GEOMAGNETIC PLASMA PROBE FOR SOLAR WIND

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Received February 14, 1969

Abstract

Magnetograms from Alibag reveal that the range $\triangle$ H of the daily variation of the horizontal component is negatively correlated with the minimum value $\triangle H_{min.}$ during a day. This relationship is largely unaffected by the degree of geomagnetic disturbance and holds good during all phases of the 11-year cycle of solar activity. From the nature of the relationship between $\triangle H$ and $\triangle H_{min.}$ it is concluded that the daily variation of the geomagnetic field at a low latitude station outside the influence of the equatorial electroject must be regarded as largely due to a weakening of the ambient field on the night side rather than an enhancement of the field on the day side due to ionospheric currents. There exists a good correlation between $(\triangle H)^2$ and the kinetic energy density of the solar wind in interplanetary space measured by IMP-1 satellite. It is suggested that $\triangle H$ is largely the result of the partial ring currents related to the convective drift of the plasma from the tail of the magnetosphere. Moreover, using the relationships established during the IMP-1 period, the annual mean kinetic energy density of solar wind for geomagnetically quiet days for the past 11-year cycle is estimated, treating the earth as a plasma probe.

Introduction

Much attention has been devoted to the daily variations S_q and D_{st} of the geomagnetic field as well as to a number of types of magnetic disturbances and planetary indices, like K_p and A_p which have been attributed to the influence of the particle radiation from the sun. The planetary indices however are not related to physical models of the magnetosphere. The present investigation illuminates a new and what appears to be a fundamental relationship that exists between kinetic energy density of the solar plasma, the daily range $\triangle H$ of the horizontal component at a low latitude station and the minimum value of the horizontal component of the magnetic field $H_{min.}$ during a period of 24 hours from midnight to midnight. It also indicates that outside the influence of the equatorial electrojet and excluding high latitudes, the daily variation is largely due to a weakening of the ambient field on the night side rather than an enhancement of the field on the day side due to dynamo currents in the ionosphere, as the classical theory has supposed. More likely, the daily variation is associated with the deformation of the magnetosphere under the influence of the solar wind and the convective drift currents that result from it. It therefore provides a method of estimating from entirely ground-based observations the kinetic energy density of the solar wind, using the earth as a plasma probe.

THE NATURE OF THE DAILY VARIATION OF H

Our study has been made using the magnetograms from the Observatory at Alibag (Geomagnetic latitude 9° 30′ N and geomagnetic longitude 143° 36′ E) for the years 1961, 1962, 1963 and 1964. Alibag is a typical station at low geomagnetic latitude, but outside the influence of the equatorial electrojet, and a magnetogram on a typical day is shown in Fig. 1.

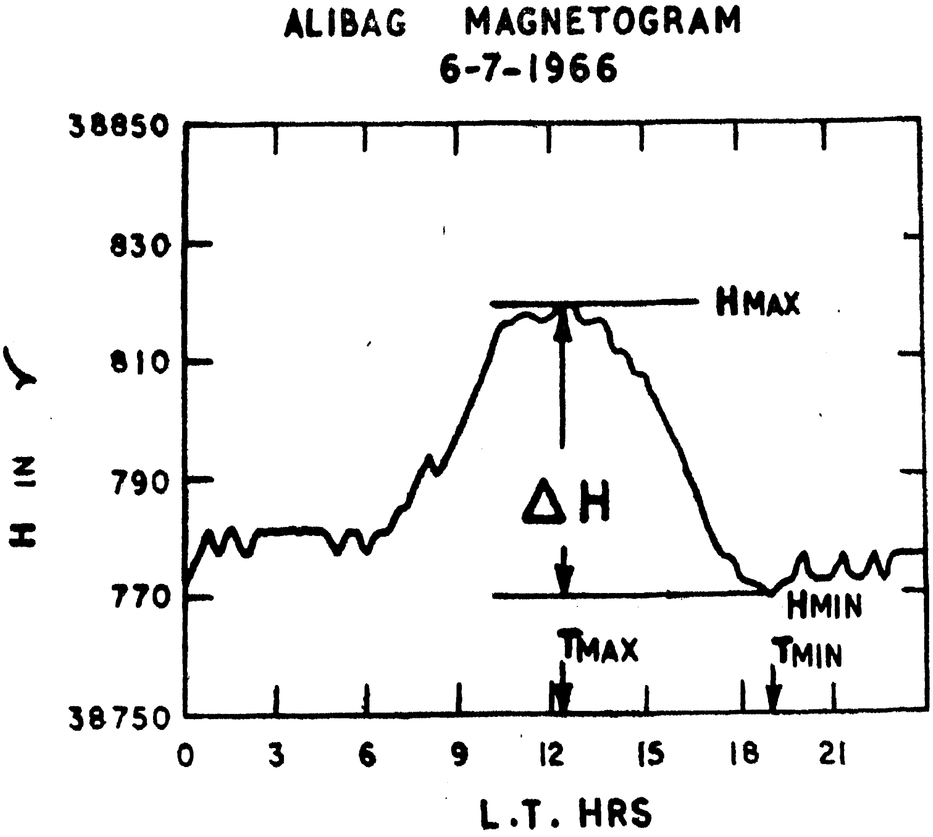

FIG. 1. A typical Magnetogram at Alibag.

Figure 2 shows for the individual years the histograms of the times of occurrence of the maximum ($T_{max.}$) and minimum ($T_{min.}$) of the daily variation of H. There is no qualitative change in the histograms from year to year. Taking all the four years together, Fig. 3 indicates the normalised histograms of $T_{max.}$ and $T_{min.}$ separately for (*a*) all days combined, (*b*) quiet days, (*c*) days with sudden commencement storms, (*d*) days with gradual commencement storms, (*e*) disturbed days and (*f*) internationally disturbed days but during which sudden commencement and gradual commencement storms did not occur. $T_{max.}$ histograms are relatively unaffected by the degree of geomagnetic disturbance. However, $T_{min.}$ occurs at 0500 hours significantly more often on geomagnetically quiet days than on all other groups of days. The almost complete absence of $T_{min.}$ between 0200 and 0600 hours on disturbed days is also noteworthy.

