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February 1968

ABSTRACT

Observations of high energy protons geomagnetically trapped in the inner Van Allen belt have been carried out since September 1962 with nuclear research emulsions recovered from low altitude, polar-orbiting satellites. Between November 1962 and June 1966, during the period of minimum solar activity, the omnidirectional proton flux at 63 MeV remained constant to within ± 7.6 percent, an error comparable to the statistical accuracy of the measurement. However, since August 1966 we have obtained substantial evidence that the proton flux is decreasing in a manner which is attributable to solar cycle variations in the density of the upper atmosphere. As of our last measurement in November 1967, the flux has diminished by more than a factor of 2 relative to the stable flux profile observed during the last solar minimum period.

Since September 1962, we have analyzed nuclear research emulsions recovered from more than 30 low altitude, polar-orbiting satellite flights of 2-7 days duration. Parameters measured for these flight experiments include the omnidirectional flux of 57-68 MeV protons, east-west asymmetry of 130 MeV protons, energy spectra for $E \geq 57$ MeV, the spatial orientation of the mirror plane, and the pitch angle distribution.[1,2] The purpose of this paper is to report from these experiments the results that pertain to the temporal behavior of the omnidirectional flux of protons at an average energy $\bar{E} = 63$ MeV.

Because of the low satellite altitudes at which the experiments were conducted (250-520 km), the trapped protons were detected at or near their minimum mirror point altitudes over a very limited region in space, the so-called South Atlantic anomaly. This region, which is centered at approximately 34° south by 34° west (geographic), is the site of anomalously low intensities of the geomagnetic field. Consequently, the inner Van Allen belt particles reach their minimum mirror point altitudes over this area. Furthermore, in a typical 4-day flight a polar-orbiting satellite traverses the anomaly approximately 12 times each in the northward and southward directions and thereby achieves a comprehensive sampling of this region. The attitude control of the vehicle was maintained throughout each flight and provided a stabilized detector platform which was oriented with respect to the zenith and to the velocity vector of the satellite.

The particle detectors were four small button-shaped stacks (4 cm diameter × 0.48 cm thick) of Ilford G.2 and G.5 nuclear emulsions placed in small stainless steel containers and mounted on the recoverable vehicle immediately beneath the 2.5 gm/cm^2 ablative shield. The position of each button on the vehicle was accurately known; in fact, for all but a few early flights, the position of the principal emulsion button from which the flux data were obtained was identical.

The quantity actually measured in these experiments is the directional flux of protons at azimuthal angle φ in the mirror plane, where φ is measured from the vector $\vec{B} \times \vec{R}$ where $\vec{R}$ is the zenith direction. The directional flux in the mirror plane at low altitude is not azimuthally symmetric as evidenced by the observation of the east-west asymmetry in proton flux.[1] We have concluded from our analysis of the altitude dependence of the east-west asymmetries,[3] that the directional flux vs. guiding-center altitudes is a power law function. Using this information, we are able to convert our directional measurements to omnidirectional flux.

Figure 1 presents the altitude dependence of the omnidirectional flux of 63 MeV protons obtained between November 1962 and June 1966. This 3.5 year interval is centered about the recent minimum in solar activity. During this period, the omnidirectional flux was remarkably stable. This stability afforded us the opportunity to establish the reproducibility and internal consistency of the flux measurements. Plotted in Fig. 1 is the omnidirectional flux $j(63 \text{ MeV})$ cm^{-2}MeV^{-1}day^{-1} versus the flux weighted average minimum mirror point altitude, $\overline{h}_{min}$. The averaging of h_{min} is taken over the satellite ephemeris in one minute intervals with the use of the Injun 3 proton flux data[4] and the Jensen and Cain 48-term expansion of the geomagnetic field.[5] Calculations using 1964-45A[6] and Telstar[7] data resulted in slight changes in $\bar{h}_{min}$ (less than 5 km relative to Injun 3 values), producing negligible effects on the flux-altitude profile. We selected the Injun 3 flux contour to analyze our data because of its overall agreement with our flux measurements. The statistical accuracy of each flux point is nominally ± 5 percent (SD). The line through the data is a least squares power law fit given by $j_c = \text{const.}\ \bar{h}_{min}^{\ 4.67\pm0.08}$. The standard deviations of the data about the least squares fit is $\sigma = \pm\ 7.6$ percent. This error limits to 5-6 percent the cumulative errors incurred by uncertainties in the satellite orientation, ephemeris information, computation errors in $\bar{h}_{min}$, etc., as well as any changes in the proton flux that we could have observed during the solar minimum period.

