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Cosmic-ray Electrons

H.C.van de Hulst

(The George Darwin Lecture delivered on 1970 November 13)*

THEME

On 5 March 1960 the newly-created Netherlands Committee for Geophysics and Space Research held its first meeting. The wave of excitement caused by the launching of the first sputnik had not yet subsided. The group which met was a continuation of our national committee for the geophysical year, but with new membership and with an added assignment: to see what our country could do in space science.

By the end of the same year we had defined a number of projects. One of these was to detect and measure cosmic-ray electrons. I shall not relate the early phases of this project, in which (in order of appearance) Jongen, Peters, Oort, Woltjer, Tanaka and Wapstra played important roles. In December 1964 a contract was signed to spend a substantial sum on building a satellite instrument for this purpose. This instrument went into orbit with the American satellite OGO 5 in March 1968, and is transmitting useful data until today. Its operating time has now been more than 2½ years; the design lifetime was a year.

In this lecture I plan to tell you something about these cosmic-ray electrons, to explain the reasons why in 1960 we selected this topic, and to check after a 10-year span whether this choice was a happy one. Let me add that I participated in the discussions from the beginning and took my part of the responsibility for the decisions, but that I am not reporting my own research work. The very scholarly and complete article by Daniel & Stephens (1970) on cosmic-ray electrons, which appeared earlier this year in *Space Science Reviews*, contains 208 references but none under my name.

HISTORICAL SETTING

The story starts with Fig. 1, which reproduces the only graph in what is probably the first theoretical paper on galactic radio waves that ever appeared (Henyey & Keenan 1940). The predicted spectrum was a free-free spectrum which was optically thin, and therefore about

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*In some parts the text has been amended by the inclusion of new material. However, no attempt has been made at a complete literature review.

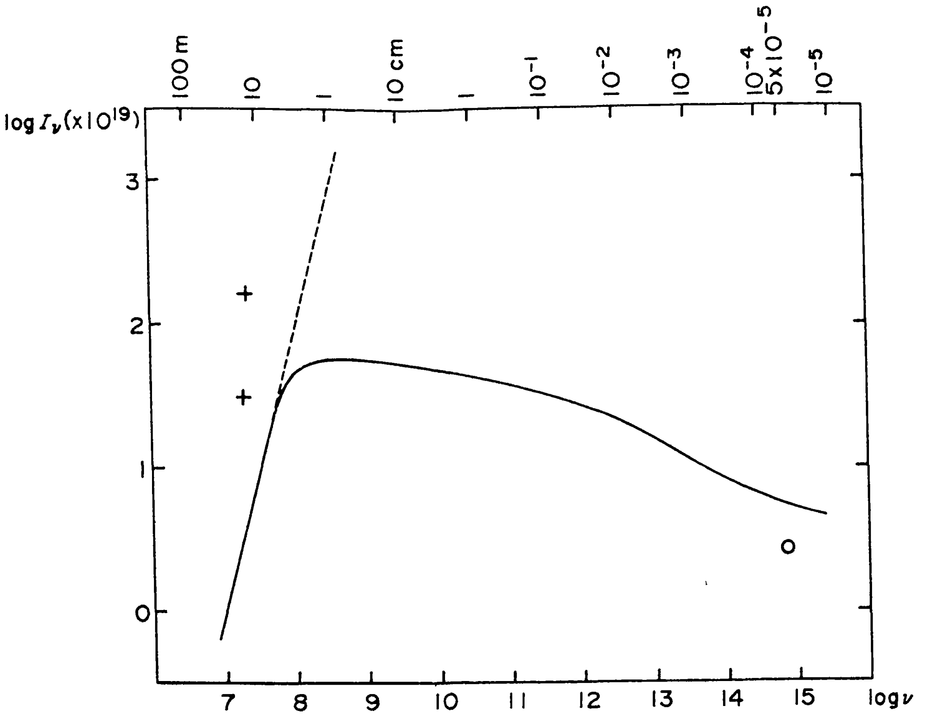


FIG. 1. The first attempt to explain the galactic radio spectrum showing that an exclusively thermal explanation does not fit the observations (Henyey & Keenan 1940).

flat, for wavelengths below 3 m. At longer wavelengths a blackbody spectrum (slope +2 in this graph) at the gas temperature of 10 000° was expected. The trouble was that Reber's measurement fitted the curve well, but Jansky's at very long wavelengths would require a 10 to 100 times hotter gas, which seemed excluded. There the question remained, and I remember from the conversations preceding the Reber–Greenstein (1947) review that there was no essential change: Jansky's points did not fit; Reber could not see what might be wrong with their calibration; but one man's work did not seem enough to get really alarmed, so the theory of thermal origin held its place.