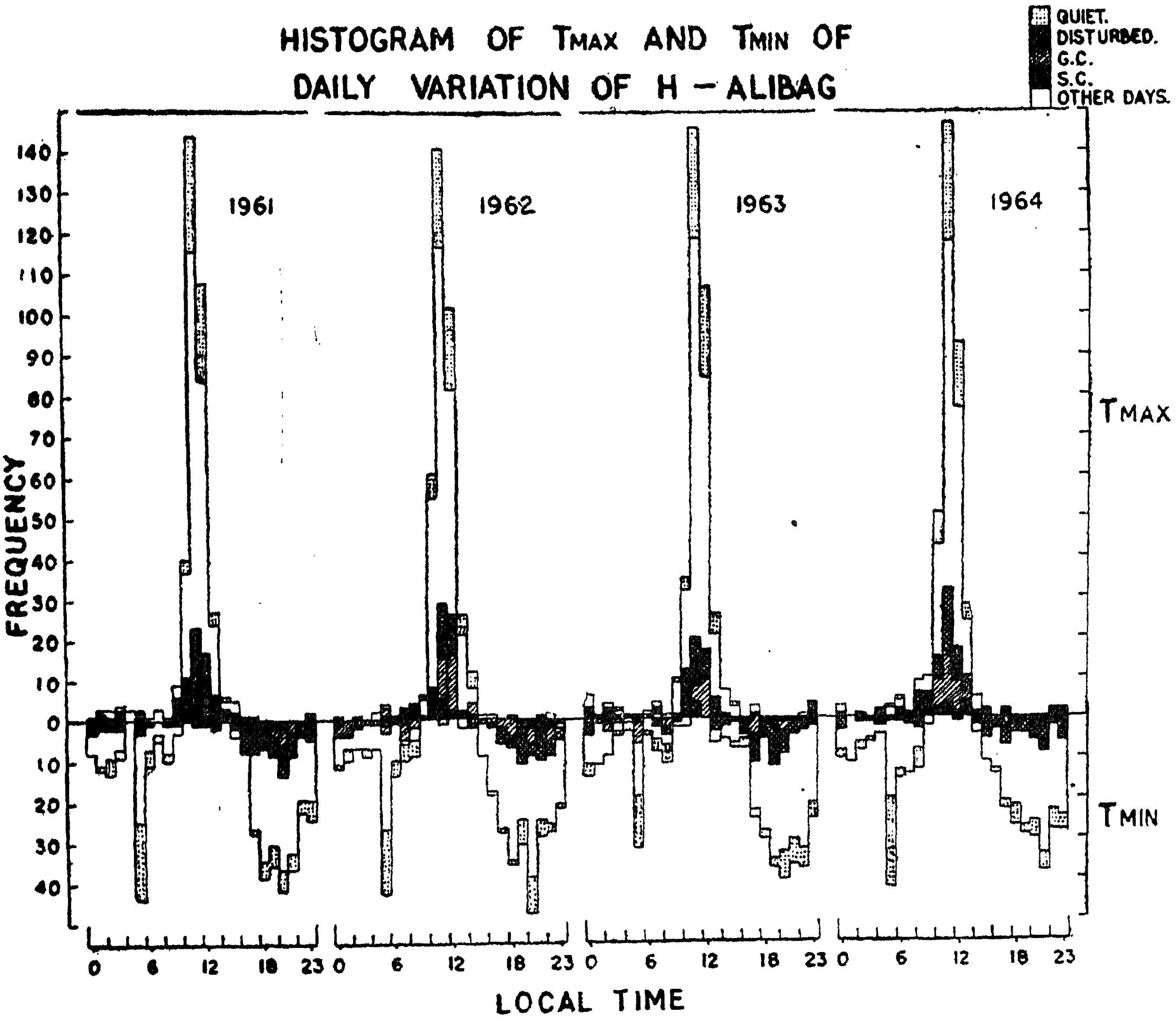

FIG 2. Histograms of the times of occurrence of maximum and minimum of the daily variation of Horizontal Force at Alibag for the years 1961, 1962, 1963 and 1964. *See* text for explanations of markings.

The histograms of ΔH during each of the four years are shown in Fig. 4. It is observed that there is a consistent shift of the histograms towards smaller values of ΔH from 1961 to 1964 approaching minimum of solar activity. The very large values of ΔH on some days during 1961 is also noticeable.

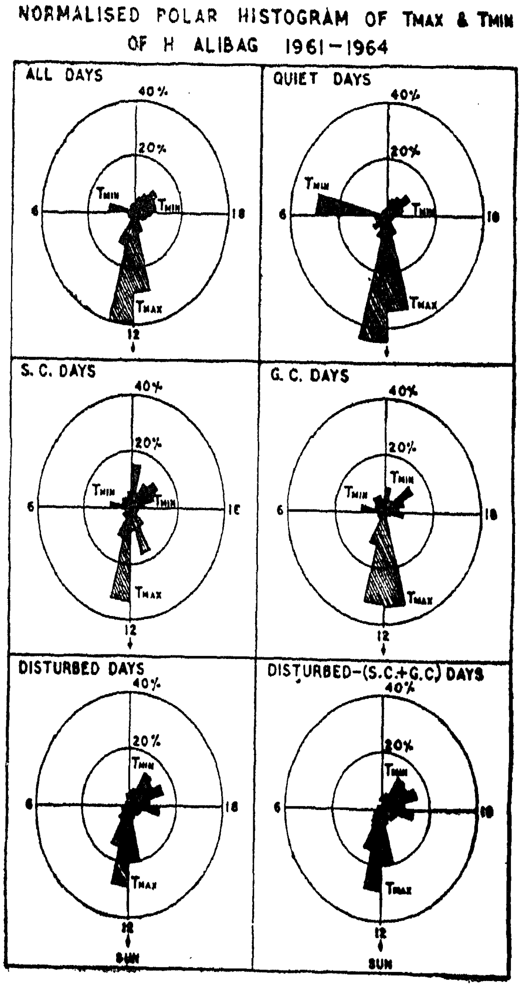

FIG. 3. Normalised polar histograms of local times of maximum and minimum of H at Alibag from year 1961 to year 1964, showing separately. (*a*) all days combined, (*b*) quiet days (*c*) days with sudden commencement storms, (*d*) days with gradual commencement storms, (*e*) disturbed days and (*f*) internationally disturbed days but during which sudden commencement and gradual commencement storms did not occur.

