



Conventions

P23

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Fluxes

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STUDIES OF
HIGH ENERGY COSMIC X-RAYS AND PROTONS
BY SATELLITE EXPERIMENTS

A Thesis submitted by

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For the Degree of
Doctor of Philosophy

in

The University of London

November 1972

ABSTRACT

Section 1

Theoretical computations based on the semi-empirical formula of Rudstam and the results of a series of irradiations of CsI crystals using proton beams are used to evaluate the importance of spallation induced radioactivity as a source of background in X-ray astronomy experiments. In particular, the U.K.5 experiment 'F' is considered. The results obtained are compared with previous observations and the relative importance of other sources of background is considered.

A review is made of previous observations of the diffuse cosmic X-ray flux in which it is shown that breaks in the spectrum could be largely due to inadequate allowance for this phenomenon.

Suggestions are made for the location of future experiments and for the correction of data for the spallation contribution.

Section 2

Data from the high energy (> 360 MeV) proton telescope, experiment S24B, carried on board the HEOS A1 satellite, is analysed for the period December, 1968 to April, 1970.

Comparison is made with time variations observed by the Deep River neutron monitor in order to determine the rigidity dependence of several Forbush decreases. Examination is made of a change in the modulation following a decrease on June 8th, 1969.

High energy particle flares are examined and time profiles and anisotropies are compared with low energy (1 - 13 MeV) proton and magnetic field data in order to obtain a more complete understanding of the propagation processes between Sun and Earth.

Quiet-time data is analysed for anisotropies and evidence is provided for a radial streaming of 1 GV cosmic rays towards the Sun in addition to the corotation component. An interpretation in terms of off-ecliptic phenomena is suggested.

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SECTION 1

A STUDY OF SPALLATION INDUCED RADIOACTIVITY
AS A SOURCE OF BACKGROUND IN SATELLITE-BORNE
X-RAY ASTRONOMY EXPERIMENTS

CHAPTER 1. X-RAY ASTRONOMY AND THE U.K.5 SATELLITE

1.1 INTRODUCTION

The extension of astronomical observations into the X- and-gamma ray regions of the electromagnetic spectrum had to await the development of techniques for carrying detectors above the major portion of the earth's atmosphere. Prior to this, the observations were limited to the relatively narrow atmospheric windows in the optical and radio wavelength bands.

When, in 1962, a rocket-borne Geiger counter, designed to search for X-radiation from the moon, gave evidence for a cosmic source of X-rays, the potential of a new field of astronomy was soon anticipated. Experience of the vast increase in knowledge that had followed the advent of radio astronomy led to a considerable effort to improve sensitivity and resolution.

The ten years that have followed this initial discovery have proved these hopes to be well founded. A rapidly increasing number of observations of cosmic X-ray sources is providing information on energetic processes in stars and galaxies, whilst the study of an intense isotropic sky background of X-radiation is proving important to the understanding of the evolution of galaxies and of the Universe itself.

High altitude balloons, rockets, space probes and orbital satellites are all used to carry the various types of detector, which between them cover the spectral range 0.25 keV to several hundred MeV in photon energy. An increasing use of satellites, with their vastly increased observing times compared with other types of vehicle, should yield much useful information in the course of the next few years. A good indication of this is the vast number of results that have come from the first totally X-ray astronomy satellite, 'Uhuru', since its launch in December, 1970. It is to be hoped

that the British satellite, U.K.5, which is to be launched in 1973 carrying six X-ray experiments, will contribute greatly to the subject. For the future, the decision to establish a manned space platform before the end of the decade provides the exciting possibility of putting X-ray astronomy on the same footing as its optical and radio counterparts.

1.2 X-RAY PRODUCTION MECHANISMS IN COSMIC SOURCES

1.2.1 Magnetic Bremsstrahlung (Synchrotron Radiation)

This type of radiation results from the acceleration experienced by a charged particle spiralling in a magnetic field and derives its alternative name from the fact that it is emitted by electrons when accelerated to relativistic energies in a synchrotron.

In astrophysical situations magnetic fields of $\sim 10^{-5}$ gauss are often contained in low density plasmas. A relativistic particle of energy E gives elliptically polarised radiation confined mainly within a narrow cone of half-angle $\theta = \frac{m_0 c^2}{E} \left(= \frac{1}{\gamma} \right)$ about its instantaneous velocity vector. The resulting spectrum then peaks at a photon energy given by

$$h\nu = 5.8 \times 10^{-9} B_{\perp} \gamma^2 \text{ eV, where } B_{\perp} = \text{perpendicular component of field in gauss.}$$

From this expression it can be seen that in a field of 10^{-5} gauss an electron energy of $\sim 10^9$ eV is required to give radio emission, whilst energies $\gtrsim 10^{14}$ eV are required to give hard X-ray photons (> 10 keV). The presence of the γ^2 factor ensures that proton contributions are negligible. The half-life against energy loss for such an electron is

$$\tau_{\frac{1}{2}} = \frac{5.1 \times 10^8}{B_{\perp}^2 \gamma} \text{ secs}$$

which becomes ~ 300 years for 10^{14} eV electrons in a 10^{-5} gauss field.

Thus it can be seen that a source of magnetic bremsstrahlung X-rays must supply very energetic electrons over a long period of time. Production of radiowaves by this mechanism is less demanding energetically and such radio sources are common.

For an homogeneous, isotropic distribution of electrons of power law spectrum

$$N_e(E) dE = K_e E_e^{-\beta} dE$$

integration over the spectrum gives a photon flux of

$$N_{ph}(E) dE = K_{ph} E_{ph}^{-\alpha} dE$$

where $\alpha = (\beta + 1)/2$

1.2.2 Inverse Compton Scattering

This process involves the scattering of microwave photons (energy ϵ) by relativistic electrons giving a high energy photon (energy ϵ') and a corresponding decrease in the electron energy. In the rest frame of the electron the situation is that of Compton scattering and in the limits

$\gamma\epsilon \ll m_0 c^2$, $\gamma \gg 1$, it can be shown that

$$\epsilon' \approx \frac{4}{3} \gamma^2 \epsilon$$

Hence for scattering on the 3K blackbody radiation, electron energies of $\sim 10^9$ eV are required to produce 10 keV X-rays. In this case, the

$$\tau_{\frac{1}{2}} = \frac{2 \times 10^{19}}{\gamma w} \text{ secs, where } w \text{ is the energy density of the radiation field in } \text{eV cc}^{-1}.$$

For 3K black-body radiation $w = 0.4 \text{ eV cc}^{-1}$, so that $\tau_{\frac{1}{2}}$ for electrons of 10^9 eV is $\sim 10^9$ years.

The power emitted per electron is

$$P_c = 2.66 \times 10^{-14} \gamma^2 w \text{ eV s}^{-1},$$

whilst the corresponding expression for synchrotron radiation is

$$P_s = 9.9 \times 10^{-4} \gamma^2 |B_\perp|^2 \text{ eV s}^{-1}$$

The formal analogy between the two mechanisms can be clearly seen, the relative importance depending on the energy densities in the magnetic and radiation fields. Clearly sources would have to be very diffuse in order to radiate by this mechanism, for otherwise the electron energy will be dissipated as synchrotron radio emission. When this condition is satisfied there is much less demand on the energy source of electrons than in the case of X-ray production by magnetic bremsstrahlung. Once again it can be shown that a spectrum of electrons of power law index β leads to a photon spectrum of index

$$\alpha = (\beta + 1)/2$$

There is no polarisation in this case.

1.2.3 Thermal Bremsstrahlung

In a hot plasma the acceleration of free electrons by Coulomb scattering in the fields of nuclei produces photons with an appreciable fraction of the electron energy. For a Maxwellian distribution of electrons in an optically thin plasma (one in which the photons produced do not reinteract) such free-free emission leads to a thermal spectrum of photons of the form $N(\nu)d\nu \propto \exp(-\frac{h\nu}{kT}) d\nu$ where T is the plasma temperature. The production of X-rays thus requires a temperature of $\sim 10^7$ K.

1.2.4 Black-Body Radiation

The other extreme of thermal emission for the case of optically thick sources is black-body radiation. In this case the spectrum is that

derived by Planck, i.e.

$$N(\nu)d\nu \propto \frac{\nu^2 d\nu}{h\nu (e^{KT} - 1)}$$

This is such an efficient method of emission that such sources, if they exist, must be very short-lived.

In between the extremes of optically thin and thick there must be many intermediate spectra.

1.2.5 Non-Thermal Bremsstrahlung

The emission of a non-thermal spectrum of electrons or protons from an accelerating region into a region of gas can both heat the gas and produce a non-thermal spectrum of photons.

1.2.6 Positron Annihilation

Annihilation of slow galactic electron-positron pairs results in photons of energy 0.511 MeV, the distribution of which yields information on diffusion rates from the galaxy.

1.2.7 Nuclear Gamma-Rays

If elements heavier than iron are produced in supernovae then it is to be expected that their transition lines (many of which are around 0.8 MeV) should be detectable when viewing the remnants of such an explosion.

1.2.8 π^0 Decay

Interactions of cosmic rays with matter or matter-antimatter annihilation produce π^0 -mesons which subsequently decay via $\pi^0 \rightarrow 2\gamma$.

The gamma-rays each have energy $\frac{1}{2}m_{\pi} c^2$ (~ 70 MeV) in the meson rest-frame.

A broad spectrum peaked on 70 MeV is thus produced. If such processes took place at large red shifts, then such spectra could contribute a flux in the region of 1 MeV.

1.3 ABSORPTION OF COSMIC X-RAYS

Photo-ionisation of atomic hydrogen renders interstellar space essentially opaque to photon energies less than 0.1 keV. In the region 0.1 keV to 1 keV, attenuation can be important on a galactic scale and can yield information on the intervening medium.

1.4 TECHNIQUES OF OBSERVATION

1.4.1 Low Energy X-rays—Proportional Counter Techniques

In the energy region up to 20 keV, X-rays are absorbed in thin-windowed, gas-filled counters operating in the voltage region such that the resulting pulse-height is proportional to the energy deposited (proportional-counter range). For energies greater than 1 keV the spectrum of X-rays is determined from the pulse-height spectrum using the detector response function. This is complicated by:-

- i) Transparency of the gas at the high energy end.
- ii) Opaqueness of the thin-window at the low energy end.
- iii) The presence of the K-absorption edges in the photoelectric absorption cross-section as a function of energy.

Energies between 0.1 keV and 1 keV are usually determined by defining suitable transmission windows by appropriate selection of window thicknesses and materials.

Viewing directions are usually defined by passive collimators but optical techniques using grazing incidence can give angular resolution down to arc seconds. Rockets are used to carry the counters above the earth's atmosphere, which is totally opaque at these energies. Such flights give typically a few minutes observing time. The advantages of the increased observing time and the ability to point at chosen sources, which result from satellite-borne detectors, are tremendous, as is readily illustrated by the flood of results from 'UHURU'.

1.4.2 Medium Energy X- and Gamma-Rays——Crystal Scintillator Techniques

X-rays deposit energy in matter by a combination of photoelectric, Compton and pair production interactions, the relative importance of these mechanisms depending on the photon energy and atomic number (Z) of the material. For high Z materials the photoelectric effect remains important until higher energies, so that heavy inorganic scintillator crystals, such as sodium iodide or caesium iodide, are used over the range from several keV to around 10 MeV. The light emitted from the interaction of an X-ray in such a crystal is proportional to the energy lost and is detected and analysed into a pulse-height spectrum by a photomultiplier and electronics. The energy range of such crystals is limited by the low light output and consequent interference of photomultiplier noise at the low energy end and by transparency at high energies. Complications occur in unfolding photon spectra from pulse-height spectra as in the higher energy region, where Compton and then pair-production interactions dominate, the energy loss of an X-ray is often only partial and a line source gives rise to a pulse-height spectrum.

Directional properties may be given to such crystals by surrounding with a passive absorbing material and leaving an aperture for the entry of X-rays. A considerable improvement results from the use of active collimators of the same material as the central crystal and with output set in anti-coincidence. In this case even partial energy losses are eliminated, as are the large number of radioactive decays that can be induced in the collimator under proton bombardment.

Instruments have commonly been carried to within a few gm.cm⁻² of the top of the atmosphere on balloon flights of a few hours duration. Rocket flights have been used in the low energy region but generally speaking long observing times are required to deal with the lower fluxes. The measurement of spectra from balloon flights is complicated by the difficulty in extrapolating fluxes to the top of the atmosphere.

Space probes and satellites have been used and offer most hope for the future once the problems of induced radioactivity and charged particle contamination have been reduced by suitable instrument design and selection of spacecraft situation. It is these problems which will form the material of the following three chapters.

1.4.3 High-Energy Gamma-Rays

For photon energies greater than 10 MeV, the pair-production mechanism of energy loss dominates and the techniques used involve conversion of the gamma-ray into an electron-positron pair in a lead slab with subsequent absorption of the secondary particles in a lead glass Cerenkov detector. Angular resolution is obtained by the use of spark chambers to define the direction of the secondaries. Balloon flights and satellites are both used.

1.5 RESULTS OF OBSERVATIONS

1.5.1 Discrete Sources

Most of the work on location of sources has been carried out in the 1-10 keV region using proportional counters. After 70 days of data, the UHURU satellite has doubled the known number of X-ray sources and the UHURU catalogue (Giacconi et al., 1971) reports 116 sources. Figure 1 represents the distribution of these sources in galactic coordinates. About $\frac{2}{3}$ of these sources lie within $\pm 20^\circ$ of the galactic plane and many of these are variable. Some of the high latitude sources may be identified with extragalactic objects.

In order to understand the physical processes that operate in a particular source it is necessary to measure its spectrum and, if possible, polarisation, and to identify it with a known optical or radio object. There are an increasing number of examples in which this is being successfully done.

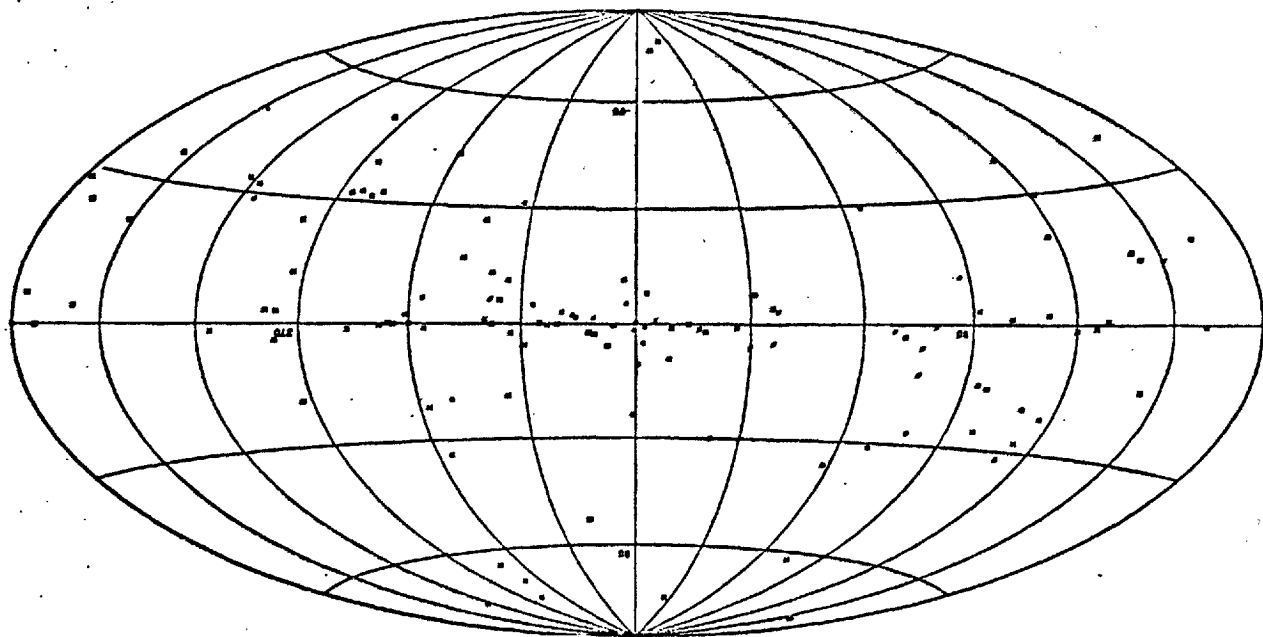


FIGURE 1: The X-ray Sky According to 'UHURU'. Equal area projection in galactic coordinates.

