ARTIFICIAL PERTURBATIONS OF THE RADIATION BELTS

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A review is given of the properties of the radiation belts which have been produced by high-altitude nuclear detonations. The low-yield, Argus devices, 1, 2, and 3, and the Soviet test of 1 November 1962 injected intense electron fluxes in narrow L-shell intervals, with peaks at L = 1.72, 2.11, 2.17, and 1.77, respectively. The energy spectra of the electrons were indistinguishable from the equilibrium fission beta spectrum, and the fluxes initially decayed at rates approximately proprotional to $(\text{time})^{-1.1}$. Across L shells the electrons diffused very slowly ($\Delta[\text{full width of peak at half maximum}]^2/\Delta[\text{time}] \approx 10^{-4}$ [earth radii]^2/day). The high-yield devices, Starfish and the Soviet tests of 22 October and 28 October 1962, injected electrons over wide ranges of L -- extending from L values near the burst locations ($L \approx 1.14$ for Starfish, $L \approx 1.8$ for the Soviet tests) to $L \approx 6$. At L values near the lower boundary, the electron spectra were similar to the equilibrium fission beta spectrum; but the spectra appeared to be softer at the higher L values. The decay rates at $L \lesssim 1.25$ were in agreement with predictions based on atmospheric scattering theory; but at $L > 1.25$ the decay rates were higher, indicating the predominance of electromagnetic interactions. In addition to injecting energetic electrons, a high-altitude detonation may also cause previously-trapped particles to be redistributed. Evidence for the occurrence of such a redistribution is presented and mechanisms which may have caused the redistribution are discussed.

INTRODUCTION

Major changes in the population and redistribution of energetic particles in the radiation belts have resulted from the detonation of nuclear devices at high altitudes. In regard to radiation damage, the most important particles which have been added to the radiation belts are the high-energy electrons emitted by fission fragments undergoing beta decay. Other particles, such as the protons and electrons emitted by neutron decay, are neither significantly penetrating nor sufficiently concentrated to form damaging fluxes. Redistribution and loss of trapped particles also occur because of the interaction of the particles with electromagnetic disturbances initiated by the nuclear explosions.

In this report the characteristics of the artificially-injected electrons and an observed redistribution of the natural trapped particles by Starfish are discussed. Nearly all of the data available on the artificial belts were obtained at times after the electrons had spread approximately uniformly around the earth. It must be remembered that within about an hour or so after a burst the electron flux east of the burst is much higher than indicated by these data. If the burst is west of the South Atlantic geomagnetic anomaly, the flux is higher, not only because the "permanently"-trapped electrons are more concentrated during their initial drift motion toward the east, but also because it includes the "transiently"-trapped electrons. Transiently-trapped electrons are defined as those electrons which have mirror points so low that they become absorbed by the atmosphere, west of the anomaly, during their initial drift motion around the earth. An estimate of the early-time flux is given in the following section.

A good reference for this subject material is the Trapped Radiation Handbook (ref. 1), particularly Section 6: "History of the Artificial Belts," by M. Walt, and Section 7: "Particle Injection by Nuclear Detonations," by G. T. Davidson and R. W. Hendrick, Jr.

EARLY TIME FLUX

A model for the injection of electrons into the earth's field by high-altitude nuclear explosions, as well as a calculation of the resulting flux of trapped betas as a function of B,L, time and geographical coordinates, are given in ref 2. In figure 1 the distributions of the beta flux at early times, based on a simplified model (ref. 1), are presented. These distributions were computed by assuming that all of the electrons which finally reached the equilibrium distribution were initially in the longitudinal sector, $\Delta\varphi$. Moreover, a dipole magnetic field and an exponential energy sepctrum which approximates the equilibrium fission beta spectrum were used in this analysis. The upper figure gives the equatorial flux as a function of longitude at various times for a source at L = 1.2, and the lower figure gives the same information for a source at L = 1.6. In both figures $\Delta\varphi$ is about the width of the sector that contained the Starfish magnetic bubble (ref. 3). The flux is given in units of the equilibrium flux. In addition to the magnitude of the enhancement, it is interesting to note fram these figures that the maximum value of the flux moves toward the east at a rate that is about the same as that of a low-altitude satellite. Hence, a satellite in a direct, equatorial orbit may remain in the enhanced flux for the entire time required for the flux to become uniform in longitude.

In order to estimate the early-time flux from the longitudinally-uniform fluxes given in succeeding sectors, higher factors than those shown in figure 1 are required. This is necessary because the early-time fluxes also contain the transiently-

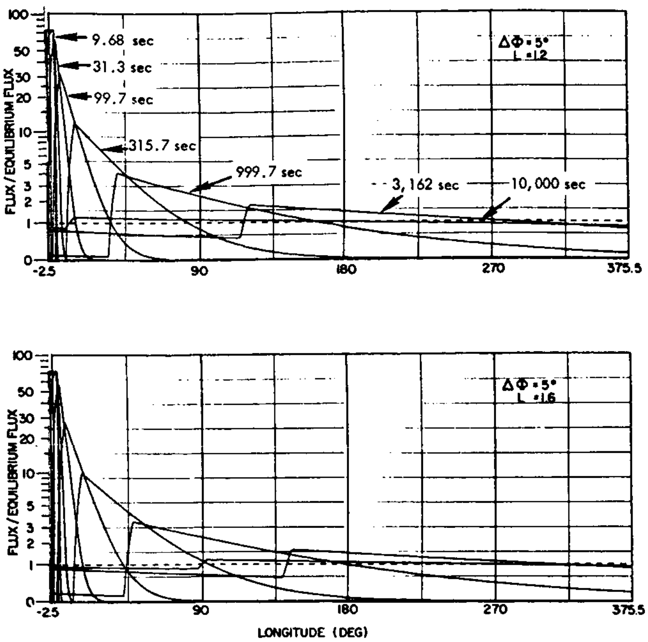

FIGURE 1.--Longitudinal distribution of injection betas at the indicated times. At t=0 the betas were assumed to be in the longitudinal sector Δφ [from Davidson and Hendrick, ref. 1].

Table 1

Properties of Electron Shells Formed by the Argus Tests

Device	Date	Location	Altitude km	L Value at Peak	$\Delta(FWHM)^2/\Delta t$ R_E^2/day	n in t^{-n} decay rate
Argus 1	27 Aug. 1958	12°W 38°S	~ 200	1.72	2.0×10^{-5}	1.17
Argus 2	30 Aug. 1958	8°W 50°S	~ 250	2.11	4.1×10^{-4}	1.15 ± .03
Argus 3	6 Sept. 1958	10°W 50°S	~ 500	2.17	5.5×10^{-4}	1.09

trapped electrons, which are not included in the simplified analysis, and the electrons which are subsequently lost by scattering processes.

THE ARGUS TESTS

The Argus tests, which were conducted in the fall of 1958, were specifically designed to produce intense electron belts (ref. 4). Three devices were detonated at altitudes higher than about 200 km in the vicinity of the South Atlantic anomaly, where the injection altitude for "permanent" trapping is a minimum. The yields of the devices were in the range 1-2 kT. Information on the electron belts formed by the explosions was obtained with the Explorer 4 satellite (refs. 1, 5-7) and with sounding rockets (refs. 8 and 9). Each device produced a narrow electron shell which was approximately centered at the L value of the burst location.