The temporal behavior of the 63 MeV omnidirectional flux between September 1962 and November 1967 is presented in Fig. 2. The fractional deviations of the measured proton flux with respect to the least squares fit to the data obtained during the stable period (Fig. 1) are plotted as a function of time. The constancy of the omnidirectional flux during the interval between November 1962 and June 1966 is readily apparent. The two dashed lines indicate the 7.6 percent standard deviation of the points about zero. The fractional deviations of the flux have been plotted for two ranges of altitude, $220 < \bar{h}_{min} < 375$ km and $375 < \bar{h}_{min} < 455$ km. During the stable period the scatter of the data in each altitude range is essentially the same, indicative of uniform temporal stability.

Variations of the proton flux are evident immediately before and after the quiescent period. The high value of the proton flux obtained from our first measurement in September 1962 is consistent with the observations of Filz and Holeman[8] who detected an abrupt order of magnitude increase in the low altitude proton flux following the Starfish nuclear detonation on July 9, 1962. By the time of our first measurement, 8 weeks later, the increased flux had decayed to a fractional excess of 0.38 relative to the subsequent stable flux. By November 1962, the flux transient was no longer evident in our data; although, in retrospect, its decay may have masked the detection of any natural flux variation through mid-1963.

Since mid-1966, significant decreases in the proton flux have been observed. The last several points in Fig. 2 indicate a progressive decrease in the proton flux, which appears to have begun its departure from temporal stability as early as mid-1965. Our latest measurement obtained in November 1967 gives a fractional deviation of 0.55.

The diminution of the proton flux was anticipated and can be attributed to solar cycle variations in the density of the upper atmosphere.[9] We have recently passed through the minimum solar active period, centered about mid-1964, and are presently on the upswing towards solar maximum activity which is expected to occur about 1969. The increased heating of the upper atmosphere results in the increase of the integrated atmospheric density traversed by the trapped radiation. Hence the proton flux is anti-correlated with solar cycle activity. A numerical computation of the solar cycle changes of the proton flux was performed by Blanchard and Hess.[9] Their predictions of the flux variations were based on the assumption of the albedo neutron theory for the source of protons and on the Harris and Priester model atmosphere[10] to calculate the losses due to nuclear collisions and ionization. The observed decrease in the proton flux since solar minimum is qualitatively in agreement with Blanchard and Hess's calculations. However, these calculations appear to overestimate solar cycle variations to the extent that by mid-1967 the observed change in flux is about 1/7 the predicted value. This discrepancy is not as serious as it appears for the following reasons: (1) The current solar cycle variation of the 10.7 cm flux, F (10^{-22} w $m^{-2}cps^{-1}$), differs from that used in the computations. (2) The empirically corrected Harris and Priester model parameter, S, can be used to give a better description of the atmosphere as a function of F.[11] Figure 3 illustrates these differences. The solid curve is the semi-annual average, $\overline{F}$, for the year 1962 through 1967. The line denoted by S is the empirically corrected Harris and Priester model parameter based on the observed $\overline{F}$. The dashed curve, S_{BH}, is the Harris and Priester model parameter used by Blanchard and Hess based on the previous solar cycle, taking S_{BH} to be the same value as the 10.7 cm flux. The net effect of introducing the current S parameter into the Blanchard and Hess calculation would be to reduce the expected solar cycle variations. Because the proton flux is approximately inversely proportional to the atmospheric densities at low altitudes, a rough estimate of the relative change in the proton fluxes can be obtained by considering the ratio of atmospheric densities between 1964 and 1967. The ratio of atmospheric densities corresponding to the change in S_{BH} between 1964 and 1967 is 0.075, which is to be compared with the value of 0.42

based on S of the present solar cycle. Hence it appears that the observed and computed solar cycle variations in the proton flux can be brought to much closer agreement by incorporating points (1) and (2) mentioned above into the Blanchard and Hess calculation.