For example, Scorpius X-1, the first X-ray source to be discovered and the most intense at low energies, has been identified with a variable, blue excess, 12.5 magnitude star, which is also a faint radio source. The X-ray spectrum is exponential and requires a temperature that varies between $4 \times 10^7 \text{ K}$ and $9 \times 10^7 \text{ K}$. There is also evidence of a spectral hardening above 40 keV. One theory pictures this source as a collapsed neutron star or white dwarf in a binary system with a larger star. The intense gravitational field of the smaller star then leads to accretion of material from the larger, with consequent heating of the gas to the temperatures necessary to bring the thermal bremsstrahlung radiation into the X-ray region.

Another type of source that has received extensive study across the

entire field of astronomy is Taurus X-1, which is identified with the famous Crab Nebula remnant of the supernova observed by Chinese astronomers in 1054 A.D. Here the source is extended across a region of about 2 light-years diameter and the X-ray spectrum is a power law of index 2.1. X-ray pulsations have been detected at the same period (33ms) as the radio pulsar NP0532 situated within the Crab and seem to form an increasing portion of the total X-ray flux with increasing energy. A recent experiment has given evidence of polarisation of the total X-ray flux, although the information on the pulsed component is inconclusive (Novick, 1972). The popular theory of the Crab would then seem to be synchrotron radiation from high energy electrons continuously accelerated by a rapidly rotating neutron star. The spectral index of the electrons must then be of the order 3.0 in the region of 10^{14} eV (see 1.2.1). Thus far Taurus X-1 is the only confirmed X-ray pulsar, but recent observations of the Vela X supernova remnant in the range 20 keV - 1 MeV have yielded evidence of X-ray pulsations at a period near to that of the radio pulsar PSR 0833-45 (Harnden Jr., et al., 1972).

Another type of regular variable is Centaurus X-3, which shows 4.85s pulsations having a regular (~ 2 day) variation in intensity and period. A popular theory for this source is an occulting binary in which a rotating or pulsating collapsed star is periodically occulted by a more massive companion. The energy source for the X-rays could then be accretion by the collapsed star. Cygnus X-1, another variable, has been identified with a spectroscopic binary, thus illustrating the importance of this type of object.

Several extragalactic X-ray sources have now been identified including M 87, the famous elliptical galaxy with the bright jet, and the quasar 3C 273. The optical and radio emissions from M 87 are polarised indicating a magnetic bremsstrahlung mechanism. Difficulties involving

the short lifetime of the high energy electrons required to give X-rays by this mechanism make an inverse Compton mechanism more plausible.

So far only six sources have been observed above 100 keV. These are SCO X-1, TAU X-1, CYG X-1, NGC 5128, GX 301-2, GX 304-1.

Several sources have been reported at energies ~ 100 MeV but thus far results have been contradictory and there have been no confirmations.

1.5.2 The Diffuse X-Ray Background

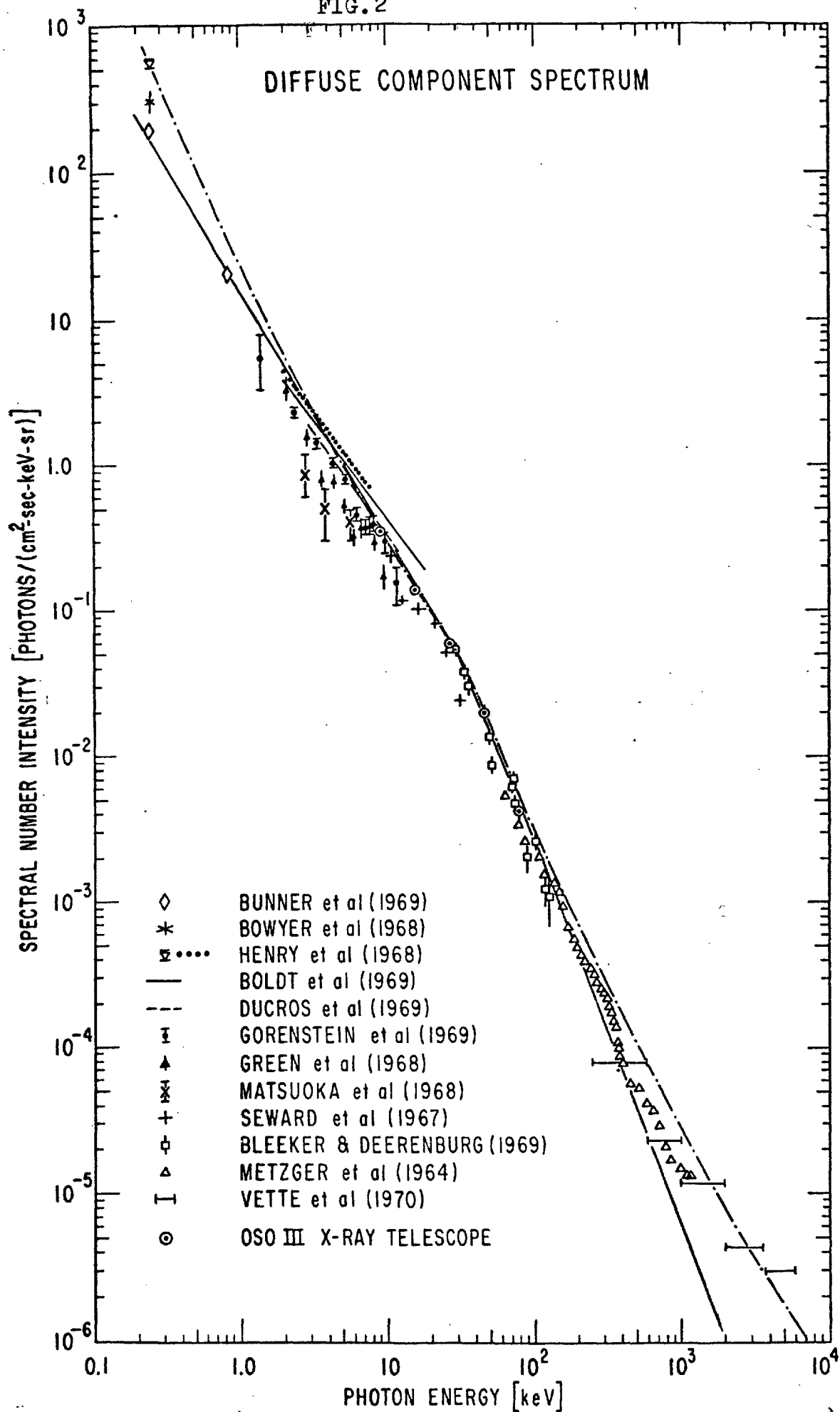
Ever since the discovery of the first X-ray source, experiments have also revealed the existence of an intense, isotropic ('diffuse') flux covering the entire X- and gamma-ray range. The isotropic flux in this spectral region greatly exceeds the contribution from the Milky Way (attempts at measuring a galactic line source have yielded only upper limits at energies greater than 10 keV and the sum of resolvable discrete sources for lower energies).

Schwartz (1969) has measured the isotropy as better than 5% over angular scales of 10° for the energy range 7.7 - 12.5 keV.

Both the measured isotropy and the intensity rule out the possibility that the X-ray background is a superposition of contributions from galaxies such as our own. In fact no known type of X-ray source when integrated over its estimated space density is capable of giving the observed flux.

Estimates based on truly diffuse production mechanisms occurring in metagalactic space also fall short by an order of magnitude. It would seem, therefore, that some sort of cosmological evolution must be allowed for, whether in galactic type objects themselves or in the density of microwave radiation in metagalactic space. Given an isotropic flux, it is to be expected that very distant sources will contribute significantly to the radiation. The only other spectral region in which the isotropic sky back-

FIG. 2



ground dominates the galactic contribution is the microwave region in which the measurements are fitted to 3K black-body radiation, hypothesised to be the result of adiabatic expansion of the universe following the 'big bang'.

Accurate measures of the isotropy will be required to resolve whether the X-ray background has an origin in discrete sources or in metagalactic space, and together with measures of the spectrum will provide evidence on the various cosmological models.

In Figure 2 (taken from Schwartz, Hudson and Peterson, 1970), the results of a large number of experiments covering the complete range have been summarised. The various spectral features that have been largely accepted so far are clearly shown. These are:-

- 1) An excess flux in the $\frac{1}{2}$ keV region
- 2) An increase in spectral exponent by ~ 1.0 in the region of 40 keV.
- 3) A flattening in the region of 1 MeV.

A criticism of the reality of these features will be given in Chapter 4 together with a review of the various theories proposed to account for the spectrum.

1.6 THE U.K.5 SATELLITE

The U.K.5 project has been designed to give the wide range of measurements on cosmic X-ray sources necessary to give a good understanding of the physical processes involved. Six experiments are to be contained in a 270 lb. spacecraft, spin stabilised at approximately 10 r.p.m. Two experiments are designed to locate new sources by scanning the entire sky utilising the satellite rotation. By means of gas jets the satellite may be pointed at objects of interest when a third experiment pointed along the spin-axis may be used for accurate source location. This experiment also incorporates a visible light photomultiplier which enables the satellite

spin-axis direction to be determined from the background of optical stars. Three other experiments are pointed along the spin-axis and give information on the low energy spectrum (2-10 keV), the polarisation, and the high energy spectrum (20 keV - 2 MeV). These three experiments can also be operated in a pulsar mode to search for X-ray pulsars (at the frequencies of known radio pulsars) in the spectral ranges 2-10 keV and > 20 keV, and to measure the polarisation of any such pulsed component of the flux.

Five of the experiments cover the range 1-20 keV and use proportional counter techniques. The sixth experiment covering the range > 20 keV utilises CsI scintillator and is the Imperial College contribution known as Expt. 'F'.

It was originally proposed to launch the satellite into a nearly circular, 550 km altitude, 33° inclination orbit by means of a Scout vehicle, fired from Wallops Island, Virginia, U.S.A. Largely as a result of the work on the importance of radioactive background induced by inner radiation belt traversals, to be presented in the following three chapters, the decision was taken to launch the satellite into an equatorial orbit using the San Marco equatorial launch platform. At present the launch is scheduled for October, 1973.

1.7 THE HARD X-RAY TELESCOPE ON U.K.5, - EXPT. 'F'

1.7.1 General Description

The finalised design of the X-ray telescope is illustrated in Figure 3. Many of the design considerations and calculations have been reported previously (Morfill, 1971).

X-rays entering the central crystal of CsI (Na activated) scintillator through the 4° acceptance cone defined by the collimator are to be pulse-height analysed into sixteen logarithmically spaced channels covering the energy range from 20 keV to 2 MeV. Active collimation is

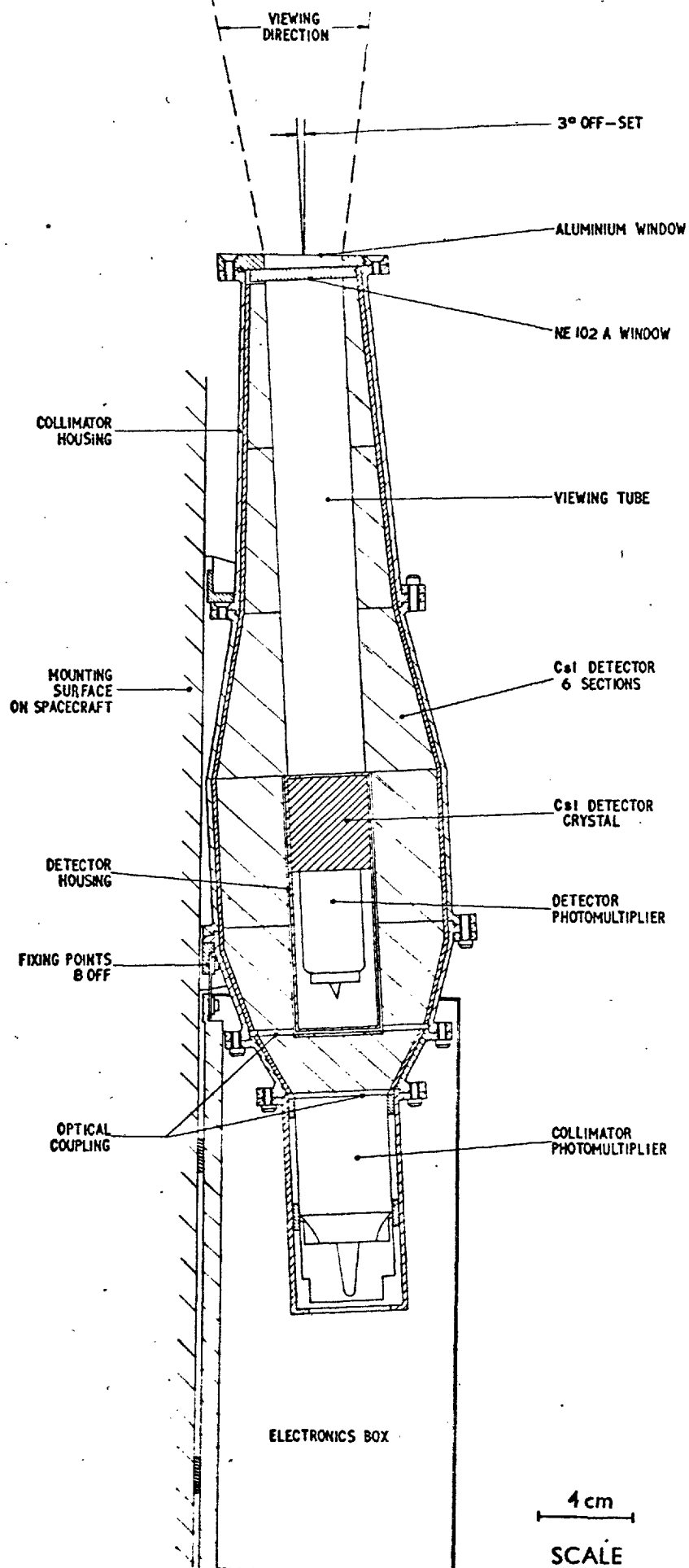
employed using six sections of CsI crystal in such a geometry that any X-ray entering the central crystal through the collimator must traverse ~ 3 cms of active material. Light pulses from the collimator and central crystal are detected by separate photomultipliers, the outputs of which are set in anticoincidence.

The aperture is covered by a thin window of aluminium which is opaque to visible light but transparent to the X-rays of interest. A thin window of NE 102A plastic scintillator, optically coupled to the collimator but shielded from the central crystal, is employed to eliminate charged particles travelling down the collimator tube. A 2 mm thick aluminium housing surrounds the collimator to reduce the dead-time of the collimator caused by charged particles. These features have been incorporated to reduce the considerable contamination of results by trapped and precipitating soft electrons that has been reported by previous observers (e.g. Schwartz, 1969).