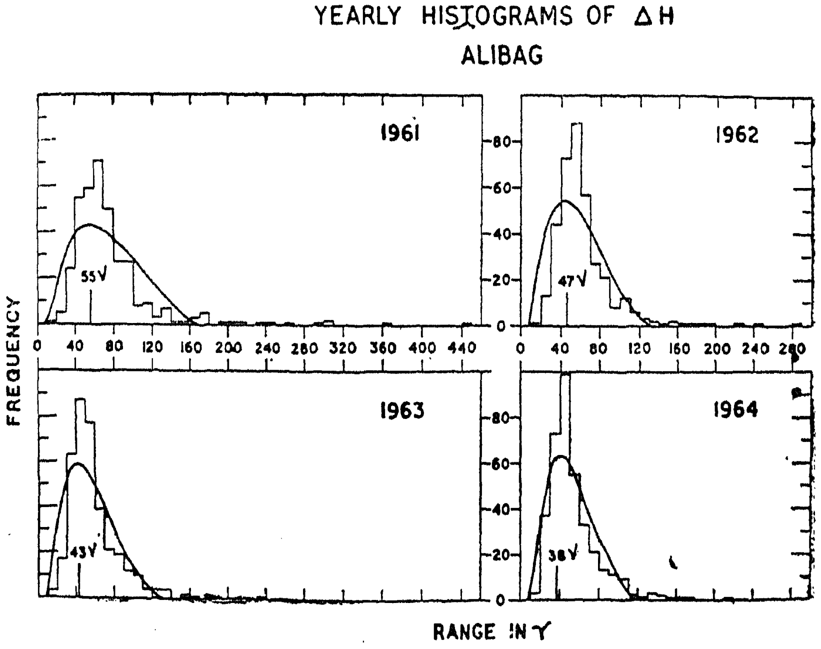

FIG. 4. Yearly histograms of ΔH for 1961, 1962, 1963 and 1964, fitted with polynomial curves.

Figure 5 shows the monthly mean $H_{\mathrm{min.}}$ from 1961 to 1964 before and after the data have been corrected for the well-known secular change of H at Alibag, which is 26 γ/year during this period.[1]

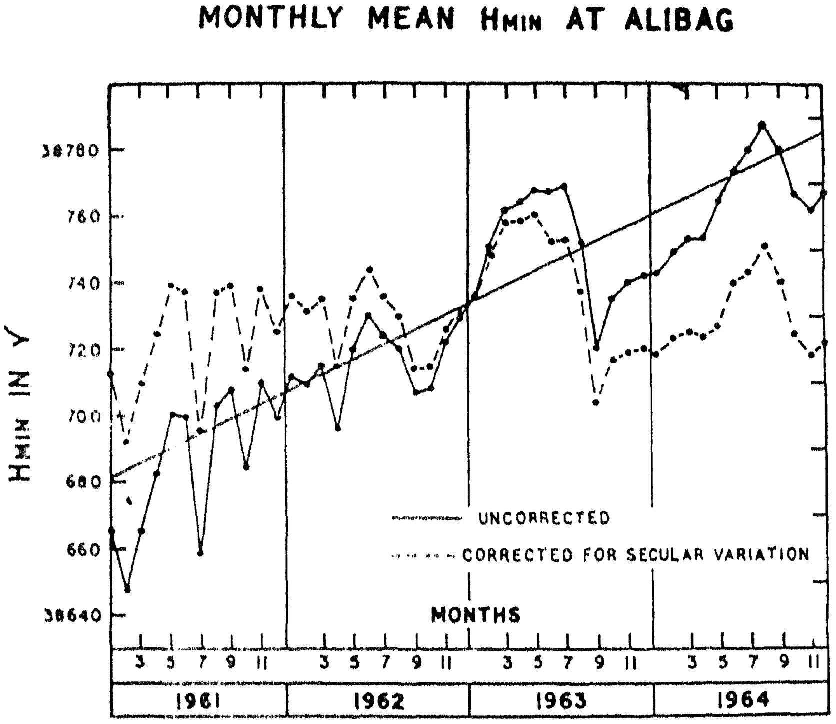

FIG. 5. Monthly mean $H_{\mathrm{min.}}$ from 1961 to 1964 before and after the data have been corrected for secular variation.

To eliminate the influence of secular changes, of long-term changes due to the 11-year variation and of seasonal changes, we have derived $H^{*}_{\mathrm{min.}}$ and ΔH^{*} by taking 27-day moving average of the daily values of $H_{\mathrm{min.}}$ and ΔH and subtracting the average values from the corresponding values on the 14th day falling in the middle of the interval. The relationship of $H^{*}_{\mathrm{min.}}$ and ΔH^{*} during each of the four years can be seen in Fig. 6 from the scatter diagrams and statistically best fit lines derived by correlation analysis. During each year, ΔH^{*} and $H^{*}_{\mathrm{min.}}$ are negatively correlated with a coefficient of about $-0{\cdot}8 \pm 0{\cdot}02$. The points in the diagram indicated by 'X' and '⊙' correspond to days when sudden commencement and gradual commencement storms occurred. It would be observed that by and large there is no qualitative difference in the relationship of ΔH^{*} and $H^{*}_{\mathrm{min.}}$ with increasing degree of geomagnetic disturbance.

The overall relationship is best brought out in Fig. 7 where data for ΔH^{*} and $H^{*}_{\mathrm{min.}}$ for each individual day for all the four years have been included. The area of each circle is proportional to the number of days having the appropriate pair of values of ΔH^{*} and $H^{*}_{\mathrm{min.}}$ By all standards, the relationship is remarkable. Since the correlation is negative so that with increasing ΔH^*, $H^*_{\text{min.}}$ decreases, we can conclude that $H_{\text{min.}}$ is, predominantly produced by the removal of the field on the night side equivalent to ΔH.

