

EVIDENCE FOR SOLAR-CYCLE CHANGES IN THE INNER-BELT PROTONS*

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Observations of high-energy photons geomagnetically trapped in the inner Van Allen belt have been carried out since September 1962. Between November 1962 and June 1966, the omnidirectional proton flux at 63 MeV remained constant to within $\pm 7.6\%$. 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.

Since September 1962, we have analyzed nuclear research emulsions recovered from more than 30 low-altitude, polar-orbiting satellite flights of duration 2-7 days. Parameters measured for these flight experiments include the omnidirectional flux of 57- to 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° S by 34° W (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 diam \times 0.48 cm thick) of Ilford G.2 and G.5 nuclear emulsions placed in small stainless-steel containers and mount-

ed on the recoverable vehicle immediately beneath the 2.5-g/cm² 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 asymmetries³ that the directional flux versus 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-yr 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 $j(63 \text{ MeV}) \text{ cm}^{-2} \text{ MeV}^{-1} \text{ day}^{-1}$ versus the flux-weighted average minimum mirror-point altitude, \bar{h}_{min} . The averaging of h_{min} is taken over the satellite ephemeris in 1-min intervals with the use of the Injun-3 proton-flux data⁴ and the Jensen and Cain 48-term expansion of the geomagnetic field.⁵ Calculations using

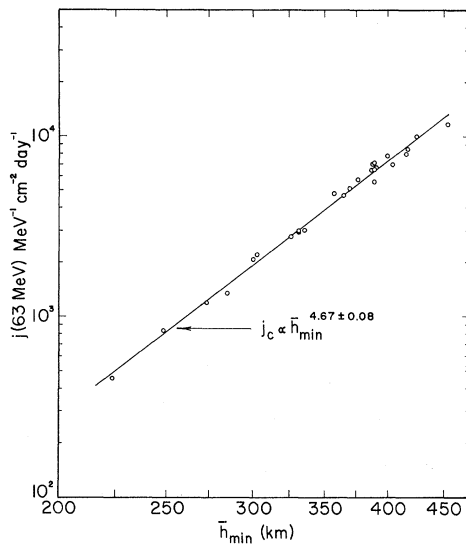


FIG. 1. Altitude dependence of the proton flux during the interval between November 1962 and June 1966. Plotted are the omnidirectional flux, $j(63 \text{ MeV}) \text{ MeV}^{-1} \text{ cm}^{-2} \text{ day}^{-1}$, versus the flux-weighted average mirror-point altitude \bar{h}_{min} . The solid line is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

1964-45A⁶ and Telstar⁷ 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 over-all agreement with our flux measurements. The statistical accuracy of each flux point is nominally $\pm 5\%$ standard deviation. The line through the data is a least-squares power-law fit given by $j_c = \text{const} \times \bar{h}_{\text{min}}^{4.67 \pm 0.08}$. The standard deviations of the data about the least-squares fit are $\sigma = \pm 7.6\%$. This error limits to 5-6% 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% standard deviation of the points about zero. The fractional deviations of the flux have been plotted for two ranges of altitude, $220 < \bar{h}_{\text{min}} < 375 \text{ km}$ and $375 < \bar{h}_{\text{min}} < 455 \text{ km}$. 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 Holeman⁸ who detected an abrupt order of magnitude increase in the low-altitude proton flux following the Starfish nuclear detonation on 9 July 1962. By the time of our first measurement, eight 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 sev-

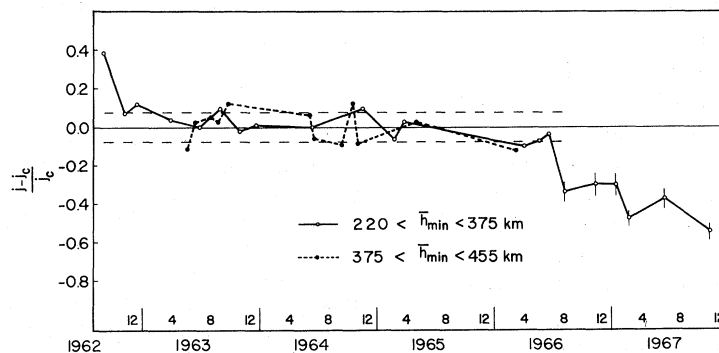


FIG. 2. Temporal behavior of the proton flux between September 1962 and November 1967). Plotted are the fractional deviations $(j - j_c) / j_c$ versus time at altitudes $220 < \bar{h}_{\text{min}} < 375 \text{ km}$ and $375 < \bar{h}_{\text{min}} < 455 \text{ km}$.