The axis of the telescope is to be off-set by 3° to the satellite spin-axis so that a modulated signal results when the telescope is pointed at a source. Each spin cycle will be divided into four time sectors in the data handling, and harmonic analysis will reveal the source strength. This technique is employed in order to resolve sources in the presence of a strong background from the diffuse flux and radioactivity. Data will also be divided into different sectors according to the orbital position of the spacecraft in order to show up any decay of activity resulting from passages through regions of high particle flux. In common with the other U.K.5 experiments, experiment 'F' will be switched off during such periods of particle irradiation.

When operating in the pulsar mode, the experiment will operate in one energy band only, chosen at the low energy end of the range. Sixteen channels are to be cycled at the frequency of the known radio pulsar under

FIG. 3 U.K.5 HIGH ENERGY X-RAY TELESCOPE



observation. The presence of an X-ray pulsar will show up as an excess number of counts in one of the channels. 64 sets of sixteen channels will be used to overcome any drifts of frequency due to quantisation of clock frequency, temperature changes or Doppler effects.

1.7.2 Spectrometer Properties

The response of a crystal scintillator-photomultiplier system to a delta-function photon spectrum is not a delta-function pulse-height spectrum but is a continuous spectrum determined by the energy lost in the crystal by the various mechanisms of photoabsorption, Compton scattering and pair-production. Even for a given energy loss, a pulse-height spectrum is produced due to statistical fluctuations in electron multiplication and variations in the light collection efficiency.

In the energy range up to 200keV the photoelectric effect dominates and an electron is emitted from an atom with a kinetic energy equal to the energy of the photon less the binding energy of the electron. This binding energy may then be reclaimed by absorption of the secondary X-ray that is emitted when the atom returns to its ground state, or else this X-ray may escape in which case a secondary 'K escape' peak is observed at an energy equal to $(E_{\text{photon}} - E_{\text{Kshell}})$.

For energies greater than 200 keV but less than a few MeV, Compton scattering dominates as an energy loss mechanism. In a single scattering of a photon of energy E through an angle θ , the energy E' of the scattered photon is given by

$$E' = \frac{E}{1 + \frac{E}{m_0 c^2} (1 - \cos \theta)} \quad \text{where } m_0 \text{ is the electron rest mass,}$$

so that the energy lost to the electron is

$$\Delta E = E - E' = \frac{\frac{E^2}{m_o c^2} (1 - \cos \theta)}{1 + \frac{E}{m_o c^2} (1 - \cos \theta)}$$

This clearly has a maximum value of

$$\frac{\frac{2E^2}{m_o c^2}}{1 + \frac{2E}{m_o c^2}}$$

A Compton plateau extending in energy up to this Compton edge is thus produced by these partial energy losses in which the scattered X-ray escapes from the crystal. There then follows a region of multiple Compton scattering terminating in a total energy loss peak produced by photoabsorption of an X-ray degraded in energy by multiple scattering. In this region there is also the possibility that a photon can pass through the crystal without energy loss and then be backscattered into the crystal from surrounding material at an energy $\frac{E}{(1 + \frac{2E}{m_o c^2})}$. A 'backscatter' peak at this energy can then result.

For energies greater than 2 MeV, pair-production becomes important. The kinetic energy of the particles is generally sufficiently low that the kinetic energy is lost before annihilation of the positron produces two 0.511 MeV gamma-rays. Either or both of these may escape from the crystal to give false peaks at $(E - m_o c^2)$ and $(E - 2m_o c^2)$.

The exact response in any instance depends on the nature and size of the crystal and its position relative to the source of X-rays. Various examples of these phenomena are illustrated in Figure 4. The first three curves show the response of the CsI crystal-photomultiplier system used in one of the irradiation experiment to be described in Chapter 2. The

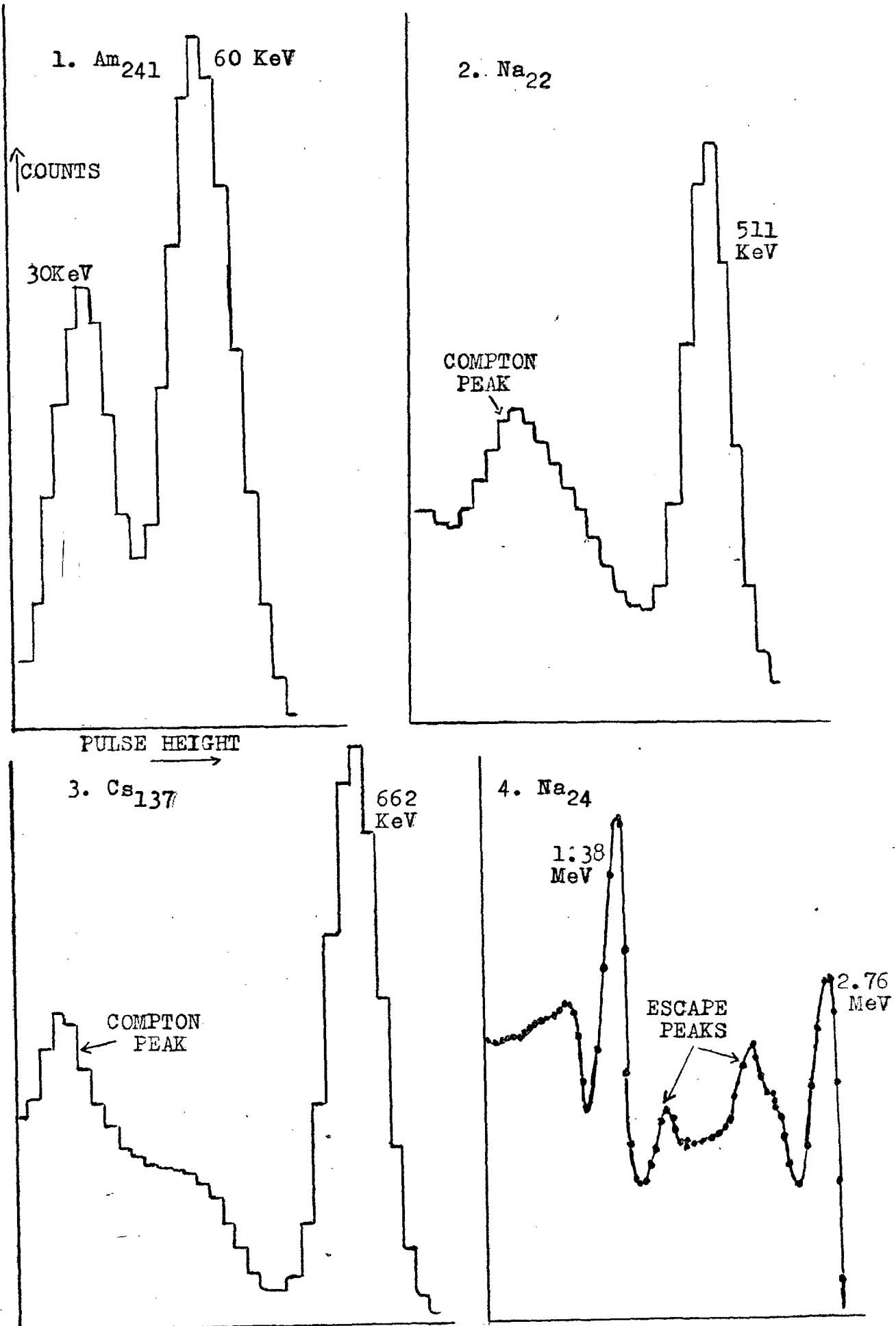


FIG.4

sources were placed in contact with a circular face of the crystal and are some of those used to calibrate the system. The fourth curve illustrating the escape of annihilation quanta is taken from work by Trombka (1970).

In the case of Expt. F, many of the partial energy losses will be eliminated by the active collimator. A Monte Carlo program for simulating the interaction of photons in the detector has been described by Morfill (1971) and will be used in conjunction with the response to calibration sources to describe the detector response. The photon spectrum can then be unfolded from the pulse-height spectrum by a method due to Trombka (1970).

1.8 THE IMPORTANCE OF BACKGROUND IN X-RAY ASTRONOMY

All source observations in X-ray Astronomy are made in the presence of a strong background from the diffuse isotropic flux. In addition there are backgrounds resulting from atmospheric X-rays, solar X-ray bursts, interactions of charged particles in the detectors and radioactivity induced in the detector materials and surroundings. Although modulation techniques may be employed to distinguish sources from background, the strength of the background limits the sensitivity of the instrument.

For example, if the counting rate in a detector due to a source is N_s counts s^{-1} and the counting rate due to background is N_B counts s^{-1} , then the condition that a source is resolved to the 3σ significance level in t seconds is

$$N_s t \geq 3 \sqrt{2N_B t}$$

$$\text{i.e. } N_s \geq 3 \sqrt{2N_B} t^{-\frac{1}{2}}$$

Clearly the time required to resolve a given source is directly proportional to the background. In the hard X-ray region, $N_s \ll N_B$ and long observation times are required.

Determination of the diffuse cosmic X-ray flux involves elimination or subtraction of every other conceivable form of background. Of these, radioactivity is the most difficult to allow for as it can neither be eliminated by data selection because of the presence of long half-lives, nor by detector design since the delayed decay of a nucleus escapes elimination by anticoincidence shielding. In addition, the presence of particular decay lines could be erroneously interpreted as cosmic gamma-ray line features. Materials of high atomic number (Z) must be used to absorb X-rays and the consequent high atomic mass number (A) of the material ensures that there is also a large cross-section for interaction with damaging particle radiation. X-ray astronomy measurements are always made from positions of high particle flux, whether cosmic ray, atmospheric albedo, or radiation belt.

Therefore it is particularly important to understand the activating process and the energy and time dependence of the resulting activity. This applies particularly to energies > 20 keV where cosmic X-ray fluxes are low.

CHAPTER 2. THEORETICAL AND EXPERIMENTAL WORK ON SPALLATION

INDUCED ACTIVITY IN SCINTILLATOR CRYSTALS.

2.1 INTRODUCTION

Significant radioactive background has previously been reported by various observers using satellite-borne detectors similar to that of Expt. 'F' on U.K.5, e.g. Peterson (1965), Schwartz (1969). These investigators found that certain parts of the satellite orbit were unusable due to contamination by induced activity and by trapped and precipitating electrons. In addition, the remaining data required considerable correction for radioactivity in order to arrive at estimates of the diffuse cosmic X-ray flux. Both experiments were contained in OSO satellites in approximately circular orbits of 550 km altitude, and 33° inclination. Such an orbit carries the spacecraft into the South Atlantic Anomaly trapped particle region for a few minutes during several orbits each day. This region (S.A.A.) is a magnetic anomaly off the coast of Brazil in which the inner belt trapped particles are brought to a lower altitude. Activity was reported to result both from such passages and from the cosmic ray dosage which varied over the orbit. Because the U.K.5 detector is designed to eliminate charged particles, it is to be expected that the radioactivity will remain as the major background problem.

Previous workers attempted to explain the observed decay of activity produced in passages through the South Atlantic Anomaly in terms of the decay of one or two radioactive isotopes which can be produced in the scintillator material by neutron capture (e.g. I_{128} and Na_{24}). It was assumed that these neutrons are produced throughout the satellite by proton bombardment, but the problem of reducing the neutron velocities to that of thermal energies has not been considered. Decay of these isotopes produces

events which appear like X-rays in the detector or add to the dead-time of the collimator. Recent reports have shown the induced activity to be a more complex superposition of various half-lives (Dennis, 1970). Because of the low counting rates, poor statistics and data gaps of satellite detectors, insufficient information is available to understand fully the origin of the background radiation. Ground-based investigations are thus required.

The importance of the radioactive decay of spallation products resulting from inner belt proton bombardment as a source of background in satellite-borne G-M counters was pointed out by Elliot (1965).

2.2 THEORETICAL PREDICTION OF NUCLIDE PRODUCTION BY SPALLATION

Theories of spallation reactions generally envisage a two step process in which an incident high energy particle firstly interacts directly with the individual nucleons in a complex target nucleus (intranuclear cascade), knocking out a few fast nucleons in the process. The residual nucleus then de-excites by evaporating a number of relatively slow nucleons and clusters of nucleons leaving a lighter residual nucleus.

Rudstam (1966) has had considerable success in fitting a wide range of radiochemical data by means of a semi-empirical, five parameter formula ('charge distribution, mass distribution' version) which gives the production cross-section, $\sigma(A_t, E, Z, A)$, for a given nucleus (Z, A) when a target nucleus (Z_t, A_t) is bombarded by protons of energy $E(\text{MeV})$.

$$\sigma(A_t, E, Z, A) = \sigma_i(A_t) \left\{ \frac{d^{2/3} A_t^{-2e/3} \exp[PA - R(Z-SA+VA^2)^{3/2}]}{1.79 \left[\exp(PA_t) \left(1 - \frac{2e}{3PA_t}\right) - 1 + \frac{2}{3} e \left(1 + \frac{1}{PA_t}\right) \right]} \right\}$$

$$\times \exp(0.0074 A_t - 0.25) \times f(E)$$

where

$$P = 20E^{-0.77} \text{ for } E < 2.1 \text{ GeV}$$

$$P = 0.056 \text{ for } E \geq 2.1 \text{ GeV}$$

$$R = 11.8 A^{-0.45}$$

$$S = 0.486$$

$$V = 3.8 \times 10^{-4}$$

$$d = 11.8$$

$$e = 0.45$$

$$f(E) = \exp(1.73 - 0.0071E) \text{ for } E < 240 \text{ MeV}$$

$$f(E) = 1 \text{ for } E \geq 240 \text{ MeV}$$

$$\sigma_i(A_t) = \pi(1.26 \times 10^{-13})^2 A_t^{2/3} \text{ cm}^2$$

Rudstam demonstrated the validity of the formula to within an overall factor of 2 or 3 for proton energies from 50 MeV to 30 GeV and for targets from $^{23}_{51}\text{V}$ to $^{83}_{209}\text{Bi}$, with some indications of validity as low as $^{13}_{27}\text{Al}$ and as high as $^{92}_{238}\text{U}$. Relative values for the different isotopes produced from a given target may be more accurate.

The formula has found wide use in the estimation of the fragmentation of heavy cosmic ray nuclei on interstellar hydrogen, and in the prediction of nuclide production by cosmic ray interactions in meteorites.

Funk and Rowe (1967) have shown that the formula can be in error by as much as a factor 60 in isolated cases for products with atomic numbers near that of the target. Waddington (1969) has taken the cross-section for single nucleon removal to be $0.08\sigma_i$ (where σ_i is the total inelastic interaction cross-section), and has considered neutron or proton loss to be equally probable. Hence the normalisation

$$\sum_{Z,A} \sigma(A_t, Z, A, E) \leq 0.92 \sigma_i(A_t)$$

is applied.

These assumptions are used in this work.

The formula also gives a considerable underestimate of the numbers of light fragments, as these are produced as evaporation products rather than residual nuclei.

The inelastic interaction cross-section (σ_i) was taken as 1260 millibarns for both Cs and I, giving an interaction length (λ) of 38 cm for CsI, and as 410 millibarns for Na, giving $\lambda = 40.8$ cm for NaI. These values are constant to within a few percent for proton energies greater than 60 MeV (see Measday and Richard-Serre, 1969). The formula was used to predict the quantities of isotopes produced in CsI and NaI crystals of the same shape as the U.K.5 central crystal (cylindrical, 5cm x 9.1cm²) for three different cases.

(i) Inner Belt Produced

The omnidirectional differential energy spectrum in the South Atlantic Anomaly was taken to have a peak flux

$$j(E) = 2 \times 10^6 E^{-2.54} \text{ protons cm}^{-2} \text{ MeV}^{-1} \text{ sec}^{-1},$$

which gives an integral flux above 100 MeV of 1000 protons cm⁻²sec⁻¹.