Table 1 lists the locations and dates of the bursts; the L value of the maximum electron intensity; the apparent cross-L diffusion coefficient, $\Delta(FWHM)^2/\Delta t$, where FWHM is the full width of the shell at half maximum; and parameters of the power law decay rate. Most of the entries in this table are from the analysis of the satellite data by George (ref. 10) and Manson et al. (ref. 7). The data, as reduced by these authors, are given in figures 2-4. Figure 2 pertains to the Argus 1 shell. Figure 2a gives the time variation of the counting rate of Channel 3 (geometric factor = 0.6 cm^2, energy threshold ≈ 3 MeV) after corrections are made for background and the dead time of the detector. The satellite pass numbers are given at the data points. The Channel 3/Channel 1 ratios in figure 2b give a measure of the energy spectrum.

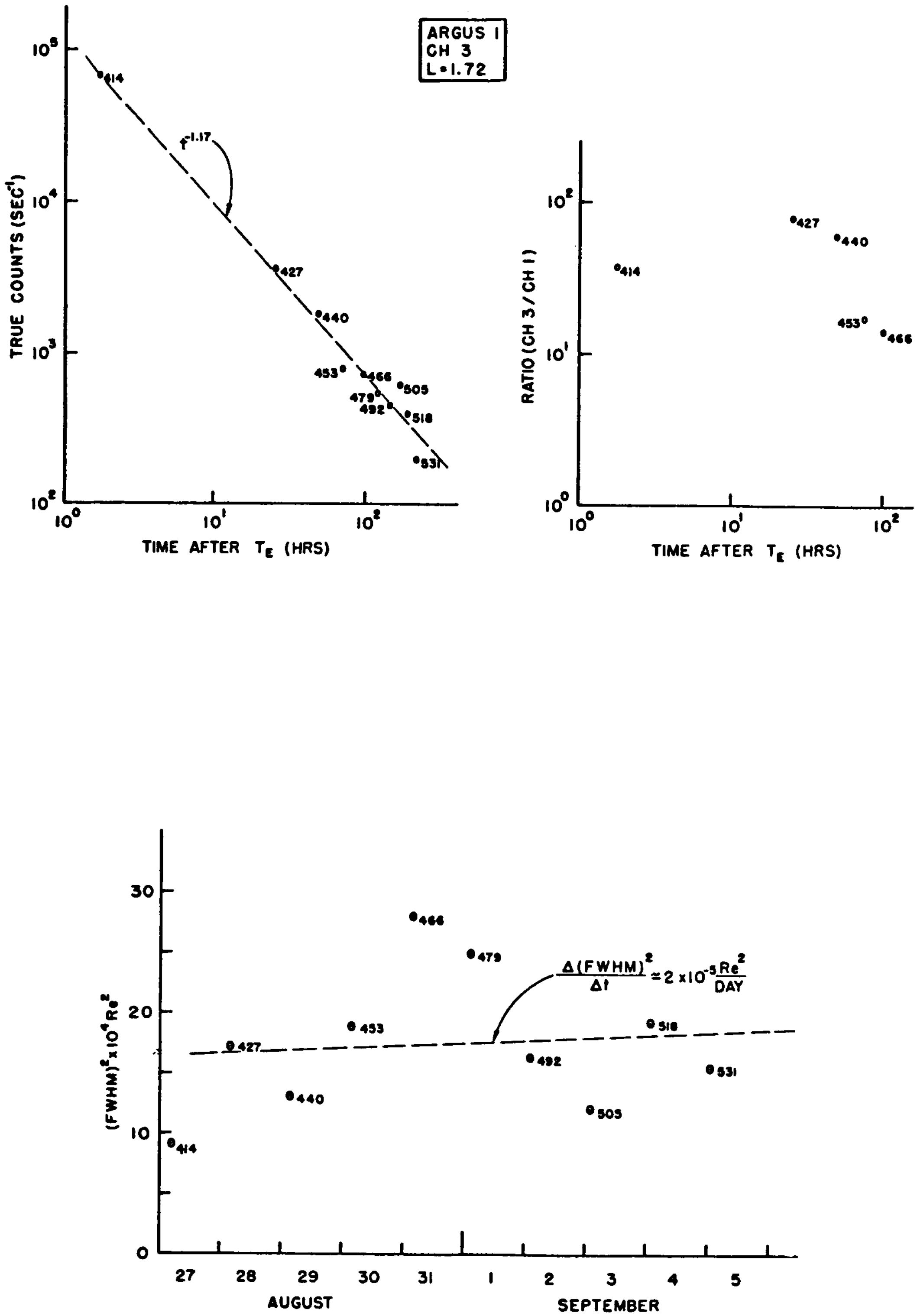

FIGURE 2.--(a) Decay; (b) Channel 3 (E > 3 MeV)/Channel 1 (E > 5 MeV) ratios; and (c) shell diffusion for Argus 1. Omnidirectional count-rates minus background are the data employed. A least squares fit to $C = C_o t^{-n}$ yields n = 1.17. B ranges from 0.225 (Pass 414) to 0.183 gauss (Pass 531). The diffusion coefficient, $\Delta(FWHM)^2/\Delta t$, for the shell was calculated by a least squares fit to the Channel 3 data [from ref. 7].

A ratio of about 100 is appropriate for the equilibrium fission beta spectrum. (Channel 1 had an energy threshold of about 5 MeV and a geometric factor similar to that of Channel 3.) Figure 2c shows the square of the measured width of the shell at the various passes. Similar data for the Argus 2 and 3 shells are shown in figures 3 and 4. Note that the scatter of the satellite data in figure 3a is so great that a decay curve for the second event is not drawn. For this event the entry in the table, $n = 1.15 \pm 0.03$, is from the sounding rocket data which were analyzed by Cladis and Walt (ref. 9).

The satellite data, as well as the sounding-rocket data for the second event, revealed that the energy spectra of the Argus 2 and 3 electrons, in space and time, were indistinguishable from the equilibrium fission-beta spectrum. A somewhat harder spectrum of the Argus 1 electrons is indicated in figure 2b.

Pitch-angle distributions of the electrons injected by Argus 1 and 2 were measured with a directional detector (Ch 2) on the satellite. Early after Argus 1 the pitch-angle distribution changed rapidly during a rotation period of the satellite. But after about a day, the distribution was approximately normal, i.e., it was about the same as that of the natural radiation. The Argus 2 electrons were found to have a normal distribution at the time of the first measurement, 1.87 hours after the burst. The maximum directional fluxes measured at 90° to the field 1.8 hours after Argus 1 and 1.87 hours after Argus 2 were 1.5×10^6 and 5.28×10^5 electrons/cm^2·sec·ster, respectively. The corresponding widths-at-half-maximum of the pitch-angle distributions were 20° and 18°.

STARFISH

The Starfish device was detonated on 9 July 1962 at an altitude of about 400 km above Johnston Island (190.5°E, 16.7°N). On the basis of the information obtained from the Argus tests, significant trapping was not expected. Over Johnston Island the minimum injection altitude for "permanent" trapping is higher than 1000 km! However, because of the high yield (1.4 MT) of the device, fission fragments jetted across field lines (ref. 11) and injected electrons to L values of 6 or more (ref. 12). The radiation damaged several satellites which were in orbit at that time. Moreover, the duration of the radiation was much greater than expected.