Although greater flux variations can be anticipated, we conclude that the change we have seen already is consistent with solar cycle changes in the upper atmosphere. Continued observations of temporal variations will be necessary in order to undertake a more precise comparison with theory. Such a program is important to the understanding of the source and loss mechanisms of energetic protons in the inner belt.

ACKNOWLEDGMENT

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FIGURE CAPTIONS

Fig. 1. Altitude dependence of the proton flux during the interval between November 1962 and June 1966. Plotted are the omnidirectional flux, j(63 MeV) $\mathrm{MeV}^{-1}\mathrm{cm}^{-2}\mathrm{day}^{-1}$, versus the flux weighted average mirror point altitude $\bar{h}_{min}$. The solid line is a least squares power law fit to the data.

Fig. 2. Temporal behavior of the proton flux between September 1962 and November 1967. Plotted are the fractional deviations $(j - j_c)/j_c$ versus time at altitudes $220 < \bar{h}_{min} < 375$ km and $375 < \bar{h}_{min} < 455$ km.

Fig. 3. Plot of the semiannual average 10.7 cm flux, $\bar{F}$, in units of 10^{-22} watts $\mathrm{m}^{-2}\mathrm{cps}^{-1}$, versus time. Curve labeled S is the corresponding atmospheric model parameter of Harris and Priester (Ref. 9). Dashed curve denoted by S_{BH} is the Harris and Priester model parameter assumed by Blanchard and Hess (Ref. 7).