A ten minute passage through the belt at such a flux level was used in computing the spallation in the worst possible case for the U.K.5 detector. Taking the mean path length of a proton in the satellite material and collimator as equivalent to 18 gm.cm⁻² of CsI, allowance was made for energy loss to give a modified spectrum $j'(E)$, which was used to compute the numbers of each isotope produced via

$$N_B(Z,A) = 600 \int_{100}^{2500} \frac{\sigma(A_t, E, Z, A)}{\sigma_i(A_t)} (1 - e^{-\frac{t}{\lambda}}) \times \text{G.F.} \times j'(E) dE$$

where

t = thickness of crystal, G.F. = omnidirectional geometric factor.

The lower limit of 100 MeV was taken since below this energy the modified spectrum $j'(E)$ has been considerably flattened by ionisation energy loss in the collimator. Also, below this energy the range due to ionisation loss is less than an average path length of a proton within the crystal and only a small fraction undergo nuclear interactions before being brought to rest (Measday and Richard-Serre, 1969).

There are very few inner belt protons above 2500 MeV so that this upper limit was taken to restrict integration to a reasonable number of points. This calculation is thus based on a total dosage at the satellite of 6×10^5 protons $\text{cm}^{-2} > 100$ MeV for one passage through the S.A. Anomaly, resulting in 3×10^5 interactions in the central crystal.

(ii) Production by a Mono-energetic Beam at 155 MeV

A dosage giving 3×10^5 interactions was chosen for convenience of comparison with (i). This energy was chosen for comparison with the experimental results obtained using the 155 MeV proton synchrocyclotron at A.E.R.E., Harwell.

(iii) Production by Cosmic Rays

Because $\sigma(A_t, E, Z, A)$ is independent of energy for $E \geq 2.1$ GeV, no integration was required. For a 2 GV cut-off rigidity the integral flux of cosmic rays is $950 \text{ particles m}^{-2} \text{sec}^{-1} \text{sterad}^{-1}$ at solar sunspot maximum (Webber, 1967). This was calculated to give $0.55 \text{ interactions sec}^{-1}$ in the central crystal. Damage occurring for higher cut-off rigidities can simply be obtained by scaling these results according to the appropriate integral flux.

Figure 5 gives the mass yield curves for the three cases, all normalised to 3×10^5 interactions. The similarity of the spallation predicted in situations (i) and (ii) can be clearly seen. In the case of cosmic ray

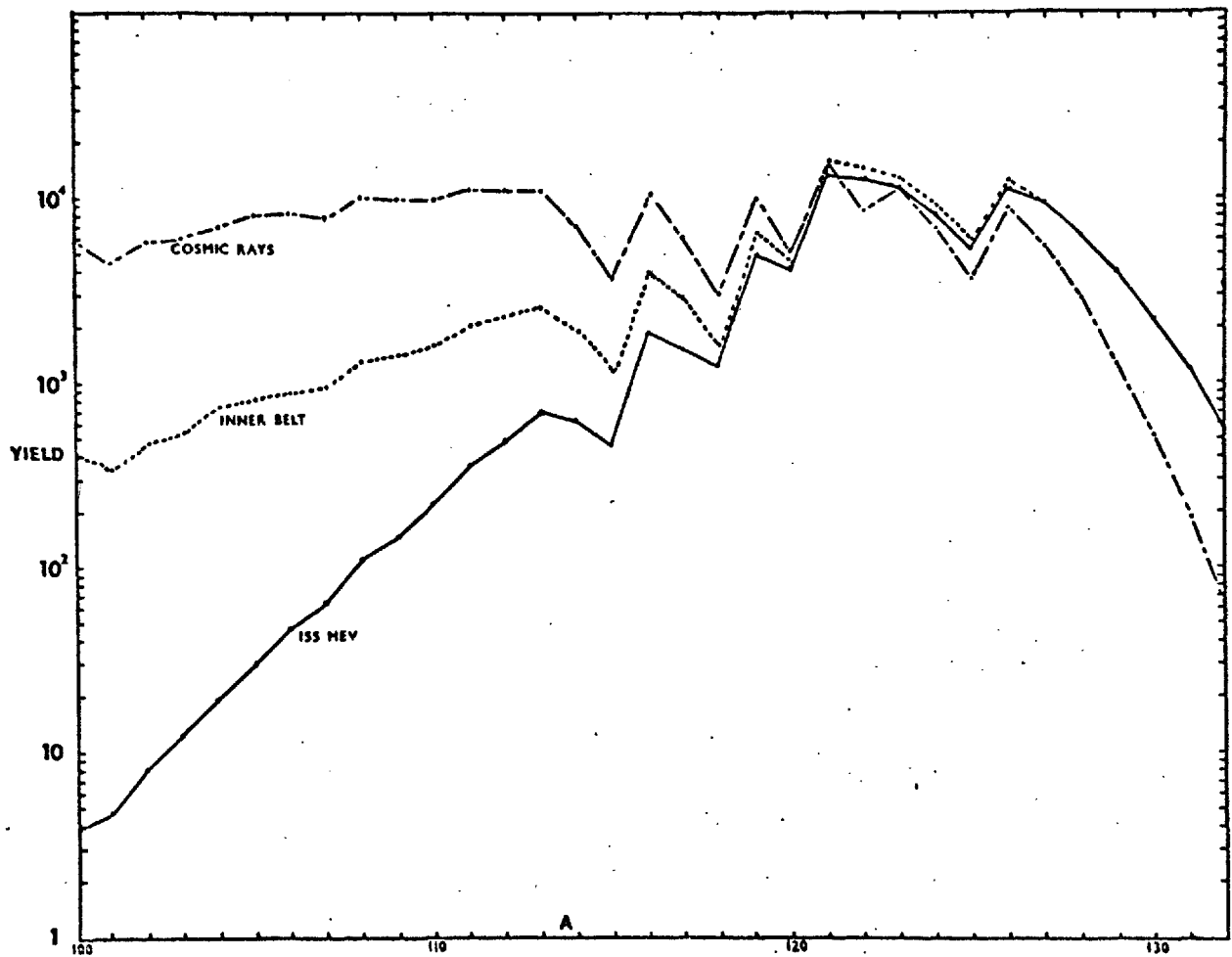


FIGURE 5: Mass yield curves predicted by the Rudstam formula for proton induced spallation in CsI, given down to atomic mass number (A) 100 and normalised to 3×10^5 interactions.

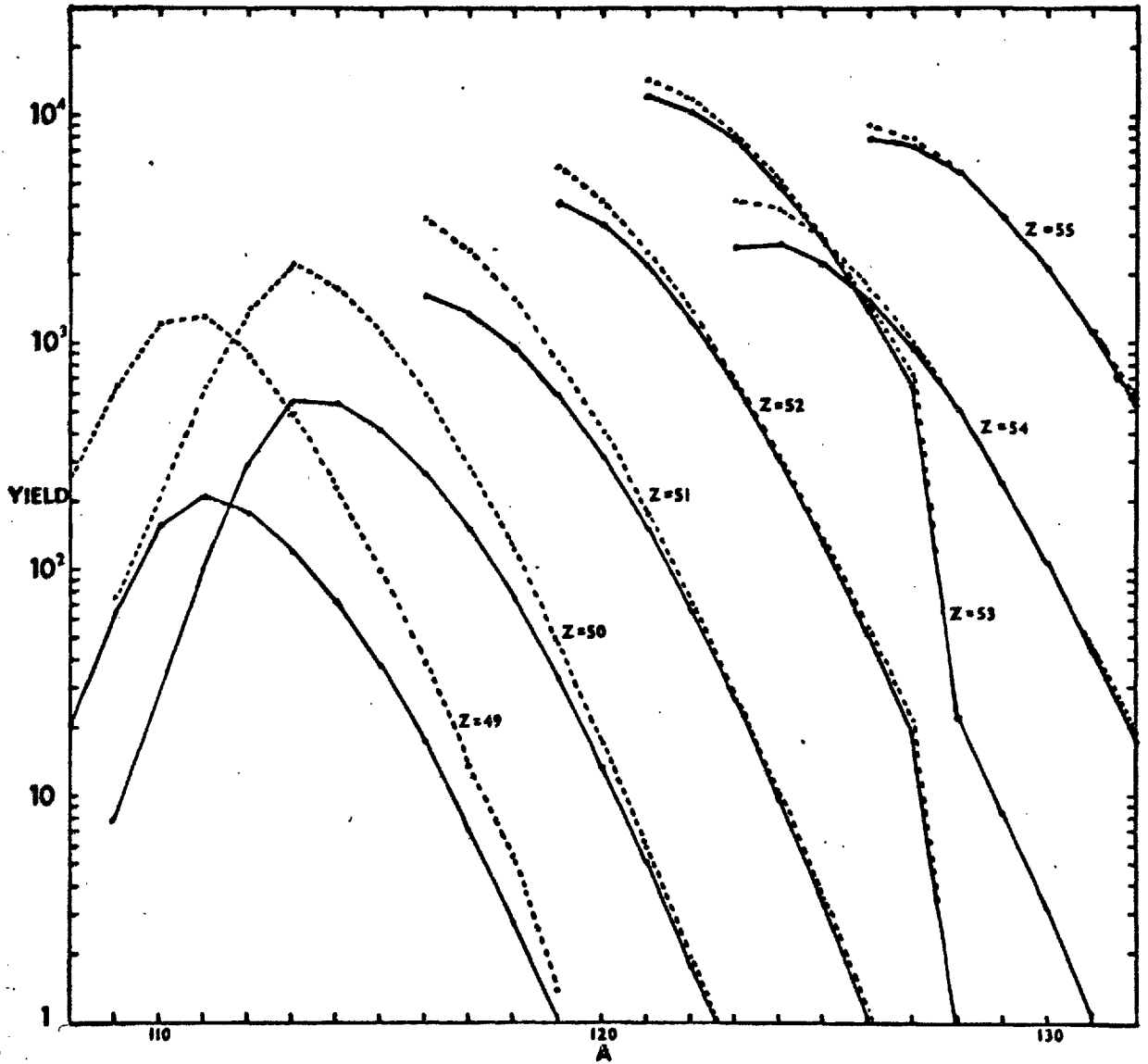


FIGURE 6: The yield of isotopes of $Z \geq 49$ as predicted by the

Rudstam formula for 3×10^5 interactions in CsI.

Inner belt produced spallation products are shown by a dotted line, 155 MeV produced spallation products by a solid line.

induced spallation, the relatively greater importance of low (Z,A) products may be noted.

Figure 6 compares production rates for cases (i) and (ii) down to $Z = 49$. It should be noted that throughout this work the total number of interactions is calculated using the total geometrical cross-section. The total number of spallation products predicted from the formula can be less than this so that the curves of Figures 2 and 3 are not normalised to contain the same area. For curves (i) and (ii) the areas contained are sufficiently similar to justify direct scaling for predicting inner belt induced activity from results at 155 MeV.

2.3 NUCLIDE PRODUCTION BY NEUTRON INTERACTIONS

Both albedo neutrons from the earth's atmosphere and neutrons produced throughout the spacecraft as secondaries in spallation interactions can contribute to activation of the central crystal. For low energy neutrons (< 1 MeV) both Caesium and Iodine have appreciable capture cross-sections. Thermal neutron capture by I_{127} has a cross-section of 6.3 b and yields the unstable isotope I_{128} ($\tau_{\frac{1}{2}} = 25$ mins, β^- 2.12 MeV (76%), 1.67 MeV (16%); γ 0.46 MeV (17%)). The equivalent cross-section for Cs_{133} is 29 b but this yields Cs_{134} of half-life 2 years, and several years would be required to build up an equilibrium decay rate. There is also an appreciable cross-section for production of the metastable form Cs_{134} ($\tau_{\frac{1}{2}} = 2.9$ hrs, γ 0.137 MeV). For Na_{23} the thermal neutron capture cross-section is 0.53 b to give Na_{24} ($\tau_{\frac{1}{2}} = 15$ hrs, β^- 0.156 MeV; γ 1.37 MeV, 2.75 MeV).

High energy neutrons (> 50 MeV) will contribute to spallation damage (the Rudstam formula is unchanged if the incident particle is a neutron).

2.3.1 The Importance of Secondary Neutrons

The case of capture of secondaries has been considered by Peterson

(1965) as the source of the observed activity in NaI. The problem of thermalising the neutrons in sufficient quantities was not resolved. Estimates based on this mechanism were in general a factor thirty too low to explain the observed activity (Peterson, 1972).

An attempt can be made to obtain an estimate of the relative importance of this process compared with direct proton interactions by considering the work of Ebeoglu et al. (1966) on nuclear cascades in iron meteorites. These workers calculate the relative reaction rates of primaries and secondaries as a function of depth for a 400 MeV proton beam incident on an iron slab. At a depth of 4 cm (31 gm.cm^{-2}) this ratio is calculated to be 2:1. For this depth an energy spectrum of secondaries is also given from which it is possible to deduce that less than 1% of these secondaries have energies sufficiently low ($< 1 \text{ MeV}$) to undergo capture. Hence the contributions of the neutron capture isotopes from this source can be of the same order of magnitude as any one of the many other isotopes produced by spallation. The majority of these secondaries will add to spallation damage. An increase by a factor 1.5 in the total number of particles is predicted for this depth.

Inner belt protons reaching the central crystal have a lower characteristic energy and on average traverse less material (18 gm.cm^{-2}) so that the above figures represent a considerable overestimate of the importance of secondaries. The above mentioned work also shows that the interaction rate of secondaries becomes equal to that of primaries at a depth of 75 gm.cm^{-2} . Thus for the relatively thin case of a spacecraft material, spallation due to primary protons will be the most important effect, with interactions of secondary neutrons of secondary importance only.

2.3.2 The Importance of Albedo Neutrons

An atmospheric neutron leakage flux spectrum as a function of

latitude has been predicted by Lingenfelter (1963). At solar sunspot maximum and 40° latitude the predicted fluxes are ($\text{cm}^{-2}\text{sec}^{-1}$):

$< 1 \text{ MeV}$	$1 \text{ to } 10 \text{ MeV}$	$> 10 \text{ MeV}$
0.190	0.091	0.017

Recent work by Preszler et al. (1972) has shown that the flux of high energy neutrons may be a factor fifty up on this estimate giving an integrated flux of $0.3 \text{ cm}^{-2}\text{s}^{-1}$ for neutrons of energy 20 - 100 MeV at 40° latitude. Thus in low altitude orbit high energy albedo neutrons can cause comparable spallation to primary cosmic rays (flux $\sim 0.6 \text{ cm}^{-2}\text{s}^{-1}$).

The relative importance of capture of low energy albedo neutrons was calculated by integration over the low energy portion of the spectrum (up to 20 MeV), making due allowance for absorption in 18 gm.cm^{-2} of satellite material. This calculation showed that for a 32° orbit, I_{128} production from such a source would occur at approximately one third the total rate of radioactive nuclide production by cosmic ray induced spallation. In an equatorial orbit the albedo fluxes would be reduced by a factor three, whilst for cosmic ray fluxes the reduction would be by a factor of ten. Capture of albedo neutrons would thus seem capable of providing a background comparable with that resulting from cosmic ray induced activity.

2.4 THEORETICAL PREDICTION OF SPECTRA RESULTING FROM SPALLATION

Tables 1 and 2 present the results of the computations described in section 2.2 for the predominant unstable isotopes used in predicting the spectrum for the case of 155 MeV irradiation of CsI. Results are presented for both NaI and CsI and are normalised to 3×10^5 interactions. In the case of NaI, there are clearly no isotopes produced with $(Z,A) > (53, 127)$, and there will obviously be an appreciable cross-section for products lighter

than $^{11}\text{Na}_{23}$. However the number of reactions from spallation of the Na atom is only one third of that from the I atom. Thus in addition to the close similarity between inner-belt and 155 MeV production, a close similarity between CsI and NaI can be seen. Results from 155 MeV irradiation can also give a good indication of cosmic ray damage.

