ON THE ENERGY FLUXES OF LOW-ENERGY PROTONS AND POSITIVE IONS IN THE EARTH'S INNER RADIATION ZONE*

by

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A large energy flux, exceeding 50 ergs$(cm^2\text{-sec-sr})^{-1}$, of low-energy protons or ions within the energy range ~ 0.5 keV to 1 MeV at low altitudes in the earth's inner radiation zone was reported by Freeman [1962] via analysis of the responses of CdS crystals borne on the earth-satellite Injun 1. To our knowledge, these early results have neither been corroborated nor contested with further *in situ* measurements to the present date. Indeed, this large energy flux is remarkable as there exists no obvious energy source to maintain these positive ion fluxes against the taxation of heavy losses due to charge-exchange with the relatively high densities of ambient neutral and charged constituents of the terrestrial exosphere at these low altitudes. For example, an order-of-magnitude estimate of the energy source required to maintain these energy fluxes of low-energy ions, assuming charge-exchange as the principal loss mechanism, provides a basis of comparison of this source with the average energy precipitated into the earth's upper atmosphere in the auroral zones. If we assume that the energy fluxes reported by Freeman are predominantly ~ 1 keV protons (energy densities ~ 2×10^{-6} $erg(cm)^{-3}$) and the spatial distribution is confined between shells L = 1.25 to L = 1.70 and a spherical surface ~ 1000 km altitude above the earth's surface (~ 10^{27} cm^3) then the total energy of these low-energy protons is ~ 2×10^{21} ergs (see also Figure 1 which includes a summary of Freeman's [1962] observations). The charge-exchange lifetimes of ~ 1 keV protons at these altitudes, without consideration of comparable Coulomb scattering lifetimes, is generously $\sim 2 \times 10^3$ seconds [Liemohn, 1961]. Hence our gross order-of-magnitude estimate of the power required to maintain this reservoir of low-energy protons is $\sim (2 \times 10^{21}$ ergs$)$ $(2 \times 10^3$ seconds$)^{-1} = 10^{18}$ ergs$(\text{sec})^{-1}$, a source strength which is comparable to that required for the average particle precipitation into the auroral regions [Frank and Van Allen, 1964; O'Brien, 1964].

Toward obtaining a more comprehensive study of these large energy fluxes of positive ions we have conducted an initial survey of measurements of the differential energy spectrums of positive ions ($100 \text{ eV} \leq \frac{E}{Q} \leq 50 \text{ keV}$) in the inner radiation zone with an array of sensitive electrostatic analyzers borne on the earth satellite OGO 3 (launch date, 7 June 1966; initial apogee and perigee, 128,500 km and 6,700 km geocentric radial distances; inclination, 31°) [Frank, 1967a, 1967b, 1967c]. Typical responses of this instrumentation during traverses of the spacecraft through the inner radiation zone have been previously given by Frank [1967b]. Of principal interest is the observation that the positive-ion electrostatic analyzers in the energy range $100 \text{ eV} \leq \frac{E}{Q} \leq 50 \text{ keV}$ yield counting rates which are unmodulated by the variations in analyzer-plate voltages and are attributable to high-energy protons and electrons deep within the inner radiation zone, $L \leq 1.6$. We have examined data obtained during several perigee passes of OGO 3 in search of a large positive ion flux and have summarized the upper limits for energy fluxes of positive ions ($Q \leq 2$) at ten locations in the inner zone in Figure 1. These upper limits have been generously calculated by assuming that the responses of the electrostatic analyzers are wholly due to a low-energy positive ion flux. No evidence for the large energy flux in the inner radiation zone as reported by Freeman has been found with the present measurements of positive ions within the energy range 100 eV $\leq \frac{E}{Q} \leq$ 50 keV. In fact a cursory examination of the summary of Injun 1 observations [Freeman, 1962] and of the present OGO 3 measurements in a B-L coordinate system (Figure 1) emphasizes that the energy fluxes reported by Freeman exceed the upper limits provided by the electrostatic analyzer array borne on OGO 3 by factors ~ 10 to 100. It should be noted by the reader that all measurements presented here in Figure 1 and in tabular form were obtained at local pitch angle $\alpha = 90°$. Several upper limits for energy fluxes nearer to the magnetic equatorial plane than the Injun 1 observations above are given in Table I. At these lower magnetic latitudes there is still no signature of a large positive-ion energy flux within the energy range 100 eV $\leq \frac{E}{Q} \leq$ 50 keV. Upper limits for negative-ion (100 eV $\leq \frac{E}{Q} \leq$ 50 keV) energy fluxes as derived from the responses of companion electron electrostatic analyzers are within a factor ~ 2 equal to the simultaneously measured upper limits for positive-ion energy fluxes reported here.