Soon after this, it fell down completely. More measurements at low frequencies confirmed the high brightness. Point sources were discovered and identified. Their brightness temperatures were a good deal higher still and, generally, the source spectra appeared to slope 'the wrong way'. Fig. 2, which is an updated version (1971) of a slide prepared for an early summer school (Van de Hulst 1959), may serve to illustrate this point. The Sun, Moon and planets approach the blackbody slope +2. The Orion nebula resembles a thermal source, saturated at low frequencies. But all other bright sources run down with slopes of −0·5 to −1, unlike anything that had been predicted.

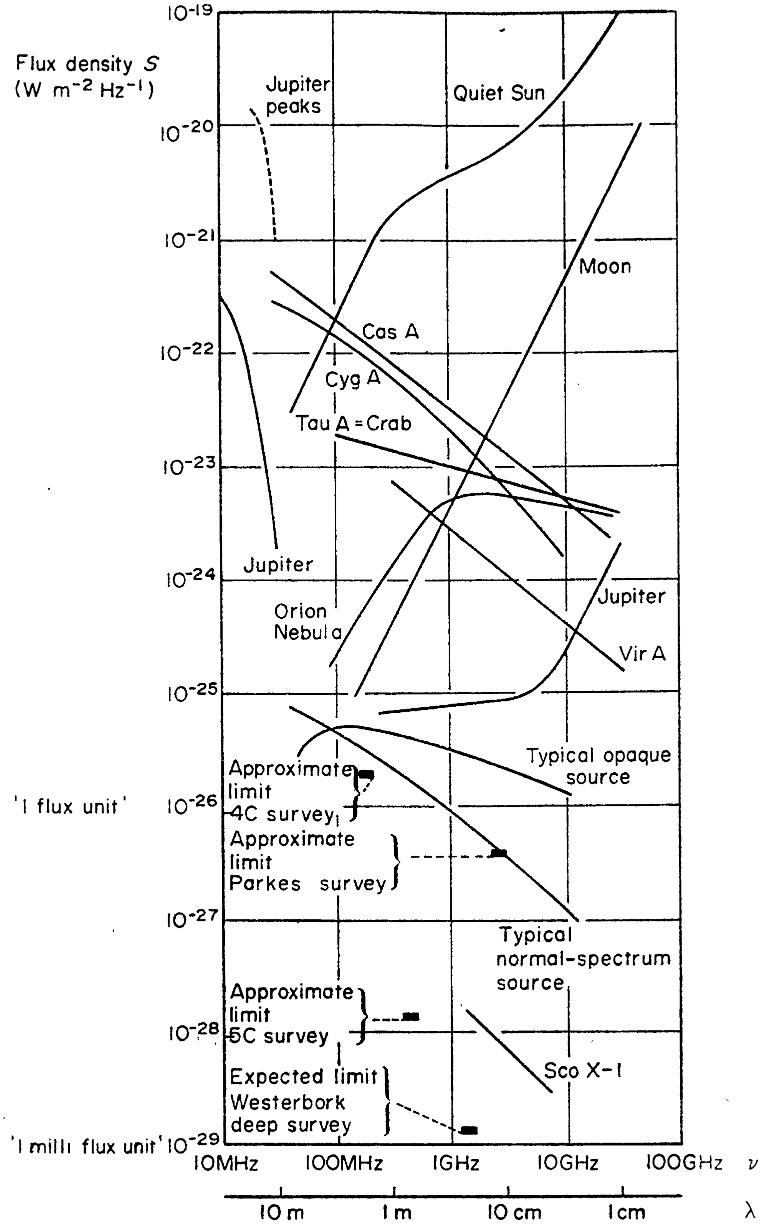


FIG. 2. A survey of the spectra of the brightest radio sources in the sky.

Please note that this figure contains no arbitrary shifts: the Sun at metre wavelengths really *is* weaker than several other sources in the sky, one of which is 500 million lightyears away. This dramatically showed that radio astronomy had stumbled on something entirely different from the gently burning stars of classical astrophysics.

