World-Wide Effects of Continuous Emission of Cosmic Rays from the Sun

V. SARABHAI AND R. P. KANE
Physical Research Laboratory, Ahmedabad, India
(Received November 17, 1952)

The Carnegie Institution barometric pressure-corrected, cosmic-ray, meson intensity data for solar time daily variation at Huancayo, Cheltenham, and Christchurch have been harmonically analyzed. Time-series covering the period 1937 to 1946 have been derived for variations of the amplitude and hour of maximum of the meson diurnal variation. These reveal that the amplitude and hour of maximum undergo large long-term world-wide changes. The time-series for mean of the diurnal amplitude observed at the three stations has high positive partial correlations with relative sunspot number and American magnetic character figure. The correlations are higher during years of low sunspot activity.

The new evidence confirms earlier experimental findings of the authors indicating that the barometric pressure-corrected, meson intensity, diurnal variation is caused by an anisotropy of the primary cosmic rays connected with the emission of high energy charged particles from the sun. In addition, it reveals that the sun is a continuous source of cosmic radiation, the activity of emission varying broadly in step with the solar cycle.

I. INTRODUCTION

SEVERAL attempts have been made in the past to establish a connection between solar phenomena and cosmic-ray intensity. Few instances of world-wide cosmic-ray effects of a transient nature associated with intense solar flares have been reported. Simpson *et al.*[1] have suggested a connection between active solar regions and 19 maxima of neutron intensity distributed over a period of 3 months and observed simultaneously at three widely separated stations. Very recently, Neher and Forbush[2] have pointed out that correlations exist between cosmic-ray intensity at both high and low altitudes and the above neutron measurements. However, it has not been possible so far to establish any significant direct effect of a continuous nature. Hogg,[3] who has examined this point with ionization chamber data, has concluded that "there is a possible but not very likely connection" between monthly averages of sunspot numbers and the cosmic-ray intensity corrected for pressure and temperature. He has further stated that what relationship does exist between cosmic rays and solar phenomena could be attributed to changes in the earth's magnetic field brought about by solar effects.

The mean daily or monthly cosmic-ray intensity which has generally been considered for the study of solar relationships is known to be affected by complex meteorological and geomagnetic factors. There is particularly great difficulty in the elimination of terrestrial influences, owing to incomplete meteorological data available for the higher levels of the atmosphere and to our imperfect understanding of the magnetic storm-time variation of cosmic-ray intensity. It is not surprising, therefore, that a relationship between mean daily or monthly cosmic-ray intensity and solar activity has proved elusive.

Sarabhai *et al.*[4] have earlier communicated experimental results obtained in Ahmedabad and at the mountain station of Kodaikanal, concerning the solar-time daily variation of meson intensity. They have examined the contribution of terrestrial influences to this variation and have been led to the view that, after correcting it for barometric pressure, the residual variation is mainly due to an anisotropy of the primaries. Since the diurnal variation at different parts of the earth has approximately similar phase, with a maximum occurring near noon local time, they have concluded that the anisotropy is caused by the emission of cosmic-ray particles from the sun. The pressure-corrected diurnal variation of mesons is, therefore, a sensitive index of continuous solar activity for the emission of cosmic rays, and we should expect changes in it of a world-wide character associated with the sun, just as in ionospheric and geomagnetic phenomena. We shall deal here with new evidence which demonstrates world-wide changes of amplitude and the hour of maximum of the diurnal variation. The relationship of these changes with solar phenomena is also discussed.

II. WORLD-WIDE CHANGES IN THE DAILY VARIATION OF MESON INTENSITY

We have examined the Carnegie Institution cosmic-ray data for meson intensity at Huancayo (H), Cheltenham (C) and Christchurch (C') for the years 1937 to 1946, as furnished by Lange and Forbush.[5] Bi-monthly mean bi-hourly values of percentage deviations from mean of pressure-corrected, cosmic-ray intensity at each station were harmonically analyzed for the diurnal variation. Adopting the notation used in harmonic dial representation, the diurnal harmonic component can be specified in terms of the percentage amplitude M^D and the hour of maximum ϕ^D expressed as an angle measured in the clockwise direction from midnight local time. Thus, for Huancayo, we had sixty values each for the amplitude $M_H{}^D$ and the hour of maximum

[1] Simpson, Fonger, and Wilcox, Phys. Rev. 85, 366 (1952).
[2] H. V. Neher and S. E. Forbush, Phys. Rev. 87, 889 (1952).
[3] A. R. Hogg, J. Atmos. Terr. Phys. 1, 56 (1951).
[4] Sarabhai, Desai, and Kane, Nature 171, 122 (1953).
[5] I. Lange and S. E. Forbush, Carnegie Institution of Washington Publications, No. 175 (1948).