Information on the decay schemes of the spalled nuclei was obtained from Tables of Isotopes by Strominger, Hollander and Seaborg (1958) and by Lederer, Hollander and Perlman (1967). Table 1 gives the short half-life decays used in predicting the spectra for times after irradiation up to one hour. Table 2 gives the long half-life decays used for predicting the spectra for times up until 68 days after irradiation. The energies presented are meant to represent the total energy loss in the crystal wherever several decays occur within the 1 μ s resolving time of the system.

These results have been used to attempt to predict the results of 155 MeV irradiation of CsI. Decay rates were calculated for various times after irradiation and the spectra were built up by drawing simple geometrical shapes to describe the energy loss spectra of the decay photons or β particles in the crystal. A smooth curve was drawn through the resultant superposition. For the case of gamma-ray decays, use was made of the Monte Carlo calculations of photopeak efficiency and Compton plateau level. The response to standard X-ray sources was used in order to estimate the resolution. Positron decays have a Fermi spectrum in kinetic energy up to the maximum energies given in the table and can deposit any energy between zero and the maximum available (maximum kinetic energy of β^+ + annihilation energy). This situation was simplified by drawing an isosceles triangle spectrum with base equal to the maximum energy available and apex at half this energy, the area contained being proportional to the decay rate of the

TABLE I SHORT TERM DECAYS

Isotope	Decay Mode and Energy (MeV)	Half-Life $\tau_{\frac{1}{2}}$ (mins)	Predicted (i) Inner Belt	Nos. Produced (ii) 155 MeV	(iii) Cosmic Rays
$^{55}\text{Cs}_{130}$	β^+ 1.97 β^- 0.442	30	3199 -	3183 -	576 -
$^{55}\text{Cs}_{128}$	β^+ 3.0 (70%) 2.5 (30%) E.C. (25%) 0.460 (20%) 0.285 (20%)	3	8623 -	8448 -	3063 -
$^{55}\text{Cs}_{127}$	E.C. γ 0.406	360	11959	11190	5743
$^{55}\text{Cs}_{126}$	β^+ 3.8 (82%) E.C. (8%) 0.426 (7%)	1.6	13947 -	12158 -	8834 -
$^{54}\text{Xe}_{125}$	γ 0.187 0.056 0.243 E.C.	1080	4324 -	3431 -	3529 -
$^{54}\text{Xe}_{123}$	β^+ 1.7 0.148	120	6584 -	4068 -	8385 -
$^{53}\text{I}_{123}$	E.C. γ 0.160	780	8340 12411	7929 12124	3322 3492
$^{53}\text{I}_{122}$	β^+ 3.0	4	11935 17598	10918 16695	6477 6806
$^{53}\text{I}_{121}$	β^+ 1.2 0.21	96	14395 21015	12345 18876	10367 10894
$^{52}\text{Te}_{127}$	β^- 0.70	560	6000 9060	6000 9060	6000 9060
$^{51}\text{Sb}_{118}^m$	β^+ 3.1	3.5	1577 2229	967 1479	2305 2422
$^{51}\text{Sb}_{117}$	E.C. γ 0.161	168	2609 3648	1376 2104	4641 4877
$^{51}\text{Sb}_{116}$	β^+ 2.4 1.3	15	3592 4969	1601 2449	7646 8035
$^{50}\text{Sn}_{111}$	E.C. 71%	35	657 865	105 198	2847 2992

TABLE II: LONG TERM DECAYS

Isotope	Energies of γ rays (MeV) and branching ratio	Half-Life $\tau_{1/2}$ (days)	Predicted		
			(i) Inner Belt	Nos. Produced (ii) 155 MeV	(ii) Cosmic Rays
$^{55}\text{Cs}_{132}$	E.C. 0.670	6.2	6000 -	6000 -	6000 -
$^{55}\text{Cs}_{131}$	E.C.	10	1716 -	1659 -	212 -
$^{55}\text{Cs}_{129}$	E.C. 0.380	1.3	5507 -	5508 -	1410 -
$^{55}\text{Cs}_{127}$	E.C. 0.406 (80%)	0.25	11959 -	11190 -	5743 -
$^{54}\text{Xe}_m^{131}$	0.163	12	70 -	67 -	9 -
$^{54}\text{Xe}_m^{129}$	0.196; 0.040	8	367 -	367 -	94 -
$^{54}\text{Xe}_{127}$	E.C. 0.370(40%); 0.203(60%)	34	1505 -	1408 -	723 -
$^{54}\text{Xe}_{125}$	E.C. 0.187; 0.243	0.7	4324 -	3431 -	3529 -
$^{54}\text{Xe}_{123}$	0.148	0.08	6584 -	4068 -	8385 -
$^{53}\text{I}_{126}$	E.C. (55%) 0.386(34%); 0.650(33%)	13	6000 9060	6000 9060	6000 9060
$^{53}\text{I}_{125}$	E.C.	60	2899 4382	2750 4206	575 604
$^{53}\text{I}_{124}$	E.C. (70%) 0.605 (95%)	4	5159 7742	4964 7591	1469 1544
$^{53}\text{I}_{123}$	E.C. 0.160	0.5	8340 12411	7929 12124	3322 3491
$^{52}\text{Te}_m^{125}$	0.110; 0.035	58	136 206	129 197	27 28
$^{52}\text{Te}_m^{123}$	0.089; 0.159	104	685 1020	652 996	273 287
$^{52}\text{Te}_m^{121}$	0.082; 0.214	154	2564 3743	2199 3362	1846 1960
$^{52}\text{Te}_{121}$	0.570(87%); 0.506(13%)	17	14395 21015	12345 18876	10367 10894
$^{52}\text{Te}_{119}$	E.C.	4.5	6082 8693	4264 6520	7176 7541
$^{51}\text{Sb}_{122}$	0.566 (66%)	2.8	71 105	65 99	31 40
$^{51}\text{Sb}_{120}$	E.C. 0.089; 0.199	6	397 574	312 477	371 389
$^{51}\text{Sb}_{119}$	E.C.	1.66	834 1192	585 894	984 1034
$^{50}\text{Sn}_m^{117}$	0.159; 0.162	14	284 397	150 229	505 530

cont'd.

Table II, cont'd.

Isotope	Energies of γ rays (MeV) and branching ratio	Half Life $t_{1/2}$ (days)	Nos Produced		
			(i) Inner Belt	(ii) 155 MeV	(iii) Cosmic Rays
$^{50}_{\text{Sn}}_{113}$	E.C. 0.392	120	2261	562	7611
			3034	859	7999
$^{49}_{\text{In}}_{111}$	0.172; 0.247	2.8	1327	212	5749
			1747	324	6042

* Single Nucleon Removal + Secondary Product

E.C. Electron Capture m Metastable nucleus

Values for CsI are given first

Values for NaI are given below

isotope. Two major difficulties in the prediction process are the lack of complete information on certain decay schemes and the uncertainty as to whether or not certain spalled nuclei would be produced in the metastable condition. It was assumed that nuclei immediately after spallation would be in the metastable condition, whilst those produced as secondary products by decay would give the normal state.

Results of such predictions are compared with experimental results in section 2.6.

2.5 THE IRRADIATION EXPERIMENTS

A series of irradiation experiments have been performed by exposing crystals similar to the central crystal of the U.K.5 detector to a beam of 155 MeV protons provided by the synchrocyclotron at A.E.R.E., Harwell. In each case the integrated dosage given to the crystal was monitored to 25% accuracy using an ionisation chamber. The ionisation chamber was calibrated at the low and high dose rate ends of the range by comparisons with a scintillation counter and a Faraday Cup respectively.

In the first irradiation, performed on July 16th 1970, a CsI crystal (cylindrical, $5\text{cm} \times 9.1\text{cm}^2$) was exposed to a dosage of 1.2×10^{10} protons accumulated over one minute. Taking the interaction length (λ) for inelastic collisions in CsI as 38 cm, this was calculated to give 9.6×10^8 interactions for the crystal orientation employed. Immediately after irradiation, the crystal was removed from the irradiation pit to a low background situation. The light-pulses resulting from radioactive decays inside the irradiated crystal were examined by a photomultiplier, pulse-height analyser system previously calibrated using standard X-ray sources, and the resulting pulse height spectrum was read out periodically using an X-Y plotter. This dosage was found to saturate the electronics and give

significant dead-time problems for several hours after irradiation, Spectral information was obtained over the range 100 keV-1 MeV for times after irradiation ranging from six hours to 100 days, after which time the activity had fallen to a level comparable with laboratory background.

In a second experiment performed on 16th December, 1970, using the same crystal, a similar procedure was employed except that a lower dosage was applied in order to resolve the behaviour immediately after irradiation. Various pulse-height analyser ranges were used to give spectral information between 20 keV and 2.4 MeV. A dosage of 4×10^8 protons accumulated over a three minute interval was calculated to give 5×10^7 interactions. This experiment gave useful information on the spectrum of decays for a period from several minutes until 2 days after irradiation.

When the importance of having complete data coverage was realised, a third experiment was planned using read-out of the P.H.A. onto paper tape in order to facilitate data collection. The experiment was carried out at Harwell on 24th March, 1972. The same crystal was this time given a dosage of 1.15×10^8 protons (1.09×10^7 interactions), whilst a second CSI crystal (cylindrical, $3.8\text{cm} \times 5.3\text{cm}^2$) was given 1.05×10^{10} protons (1.05×10^9 interactions). Three different P.H.A. ranges were used to give good coverage over the range 20 keV - 4 MeV. Calibrations have been carried out periodically to compensate for any drift. Data from this experiment enables accurate decay curves to be plotted over the entire range from 1 min. to 100 days after irradiation.

2.6 COMPARISON OF THEORETICAL PREDICTIONS AND EXPERIMENTAL RESULTS

Figure 7 compares the prediction of short term behaviour obtained using Table 1 with the experimental results of the low dose irradiation over the energy range 60 keV to 2.4 MeV. General agreement to better than a

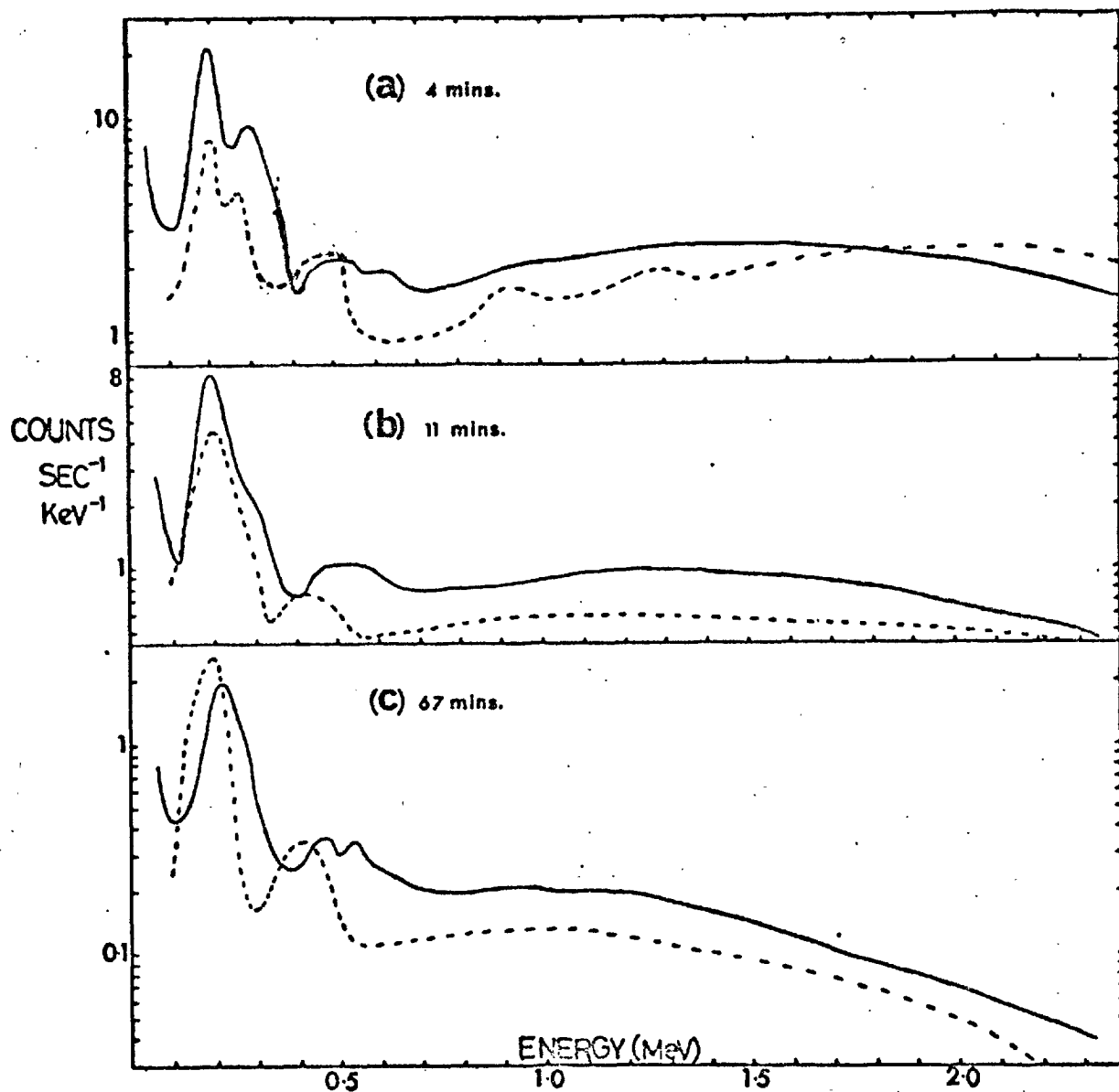


FIGURE 7: Experimentally observed spectra (shown solid) obtained from the low dose irradiation (5×10^7 interactions) compared with predictions (shown dotted) based on the Rudstam formula and the Table of Isotopes, for (a) 4 minutes, (b) 11 minutes, (c) 67 minutes after irradiation.