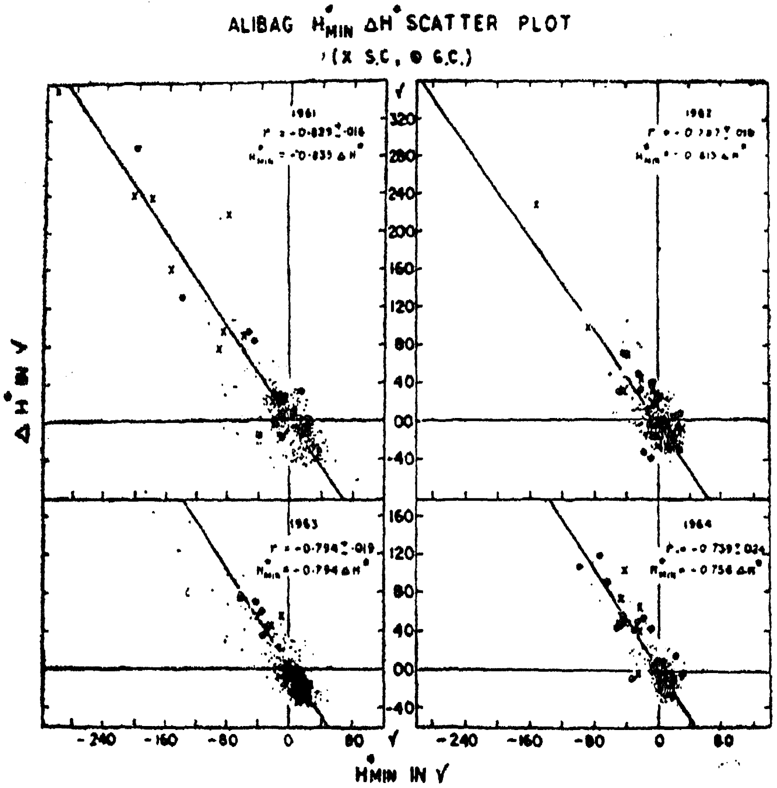

FIG. 6. Scatter plots of $H^*_{\text{min.}}$ against ΔH^* for individual years 1961 to 1964 × and ⊙ respectively indicate days on which sudden commencement and gradual commencement storms, occurred.

Figure 8 shows the scatter diagram during 1961 of $H^*_{\text{max.}}$ and ΔH^*. The correlation coefficient between the two is negligible and is statistically not significant. This confirms that the midday peak in the magnetogram at Alibag is not primarily produced by the strengthening of the field on the day side due to ionospheric currents as the classical dynamo theory suggests. On the other hand, at Trivandrum on the geomagnetic equator, the magnetic effect of the electrojet current has been experimentally verified in rocket flights.[2, 3] On the average at Trivandrum (only 1100 km. south of Alibag) the daily variation has an amplitude about 1·8 times greater than the daily variation at Alibag. Since the magnetospheric effects would not differ substantially for Alibag and Trivandrum but the ionospheric electrojet effect would, we have sought confirmation of our proposition regarding the interpretation of ΔH at Alibag being negative by taking the scatter diagram of (ΔH Trivandrum$-\Delta H$ Alibag) against ΔH Alibag (Fig. 9). The correlation coefficient between the two is negligible and insignificant, clearly confirming that the basic process operative at Alibag is not directly related to the known ionospheric effect which is important at

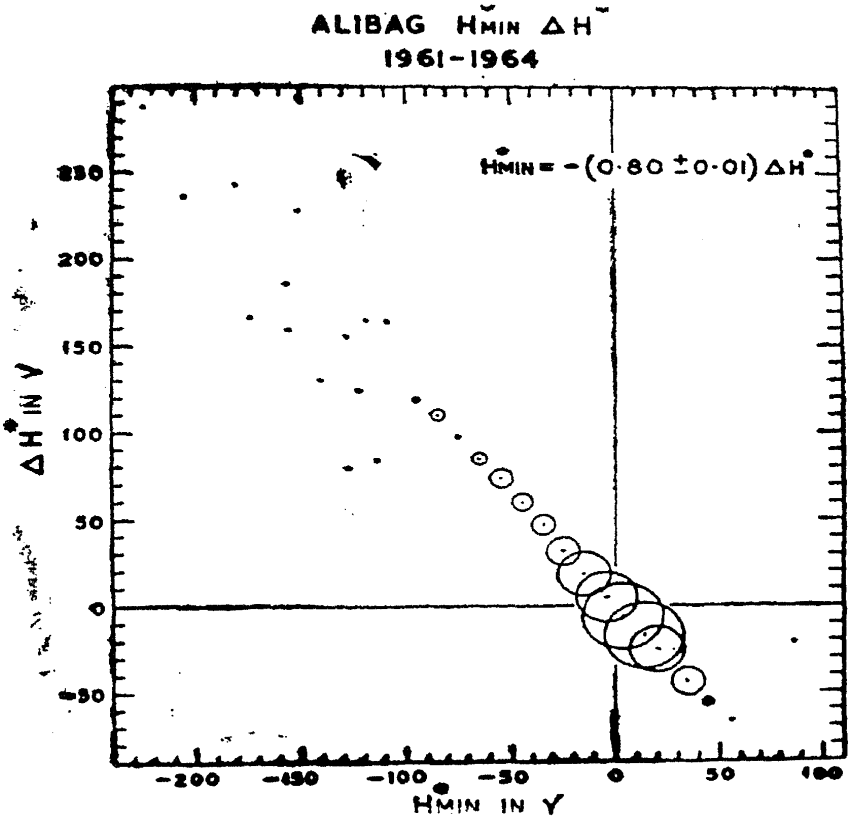

FIG. 7. $H^*_{min.}$, ΔH^* relationship combining values for the years 1961 to 1964.