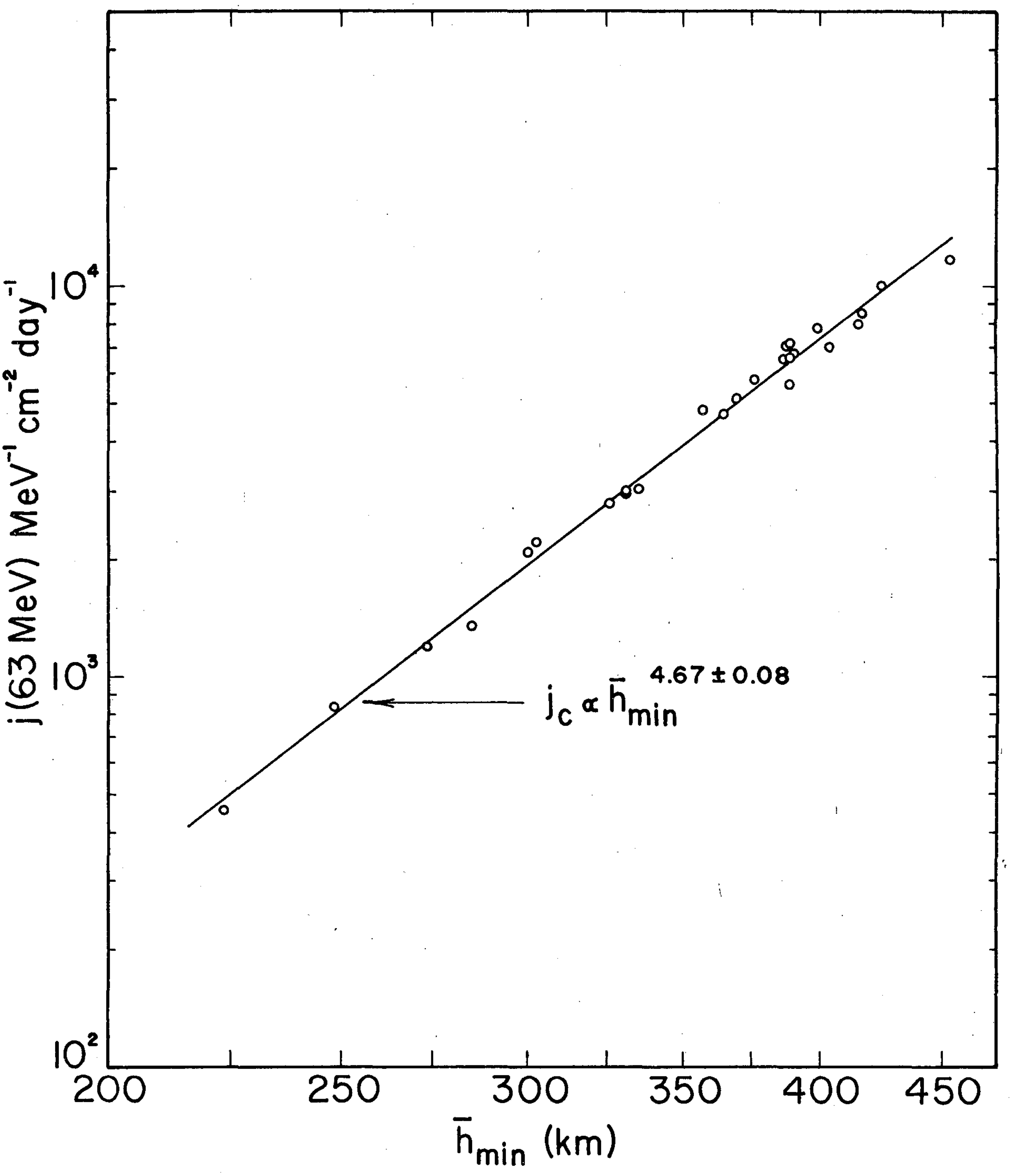

$j(63\text{ MeV})\ \text{MeV}^{-1}\text{cm}^{-2}\text{day}^{-1}$
10^2
10^3
10^4
200
250
300
350
400
450
$\bar{h}_{\min}$ (km)
$j_c \propto \bar{h}_{\min}^{4.67\pm0.08}$
XBL682-1859