The distribution of the injected electrons is still controversial as discussed by Walt in ref. 1. The satellites in orbit at the time of the burst were too low (< 1000 km) to observe the full distribution and they did not contain detectors which were designed to detect high fluxes of fission-fragment betas. It appears that the best data on the Starfish injection was obtained by the Telstar satellite, which was launched the next day after the Starfish burst. The satellite was in a good orbit (apogee, 5630 km; perigee, 955 km; inclination, 44.7°), but the data are still somewhat ambiguous because of the uncertainty in the background electron flux. The flux contours in R,λ coordinates shown in figure 5 were obtained by Newkirk and Walt (in ref. 1) from an analysis of the Telstar data taken 2 days after Starfish. These data were taken with a solid-state detector which had an energy threshold of about 400 keV (ref. 13). It was not possible to subtract the background; therefore, these fluxes include the natural electrons of energies greater than 400 keV. However, since these fluxes were observed to decay at later times and no unusual geomagnetic activity was recorded several days before the event, the background contribution may have been small.

By using the jetting-debris model described in ref. 14, a distribution of betas similar to that shown in figure 5 was computed for a Starfish-type burst. The daily fluence of the betas incident on circular-orbit satellites is shown in figure 6 (ref. 1), where the daily fluence is plotted as a function of the altitude of the satellite for various orbital inclination. Satellites in the inclined orbits receive high fluences at low altitudes, as shown in the figure, because they traverse the region of the South Atlantic anomaly.

The energy spectrum of the electrons, as discussed by Walt in ref. 1, was similar to an equilibrium fission beta spectrum at L values less than about 1.25, but it became softer toward higher L values.

The decay rate of the trapped betas was found to depend sensitively on B and L. At $L \lesssim 1.25$, the decay rate was found to be in good agreement with theoretical results (ref. 15) based on the scattering of the electrons by the atmosphere. An example of the experimental data on the decay rate and the comparison with the theoretical curves is shown in figure 7 (ref. 16). The experimental data taken at the lower altitudes are displaced downward, as shown in the figure, when corrections are made for the enhanced background of high-energy protons produced by Starfish. This background, which was observed by Filz and Holeman, ref. 17, will be discussed later. A compilation by Davidson (ref. 1) of the apparent, e^{-1} decay time, as determined from data on the decay of betas injected by various nuclear detonations, as a function of L, is shown in figure 8. The theoretical curve of Walt (ref. 29) is also shown in the figure. Note that above L values of about 1.25, the apparent loss rate is higher than that which results from collisions. In this region the increased importance of electromagnetic interactions is indicated.

THE HIGH-ALTITUDE SOVIET TESTS

In late 1962 the Soviets detonated three devices which injected high fluxes of betas into trapped orbits. The bursts occurred on 22 October, 27 October, and 1 November. Contours in R,λ coordinates of the omnidirectional flux derived from the Telstar data for the first and second events are shown in figures 9 and 10, respectively (from refs. 1 and 14). The dashed lines are extrapolations of the flux from the measured regions. Note that, as in the case of Starfish, the betas were distributed over a wide region of the magnetosphere. In each event the intensity increased sharply at the inner boundary, $L \approx 1.8$, reached a double maximum with peaks at $L \approx 1.8$ and 2.2, and decreased monotonically toward higher L values.

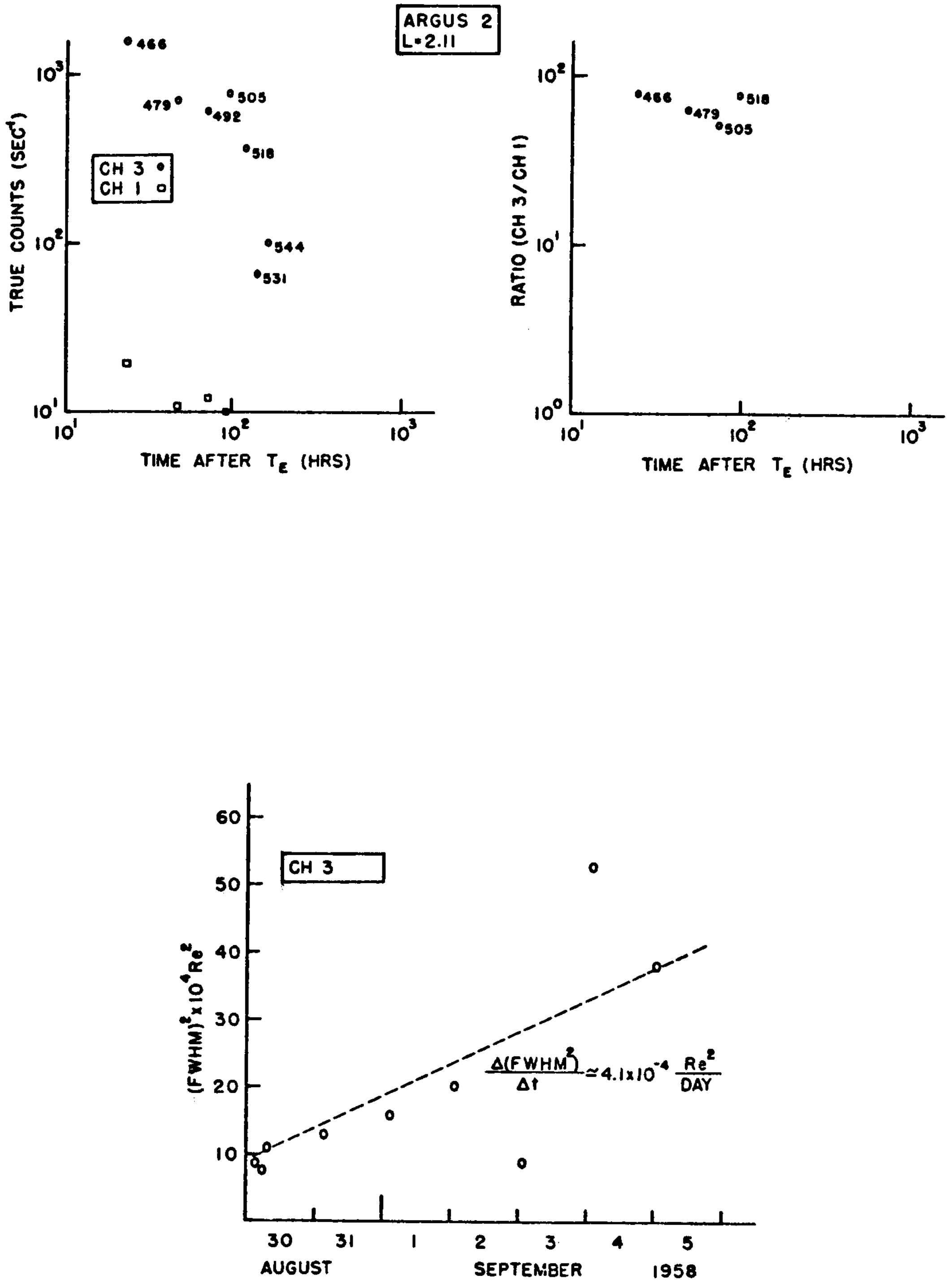

FIGURE 3.--(a) Decay; (b) Channel 3 (E > 3 MeV)/Channel 1 (E > 5 MeV) ratios; and (c) shell diffusion for Argus 2. B values range from 0.248 (Pass 466) to 0.222 gauss (Pass 531). A least squares fit to the count-rate data was not made due to the scatter of the data [from ref. 7].