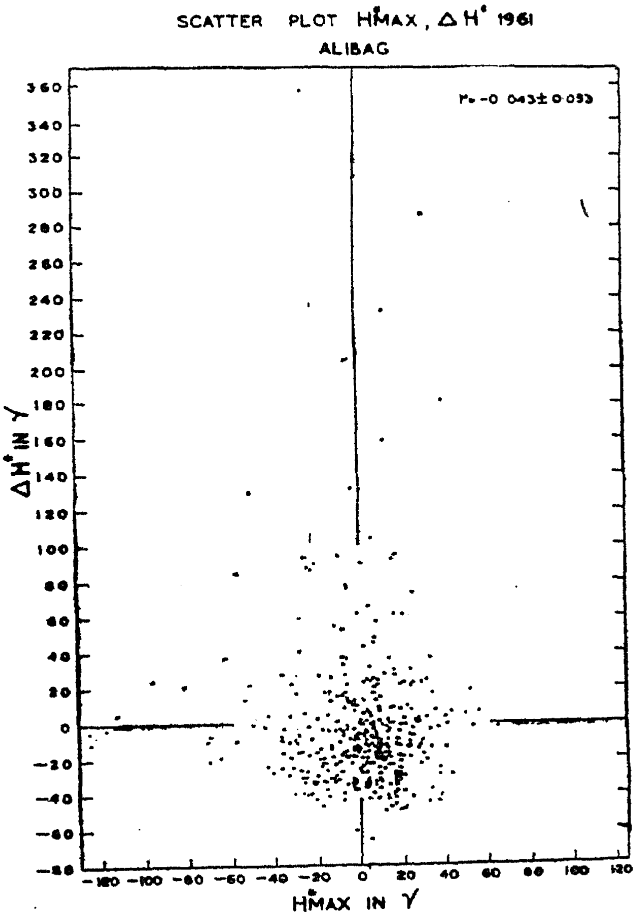

FIG. 8. Scatter diagram showing the relation between $H^*_{max.}$ an ΔH^* for the year 1961 for Alibag.

Trivandrum. Rocket studies at middle latitudes have attempted the detection of the dynamo currents in the E region through their magnetic effects.[a, b] While the results have been partially successful, the phenomena appear variable and not directly according to what we had expected on the basis of the classical model of ionospheric current systems.

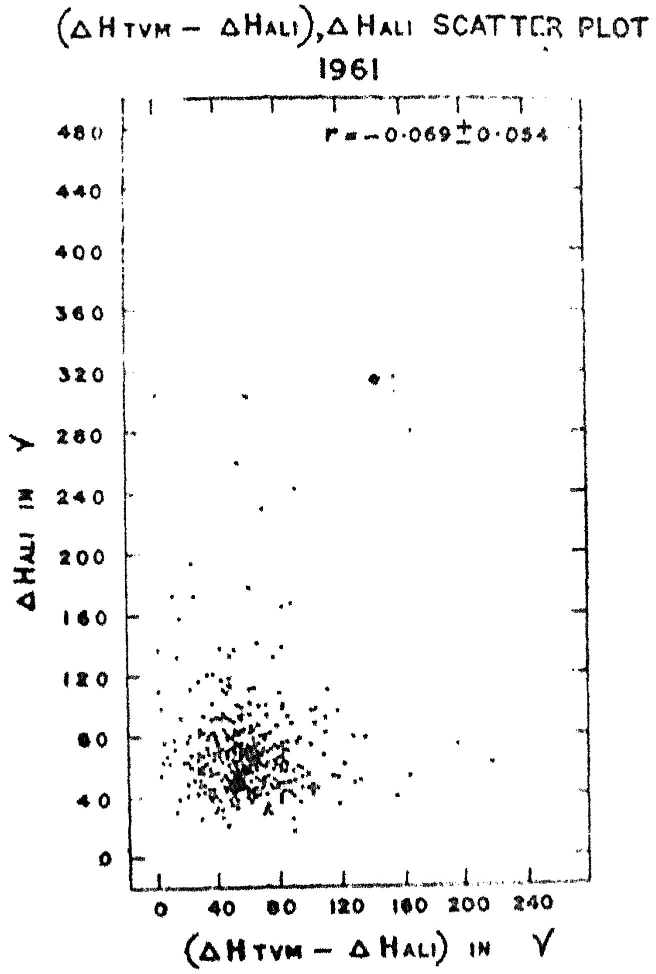

FIG. 9. Scatter diagram of (ΔH Trivandrum − ΔH Alibag) against ΔH Alibag for the year 1961.

CHANGES OF ΔH AND KINETIC ENERGY DENSITY OF INTERPLANETARY PLASMA DURING SOLAR CYCLE

During the IMP-1 period (27-11-1963 to 22-2-1964), a fairly well-established sector structure has been observed[4] in interplanetary plasma, indicating the stability of regions of solar activity.

The solar wind parameters have been experimentally measured by the M.I.T. plasma probe. Pai *et al.*[5] have reported the three hourly averages of the plasma velocity (V_s), density (N_s), flux (ϕ_s) and kinetic energy density (K.E.). From these, daily values have been obtained for each parameter. The super-position of successive 27-day values provides the average values of the solar wind parameters for each heliographic longitude at central meridian passage (C.M.P.). Similarly the values of $H_{min.}$ and ΔH have been computed and are plotted in Fig. 10 along with the values of ΣK_p.