TABLE I

UPPER LIMITS FOR ENERGY FLUXES
OF LOW-ENERGY POSITIVE IONS IN
THE EARTH'S INNER RADIATION ZONE

OGO 3
$100 \text{ eV} \leq \frac{E}{Q} \leq 50 \text{ keV}$
June-July, 1966

L, earth radii	B, gauss	Energy Flux*(upper limit), $erg(cm^2\text{-}sec\text{-}sr)^{-1}$
1.34	0.150	2.0
1.35	0.128	4.4
1.54	0.109	2.2
1.59	0.117	2.6

*At local pitch angle $\alpha = 90°$

Since the Injun 1 observations with CdS crystals cover the energy range ~ 500 eV to ~ 1 MeV, there remains the possibility that the energy flux is shared predominantly by positive ions in the energy range exceeding that of the OGO 3 electrostatic analyzer, or ~ 50 keV to 1 MeV. In order to investigate this possibility we have analyzed unpublished Injun 4 (launch, 21 November 1964; initial apogee and perigee altitudes, 2502 km and 527 km; inclination, 81°) observations of proton $E > 30$ keV energy fluxes (d. c. scintillator, courtesy of J. D. Craven) and of proton $0.5 \leq E \leq 4.2$ MeV intensities (solid-state detector, courtesy of S. M. Krimigis and T. A. Armstrong) during January 1965 in order to provide the upper limits for these proton energy fluxes as summarized in Table II. Again these energy fluxes are less than the Injun 1 values by factors ~ 10 to 100.

It is possible that (1) the large energy fluxes of positive ions are present only near local midnight where all Injun 1 measurements were obtained [Freeman, 1962] and hence that the OGO 3 observations during local day presented here simply imply that these low-energy positive ions are confined to a restricted local-time range centered near local midnight (the Injun 4 measurements are also near local midnight) or (2) these low-energy positive ions have disappeared via an occasional loss mechanism over the period extending from mid-1961 to 1966. However, on the basis of our present findings of upper limits for these energy fluxes which are less by factors of 10 to 100 when compared to the energy fluxes reported by Freeman over a large region of the inner zone we conclude that most probably energy fluxes of positive ions (500 eV $\lesssim E \lesssim 1$ MeV), ~ 50 ergs $(cm^2\text{-sec-sr})^{-1}$, are not a feature of the inner radiation zone.

TABLE II

SEVERAL UPPER LIMITS FOR ENERGY FLUXES OF PROTONS IN THE EARTH'S INNER RADIATION ZONE

INJUN 4
January 1965

L, earth radii	B, gauss	Energy Flux*(upper limits), $erg(cm^2\text{-sec-sr})^{-1}$ protons+ $E > 30$ keV	Energy Flux*(upper limits), $erg(cm^2\text{-sec-sr})^{-1}$ protons± $0.5 \leq E \leq 4.2$ MeV
1.35	0.151	2.5	5×10^{-4}
1.49	0.182	0.2	6×10^{-3}
1.50	0.167	1.5	- -
1.51	0.170	1.0	2.6×10^{-4}
1.55	0.179	0.7	1.4×10^{-2}

*At local pitch angle $\alpha = 90°$
+Courtesy of J. D. Craven
±Courtesy of S. M. Krimigis and T. A. Armstrong

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Figure Captions

Figure 1. Comparison of Injun 1 observations of large energy fluxes of protons or positive ions (500 eV $\lesssim$ E $\lesssim$ 1 MeV) [Freeman, 1962] and OGO 3 measurements of the upper limits for energy fluxes of positive ions (100 eV $\leq \frac{E}{Q} \leq$ 50 keV) in the earth's inner radiation zone.

