrical conductivity of the plasma causes the magnetic field lines to be effectively "frozen" or "trapped" into the plasma. In interplanetary space for example, the kinetic energy density of the plasma is normally greater than the magnetic energy density, so that the field is carried along by the plasma.

At this point, after having roughly outlined the nature and properties of the plasma streams, we can consider the question of the interaction of this plasma with the geomagnetic field. Since the solar wind is supersonic, the situation at the boundary between the plasma and the geomagnetic field resembles the flow of a high velocity compressible fluid around an obstacle. The radius of this so called "cavity" is determined by the equilibrium of the solar wind pressure ($1/2\rho v^2$) and the geomagnetic energy density ($B^2/8\pi$), and is typically about 10 earth radii (see Figure 1), at the point where the direction of the solar wind is perpendicular to the geomagnetic boundary. At locations away from the normal to the boundary, the distance from the center of the earth to the boundary becomes greater. On the back side of the earth the wind cannot "push" against the field but instead is thought to drag away the lines of force and extend them into a long tail. Direct experimental evidence of this model is provided by very recent data from Explorer XIV (see Figure 1). This geomagnetic cavity is generally referred to as the "magnetosphere".

SOLAR COSMIC RAYS

A. *Sources of Solar Cosmic Rays.*

Having examined the solar wind, which is continuously present, we shall now discuss the somewhat abrupt increases in the emission of higher energy particles from the sun, whose effects on the earth range from intense aurorae, to geomagnetic storms, and Forbush decreases. We shall define and discuss each one of these geophysical phenomena in detail, but let us for a moment turn our attention to the causes that give rise to these events.

The photosphere, that is, the visible surface of the sun, has a temperature of about 6000°K. Above the photosphere the temperature of the gas decreases slightly and then rises rapidly to form the chromosphere (so named because of its red color) and the solar corona, which is a region of hot (10^{6}° K), tenuous, ionized gas extending far out from the sun and into interplanetary space. Into this picture of the quiet sun there appear from time to time regions of disturbance whose most obvious characteristic is the sunspot. The sunspots have associated with them magnetic fields up to 3,000 gauss and characteristic dimensions of the order of 10^4 km. A small fraction of stellar energy is stored in these magnetic fields under conditions which frequently lead to instabilities and the sudden release of a substantial fraction of the stored magnetic energy in the form of light, x-rays and kinetic energy imparted to the highly ionized gas. The solar flare is an outstanding example of this process; it is a bright cloud materializing above the photosphere in a period of a few minutes and lasting perhaps half an hour. Ultraviolet light and x-rays may be detected at the earth within minutes of the flare onset. The results of large flares may be observed at the earth one or more days later as aurorae, magnetic storms, cosmic ray decreases, etc. A large flare with dimensions of the order 4 x 10^4 km may radiate 10^{32} to 10^{33} ergs of energy during its life of 100 seconds.

These, then, are the sources of the solar cosmic rays observed at the earth. Nearly every solar cosmic ray event so far observed can be correlated fairly well with a solar flare, although not all flares produce particles that can be detected near the earth. This last statement is not exactly rigorous, because of the limitatio nof our detection techniques until the advent of the satellite era. The early observations of solar cosmic rays were made by means of ground-based neutron monitors and ion chambers, and the range of detectibility of particles was thus limited to energies above 1 BeV. Ballons flying at the top of the atmosphere reduced this threshold to approximately 80 MeV, and the use of satellite-borne detectors has lowered this limit further to