$\phi_H{}^D$. Similar sets of values were obtained from the other stations. In order to eliminate the seasonal effect, moving averages of six consecutive bi-monthly values of M^D and ϕ^D were taken. We thus obtained values of M^D and ϕ^D for annual mean diurnal variation centered at 55 successive bimonthly epochs. Further moving averages over three successive annual mean values were taken to smooth the data.

The time-series for each station for M^D and ϕ^D are plotted with coinciding mean values in Figs. 1 (a) and 1 (b) respectively. Figure 1 (c) shows the series for Zürich sunspot number R and Fig. 1 (d) for the American magnetic character figure C_A. Both these time-series were derived from the original bimonthly values in the same manner as described above for M^D and ϕ^D.

The most remarkable feature shown by Figs. 1 (a) and 1 (b) is that the amplitude and the hour of maximum of the diurnal variation do not remain constant through the years but undergo long-term changes of 30 to 40 percent which are world-wide in character. With the time-series for the mean amplitude $M_T{}^D=(M_H{}^D+M_C{}^D+M_{C'}{}^D)/3$, which has been drawn in the figure as a continuous line, the variations of amplitude at the individual stations have high positive correlations exceeding $+0.85$. Similarly, the mean hour of maximum $\phi_T{}^D$ is highly correlated with the values at the individual stations. The time-series for $M_T{}^D$ and $\phi_T{}^D$ represent therefore, world-wide variations of amplitude and hour of maximum of the diurnal variation.

An examination of Fig. 1 (a) reveals that during the period 1937 to 1940 (designated as Group I) which corresponds to the years when the sunspot number R is above its mean value for the 10 years, the variation of the meson diurnal amplitude at Huancayo differs substantially from the variation of the diurnal amplitude at Cheltenham or at Christchurch. It appears, therefore, that during the period of high sunspot activity, the mountain station of Huancayo is affected by anisotropic low energy, cosmic-ray particles which cannot make their effect felt at sea level. For the years 1941 to 1946 in Group II corresponding to low sunspot activity, there is no significant difference between the variations of the diurnal amplitude observed at different stations.

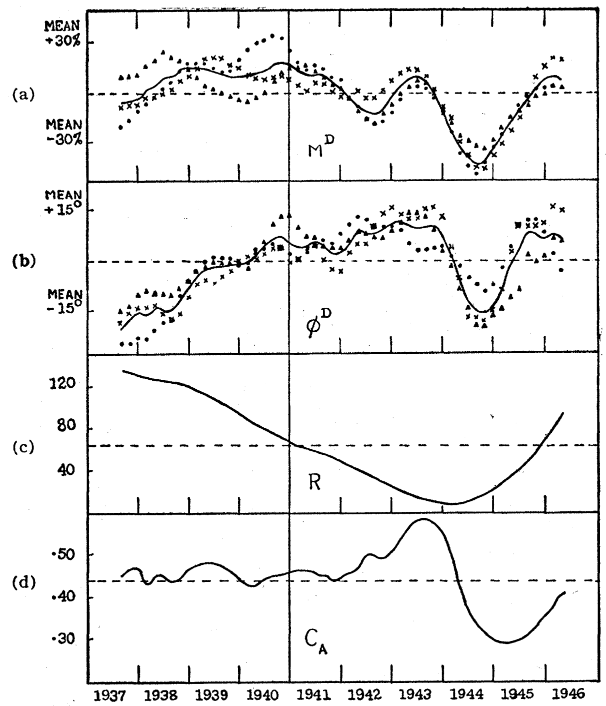

FIG. 1. Time-series for annual mean values during period 1937–1946 of (a) M^D meson diurnal amplitude; (b) ϕ^D meson diurnal hour of maximum; (c) R Zürich sunspot number; (d) C_A American magnetic character figure. The results from individual stations are indicated by ▲ for Huancayo, × for Cheltenham, and ● for Christchurch.

III. THE AMPLITUDE AND THE HOUR OF MAXIMUM OF THE DIURNAL VARIATION

The hour of maximum of the meson diurnal variation would depend on the deflection of the charged primaries from the sun in the geomagnetic field. Hence, the long-term, world-wide variations of ϕ^D may be attributed to changes in the energy spectrum or in the ratio of positive to negative particles of the radiation which causes the anisotropy.

An interesting relationship exists between the world-wide changes of amplitude and the hour of maximum of the meson diurnal variation. For Group II, corresponding to low sunspot activity, the correlation between the two is $+0.87$. This means that an increase of amplitude is associated with a shifting of the maximum to later hours. This can arise for positive primary particles if an increase of amplitude is accompanied by a shift of the energy spectrum towards higher energies. For negative primary particles, it may arise from an increase of amplitude being due to the addition of low energy particles which would shift the energy spectrum towards lower energies. Both effects may be operating simultaneously at some periods, but the effect of low energy negative particles would presumably be more evident at a high level station such as Huancayo. Further analysis of data, which is in progress now, is expected to throw some additional light on the sign and energies of the solar primaries causing the anisotropy of cosmic radiation at different times of the solar cycle. Group I, corresponding to years of high solar activity, is particularly interesting for this purpose.