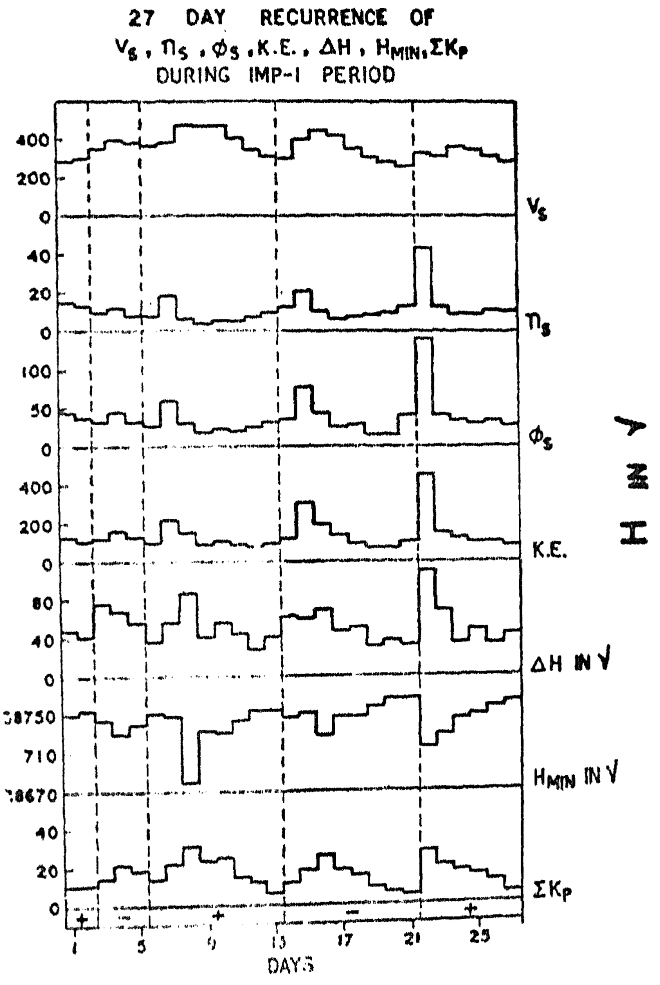

FIG. 10. 27-day recurrences during IMP-1 period of (*a*) Solar wind velocity (V_s) Km./Sec, (*b*) Solar wind number density (n_s) protons/cm.^{3}, (*c*) Solar wind flux (ϕ_s) in units of $1 \cdot 16 \times 10^7$ cm.$^{-2}$ sec.$^{-1}$, (*d*) Kinetic energy density (K.E.) in units of $8 \cdot 8 \times 10^{-11}$ ergs/cm.^{3}, (*e*) Δ H at Alibag in gammas, (*f*) $H_{min.}$ at Alibag in gammas and (*g*) Daily total of K_p (ΣK_p).

Table I indicates the correlation coefficients between the geomagnetic and the solar wind parameters. It is observed that ΔH is best correlated with K.E. and is insignificantly so with V_s. The correlation coefficient of ΣK_p is best with V_s, in agreement with the observations of Snyder *et al.*[6] However, the correlation cannot be directly related to physical models, since the equations are dimensionally not balanced. ΔH has the dimensions $M^{1/2} L^{-1/2} T^{-1}$ and therefore a meaningful physical relationship can be expressed by considering $(\Delta H)^2$ and kinetic energy density of the solar plasma, both having the same dimensions. The correlation between the two is 0·78 ± 0·08 for the 27-day superposed values for the IMP-1 period.

The scatter diagram is shown in Fig. 11. The expression connecting the two quantities is

K.E. density $= (20 \pm 11) \times 10^{-10} + (3 \cdot 65 \pm 0 \cdot 45)\, 10^{-12} \times (\Delta H)^2$ ergs/cm.^{3} (1)

Based on expression 1 which provides a calibration of $(\Delta H)^2$ with the measured kinetic energy density of the solar plasma during the IMP-1

TABLE I

Correlation coefficients between the geomagnetic and solar wind parameters

	V_s	n_s	ϕ_s	K.E. density
ΔH	0·29±·18	0·60±·13	0·66±·11	0·73±·09
$H_{\min.}$	−0·63±·12	−0·16±·19	−0·27±·18	−0·40±·16
ΣK_p	0·79±·07	0·23±·17	0·37±·17	0·56±·14

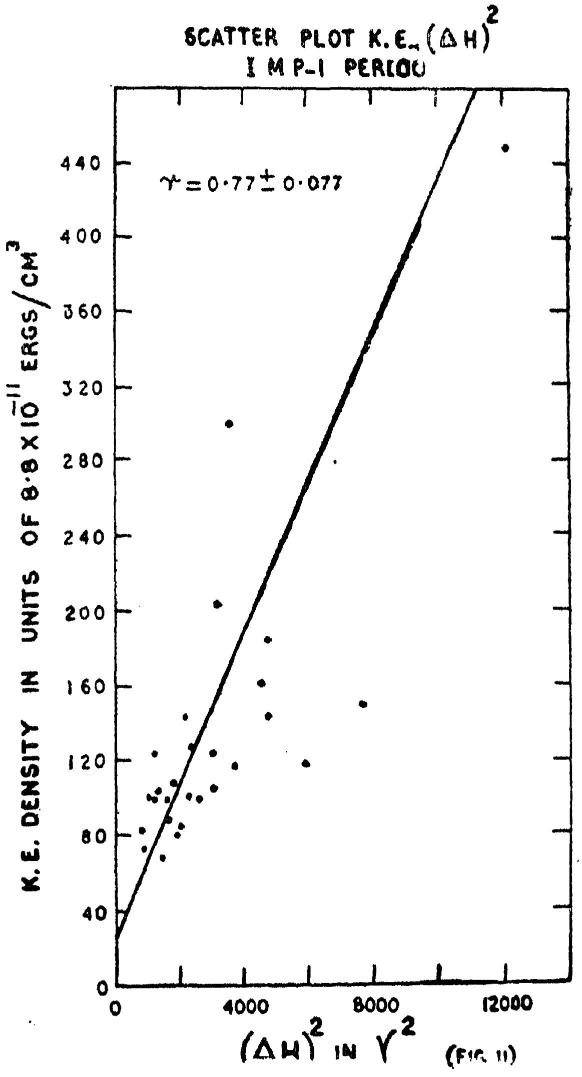

FIG. 11. Scatter plot of K.E. density of the solar wind and $(\Delta H)^2$ of Alibag.

period, we have derived the solar cycle changes of kinetic energy density from the changes of Δ H each year from 1954 to 1964. These are shown in Fig. 12 and the values of the parameters are indicated in Table II. The derivation has been done for internationally quiet days and for all days in each year. It is observed that the derived kinetic energy density follows closely the change of the solar activity over the 11-year period as indicated by the Zurich sunspot number. We shall discuss in a separate communication the interesting implications of the differenee in the 11-year cycle change of the kinetic energy density for quiet days and for all days.