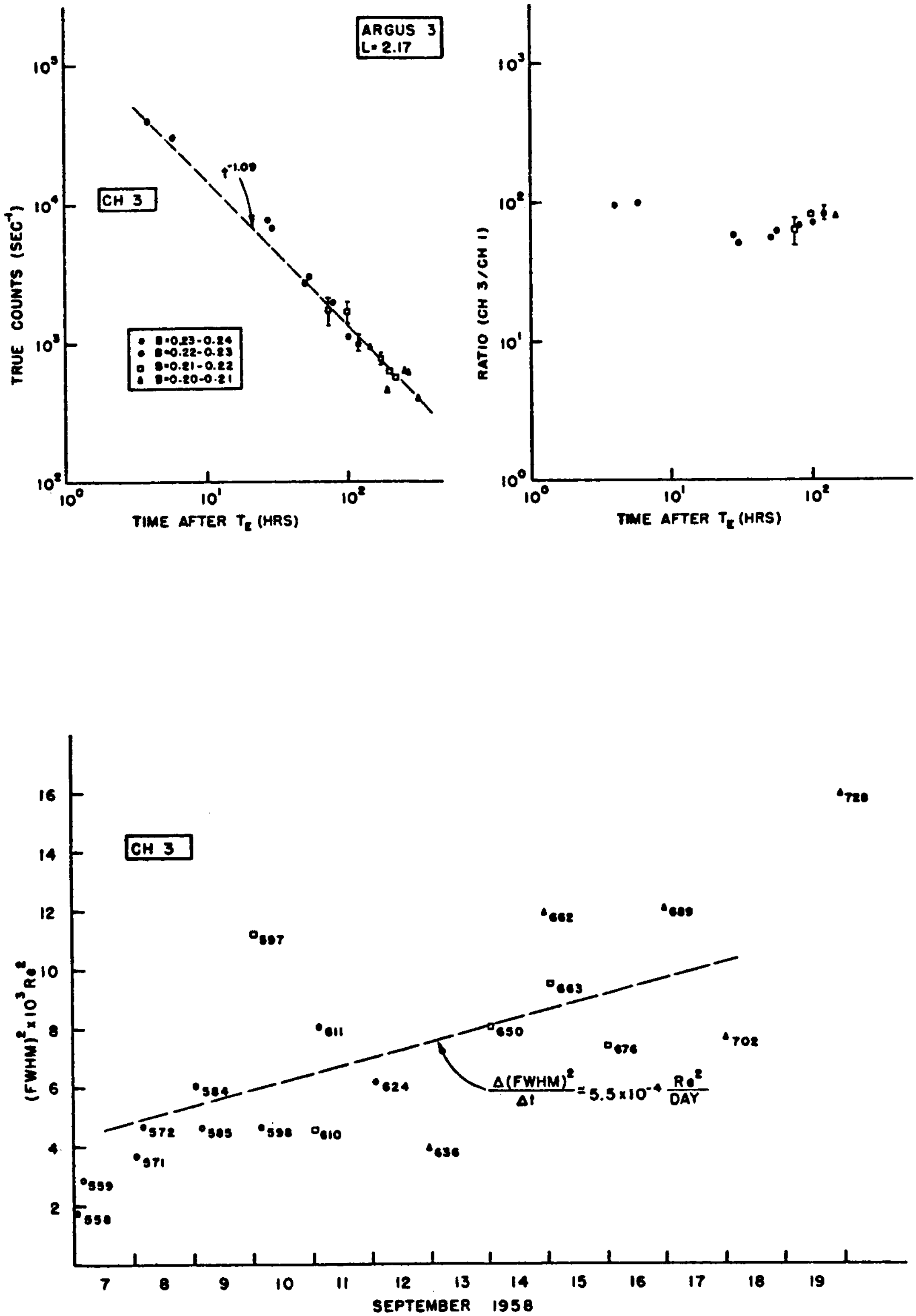

FIGURE 4.--(a) Decay; (b) Channel 1 (E > 3 MeV)/Channel 1 (E > 5 MeV) ratios; and (c) shell diffusion for Argus 3. The range of B values is indicated. The time decay of the count rate is proportional to $t^{-1.09}$ [from ref. 7].

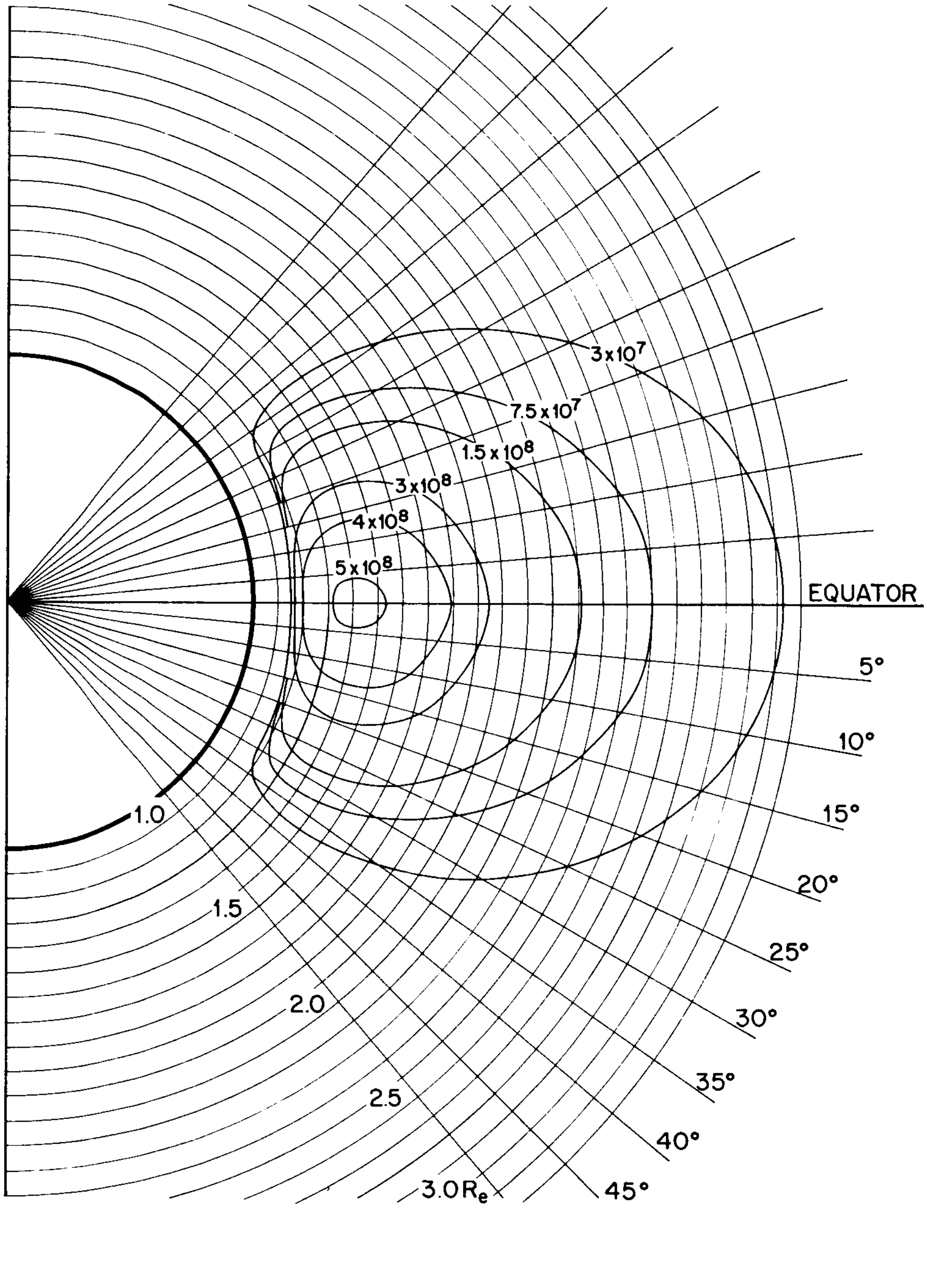

FIGURE 5.--Flux contours two days after Starfish, as determined from Telstar data by Newkirk and Walt. The numbers are the intensities ($cm^{-2}sec^{-1}$) of fission spectrum electrons required to give the observed counting rates of the Telstar solid-state detector having a threshold of about 400 keV [from Walt, ref. 1].