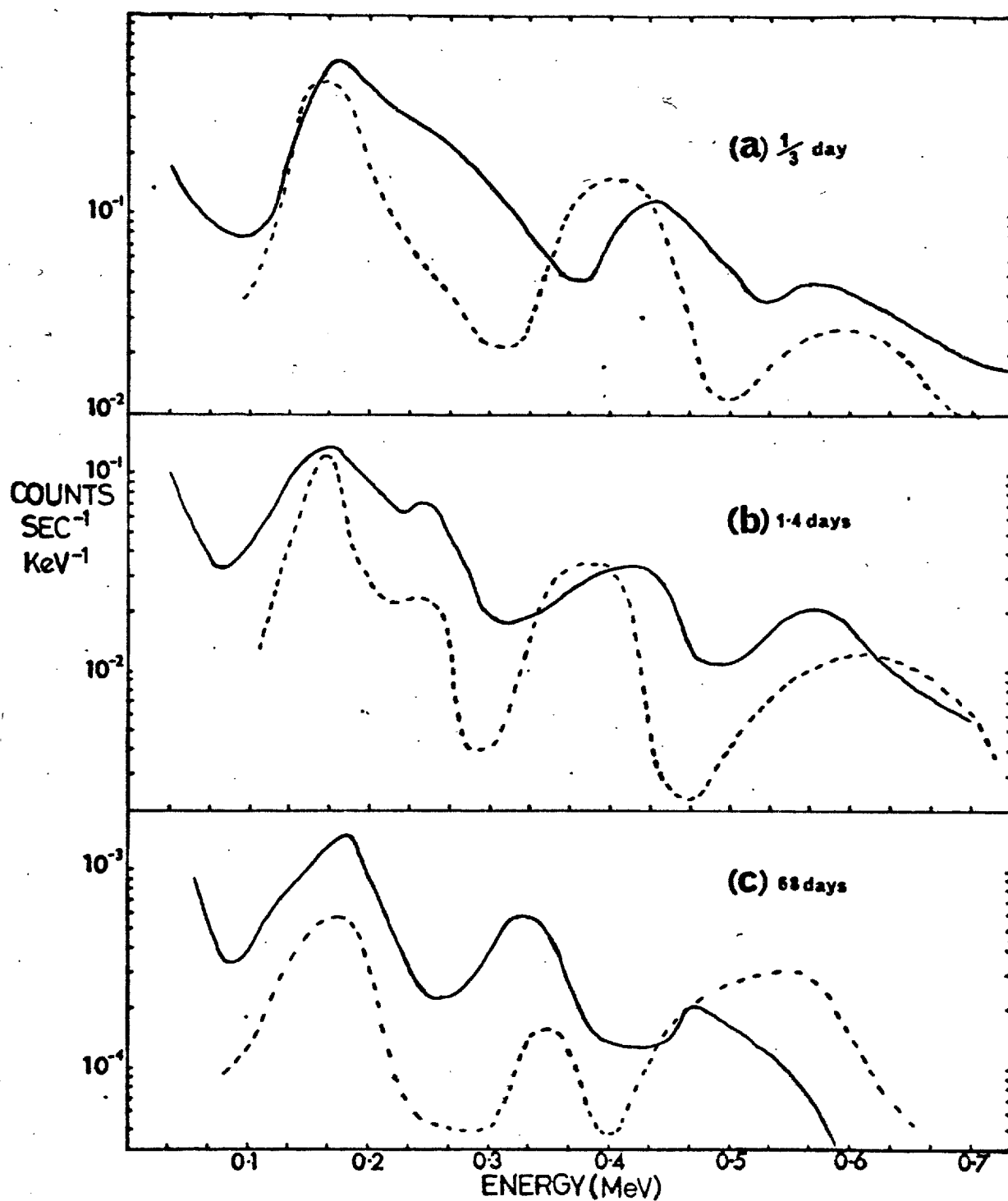


FIGURE 8: Experimentally observed spectra (shown solid) from the high dose irradiation (but normalised to 5×10^7 interactions) compared with predictions (shown dotted) based on the Rudstam formula and the Table of Isotopes, for (a) $\frac{1}{3}$ day, (b) 1.4 days, (c) 68 days after irradiation.

factor of three in absolute intensity and 15% in energy is obtained.

Experiment would seem to show an annihilation line at 510 keV which is not predicted. An order of magnitude estimate indicates that this could result from the escape of positrons into the surrounding lead shield with re-entry of some of the annihilation X-rays into the crystal. This is confirmed by the fact that the decay of the peak tracks well with the decay curve for energies greater than 1 MeV, at which energies the spectrum is due almost entirely to the short half-life β^+ decays. This feature will be reduced when active collimation is employed in the U.K.5 detector.

Figure 8 compares the long-term behaviour predicted from Table 2 with some results of the high dose irradiation for energies from 60 keV to 700 keV. Better than order of magnitude agreement over the entire range of the experiments (4 mins to 68 days) can thus be seen. Activity levels between peaks are underestimated by this process as they are a superposition of a large number of decays not taken into account.

These comparisons take no account of structure below 60 keV. As can be seen from figure 10 of Chapter 3, this comprises a single peak at about 40 keV. This peak can be well explained as a superposition of all electron capture decays resulting in emission of X-ray quanta equal in energy to the K shell electron. These energies range from 35.9 keV for Cs isotopes to 29.2 keV for Sn isotopes. From Table 1 this would predict a level of $0.02 \text{ keV}^{-1} \text{ sec}^{-1}$ after 1 hr on the scale of figure 9 which compares favourably with $0.05 \text{ keV}^{-1} \text{ sec}^{-1}$ observed experimentally.

2.7 CONCLUSIONS

These results indicate that the activation of CsI by 155 MeV protons is well understood in terms of spallation and that the Rudstam formula, when used in conjunction with radiochemical data, can yield good predictions of both the magnitude and the energy loss spectrum of activity.

In addition, the Rudstam formula predicts a close similarity between the results of 155 MeV irradiation and inner-belt irradiation. A comparable activation level (to within 10%) and similar features will result from irradiation of NaI. A good indication of cosmic ray induced activity is also given by these experimental results.

CHAPTER 3 - EXTRAPOLATION OF IRRADIATION RESULTS TO SATELLITE CONDITIONS AND COMPARISON WITH PREVIOUS OBSERVATIONS OF BACKGROUND.

3.1 PREVIOUS BACKGROUND OBSERVATIONS AND THEIR TREATMENT

Radioactive background has been observed in all cosmic gamma-ray experiments which are carried into regions of trapped particle radiation. These include the complete OSO series of satellites which have nominal orbits at 550 km altitude and 33° inclination, and the ERS-17 satellite. Table 3 gives a summary of the essential characteristics of the major experiments considered in this thesis. No activity has been reported for the Ranger 3 and ERS-18 experiments which were in interplanetary space, but it will be shown later that considerable corrections need to be applied to their data. In these cases the contribution of radioactivity probably remained undetected because the equilibrium between cosmic ray production and decay is soon established making time variations of counting rates difficult to detect.

Previous attempts to explain the activation and correct data have involved the identification of one or two specific half-lives. In his analysis of OSO 1, Peterson (1965) identifies a half-life in the range 20 - 30 minutes with the 25 minute decay of I_{128} (β^- , 2.12 MeV). The production mechanism for this isotope was hypothesised to be by capture of neutrons produced throughout the spacecraft by (p,n) reactions. Observation of a longer half-life in the data obtained from OSO 3 led Schwartz (1969) to identify the activity as the 15 hour decay of Na_{24} (β^- , 1.39 MeV). This could be produced in the central crystal by neutron capture or throughout the spacecraft by the reaction $Al_{27} (n, \alpha) Na_{24}$. In the latter case the contribution to the rate in the central crystal would have to be due to leakage through the collimator of gamma-rays from the daughter Mg_{24} (γ 1.37, 2.75 MeV).

The spectrum of secondary neutrons peaks at around 5 MeV at which energy the neutron capture cross-sections are less than 0.15 mb for Na_{23} and

TABLE 3 - SATELLITE X-RAY EXPERIMENTS

Experiment	Date	Satellite Orbit	Central Crystal	Collimator	Opening Angle	Geometric Factor Photons	Other Background reported
OSO I Peterson, Univ. of Minnesota 0.05-3MeV	7.3.62	32.85° 553-595 km T=96mins	NaI t=5.4cm ² A=19.7cm ² M=390gm	None	Omni-directional		
OSO 3 Schwartz, Peterson U.C.S.D. 7.7-210keV	8.3.67 to 28.6.68	32.87° 534-564 km T=96mins	NaI t=0.5cm ² A=9.57cm ² M=17.6gm F=0.077	CsI l _{min} = 1.95cm l _{av} = 2.76cm h=12.32 cm	23° FWHM	1.35 cm ² sr	Electron of energ 280-390 keV through aperture
OSO 5 Frost, Dennis, G.S.F.C. 15-250keV	22.1.69	32.95° 536-561 km T=96mins	CsI t=0.64cm ² A=71cm ² M=205gm F=0.166	CsI l _{min} = 3.2cm	39° FWHM	34 cm ² sr	Electron of ~ 0.5MeV
U.K.5 Imperial College 0.02-2MeV	1973	Activity calculated for 33°, 550km 0°now decided T~100mins	CsI t=5cm ² A=9.1cm ² M=205gm F=6.5x 10 ⁻⁴	CsI l _{av} = 3cm directional	8° FWHM 0.7 omnidirectional	0.13 cm ² sr	Electron eliminat ed by NE102A
Ranger III Metzger J.P.L. 0.07-4.4MeV	1962	Space Probe Data Ob- tained for 40 hr @7x10 ⁴ km →4x10 ⁵ km	CsI t=7cm ² A=38.4cm ² M=1212gm F≈0.77	None	Omni-directional	54cm ²	
ERS-18 Vette etal. 0.25-6MeV	28.4.67 Data obtained May, June 1967	15,000km -117,00km T=48hrs	NaI t=7.65cm ² A=31.5cm ² M=882gm F=0.77	None	Omni-directional	54cm ²	cont'd.

t = thickness; A = Cross-sectional area; M = Mass; l = path length of photon reaching central crystal; T = Orbital Period; F = Geometric Factor
 $\div$ Mass.

less than 90 mb for I_{127} . Attempts to quantitatively explain the observed levels of activation by a neutron capture model have therefore come out at least a factor thirty too low (Peterson, Schwartz, 1972). The cross-section for $Al_{27} (n, \alpha) Na_{24}$ peaks at 130 mb at 13 MeV. In this case the leakage spectrum has proved inadequate to describe the details of the background spectrum observed in OSO 3 and ERS-17 and is totally incapable of explaining the background peaks reported for OSO's 2 and 5 (Dennis, 1972) and OSO 7 (Forrest, 1972).

In the case of spallation induced activity, the entire geometrical cross-sections (1260 mb for Cs and I, and 410 mb for Na) are effective in producing a count in the central crystal. Thus the direct production of spallation products in the central crystal is a far more viable mechanism for background production than mechanisms involving several stages occurring throughout the spacecraft, each with a smaller cross-section than that for spallation.

The 25 minutes and 15 hour half-lives that have been observed correspond closely to the amounts of time available to observe decays. There is approximately an hour in between successive inner-belt passages and then about 15 hours clear in each day before the next set of passages. Figures 11 and 14 show that half-lives of these orders show up in the superposition of decays produced by spallation. More recent detailed investigations of the background (Dennis, 1970) have shown that a large number of half-lives are produced, including a number of long-lived isotopes, which build up the counting rates throughout the satellite history. These results are well explained by spallation (see section 3.5).

Evidence that radioactive background results from protons entering the detector from outside the satellite has been provided by Leong (1970) in his analysis of results from the M.I.T. Gamma-Ray Telescope, which was carried on OSO 3. Induced activity was observed in a CsI crystal which had

2.75 gm.cm^{-2} of frontal shielding but not in a NaI crystal which had 40 gm.cm^{-2} of such shielding. Both crystals possessed a considerable amount of side shielding. Neutrons or gamma-rays generated throughout the satellite would not be affected by this difference in frontal shielding. A half-life of around 28 minutes was identified and a proton capture reaction giving I_{128} was postulated. Clearly spallation would provide a better explanation.

3.2 ACTIVITY LEVELS AND DOSAGES

Various activation levels have been reported for the OSO experiments described in section 3.1. For OSO 1, Peterson (1965) reported an activation of $0.08 \text{ counts g}^{-1}\text{s}^{-1}$ immediately after passage through the S.A.A. for photon energies between 0.3 and 3 MeV. Schwartz (1969) described activation levels varying between 0.4 and 2.0 $\text{counts g}^{-1}\text{s}^{-1}$ in the energy range 12.5 to 210 keV for the OSO 3 telescope. The levels detected for OSO 5 by Dennis (1970) in the range 30 keV to 250 keV are similar to those for OSO 3. There is thus an order of magnitude discrepancy between the activation level reported for OSO 1 and that for OSO's 3 and 5. Only a factor two of this can be accounted for by the higher energy threshold (0.3 MeV) of the OSO 1 experiment, as the spectrum of decays is flat. Dennis has reported a considerable variation of activation resulting from the differing penetrations of the anomaly region which accompany the precession of apogee. This effect should give an increased dosage for OSO 1 compared with 3 and 5 because of the higher orbit altitude.

In chapter 2 an integrated proton dose of $6 \times 10^5 \text{ cm}^{-2} > 100 \text{ MeV}$ was used in computing the activation for a worst case anomaly passage. Later in this chapter a model of four such successive passages per day is used to describe the history of satellite irradiation. Mapping of satellite orbits onto the flux contour maps of Stassinopoulos (1970) shows this model

to be a reasonable approximation (see e.g. Peterson, 1965). When the results of the 155 MeV irradiation experiments are normalised to this dosage it is found that the result is to underestimate the OSO's 3 and 5 observations by a factor four. The OSO I observations are overestimated by a factor two.

Work by Lavine and Vette (1970) has now become available which estimates orbital integrations of proton dosages from model proton environments based on experimental observations. For a 30° inclination, 556 km altitude orbit, this work estimates a daily dosage of $3.5 \times 10^6 \text{ cm}^{-2} > 100 \text{ MeV}$. This is a 50% increase on the model adopted for U.K.5. For U.K.5 a model of uniform shielding of the central crystal by 18 gm.cm^{-2} was adopted, limiting the protons of interest to those of energy greater than 100 MeV. Both the OSO 3 and OSO 5 detectors had considerably larger opening angles (23° and 39° FWHM, respectively) compared with the U.K.5 instrument (8° FWHM) so that many more of the soft protons would be effective in producing activity in the central crystal. Lowering the energy threshold to 50 MeV increases the effective irradiating flux by a factor 1.7. Combining these two factors implies that the levels of activation observed on OSO's 3 and 5 are well explained quantitatively by spallation (better than a factor two). Actual measurements on trapped high energy protons are scanty and the model environments only give agreement with measurement to within a factor two so that this agreement is the best that can be expected.

The lower activation level observed on OSO 1 can then be explained on the spallation model by the greater amount of shielding that this crystal possessed. The results of Leong (1970) mentioned in 3.1 indicate a factor ten reduction in activation when shielding is increased from 2.75 to 40 gm.cm^{-2} . This shielding will remove low energy protons by ionisation, the energy threshold for proton penetration being increased from 50 MeV to

200 MeV for such an increased depth. Calculations of the average shielding have not been carried out but the OSO 1 detector crystal was buried in a considerable amount of material and was in part shielded by neighbouring crystals and a lead collimator. These considerations would indicate that a certain amount of passive shielding can be useful in reducing background caused by inner belt protons.

3.3 PREDICTION OF ACTIVATION PROBLEMS FOR U.K.5 FOR THE CASE OF A 33° INCLINATION ORBIT.

3.3.1 Inner Belt Activation

In Chapter 2 it has been shown that the Rudstam formula gives a good explanation of the activity caused by 155 MeV protons and that the formula predicts a close similarity between the spallation produced at this energy and that due to an inner belt spectrum. Hence scaling the experimental results by the appropriate dosage should produce a good estimate of the activity caused by passage through the South Atlantic Anomaly.

Figures 9 and 10 present the experimental results scaled to the dosage (6×10^5 protons cm^{-2}) used in the theoretical prediction of nuclide production for the worst case of S.A. Anomaly traversal. The considerations of section 3.2 indicate that this probably underestimates the problem by a factor 2 to 4. Figure 9 gives information over the energy range from 50 keV to 2.3 MeV. Figure 10 gives the details of the low energy part of the spectra from 20 keV to 500 keV.