IV. SOLAR RELATIONSHIP OF MESON DIURNAL AMPLITUDE

The total and partial correlation coefficients of the meson diurnal amplitude $M_T{}^D$ with relative sunspot number R and the American magnetic character figure C_A are indicated in Table I for all years, and for years in Group II corresponding to low solar activity.

The high and significant values of the partial corre-

TABLE I. The total and partial correlation coefficients of the amplitude of the meson diurnal variation with relative sunspot number and American magnetic character figure. Group II years refer to a period of low solar activity.

Correlation	All years	Group II years
$r_T{}^M{}_R$ between $M_T{}^D$ and R	+0.58	+0.57
$r_T{}^M{}_{CA}$ between $M_T{}^D$ and C_A	+0.48	+0.56
$r_T{}^M{}_{R.CA}$	+0.65	+0.88
$r_T{}^M{}_{CA.R}$	+0.57	+0.86

lations of $M_T{}^D$ with R and C_A in Group II indicate that during years of low sunspot activity, regions responsible for cosmic-ray emission from the sun undergo a change in activity similar to that of the sunspots. It appears, therefore, that the active regions of the sun emitting high energy primaries whose effects are detectable at sea level have to be near the heliographic equator, as at periods of low sunspot activity, to be effective in producing an anisotropy of the cosmic radiation near the earth. This is analogous to what holds good for the corpuscular solar radiation responsible for magnetic storms and auroral activity. In view of this, it is not surprising that during the early part of the solar cycle, there is a lag of the cosmic-ray time-series with respect to the sunspot series. An examination of the time-series for solar activity confined to low heliographic latitudes is now in progress. The time-series for amplitude $M_H{}^D$ at Huancayo has better partial correlations than the mean amplitude $M_T{}^D$ with R and C_A for all the years. This is suggestive of the possibility that for emission of low energy cosmic-ray primaries from the sun whose effects are detectable only at mountain stations, the active regions can be further away from the solar equator than for high energy primaries.

While in years of low sunspot activity, there is a low and nonsignificant negative correlation between sunspots and the magnetic character figure C_A, the high positive partial correlation of C_A with cosmic-ray diurnal amplitude is very significant. It appears that this connection between cosmic rays and the magnetic activity is not a direct one. On the other hand, it probably implies that the M regions on the sun, believed to be responsible for the solar corpuscular emission causing magnetic disturbances, can themselves emit particles of cosmic-ray energy or are associated with regions which can do so. Hogg's assertion that solar effects on cosmic rays are only observed when they are simultaneously accompanied by geomagnetic disturbances is not tenable on account of the high partial correlation of diurnal amplitude with sunspot numbers.

A nonpersistent 27-day recurrence tendency in cosmic-ray intensity has been reported by several workers. In spite of differences in detail of the cosmic-ray pulses and magnetic pulses in the Chree diagrams, it has been believed by some authors that the cosmic-ray pulses are caused by geomagnetic disturbances. In view now of the other solar relationships of cosmic-ray intensity, a 27-day recurrence tendency in cosmic rays not necessarily directly connected with geomagnetic effects is understandable.

V. CONCLUSIONS

The facts presented here have far-reaching implications. They confirm our earlier view that the pressure-corrected diurnal variation of mesons is mainly due to an anisotropy of the primary radiation and is not caused by a positive upper air temperature effect. An explanation of the diurnal variation of mesons in terms of direct geomagnetic or heliomagnetic effects cannot be seriously considered in view of the marked latitude dependence which would be expected. We shall discuss separately, along with full details of the present work, the implications of our findings on current theories and past experimental results concerning the diurnal variation, with particular reference to the measurements from definite directions by Alfvén and Malmfors[6] and Elliot and Dolbear.[7]

Earlier work has shown that the sun can give rare bursts of high energy particles during some flares. There is also an association between some peaks observed in day-to-day changes of neutron and charged particle cosmic-ray intensity and the central meridian passage of active regions. The new evidence presented here demonstrates that the sun is a continuous source of cosmic radiation giving rise to a diurnal variation of the meson intensity on the earth. The level of activity for continuous solar cosmic-ray emission is not constant but varies substantially with the years broadly in step with the general solar cycle.

We are grateful to Professor K. R. Ramanathan for very valuable discussions and to Mr. K. A. Gidwani for assistance in computation of data. We owe our thanks to the Atomic Energy Commission of India for support given.

[6] H. Alfvén and K. G. Malmfors, Arkiv Mat. Astron. Fysik **29A**, No. 24 (1943).

[7] H. Elliot and D. W. N. Dolbear, J. Atmos. Terr. Phys. 1, 205 (1951).