Cosmic-Ray Effects from Solar Flares and Magnetic Storms

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Cosmic-ray data taken during the period of a solar flare and the magnetic storm that followed 26.5 hours later during July, 1946, are reported. The results following the flare agree with those of other investigators and, in addition, serve to establish the fact that the start of the cosmic-ray effect and the visual part of the solar flare were simultaneous. It is pointed out that increases of cosmic rays during solar flares suggest a mode of origin of the rays. The lack of effect of most solar flares on cosmic-ray intensity is noted and differences in intensity of the flares given as a possible reason. A high altitude balloon flight with an electroscope during the magnetic storm gave results in agreement with the current-sheet hypothesis of such storms but a serious objection to this hypothesis is given.

FORBUSH[1] has reported a sudden increase in cosmic-ray intensity following a solar flare on July 25, 1946. He had noted a similar effect in 1942. His previous observation had been confirmed by Duperier.[2] This last increase was also observed in England by Dolbear and Elliott.[3] During the period of this phenomenon we had an unshielded self-recording electroscope in operation at the Mount Wilson Observatory. The results from this instrument agree with those noted above and were briefly as follows: On July 25, 1946, after an intense flare over a spot on the sun, the cosmic-ray intensity increased about 18 percent. The prominent part of the increase was over in about ten hours. However, the intensity was still 1 or 2 percent above normal when a sudden large magnetic storm began 26.5 hours after the start of the flare. At this time there was a decrease in intensity of the type usually noted during magnetic storms.[4]

No increase in cosmic rays was reported by Forbush for the flares of either 1942 or 1946 at the equator. This suggests that, as Forbush has pointed out, the cosmic-ray increase was due to charged particles emitted by the sun and that their maximum energy was not sufficient to permit them to reach the earth at the magnetic equator but did permit them not only to come in at a magnetic latitude of 40° but also to penetrate the earth's atmosphere to sea level. The energies of at least some of these particles then seems to be less than 10 Bev but greater than 6 Bev.

One objection raised to the assumption that particles of these energies were actually emitted by the sun at this time is that the cosmic-ray "flare" did not occur simultaneously with the visual flare as one might expect for particles of these energies. The published data seem to indicate such a difference in times. This particular difficulty may possibly be removed by the following result. Our instrument gave readings every fifteen minutes; when hourly readings, corrected for barometric variations, are plotted against the time, it is seen that the cosmic-ray increase began at about the same time as the flare. Figure 1 shows the percentage increase in cosmic-ray intensity during this period. Plotted also is an optical observation of the flare, the relative change in the line width of the alpha-line in the Balmer series of hydrogen, as observed in the flare by M. A. Ellison[5] in Great Britain. These two results strongly suggest that the visual flare and the cosmic-ray "flare" began simultaneously. They reached their respective maximums, however, 2.2 hours apart. It is interesting to note that both the rise and fall of the cosmic-ray effect was exponential, as shown in Fig. 2.

[1] S. E. Forbush, Phys. Rev. **70**, 771 (1946).
[2] A. Duperier, Proc. Phys. Soc. **57**, 473 (1945).
[3] D. W. N. Dolbear and H. Elliott, Nature **159**, 58 (1947).
[4] T. H. Johnson, Rev. Mod. Phys. **10**, 193 (1938).
[5] M. A. Ellison, Nature **158**, 450 (1946).

According to the observations at Mount Wilson[6] solar flares occur at rates of from 2 to 10 per hundred hours. The majority of such flares would seem to be ineffective as regards cosmic rays or the effect would have been observed oftener. For example, a flare was observed July 21, 1946, four days before the one under discussion with no appreciable influence on cosmic rays. It is possible that the effective ones are characterized by unusually great intensity. Ellison[5] reports that this flare showed characteristics such as enhancement of the continuous spectrum which suggest unusually great intensity. Johnson and Korff[7] have reported a balloon flight with a Geiger counter during which a flare took place with no observable effect. This might be explained in two ways: (a) the flare may not have been an effective one, or (b) the flare may have occurred at such a time that its effect had not become noticeable during the time of the flight.

The fact that our sun appears to give off electrically charged particles at rare intervals having energies lying in the cosmic-ray region suggests a possible mode of origin of cosmic rays. It is at once apparent, however, that due to the infrequent occasions when our sun has given rise to such particles, that it cannot be a representative star if all cosmic rays have their origins in such flares. This is due to the fact that the total energy in visible star light is about the same as the total energy in cosmic rays[8] and our sun emits far more energy in visible light than it does energy in the cosmic-ray region.