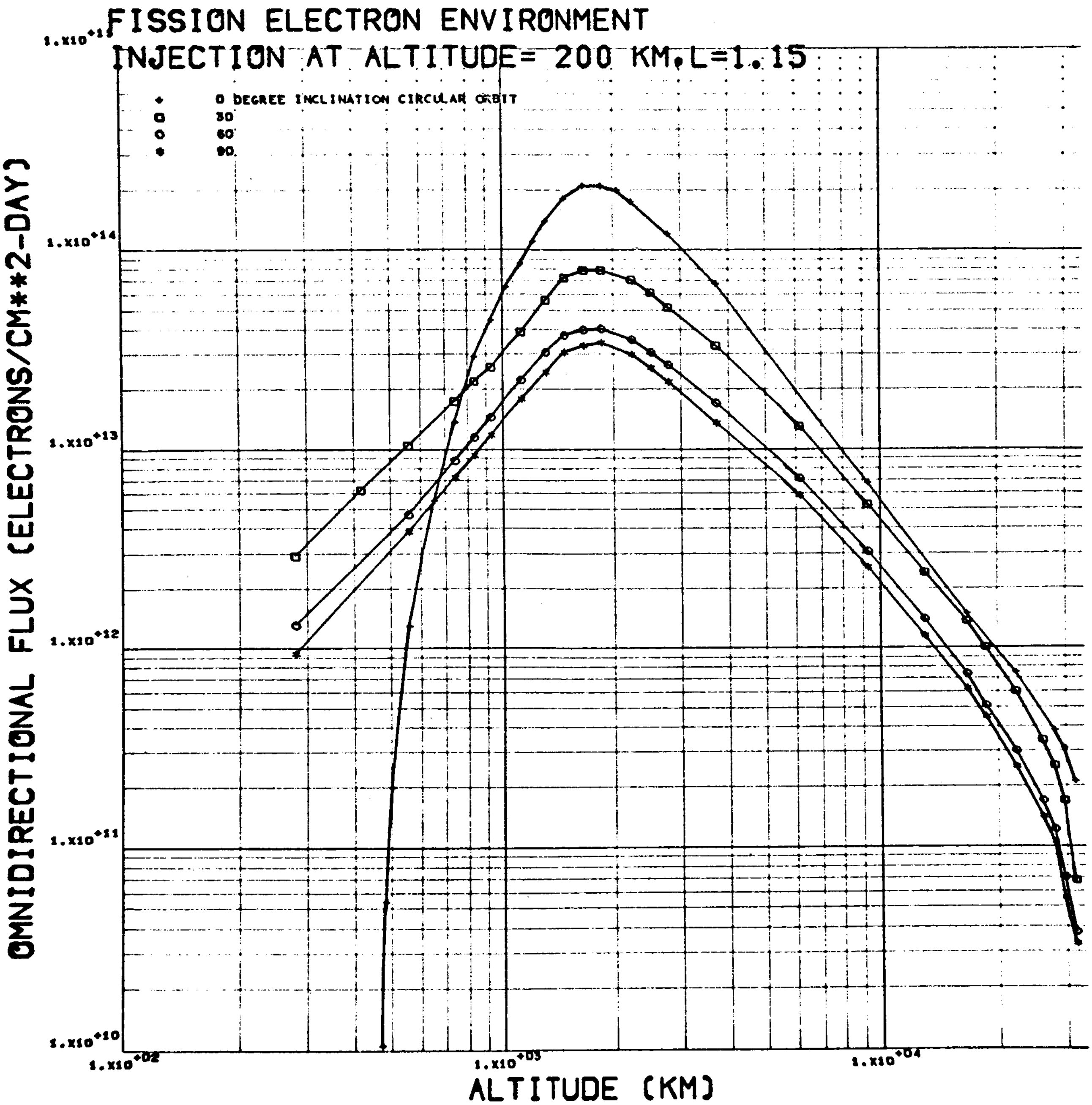

FIGURE 6.--Daily omnidirectional fluence of fission electrons incident on circular orbit satellites as function of satellite altitude for specified orbital inclinations (1-megaton fission yield) [from Crowther and Harless, ref. 1].