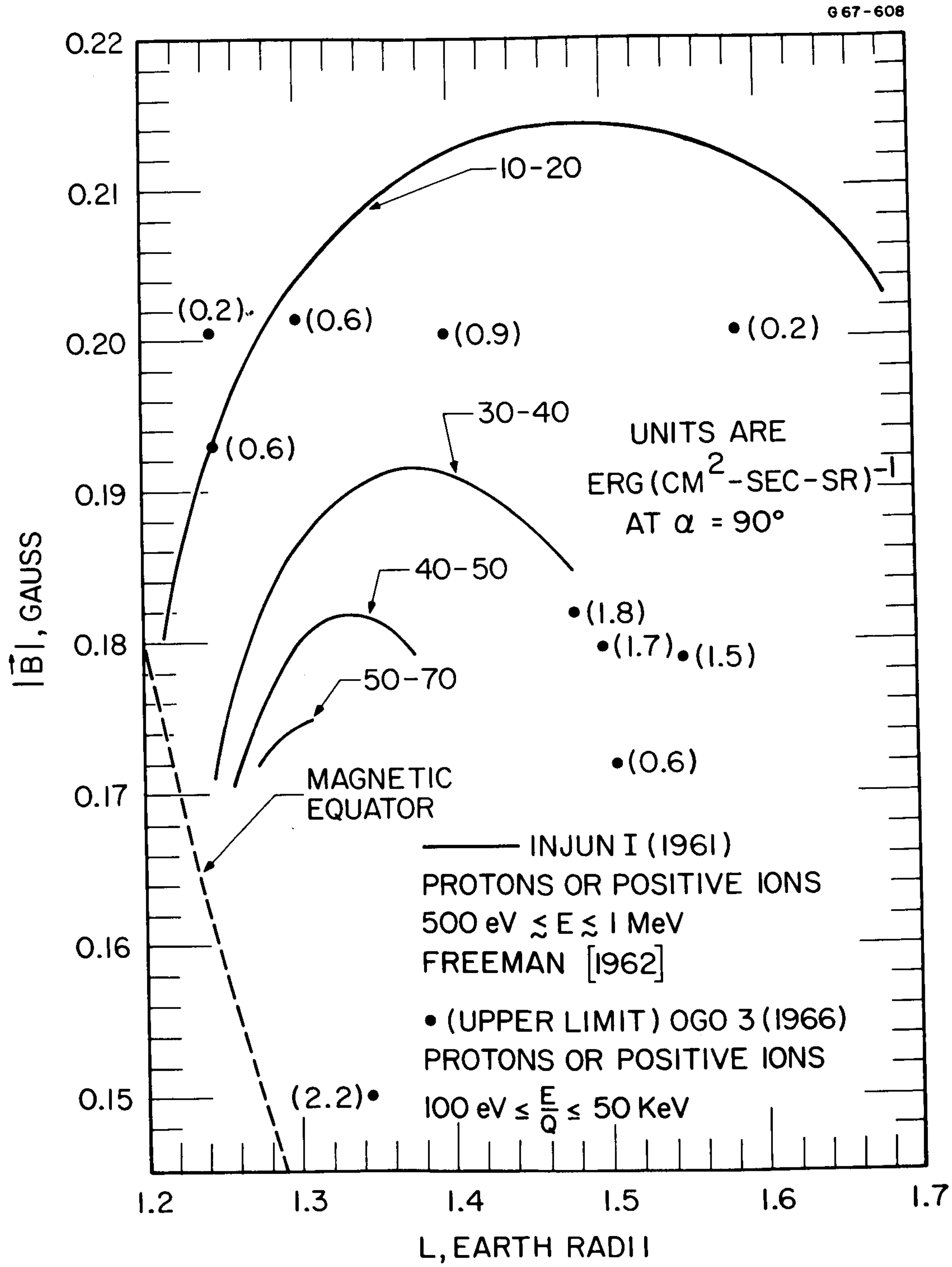
G 67-608
0.22
0.21
0.20
0.19
0.18
0.17
0.16
0.15
|B|, GAUSS
1.2
1.3
1.4
1.5
1.6
1.7
L, EARTH RADII
10-20
30-40
40-50
50-70
(0.2)
(0.6)
(0.9)
(0.2)
(0.6)
(1.8)
(1.7)
(1.5)
(0.6)
(2.2)
UNITS ARE
ERG (CM²-SEC-SR)⁻¹
AT α = 90°
MAGNETIC
EQUATOR
INJUN I (1961)
PROTONS OR POSITIVE IONS
500 eV ≲ E ≲ 1 MeV
FREEMAN [1962]
• (UPPER LIMIT) OGO 3 (1966)
PROTONS OR POSITIVE IONS
100 eV ≤ E/Q ≤ 50 KeV

Figure 1

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A search for the large energy fluxes of low-energy protons or positive ions ($500 \text{ eV} \lesssim E \lesssim 1 \text{ MeV}$) in the earth's inner radiation zone as previously reported by Freeman via the analysis of the responses of CdS crystals borne on the earth-satellite Injun 1 is reported here utilizing recent measurements of energy fluxes of protons and positive ions within the energy range 100 eV to 4.2 MeV with earth-satellites OGO 3 and Injun 4. These recent measurements provide upper limits for these proton and positive-ion energy fluxes which are less by factors ~ 10 to 100 when compared to the Injun 1 observations during 1961. The upper limits reported here strongly indicate that large energy fluxes of low-energy protons or positive ions, ~ 50 ergs $(cm^2\text{-sec-sr})^{-1}$, are not a feature of the inner radiation zone.

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Inner Radiation Zone						
Magnetosphere						
Trapped Radiation						

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