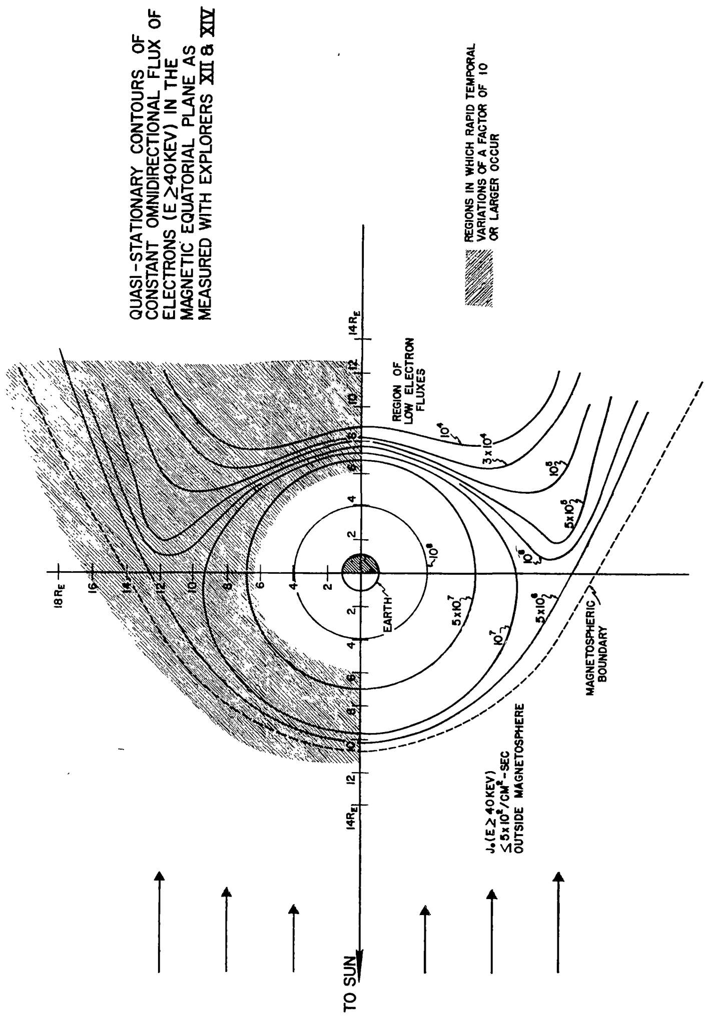

Figure 1. The geomagnetic cavity or "magnetosphere" as measured by Explorer XIV during October-December 1962 and by Explorer XII during August-December 1961. (Courtesy of J. A. Van Allen, L. A. Frank, and E. Macagno.)[6]

approximately 0.1 MeV. It is conceivable then, that there were protons associated with every flare but our instruments were not sensitive enough to detect them.

B. *Energy Spectrum and Intensities.*

The number of protons in a given event varies as a function of energy and sometimes as a function of time. It appears that in general, there are more particles at low energy than there are at high energy, although there are exceptions to this rule. One can frequently represent the number as a function of energy by $N(E>E_o) = K(t)\ E^{-\gamma}$, where values of gamma range from 1 to 6 over various energy intervals. However, it is recognized that the power law spectrum is a convenience at best, and that energy dependence varies from event to event. Recently(7) an exponential rigidity spectrum of the form

$$J = J_o\ e^{-P/Po}$$

(where P is the momentum/unit change)

has been proposed which appears to be rather successful in accounting for many solar proton events, although its usefulness seems to be limited to energies greater than 10 MeV(2) The nuclear composition of the radiation varies from event to event, with typical values of 90% protons, approximately 10% alpha particles, with a fraction of a percent of heavier nuclei.

The intensities of solar cosmic rays vary widely from one event to another. Huge events have been observed with fluxes $> 10^5$ particles/cm^2 sec of energy > 1 MeV. The largest total number of solar protons from a single event was observed during November 12-16, 1960; a total of 2 x 10^9 particles/cm^2 of energy >30 MeV was observed during that period.(8)

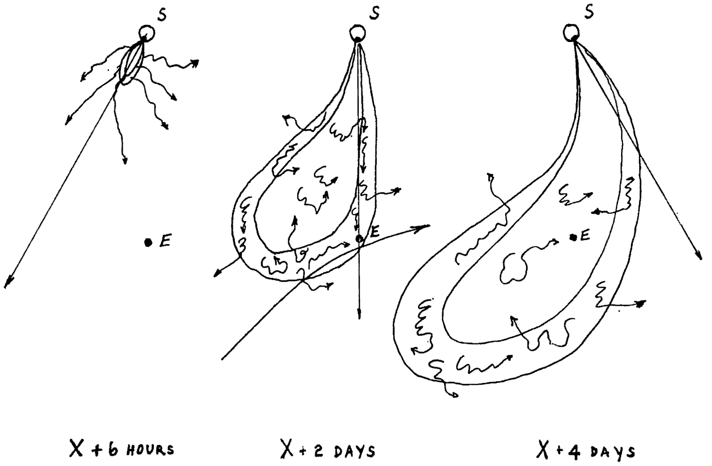

Figure 2. The "magnetic bottle" model proposed by Gold. S stands for "sun" and E stands for "earth." X is the time of the flare onset. The various lines with arrows indicate particle trajectories. Notice how at X + 2 days, primary cosmic rays are deflected away from the earth, bringing about the Forbush decrease (see text). (Courtesy of J. A. Van Allen.)

C. *Propagation and Storage.*

Solar cosmic rays emitted in a particular flare arrive at the earth not directly, following a straight line path, but with delays ranging from minutes to hours and days, depending on the energy of the particles. In fact, the higher energy particles arrive at the earth soon after the beginning of the flare from a direction indicating that they come from the sun. As time passes, however, isotropy is established and particles of all energies arrive at the earth from all directions, although the solar flare has long since disappeared. These observations seem to indicate that the particles are accelerated during a short period of time and are subsequently stored or trapped in interplanetary magnetic fields, to be lost in the course of time from the solar system or arrive at the earth, perhaps through the process of diffusion. This storing and delay in the arrival of the particles can be explained on the basis of the "magnetic bottle" concept proposed by Gold and shown schematically in Figure 2. An alternative explanation is given by Parker's "blast" model.(3) The details of these models are outside the scope of this paper. Both models are consistent with the fact that in times of considerable solar activity, the arrival at the earth of solar cosmic rays from a second flare in the same solar region as a recent preceding flare usually is quicker than the arrival of the rays from the first flare. The field lines are apparently continuous all the way back to the sun and thus form a magnetic path through which later particles can readily propagate.