The long-term behaviour can be obtained from the experimental curves of Figure 8 by scaling by the factor 6×10^{-3} . For comparison Figures 9 and 10 also include the expected background counting rate spectrum due to the diffuse cosmic X-ray background. The spectrum was taken as 26 E^{-2} photons $\text{cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ keV}^{-1}$ and both entry through the telescope aperture and

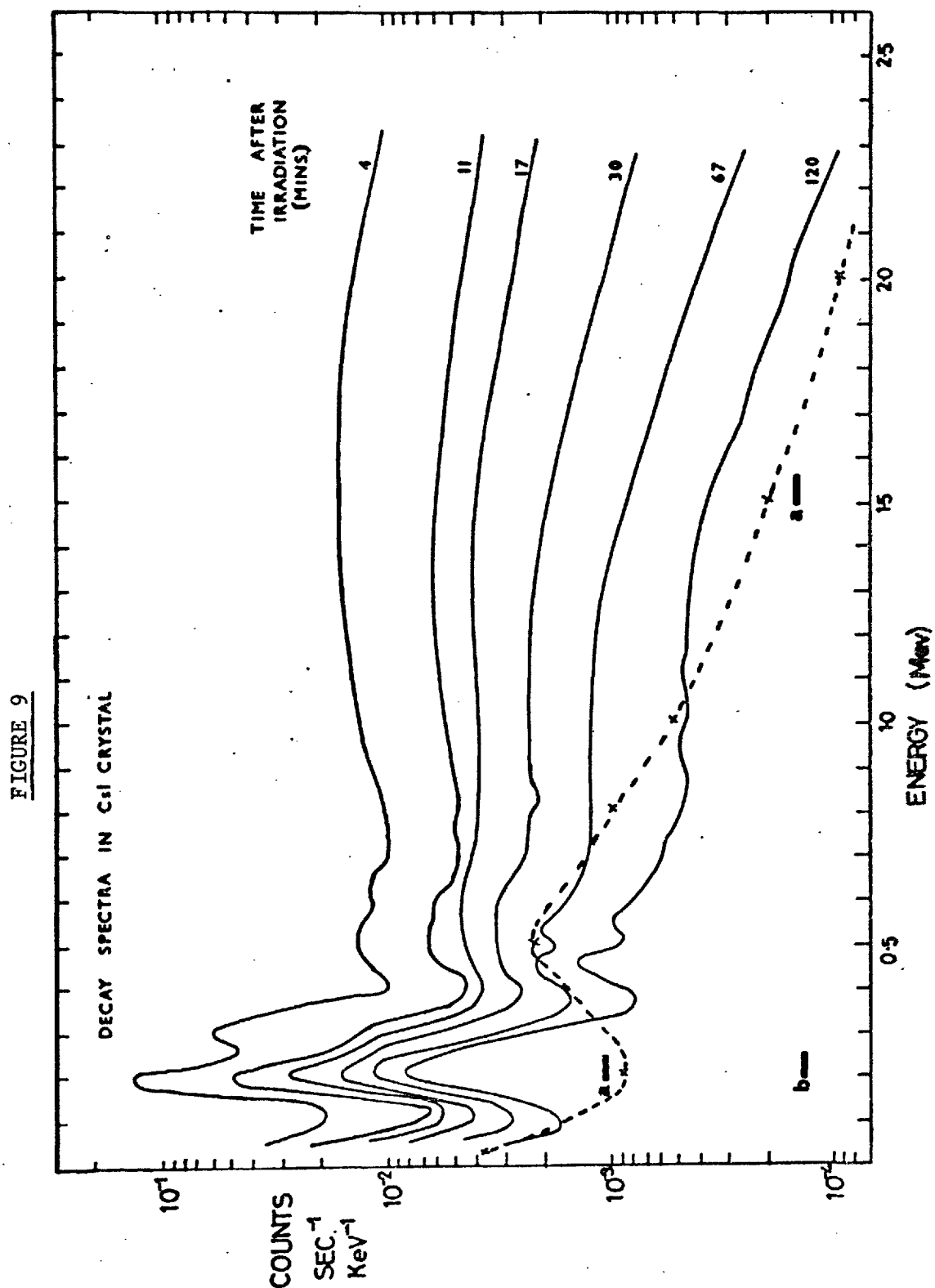


FIGURE 9: Predicted spectra (shown solid) for worst case inner belt traversal by U.K.5. Dotted curve gives estimated count rate due to diffuse cosmic X-ray flux. 'a' gives estimated background level due to cosmic ray activation for a 2 GV cut-off and 'b' the same for 14.9 GV cut-off.

FIGURE 10

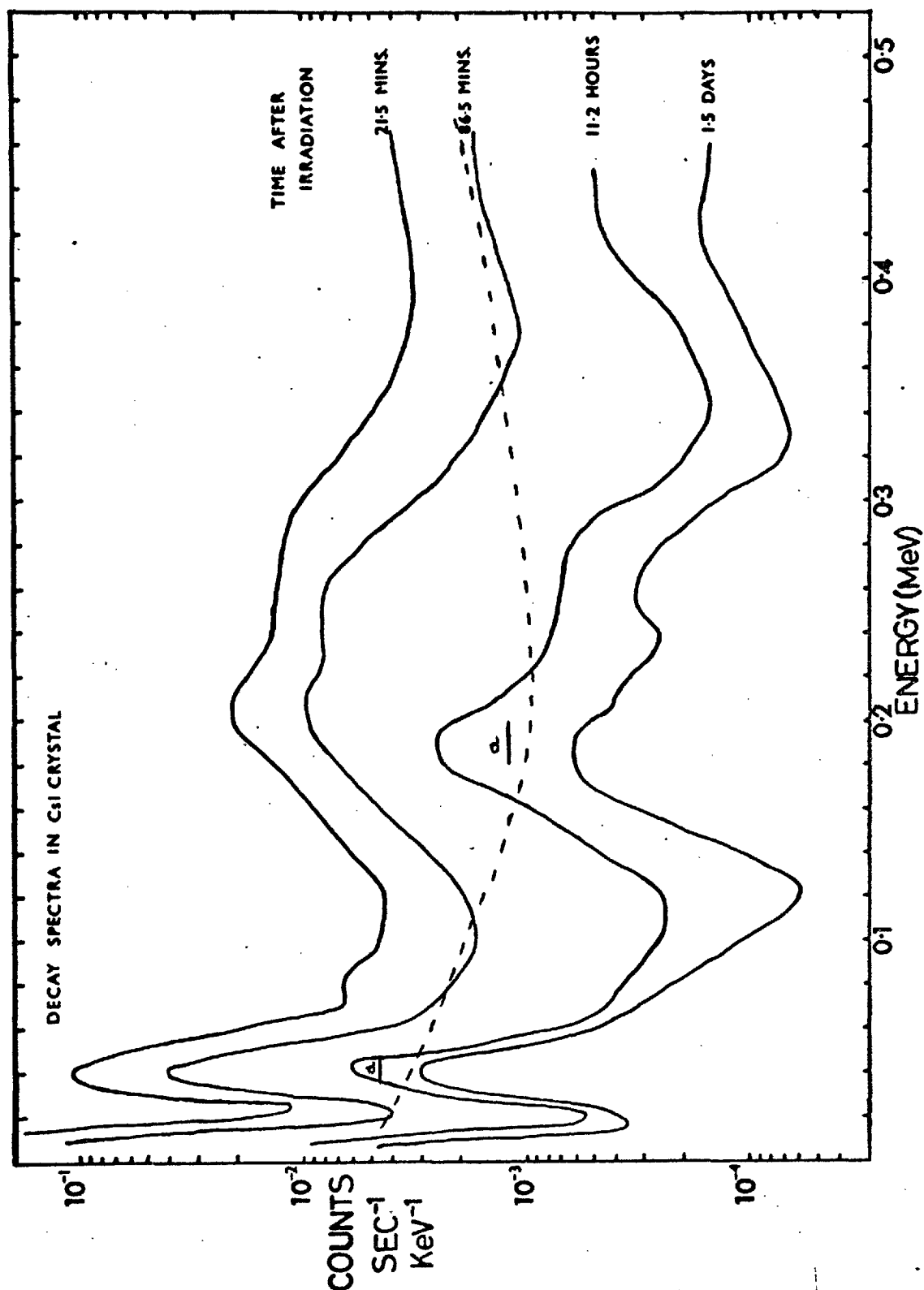


FIGURE 10: Some predicted spectra due to inner belt spallation for the low energy X-ray region, compared with the estimated diffuse flux contribution (shown dotted).

FIGURE 11.

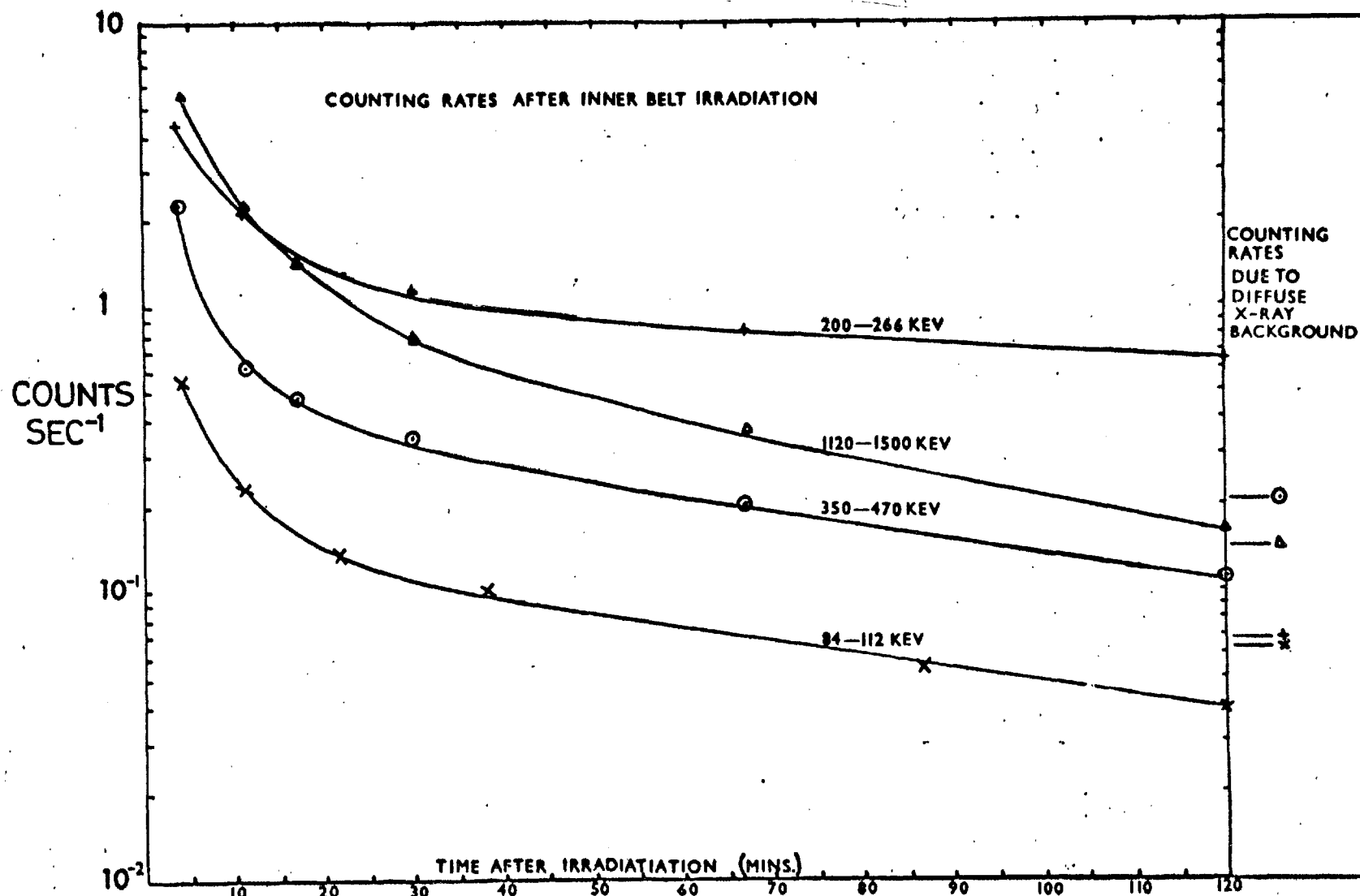


FIGURE 11: Predicted counting rates as a function of time after inner belt irradiation for four energy channels, compared with estimated counting rates due to the diffuse cosmic X-ray flux (shown at right hand side).

leakage through the collimator, as predicted by a Monte Carlo technique, have been considered. It can be seen that the activity takes over 2 hrs to fall to a comparable level.

Figure 11 shows how the counting rate would die away as a function of time for certain of the energy channels that are to be employed in the U.K.5 experiment. The effect of superposing a large number of half-lives is clearly shown

3.3.2 Cosmic Ray Activation

In addition to these intermittent passages through the S.A. Anomaly, the satellite will be subject to a flux of cosmic rays that varies with the magnetic latitude. If the flux were constant, an equilibrium situation would be reached when the decay rate of each isotope would equal its production rate. A worst case estimate of the cosmic ray induced background can be obtained by considering a constant flux appropriate to the highest magnetic latitude that the satellite attains. This was taken to give a 2 GV rigidity cut-off.

As has been shown above, the spectrum to be expected will differ somewhat from that due to inner belt irradiation. However a comparison of activity levels can be made by considering the peaks at around 200 keV and 1.5 MeV. The predicted levels of these peaks for a 2 GV cut-off are marked in on Figures 9 and 10, as are the levels predicted for an equatorial orbit at 14.9 GV cut-off. These levels are presented for solar sunspot maximum. At sunspot minimum the 2 GV levels would be increased by a factor 1.6 and the 14.9 GV levels by 1.1.

These results are presented for the central crystal of the U.K.5 detector. The effect of the collimator will be to remove some of the partial energy losses, but this will be compensated by a contribution due to activation of the collimator. To a first approximation these

effects will cancel each other, but further irradiation experiments should be performed using both collimator and central crystal.

3.4 THE BUILD-UP OF ACTIVITY

3.4.1 Introduction

The results presented in the previous section are for a single irradiation at a typical South Atlantic Anomaly dosage. In practice a satellite in an inclined orbit will make several successive passages through the S.A. Anomaly at a period approximately equal to that of its orbit (96 mins for 550 km altitude) and will then spend a number of orbits when there is no such irradiation. Groups of passages through the radiation belt will reoccur with a period of one day. There will then be a gradual change in the activity spectrum and the shape of decay curves throughout the satellite history due to the superposition of the effects of a large number of irradiations. In addition there will be a build-up of background counting rate due to the long half-life isotopes.

The variation of decay rates with satellite history can always be computed up to a time T days after launch if the history of satellite irradiation is known and decay curves after a single δ -function irradiation are known up until T days after irradiation.

3.4.2 Estimation of Build-Up from Decay Rates

The procedure for computing such decay rates may be formalised mathematically as follows. Suppose that a decay $R(t)$ counts sec^{-1} is measured for a certain energy channel as a function of the time (t) after a δ -function dosage (D_c). $R(t)$ will be some superposition of exponential functions, e.g.

$$R(t) = \sum_r \frac{a_r}{\tau_r} e^{-\frac{t}{\tau_r}}$$

Then if the detector receives dosages $D_1, D_2, \dots, D_n$ at times $t_1, t_2, \dots, t_n$ after launch, the resultant decay rate at time T is given by

$$R(T) = \frac{1}{D_c} \sum_{r=1, n} D_r R(T - t_r)$$

where t_n is the last irradiation before time T .

If D_r becomes a continuous function $D(t)$ per unit time, as is the case with cosmic ray activation, then the summation becomes the integral

$$R(T) = \frac{1}{D_c} \int_0^T D(t) R(T - t) dt$$

If the dosage is constant with time ($D(t) = D$) then $R(T)$ is clearly the area under the normalised decay curve up to time T . Two special cases for $R(t)$ are worth consideration:

i) Single Exponential Decay

In this case $R(t) = \frac{KD_c}{\tau} e^{-\frac{t}{\tau}}$ where K is a constant. Then for constant dosage,

$$\begin{aligned} R(T) &= \frac{KD}{D_c \tau} \int_0^T e^{-\frac{(T-t)}{\tau}} dt \\ &= \frac{KD}{D_c} \left[1 - e^{-\frac{T}{\tau}} \right] \end{aligned}$$

Thus it can be seen that saturation is reached after only a few half-lives.

ii) $\frac{1}{t}$ decay law

Superposition of a large number of half-lives can give a decay which approximately follows a $\frac{1}{t}$ decay law over some range of time.