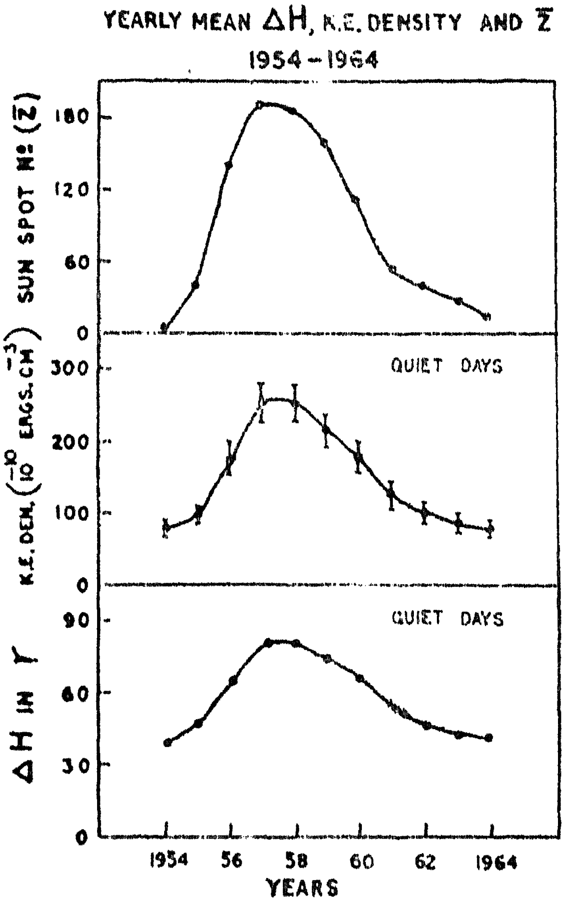

Fig. 12. Yearly mean of (1) Zurich sunspot number ($\bar{Z}$), (2) derived kinetic energy density (K.E.) of the solar wind for internationally quiet days in units of 10^{-10} ergs/cm.^{3} and (3) ΔH in gammas for Alibag for the years 1954 to 1964.

Discussion

Much evidence has been accumulating recently to indicate that a simple representation of dynamo currents on a spherical ionospheric shell is inadequate to explain the observed daily changes of the magnetic field on the surface of the earth even during geomagnetically quiet days.[7–9] The fundamental character of the relationship of ΔH^* and $H^*_{\min.}$ during the period of a solar cycle is best brought out in Table III,

TABLE II

K.E. density of the solar plasma for 1954 to 1964 derived from yearly mean ΔH

Year	ΔH quiet days gammas	ΔH All days gammas	K.E. density quiet days in unit of 10^{10} ergs/cm.^{3}	K.E. density All days in units of 10^{10} ergs/cm.^{3}
1954	41	55	81 ± 13	130 ± 17
1955	46	62	97 ± 14	168 ± 19
1956	65	88	174 ± 20	303 ± 33
1957	80	95	253 ± 28	349 ± 38
1958	80	101	253 ± 28	392 ± 43
1959	73	101	215 ± 24	392 ± 43
1960	66	94	179 ± 21	343 ± 32
1961	53	74	123 ± 16	220 ± 25
1962	47	61	101 ± 14	156 ± 19
1963	42	57	84 ± 13	139 ± 18
1964	40	53	78 ± 13	123 ± 16

TABLE III

Correlation coefficients and slopes between $H^*_{\text{min.}}$ *and* ΔH^*

Year	Correlation coefficient	Slope
1954	−0·61 ± ·03	0·620
1955	−0·60 ± ·03	−0·630
1956	−0·72 ± ·03	−0·730
1957	−0·88 ± ·01	−0·880
1958	−0·80 ± ·02	0·797
1959	−0·79 ± ·02	−0·800
1960	−0·83 ± ·02	−0·850
1961	−0·83 ± ·02	−0·835
1962	−0·79 ± ·02	−0·813
1963	−0·79 ± ·02	−0·794
1964	−0·74 ± ·02	−0·756

Disregarding for the time being the small but systematic difference in the slope of the regression line during the years from 1957 to 1962 compared to the years of low solar activity 1954 to 1956 and 1963 to 1964, we note that the broad features of the ΔH^*, $H^*_{min.}$ relationship are relatively constant. The results from synchronous A.T.S.-1 satellite,[10, 11] show that on the night side even at 6·6 R_e on geomagnetically quiet days the magnetic field in the anti-solar direction is less than the field in the sub-solar direction by about 25 to 30 gammas. Thus the reduction of the field on the night side is the predominant factor in the daily variation of the horizontal component of the earth's magnetic field at low latitude stations, except in the belt of ± 3° to 5° close to the geomagnetic equator where the effects of the electrojet in the ionosphere are also present. Since the latter represents an increase of field in the day time, the two factors together augment the overall daily variation that is observed at the geomagnetic equator.

Recent models explaining the shape of the magnetosphere and many of its features, particularly the tail and the neutral sheet, lead to the following:

(1) The compression of the geomagnetic field in the sub-solar direction due to the pressure of the solar plasma should produce an enhancement of H on the day side and a decrease on the night side. According to Mead's model,[12] the diurnal variation of H should be about 4 gammas, for a stand off distance of about 10 r_e. Even though the effect is connected with the kinetic energy density of the impinging plasma, this makes a minor contribution to the observed ΔH which is about an order of magnitude larger.

(2) There is a convection of the solar plasma along the sides of the magnetosheath and return through the tail[13–16] as diagrammatically visualised in Fig. 13. The computations due to Roederer[17] reveal that particles mirroring at low latitudes on the night side pseudo-trapping region (particles mirroring with less than 180° longitudinal drift for the guiding centre) are seen to abandon the magnetosphere through the boundary at 30° to 40° latitude before reaching the noon meridian (Fig. 14). This westward current which exists only for the night side decreases the horizontal field during night time for low latitude stations. At high latitudes, no trapping is possible and the daily variation due to magnetospheric drift currents is not important. At intermediate latitudes between 40° and 60° a pseudo-trapping region exists on the sunlit side but not on the night side, and in consequence there could be some reduction of the field on the day side. The state of affairs offers an alternative and a more plausible explanation