D. *Effects of solar Cosmic Rays*

So far we have seen how the solar cosmic rays are produced, and have presented the prevailing ideas as to their storage and propagation through interplanetary space. Now we shall examine the effects that are produced as a consequence of the arrival of these particles in the vicinity of the earth. These effects are generally not well understood.

Soon after the appearance of an optical flare on the sun, protons begin to arrive at the polar caps of the earth. By entering the atmosphere, they loose their energy by ionization and hence increase the electron density in the ionosphere. The increase in electron density produces absorption of radio waves that strike the atmosphere, and in particular cosmic radio waves. That is, there is a decrease in the intensity of cosmic radio noise, and this decrease can be used to estimate the number of particles incident on the atmosphere. The phenomenon is commonly know as "Polar Cap Absorption", and has been extensively used to study solar proton events during the last few years.

But the oldest, most spectacular and least understood effect of solar protons is the geomagnetic storm phenomenon. The storm consists of a sudden increase in the value of the horizontal component of the geomagnetic field (sudden commencement), followed by a large decrease (main phase), and a slow recovery (recovery phase) to the previous unperturbed value. The storm begins typically one to two days after the flare on the sun and appears to coincide with the arrival of a low energy plasma cloud from the sun. The details of the interaction of

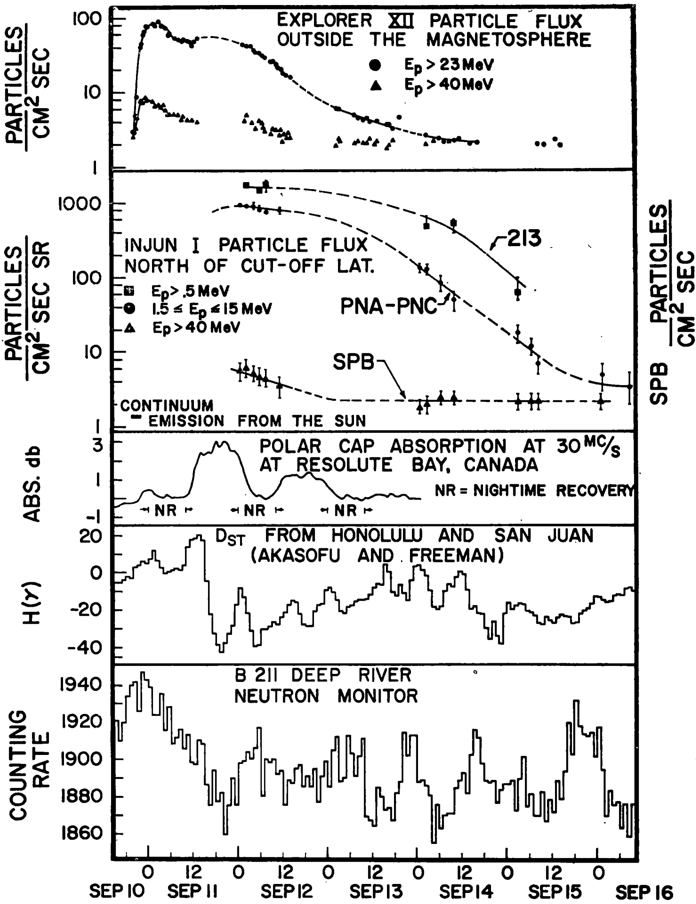

Figure 3. A correlation of essentially all the phenomena involved during a solar cosmic ray event. Increased particle flux, polar cap absorption, a geomagnetic storm, and finally a Forbush decrease are indicated in this figure. Data are taken from the September 10, 1961 event.

this plasma cloud with the earth's magnetic field and the Van Allen radiation belts is one of the most challenging and least understood problems in geophysics today. In principle, the main phase decrease in the field could be explained by a westward ring current which would produce a magnetic field in opposition to that of the earth. But how is this current produced? Is it formed by the particles in the solar plasma cloud or is there some mechanism inside the earth's magnetosphere which accelerates particles and injects them into the radiation belts to form a ring current? Answers to these and many other important questions cannot be given at the present time because of inadequacies in both theory and experiment. It is hoped that more sophisticated experiments and better understand-