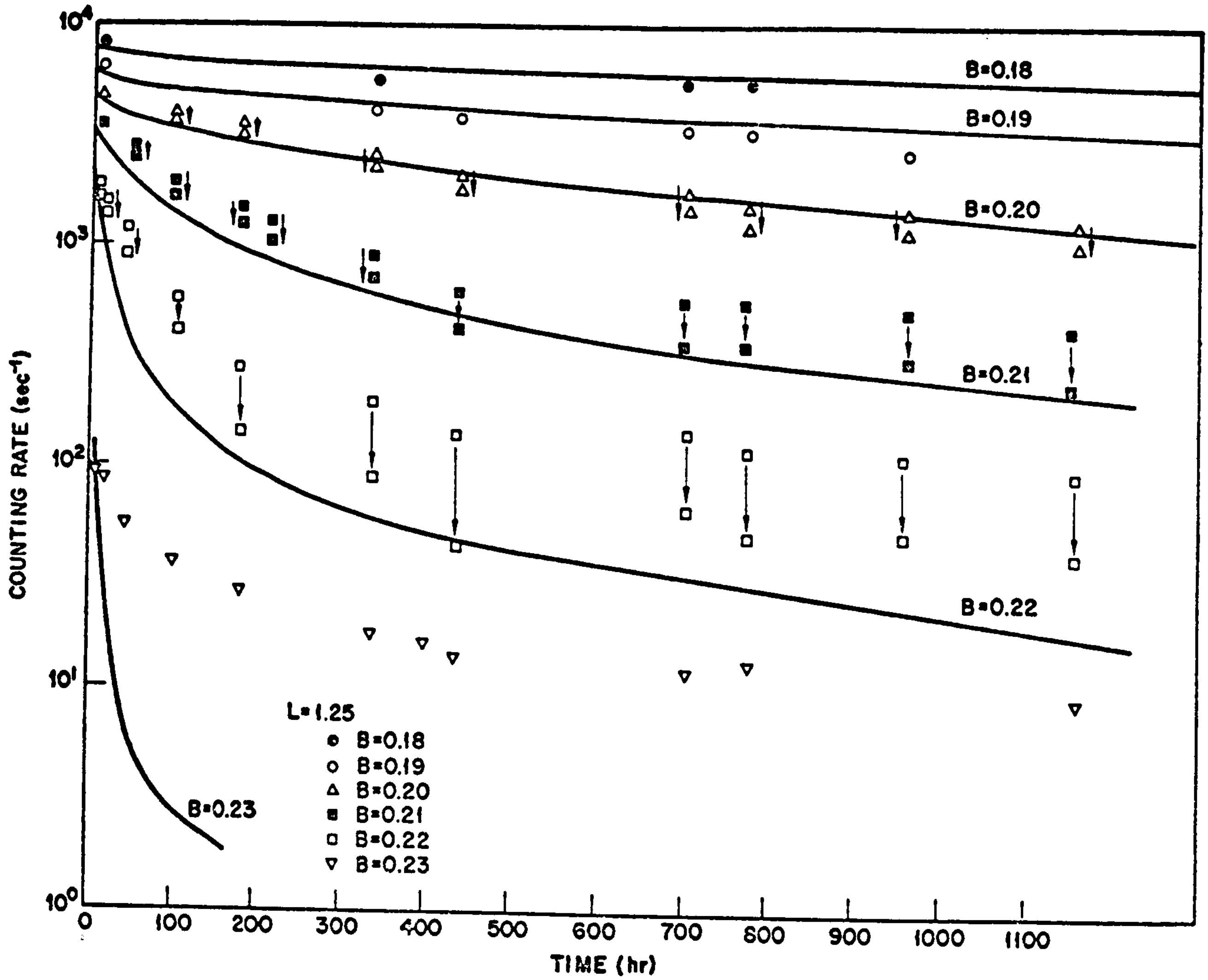

FIGURE 7.--Comparison of experimental and theoretical (solid lines) values for the time decay of the Starfish radiation belt (ref. 16). The lower sets of points for B = 0.20, 0.21, and 0.22 gauss have been corrected for the enhanced proton background observed by Filz and Holeman (ref. 17) [from Walt, ref. 1].

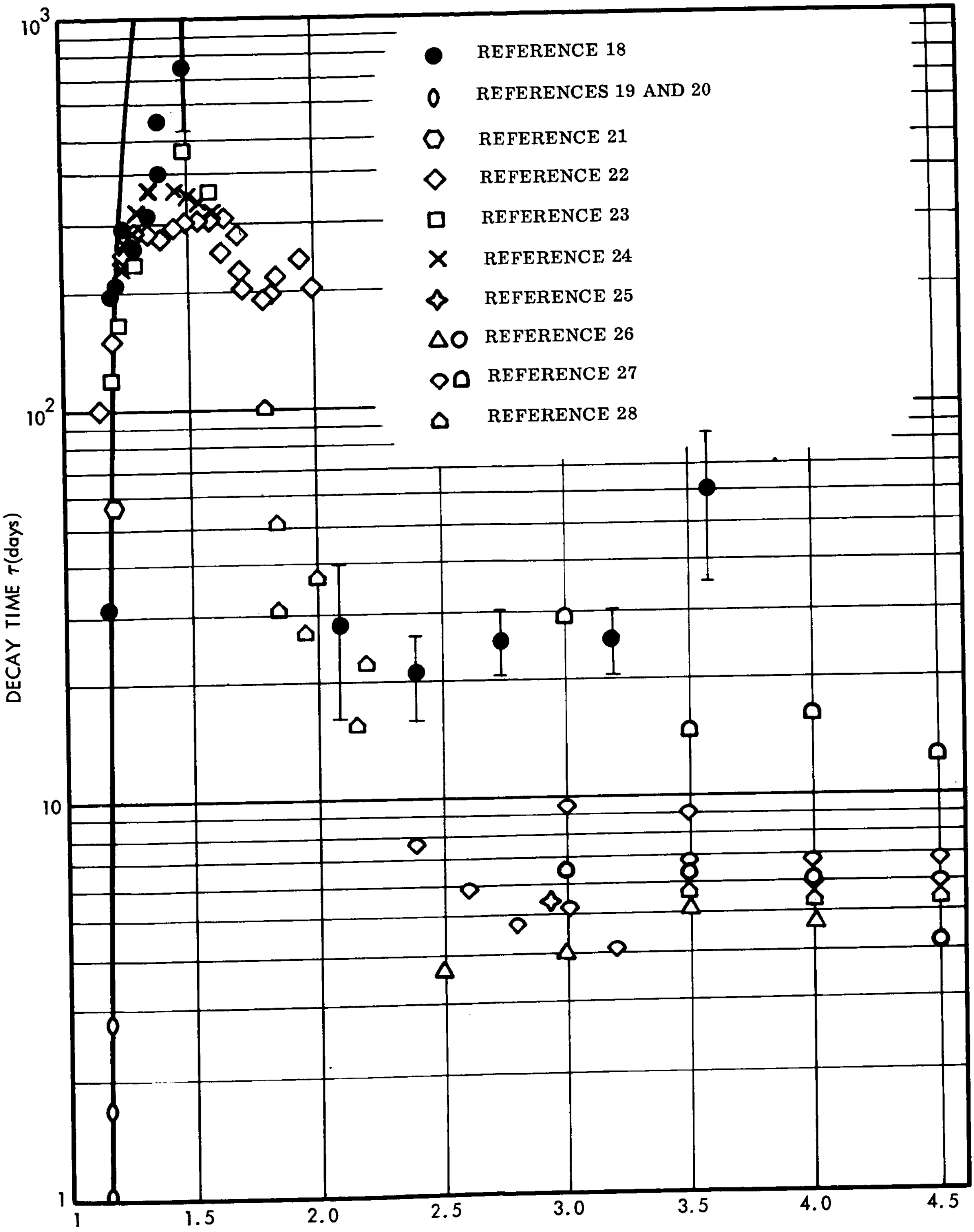

FIGURE 8.--Compilation of apparent e^{-1} decay times from experimental measurements of trapped electrons injected by nuclear tests [from Davidson and Hendrick, ref. 1].

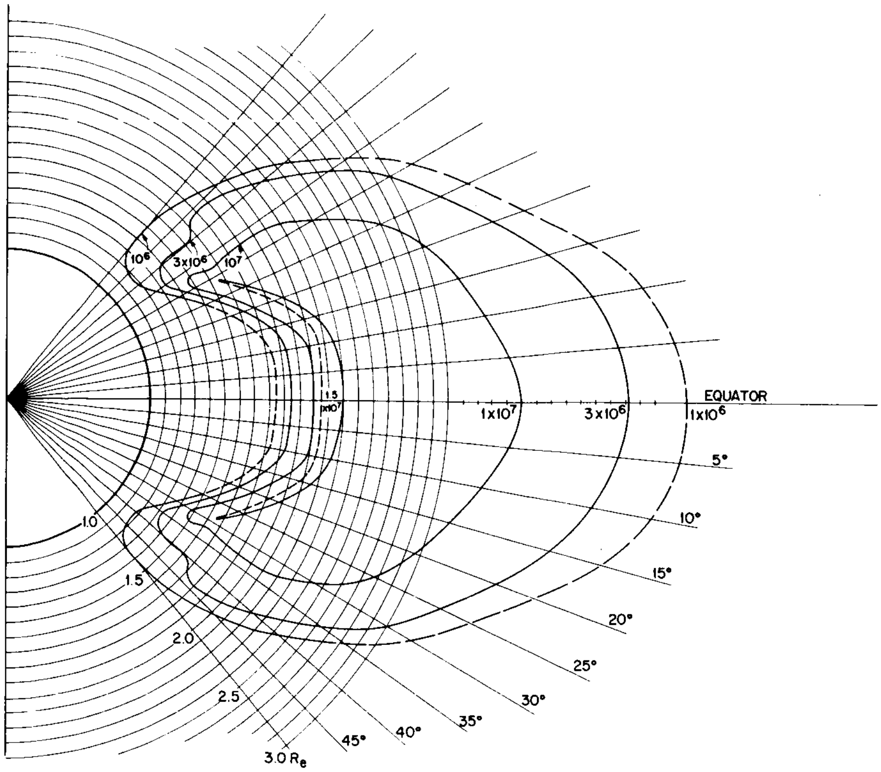

FIGURE 9.--Omnidirectional flux ($cm^{-2}sec^{-1}$) contours (Telstar data) immediately following the Russian test of 22 October 1962 [from ref. 14].