An independent start of my story, even older, and equally unexpected, was the discovery of cosmic rays around 1911. The name 'cosmic radiation' which was soon given to this puzzling phenomenon, was a double confession of ignorance. 'Cosmic' meant: 'coming from outside the Earth, but we don't know from where'. 'Radiation' or 'rays' meant: 'something propagating, but we don't know what'. In spite of the obvious cosmic interest, this subject was long left to the physicists; the astronomers hardly reacted. Eddington (1926) shows broad vision in describing the 'diffuse matter in space' in the last chapter of his famous book, but he forgets the cosmic rays.

The change came in 1948–1949 with many events. Among these, Fermi's proposal for an acceleration mechanism of cosmic-rays in interstellar space is perhaps best known. About the same time it was first clearly recognized that cosmic rays had a similar energy density to the stellar radiation field and the random motions of the Galaxy; the interstellar polarization (and thereby the magnetic field) was discovered; and the first more than passing discussions of interstellar gas dynamics were held.

The recognition that radio astronomy and cosmic rays, two quite different things and at opposite extremes of the energy spectrum, should have an intimate relation, dates also from that time. The saying that the extremes touch is not necessarily true in science, unless we can see how. Ryle (still in 1949) made a suggestion. He refers to the brightness temperature of the recently discovered discrete sources of radio waves and continues as follows:

> 'It is possible that some special radiating process might be responsible for the emission of radiation having an intensity greater than that corresponding to the electron temperature; in the absence of such a process, the radiation can only be accounted for by assuming that the electrons have a random energy corresponding to the thermal energy at a temperature of 10^{14} deg.K. (the mean energy of an electron is then about 10^{10} eV). The maintenance of this electron energy implies the existence of mechanisms capable of accelerating particles to cosmic ray energies. It is therefore suggested that the sources of intense radio-frequency radiation may also be responsible for the emission of cosmic-rays.'

Neither the grounds, nor the conclusions of this argument turned out to be exactly right, but the link was established. Fortunately, I do not have to write a history book. I know too well that almost any new idea in science has complex roots and that the important events outside the published papers are hard to retrieve. A definite explanation of the non-thermal radio emission soon appeared: the synchrotron radiation by cosmic-ray electrons. First, it was just suggested, then defended with force, and at last generally accepted. I was personally won over in 1955 when the polarization of the white light of the Crab nebula, predicted by Shklovsky, was so beautifully confirmed by experiment.

MAIN RESULTS

It should not surprise you, after listening to this bit of history, that the committee 10 years ago took the attitude: 'We have been looking at these electrons so long through their synchrotron emission. Now that the chance comes to catch them directly, let's do so.' A strong point was also made of the fact that various estimates of the strength of the magnetic field yielded a number of electrons that could not be far below the then observed upper limit of 1 or 2 electrons per 100 protons. The now established electron content of the cosmic rays is indeed 2 per cent.

The case has now been stated, and just what have we learned? First, our group was by no means the only one in the world to select cosmic-ray electrons as a research subject. A variety of techniques has been employed and a wide range of energy has been covered. A full summary would already require a long explanation. Instead, we have made a