eral 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 solar minimum-activity 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 anticorrelated 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 atmosphere¹⁰ 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 correct 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 semiannual average, \bar{F} , for the year 1962 through 1967. The line denoted by S is the empirically correct Harris and Priester model parameter based on the observed \bar{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 propor-

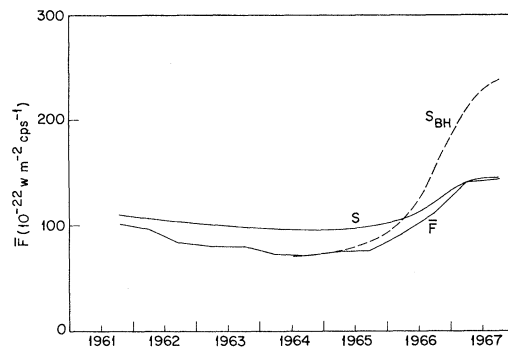


FIG. 3. Plot of the semiannual average 10.7-cm flux, \bar{F} , in units of 10^{-22} W m⁻² cps⁻¹, versus time. Curve labeled S is the corresponding atmospheric-model parameter of Harris and Priester (Ref. 9). Dashed curve denoted by S_{BH} is the Harris and Priester model parameter assumed by Blanchard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

tional 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.

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POSSIBILITY OF STRONG INTERACTIONS FOR THE INTERMEDIATE BOSON*

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It has been pointed out in the past that the hypothetical vector mesons of weak-interaction theory could well enjoy strong interactions of the form $f W_\mu^\dagger W^\mu H$, where H is some function of hadron fields, without directly contradicting experimental information on low-energy processes.¹ This possibility now seems much more attractive since it provides a "simple" explanation for the recently discovered failure of the high-energy cosmic-ray muon flux to obey the "sec θ " law.² On the other hand, it is not clear that it is consistent with the rather detailed picture of low-energy weak processes which has been built up over recent years, so the question must be re-examined with some care. It is the purpose of this paper to present a theory of strongly interacting W 's which maintains all the important features of the conventional theory for low-energy weak processes, while permitting significant deviations from them at high energies. The appearance of new physics at high energies seems an inescapable consequence of giving the W 's strong interactions, and should be regarded as a challenge to experiment rather than as a defect of the theory.

We wish to describe a system comprising leptons, hadrons, and a single, charged, vector meson. The Lagrangian should differ from the conventional one only by the addition of a strong-interaction term quadratic in the vector-meson field. For reasons which will become apparent as we go along, we choose

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu}^\dagger F^{\mu\nu} (1+S) - \frac{1}{2} m_W^2 W_\mu^\dagger W^\mu + g(W_\mu^\dagger J_\mu + W_\mu J_\mu^\dagger) + \mathcal{L}_h + \mathcal{L}_l, \quad (1)$$

where W is the vector-meson field; $F_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu$; S is a scalar object constructed out of hadron fields, involving no derivatives, and invariant under $SU(3) \otimes SU(3)$ transformations on the hadron fields; \mathcal{L}_h is the usual hadronic Lagrangian; \mathcal{L}_l is the free Lagrangian for leptons; and J_μ is the usual weak current,

$$J_\mu = J_\mu^h + J_\mu^l,$$

$$J_\mu^l = \bar{\mu} \gamma_\mu (1-\gamma_5) \nu_\mu + \bar{e} \gamma_\mu (1-\gamma_5) \nu_e,$$

$$J_\mu^h = \cos\theta (V_\mu^\dagger \pi^\dagger - A_\mu^\dagger \pi^\dagger) + \sin\theta (V_\mu^\dagger K^\dagger - A_\mu^\dagger K^\dagger).$$

This differs from the usual theory of boson-mediated weak interactions only through the addition of $\mathcal{L}_I^W = -\frac{1}{4} F_{\mu\nu}^\dagger F^{\mu\nu} S$. Such a theory is, of course, not renormalizable because of the derivative coupling of the vector meson. In spite of this, we shall be able to prove interesting theorems about the theory, and show that, if it exists, it does not lead to a contradiction with what we know about weak interactions. The same does not seem to be true of the simple renormalizable theories which one can write down. In any event, recent progress in quantum field theory³ leads one to hope that nonrenormalizable fields may eventually be put on a sound mathematical basis, so that there is no real reason to abandon the richness provided by nonrenormalizable theories.

Let us first study the strong-interaction properties of this theory and verify that the usual conservation laws hold. The hadron fields are presumed to provide a representation of $SU(3) \otimes SU(3)$. If we set $g=0$ and make an infinites-