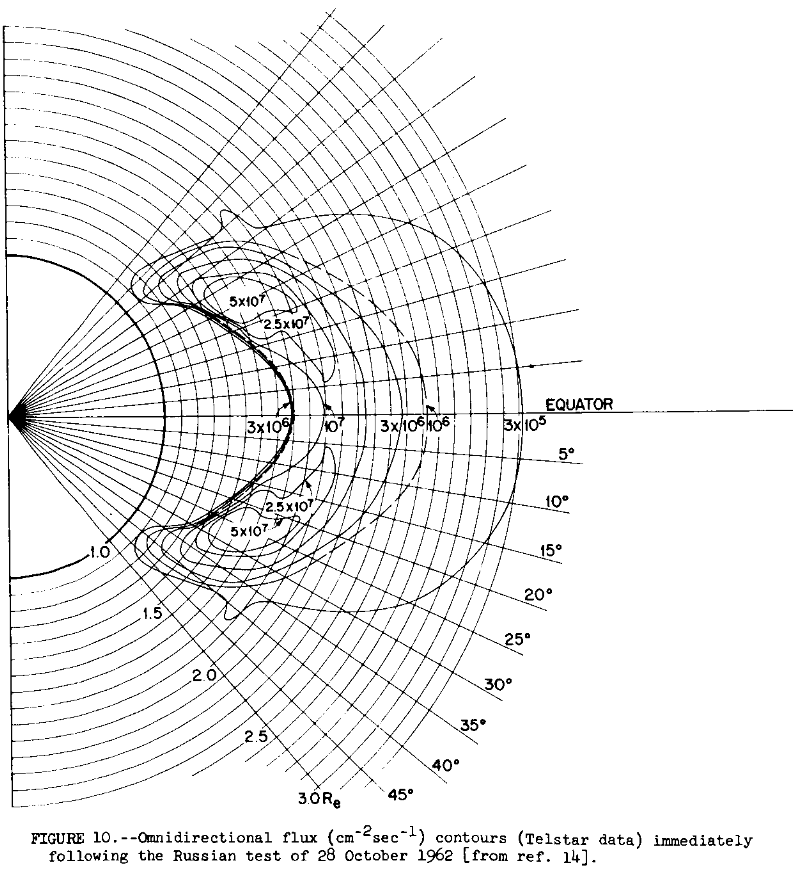

FIGURE 10.--Omnidirectional flux ($cm^{-2}sec^{-1}$) contours (Telstar data) immediately following the Russian test of 28 October 1962 [from ref. 14].

The daily fluences of betas incident on circular satellites were evaluated (ref. 1) for a distribution, derived from the jetting-debris model, which was similar to that shown in figure 9. These fluences are given in figure 11.

The 1 November event produced a narrow electron belt similar to those formed by the Argus tests. It was centered at L = 1.766 with an initial full-width-at-half-maximum of about 250 km. Two days after the test, the omnidirectional flux of electrons greater than 0.5 MeV was about 1.5 x 10^8/cm^2·sec, as discussed by Brown (ref. 13). From observations on the increasing width of the electron shell, with time, Brown determined the cross-L diffusion coefficient to be 7 x 10^{-5} R_E^2/day.

The energy spectrum of the electrons injected by the 1 November event was similar to an equilibrium fission beta spectrum. However, the spectra of the electrons injected by the first and second events differed appreciably from the beta spectrum in some regions of the magnetosphere (e.g., see ref. 13).

EARLY-TIME REDISTRIBUTION EVENTS

A nuclear burst in the magnetosphere, with super-Alfvénic plasma streaming from the point of detonation and high currents along field lines, creates hydromagnetic disturbances such as shock waves, turbulence, and hydromangetic waves. Interactions of the injected betas, as well as the natural trapped particles, with these disturbances may cause the particles to be redistributed. The redistribution may occur not only by diffusion, but also by transport due to large-scale electric and magnetic fields (refs. 30 and 31).

The redistribution of emitted betas is indicated by the electron belts produced by Teak and Orange (refs. 1 and 32). These events occurred in 1958 on 1 August and 12 August over Johnston Island. Although the yields of the devices were in the megaton range, beta trapping would not normally be expected: the altitudes of the bursts were too low, with Teak at 77 km and Orange at 43 km, and the earth's field in the region of Johnston Island is high, requiring injection at altitudes greater than 1000 km. Nevertheless, Teak formed a narrow electron belt, centered at L = 1.2 with a full-width-at-half-maximum of about 110 km, which was observed for about 3 days. The maximum directional intensity, normal to the field, was about 1.4 x 10^5/cm^2·sec·ster. Orange produced a similar belt, but of lower intensity, which was observed for about a day.

The redistribution mentioned previously of natural trapped protons by the Starfish burst was observed by Filz and Holeman (ref. 17). The experimental data of Filz and Holeman, obtained in a series of experiments with nuclear emulsions recovered from low-altitude polar-orbiting satellites, are shown in figure 12. The abrupt increase of the flux, especially at low altitudes, after the Starfish event is evident from these data. A theoretical investigation of the redistribution (ref. 33) revealed that two processes were capable of accounting for the observations. One was the interaction of the protons with the hydromagnetic waves produced by the burst. The other was the Fermi mechanism whereby the protons were accelerated along the field line by multiple reflections from a magnetic field inhomogeneity that propagated along the field line with the local hydromagnetic velocity.

Moreover, large-scale electric fields, arising from the early-time azimuthal-drift motion of the injected betas (ref. 30) would cause the betas to be convected to higher L values. This convection process, which would lower the energies of the electrons, may be responsible for the softening of the betas observed at high L values after the Starfish and the first two Soviet events.