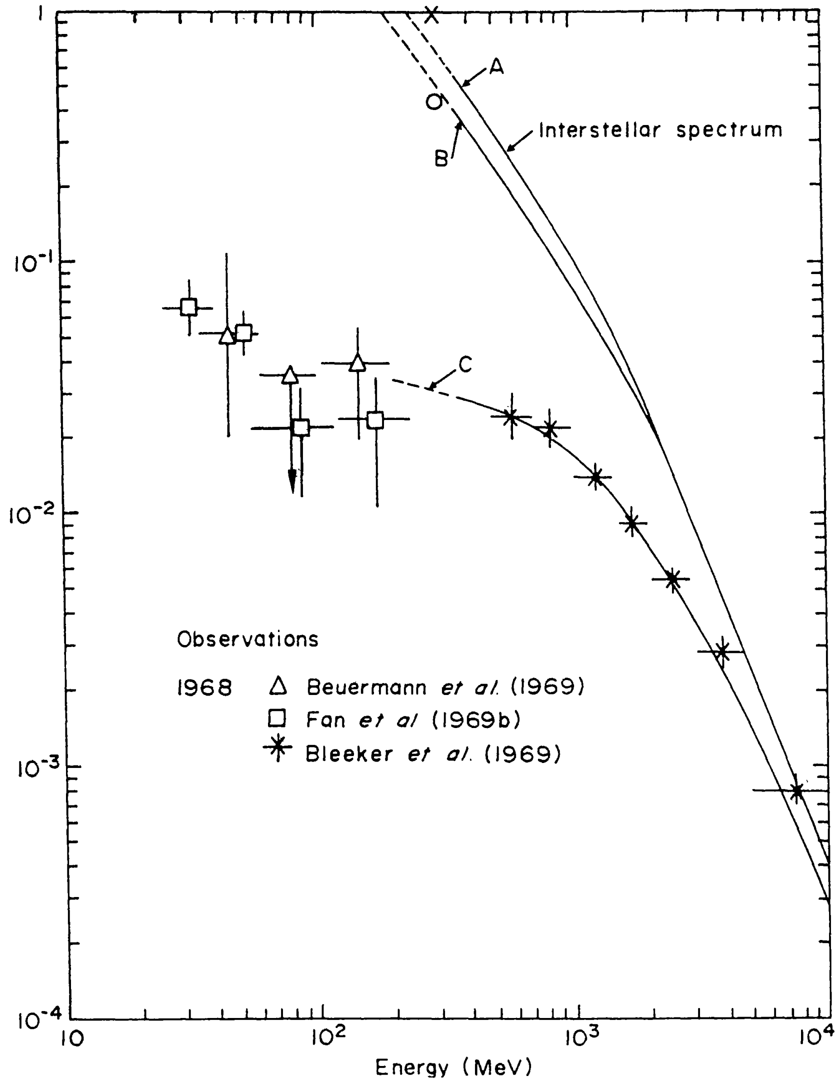


FIG. 3. The near-Earth spectrum of cosmic-ray electrons in 1968 compared with the interstellar spectrum derived from radio astronomy (Burger 1971).

selection in Fig. 3: all measurements shown there refer to the year 1968, below 200 MeV only the most reliable measurements (Beuermann *et al.* 1969; Fan, l'Heureux & Meyer 1969) and above 500 MeV (= 0·5 GeV) only those of our group (Bleeker *et al.* 1970). The abscissa is the electron energy; since the range of values is well above the rest energy of 0·51 MeV, it makes no difference whether we mean kinetic or total energy. There is a clear knee (or bend) in the spectrum near 1 GeV.

The restriction to one year, or a set of years, is wise because of the solar modulation to which I shall return later. The measurements in the course of the years unmistakably show that the solar wind managed to keep the electrons away from us more effectively during 1968 and the following years of solar maximum than during the solar minimum in 1966.

INSTRUMENTS

On the point of the instruments I certainly have no competence, so I shall be sketchy. In principle you take a collection of counters sensitive in various degrees to electrons, protons, γ-quanta and their secondary products. You then select such a combination of the outputs from these counters that you isolate as well as possible the events associated with an incoming particle of a certain kind, say, an electron. The design has to aim at good isolation *and* at good efficiency, but only tests on various particles in accelerator beams will show how successful the design was. All of this has to be done for a wide range of energies and for different lines of incidence (vary direction and position!).

A diagram of the detector used in our satellite experiment (Swanenburg 1971) is shown in Fig. 4. It consists of five separate counters. We decided to read out the pulse heights by which all counters respond to an event; this provided many useful checks on the internal consistency of the results. Incidentally, the outer counter is the so-called guard- or veto-counter. Its signals are lead to a gate in the electronics box which for today's meeting has been adorned with the device: *quicquid nitet non notandum.*

A similar detector, heavier, simpler, and cheaper, was flown several times from a balloon. Here we had a pleasant, but somewhat embarrassing, surprise: we did not need a satellite to detect the electrons. The reason was that the balloons went a lot higher than was first considered possible. Also, the electrons could be isolated in a cleaner fashion than expected. This balloon experiment was repeated during successive years so as to follow the cycle of solar activity. Yet the satellite experiment has not lost its purpose. It is superior in the total time of observation, and in the fact that discrimination against the background is eased as the satellite moves in an eccentric orbit.