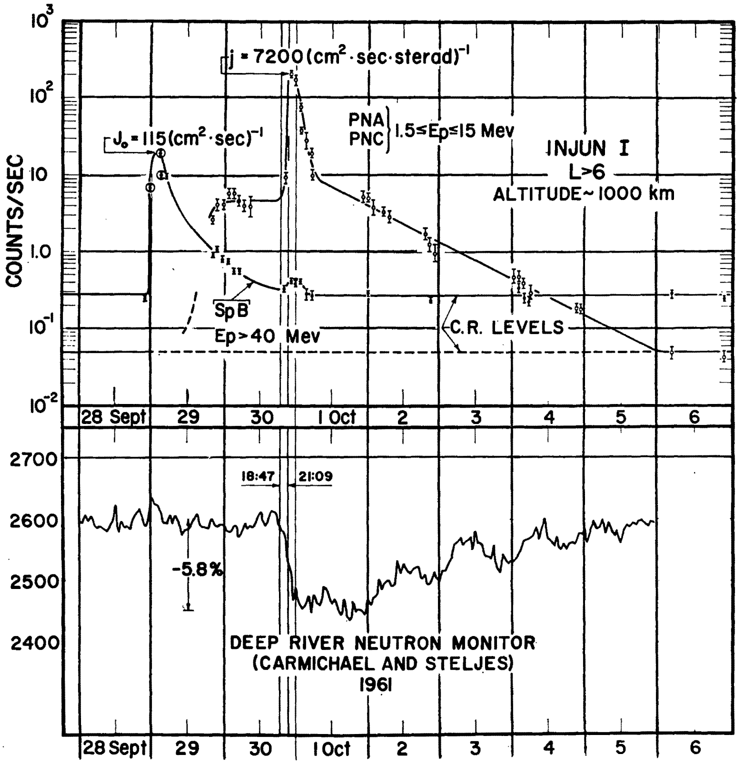

Figure 4. The arrival of the so called "plasma cloud" of low energy protons is explicitly associated with the Forbush decrease shown in the lower part of the figure. The data are taken from the September 28, 1961 solar proton event. (Courtesy of J. A. Van Allen.)

ing of the new science of magneto-hydrodynamics will finally illuminate the underlying mechanisms of the geomagnetic storm.

Another phenomenon associated with solar cosmic rays is the reduction in intensity of galactic cosmic rays, known as Forbush decrease. The decrease is usually explainable on the basis of the deflection of primary cosmic radiation by the enhanced interplanetary magnetic field which envelops the earth for a few days after a solar flare.

The phenomena described above are shown in the following figures. Figure 3 shows very clearly the correlation between the particle flux in the vicinity of the earth and the associated PCA, geomagnetic storm and Forbush decreases. Figure 4 shows the explicit association of the Forbush decrease with the increase in the intensity of low energy protons. Figure 5 shows the appearance of the solar flare and the subsequent increase in the counting rates of satellite and ballon detectors; the associated PCA is also shown.

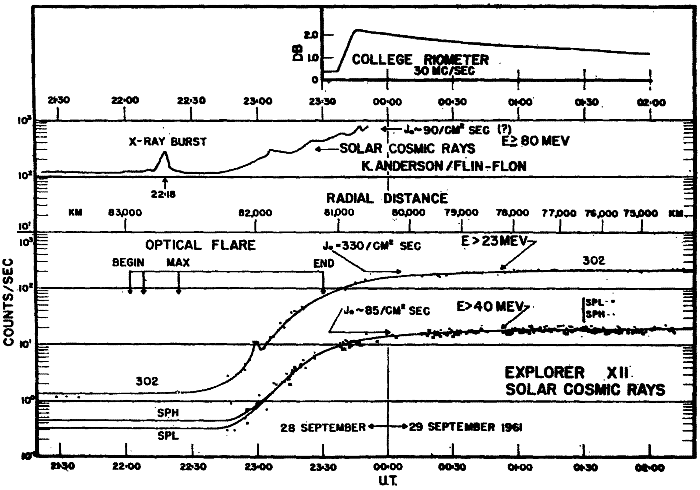

Figure 5. Here the time-sequence of the optical solar flare, x-ray burst, and subsequent increase in the counting rates of balloon and satellite born detectors is shown. The correlation with the solar cap absorption is evident. Data are taken from the September 28, 1961 solar cosmic ray event. (Courtesy of J. A. Van Allen.)

Finally a word should be said about the threat that solar cosmic rays may pose to manned space travel. For an answer we quote a passage from the "Review of Space Research" published by the National Academy of Sciences:[4] "It has been suggested that a thoughtful distribution of the payload necessary for sustenance of manned space flight can provide about 10 gm/cm^2 shielding without *ad hoc* additional shielding. With 10 gm/cm^2 protection the space traveler would have received 20 rads of exposure in the largest solar cosmic ray event yet observed. A dose of 20 to 60 rads is almost certainly not an unreasonable amount for an astronaut to risk, and it would apparently have been experienced only once during the last ten years".

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