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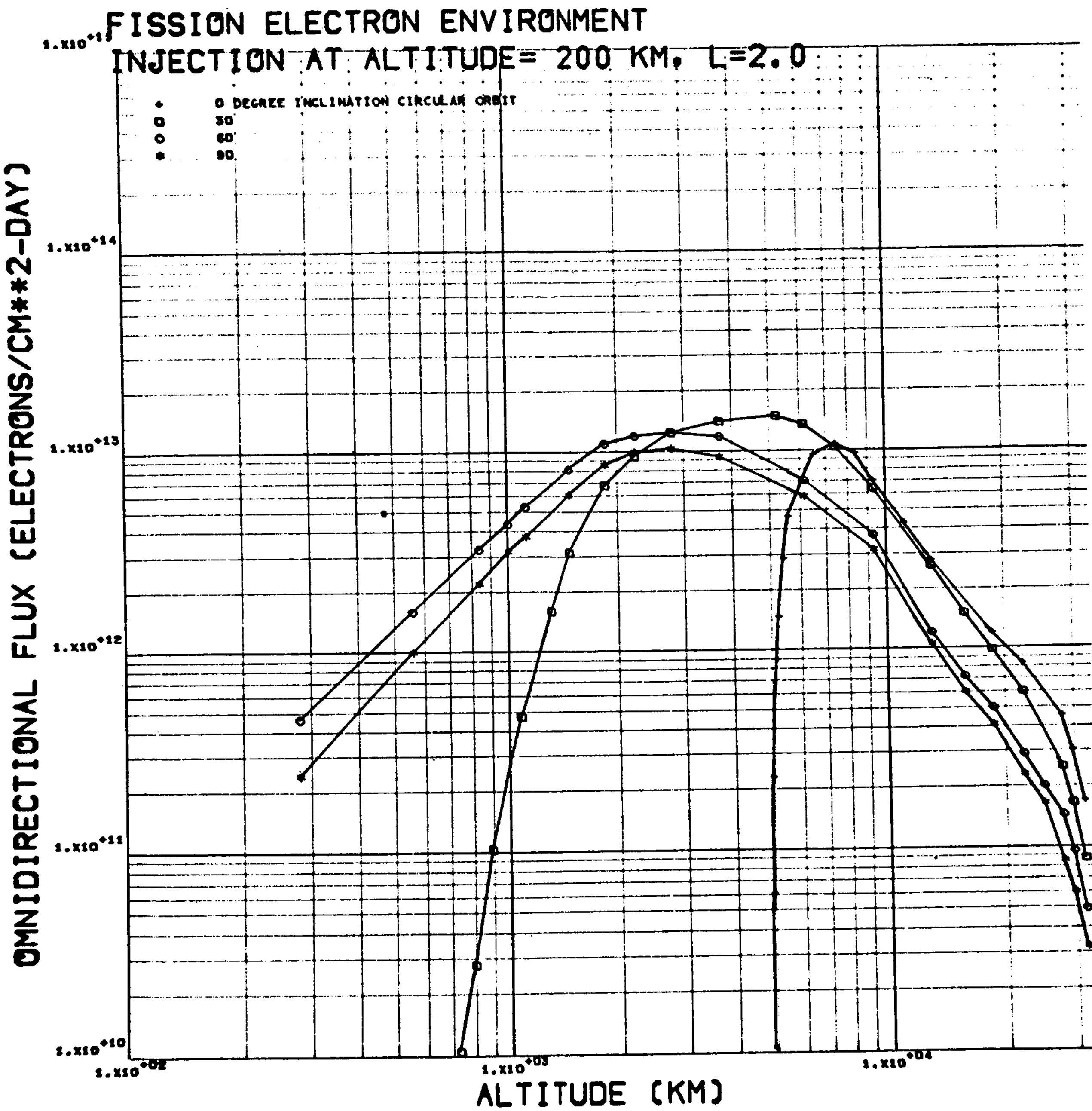

FIGURE 11.- Daily omnidirectional fluence of fission electrons incident on circular orbit satellites as function of satellite altitude for specified orbital inclinations (1-megaton fission yield) [from Crowther and Harless, ref. 1].

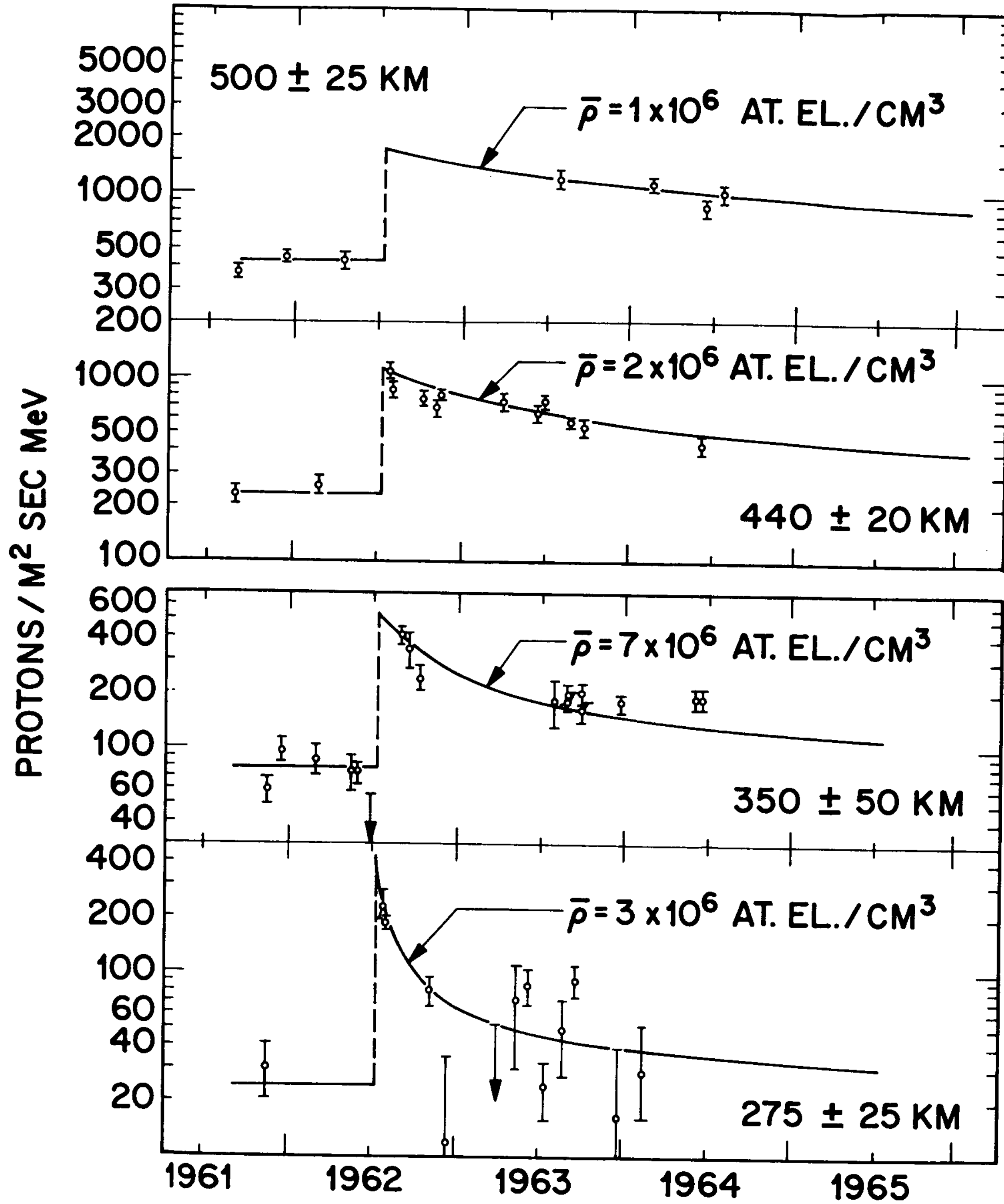

FIGURE 12.--Time variation of the 55-MeV prpton flux for altitudes of H_c = 275, 350, 440, and 500 km from August 1961 to July 1964. The solid curves drawn for the period after July 1962 are the theoretical curves based on the first data point following July 1962 [from ref. 17].