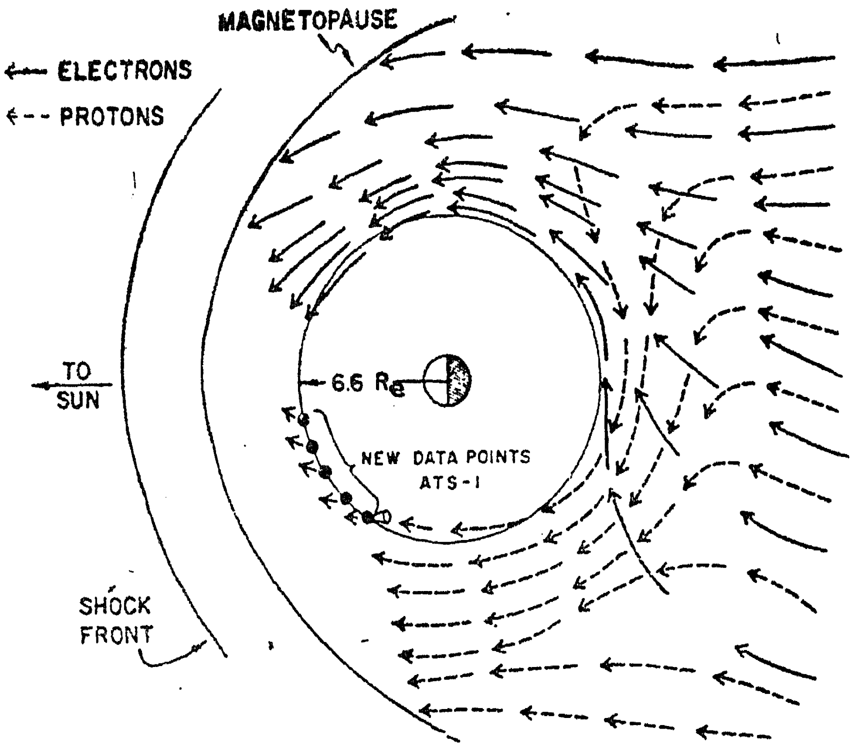

FIG. 13. A diagrammatic representation of the flow of energetic plasma through the magnetosphere in the equatorial plane, taken from J. W. Freeman, Jr., *J. Geophy. Res.*, 1968, 73, 4151–57.

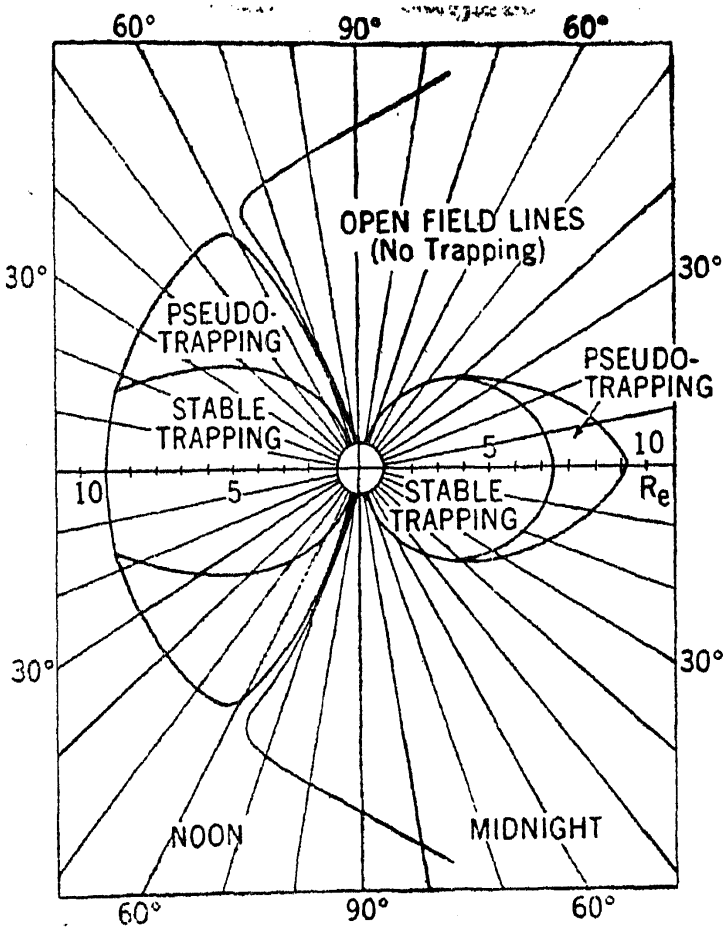

FIG. 14. Location of pseudo-trapping regions in the Mead-Williams model. J. G. Roederer, *Int. Sym. on Physics of the Magnetosphere*, Washington, D.C., September, 3–13, 1968. Particles mirroring inside these regions are unable to complete a drift around the earth.

than the classical dynamo theory of ionospheric current with foci at 40° geomagnetic latitude N and S to explain the observations, that the daily variation of the horizontal component of the magnetic field changes phase at 40° latitude.

(3) The stand off distance of the magnetopause (r_S) at the sub-solar point is inversely proportional to the sixth root of K.E. density of the solar wind. The higher the value of K.E. density, lower is the value of r_S, which means removal of more particles on the day side for low latitudes. Therefore, for days with high K.E. density, the pseudo-trapping region is pronounced and with the removal of the field on the night side large values of $\triangle$H are observed. Existing theory does not indicate the constant in the relationship between K.E. density and the magnetic field changes produced by the currents but the remarkable feature which comes out of the present analysis is that the relationship is a simple one and is given by expression (1). While the dimensions of the neutral sheet and its minimum distance from the earth are not yet derivable from the existing models of the magnetosphere, it is clear that in the V_3 belt the minimum radial distance of the longitudinal drift of protons would be smaller than for electrons.

(4) While we suggest that $\triangle$H at low latitude stations outside the influence of the electrojet can be related to the strength of the drift currents in the pseudo-trapping region $H_{min.}$ can decrease not only due to these currents but also by those which are in the stable trapping region. Moreover, though conditions in the pseudo-trapping region can only be observed on the night side, the effects of the currents in the stable-trapping region can demonstrate themselves by lowering $H_{max.}$ and the daily mean value of H as is observed during geomagnetic storms.

(5) The most tentative aspect of the present communication is the correlation between $\triangle$ H and the solar wind parameters. This is because the data for the latter were available to the authors only for 3 months. There is today extensive data concerning solar wind and this is being analysed. This will permit a confirmation of the suggestion made by us that the K.E. density can be directly related to $(\triangle H)^2$ and in consequence that the earth can be used as a plasma probe.

ACKNOWLEDGEMENTS

We are grateful to the Director of the Colaba and Alibag Observatories of the India Meteorological Department and to H. S. Bridge and the Plasma Group at M.I.T. Cambridge for the basic data on which the present study is based. We are also grateful to the Department of Atomic Energy for support.

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