Fig. 1

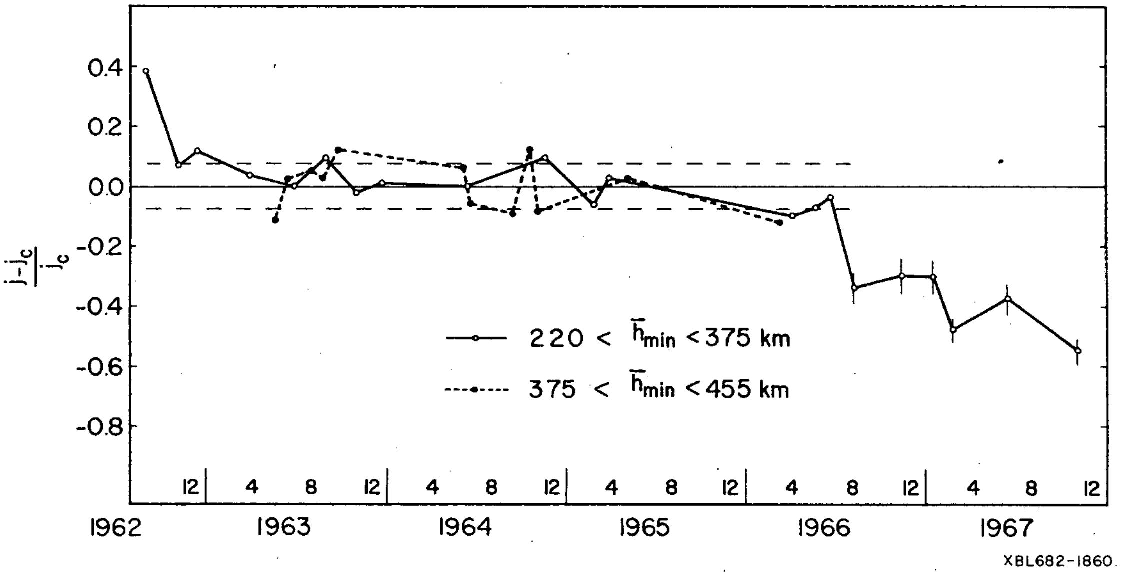
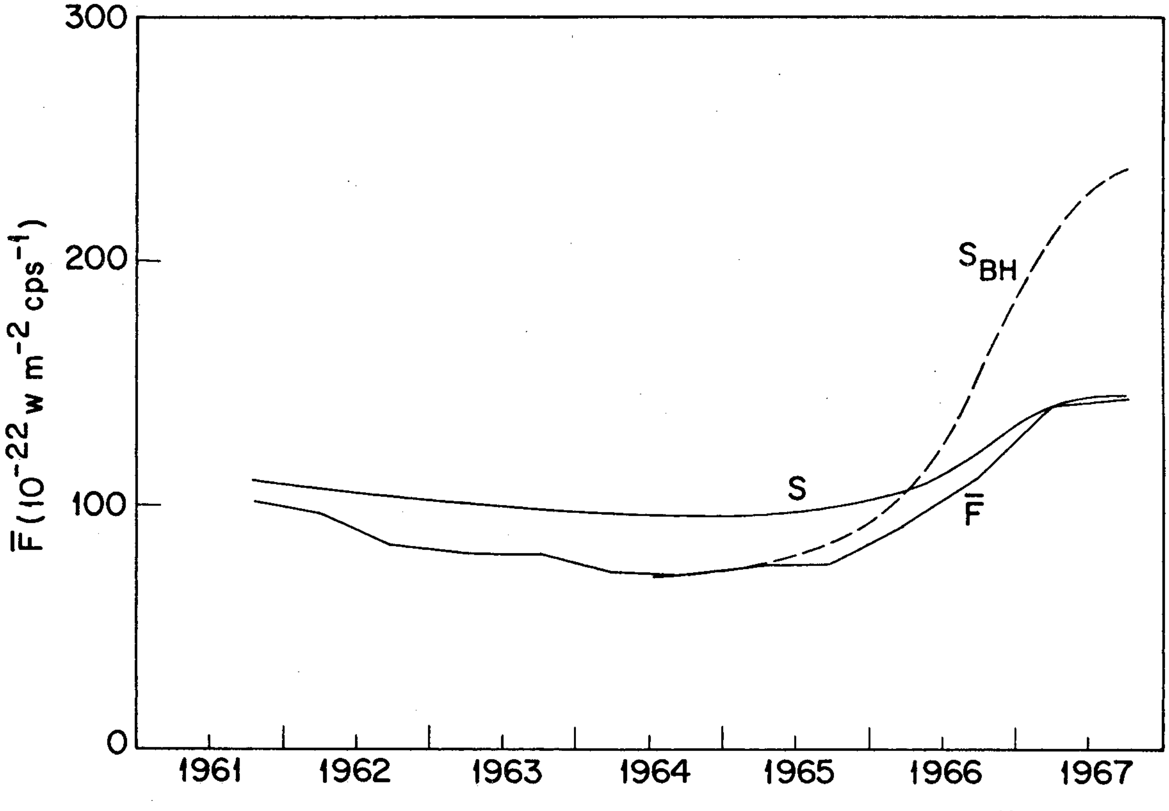

0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
$\frac{j-j_c}{j_c}$
220 < $\bar{h}_{min}$ < 375 km
375 < $\bar{h}_{min}$ < 455 km
12
4
8
12
4
8
12
4
8
12
4
8
12
4
8
12
1962
1963
1964
1965
1966
1967
XBL682-1860

Fig. 2



XBL682-1861

Fig. 3

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