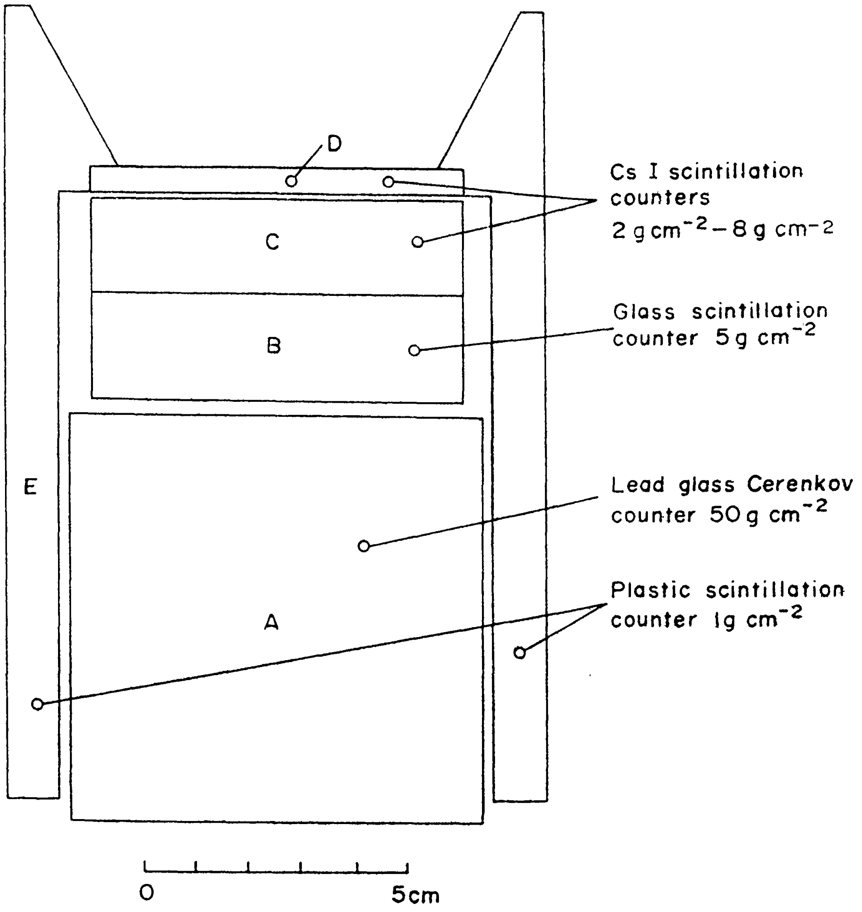


FIG. 4. Diagram of the electron detector of the Leiden experiment carried on OGO V (Swanenburg 1971).

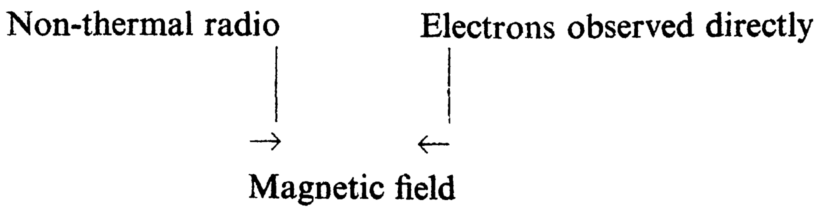
Other surprises were very *un*pleasant. During one attempted balloon launch of yet another, extra large detector, which was constructed to measure the high-energy end of the spectrum, the instrument reached 40 m instead of 40 km altitude, and came down as if Galilei had dropped it from the tower of Pisa. Fortunately, the damage could be repaired, and the thesis based on measurements made with this instrument in two later flights has appeared (Scheepmaker 1971).