For charged particles to leave the sun, particularly near its equator where a general magnetic field of the sun would make escape most difficult, some mechanism such as that suggested by Vallarta[9] would need to be invoked.

It should be pointed out that no decrease in the general magnetic fields either of the sun or the earth seem to explain this sudden increase in cosmic-ray intensity. Any decrease in the sun's field would affect only those particles having energies below about 2 Bev and these do not send their effects down to sea level. Any decrease in the earth's magnetic field would affect the equatorial regions at sea level but should not be felt at sea level farther north or south than about 40° geomagnetic latitude (see below). Any increase in the magnetic fields of either body could only decrease the cosmic-ray intensity. Magnetic records showed no unusual changes of the earth's magnetic field at the time of the flare.

The fact that no particular direction in space, in particular the direction of the Milky Way, appears to be a preferred direction for the incoming cosmic rays would not seem to be an objection to a theory of stellar origin because it has recently been discovered[10] that many stars possess large magnetic fields. It would be expected then that cosmic rays originating at a particular point would be rendered practically isotropic after passing through a number of stellar fields.

The magnetic storm following the flare by 26.5 hours and its effect on cosmic rays was of the kind usually noted. The ratio $H\Delta I/I\Delta H$ was about 10 which is of the order of magnitude observed in other storms. While the cosmic-ray intensity was at its lowest during this storm, a high altitude balloon flight with an electroscope was made near Fort Worth, Texas. The ionization was lower than that observed during previous and following flights. The peak of the curve was about 18 percent below that of the average for the flights made at Fort Worth during the

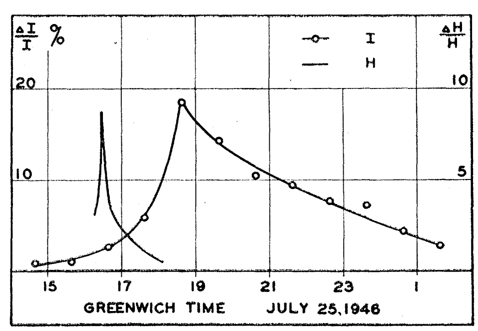

FIG. 1. Curves of (I) hourly readings of the percent increase of the cosmic-ray intensity above its pre-flare average; (H) the relative increase in the width of the H_α line above its normal value (Ellison[5]).

[6] Elizabeth Sternberg Mulders, Astro. Soc. Pac. **59**, 16 (1947).

[7] S. A. Korff, Rev. Mod. Phys. **11**, 211 (1939).

[8] I. S. Bowen, R. A. Millikan, and H. V. Neher, Phys. Rev. **44**, 246 (1933).

[9] M. S. Vallarta and O. Godart, Rev. Mod. Phys. **11**, 180 (1939).

[10] H. W. Babcock, Phys. Rev. **72**, 83 (1947).

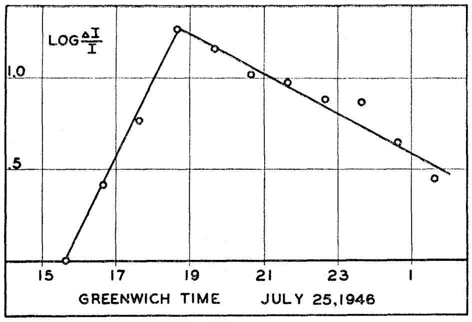

FIG. 2. Logarithm of the percent increase of cosmic-ray intensity above its pre-flare average.

summer of 1946. At the same time, the electroscope at Mount Wilson read 5 to 6 percent below normal. This should be comparable to the ground level reading at Fort Worth, as the two differ but slightly in magnetic latitude. The curve of ionization *vs.* depth below the top of the atmosphere was very similar to the one ordinarily obtained at San Antonio, 3.2° (magnetic) further south; it is not included here because the barometer data are not reliable. This is just the sort of thing predicted by any theory which treats magnetic storms as a weakening of the effective dipole moment of the earth.

Objections based on cosmic-ray phenomena have already been raised to theories such as the current-sheet theory which results in the weakening of the earth's dipole.[4] We should like to point out another objection. Changes in the dipole moment will shift the latitude of entry of a given energy particle either north or south. If one considers the sea level latitude effect, it is evident that the edge of the plateau usually found near 40° (magnetic) will shift either north or south, but unless this shifting is tremendous no change in sea level intensity should be felt in the high latitudes. However, there are reports of changes in cosmic rays as far north as 75° during storms[7] while the facts just reported (which ought to be quite typical) indicate that the latitude shifts would be only a few degrees.

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