MODULATION

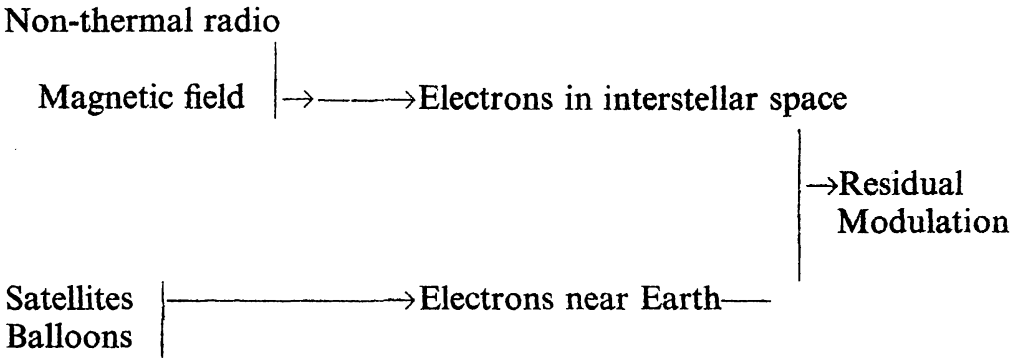
The fact that different numbers of cosmic-ray electrons are picked up near the Earth as the years proceed, clearly means that we have *not* reached our initial aim: to measure the actual density of such electrons in interstellar space. A 'modulation' exists and a 'residual modulation' may still persist at solar minimum when the influence of the Sun is smallest.

This fact forces us to rearrange the problem. The following diagrams contrast the solution we originally had in mind (old) with the way it is stated now (new, Burger 1971).

OLD



NEW



It is obvious that the 'old' problem would have been overdetermined because one spectrum would have to be matched to another spectrum by adjusting only one number. The 'new' problem seems underdetermined: it derives a spectrum from a spectrum, but it also claims to yield the magnetic field value. This sounds fishy, because a smaller field could, for instance, be compensated by putting in more electrons. Fortunately, this is not entirely true. First, we can lean on the 'old' solution at energies >3 GeV, where the modulation must be small. Secondly, the 'knee' in the electron spectrum causes a 'bend' in the radio spectrum, and the position of this bend fixes the magnetic field. Different authors have shown that a fine fit to the observed radio spectrum may be obtained.

Another uncertainty arises. We wish to derive the volume emissivity from the observed radio brightness, but we do not know exactly how to distribute the observed emission along the line of sight. As in so many other astronomical problems, having to guess at distances tends to spoil the accuracy! Fortunately, there is again a way out. It is possible to find ionized hydrogen regions, about 2 kpc away, that act as opaque screens whose distances are known from the associated stars (Bridle 1968). The average volume emissivity in front of those screens is still affected by uncertainties in the observation and calibration, but upon fitting a synchrotron spectrum more of the uncertainty goes into the magnetic field than into the interstellar electron spectrum. Therefore, the estimates A and B in Fig. 3 are not far apart.

Fig. 3 brings the interstellar electron spectrum (A or B) and the near-Earth spectrum (C) together. The vertical difference is the residual modulation. Burger (1971), from whose thesis this illustration is taken, goes on to show that the change in modulation from 1966 to 1968 has a different dependence on rigidity from the total (residual) modulation in 1966. The rigidity dependence observed with the same instrument in a Forbush decrease is again different (Baixeras 1971). These differences lead to interesting conclusions about the modulation process itself, which I must skip.

LOW-ENERGY PROTONS

The knowledge thus gained adds a clue to solving an entirely different problem. It has been known since the early studies by Spitzer that the cool regions of the interstellar gas live on a very meagre energy budget. Every tiny bit of earning helps and, among possible sources of some heating, sub-cosmic-rays or suprathermal particles may be important. Protons with energies near 10 MeV would be the strongest contributors, they are now usually called low-energy cosmic rays (LECR). It was also found that the ionization in these regions and, therefore, their electron density strongly depends on the LECR, with the soft X-rays as a close competitor (see Habing & Goldsmith 1971). The interesting consequences for the observable infra-red spectrum have been discussed by Pottasch (1968). Another observable consequence is the dispersion of pulsar signals.

All of this makes it desirable to find out more about the LECR. But how can we know how many such protons are present? In order to observe them at all, we need a space vehicle to take the instruments far enough outside the Earth's magnetic field (Meyer 1969). But even then, we do not know the true interstellar density unless we can get rid of the modulation. Sending the instruments by space ship beyond the Jupiter orbit is not so easy. Next Monday (1970 November 17) a 'preproposal briefing meeting' is held at Washington about the first 'grand tour', which has not, however, been authorized yet. Another 10 or 15 years (of preparation and flight time together) will elapse before a modulation experiment on this mission, if included, will give us the experimental answer to our question. So we have ample time to let the theorists have their say.

They claim that in the range of energies of interest to us the 'grip' of the solar wind on all cosmic rays is through the Lorentz force only. The irregular magnetic fields carried along by the solar wind try to