In this case $R(t) = \frac{KD_c}{t}$ and

$$R(T) = \frac{KD}{D_c} \int_0^T \frac{dt}{T-t}$$

Clearly this decay law cannot hold down to $t = 0$ so that an arbitrary lower limit $t_{\min}$ must be set to t in which case

$$R(T) = \frac{KD}{D_c} \log_e \left(\frac{T}{T_{\min}} \right)$$

3.4.3 Estimation of the Build-Up Problem for U.K.5 in Inclined Orbit

An estimate of the severity of this effect was made for the 200 to 266 keV channel of U.K.5, which contains a particularly well marked peak in both short and long term behaviour. A simplified irradiation model was used involving four successive equal dosages ($6 \times 10^5 \text{ cm}^{-2} > 100 \text{ MeV}$) at 90 min. intervals followed by the remaining 19.5 hrs each day without irradiation. Decay curves were plotted from the experimental irradiation results and the technique described in section 3.4.2 was used to predict the build-up with the day number after launch of the minimum radioactive background rate observed in each day. The results of this calculation are illustrated in Figure 12 where comparison

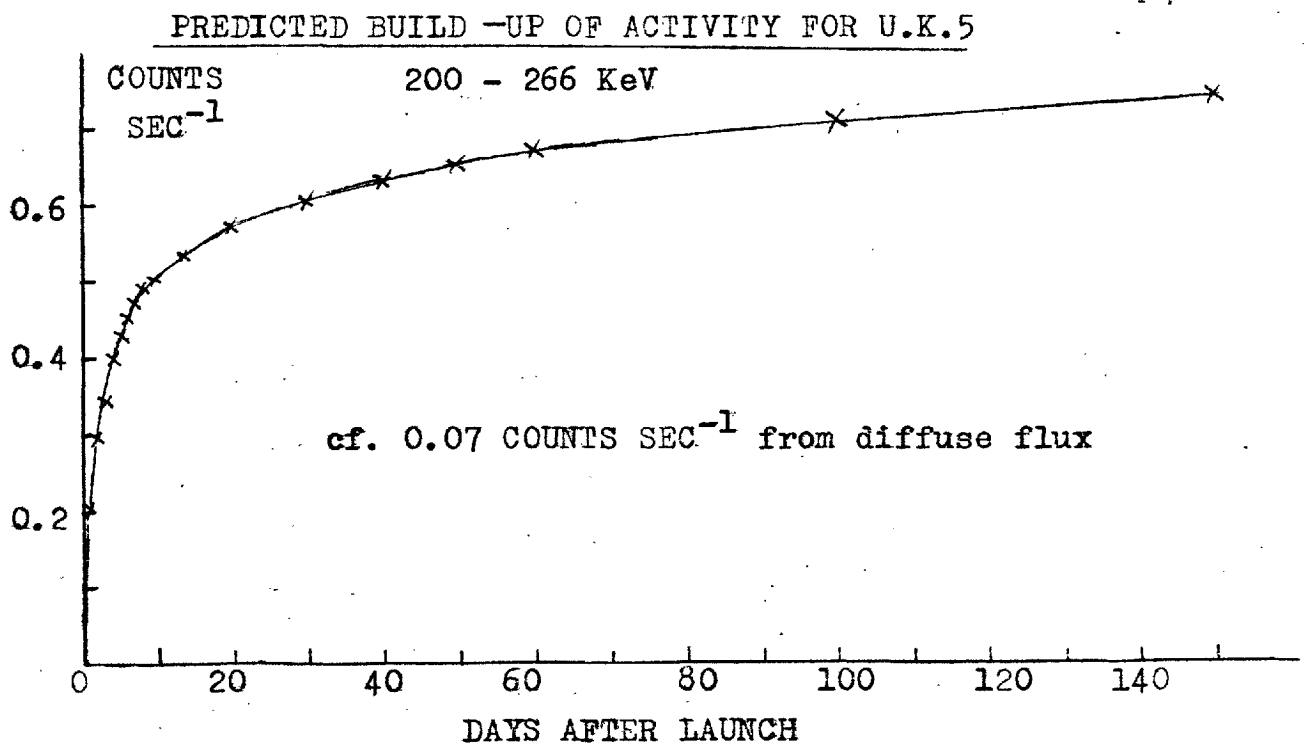


FIG.12

is made with the counting rate to be expected from diffuse cosmic X-rays. As mentioned before this could well underestimate the problem by a factor 2 to 4.

It can clearly be seen that at no time after the first Anomaly passage will the radioactive background be less than the diffuse X-ray background and the built-up level will soon be in excess by at least an order of magnitude. Inspection of the spectrum shown in Figures 9 and 10 shows that this will also be the case in the region around 40 keV, whilst in between these energies the levels built-up will still be greater than the diffuse contribution.

3.5 COMPARISON OF PREDICTIONS BASED ON IRRADIATION RESULTS WITH SATELLITE OBSERVATIONS OF BACKGROUND

3.5.1 The OSO 2 Scintillator Experiment

In this case the detector comprised a cylindrical central crystal of CsI ($5.1 \text{ cm}^2 \times 5.1 \text{ cm}$, $M = 117 \text{ gm}$) in an anticoincidence cup of the same material.

Dennis (1972) has recently re-examined the results of this experiment for background and has estimated the spectrum of activation by subtracting the orbital average of the counting rates obtained immediately before the satellite commenced a set of radiation belt passages from the orbital average obtained immediately afterwards. In Figure 13, the resulting spectrum is compared with the results of the irradiation experiment obtained after eight hours. Normalisation of activity levels is arbitrary in this case but good agreement in the shape of the spectrum can be seen. There were considerable difficulties in the calibration of the OSO 2 instrument and the fit is good to within the errors involved in this.

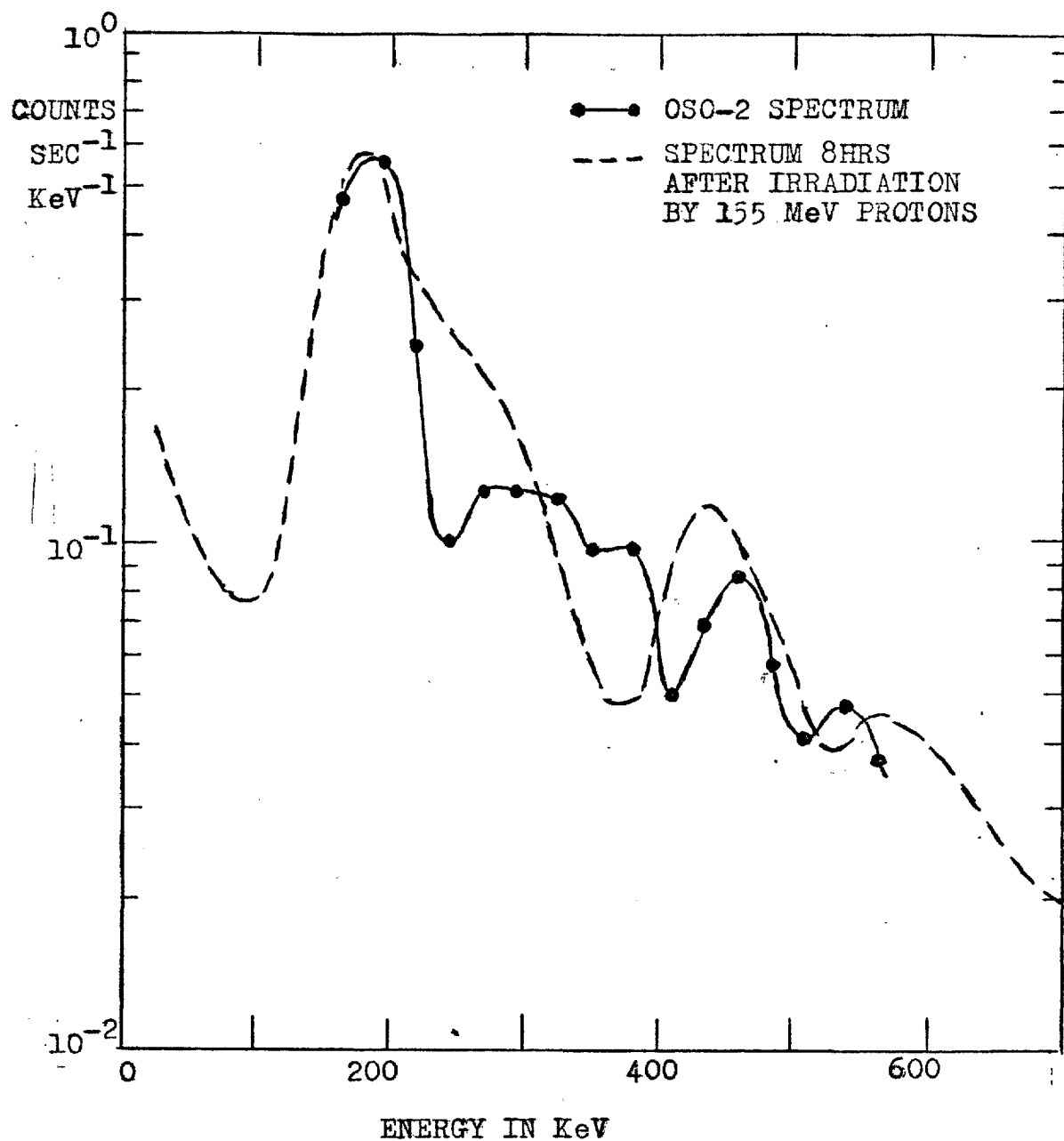


FIG.13

OSO-2 SPECTRUM OF INDUCED ACTIVITY
COMPARED WITH IRRADIATION RESULTS

3.5.2 The OSO 3 X-Ray Telescope

In his analysis of OSO 3 data, Schwartz (1969) ascribed the observed background to leakage through the collimator of the gamma-rays (1.37, 2.75 MeV) resulting from the 15 hr. decay of Na_{24} produced throughout the spacecraft by the reaction $\text{Al}_{27}(\text{n}, \alpha)\text{Na}_{24}$. The first two weeks of data were ignored and the remaining data was least squares fitted to a constant rate plus a component decaying with a 15 hr. half-life with respect to time out of the belt.

In Figure 14 the technique described in section 3.4.2 has been used to estimate the variation in the decay curves with time after launch for two of the energy channels used in the OSO 3 experiment. Four dosages at $6 \times 10^5 \text{ cm}^{-2}$ were used and the results from the CsI crystal were directly scaled to the mass of the OSO 3 central crystal of NaI. It can be seen that the decay curve attained after two weeks of satellite history could readily be mistaken for a 15 hr. half-life decay, particularly when the first half-hour's data out of the belts is ignored as was the case for OSO 3. The results of fitting 15 hr. decays to such curves are compared with the correction factors obtained by Schwartz in Figure 15. It can be seen that the correction factors did in fact show a peak in the 22-38 keV channel. On the model of gamma-ray leakage through the collimator, this is explained with difficulty as K-escape from the collimator into the central crystal when the threshold for triggering the collimator anti-coincidence had risen to $\sim 1 \text{ MeV}$. The presence of spallation induced K-capture decays in the central crystal is a far more viable explanation. As explained in section 3.2 a factor four increase in dosage is needed to normalise the two peaks. The fact that the predicted peak falls at slightly higher energy to the observed is probably due to the fact that CsI has been compared with NaI. In the former case the highest K-shell energies are at 36 keV, and in the latter case at 33 keV. Although the 22 - 38 keV

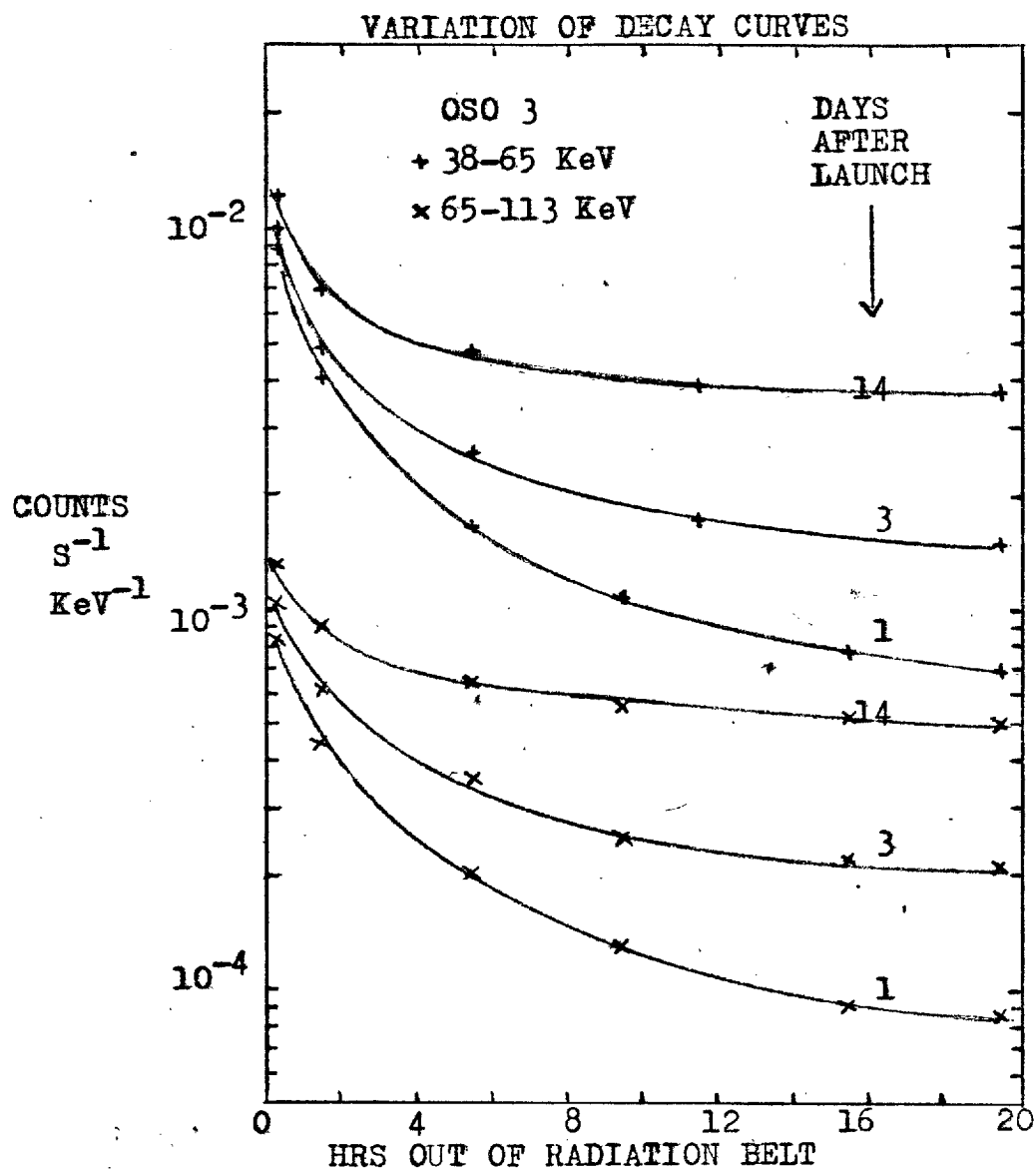


FIG.14

Decay curves predicted from irradiation results.

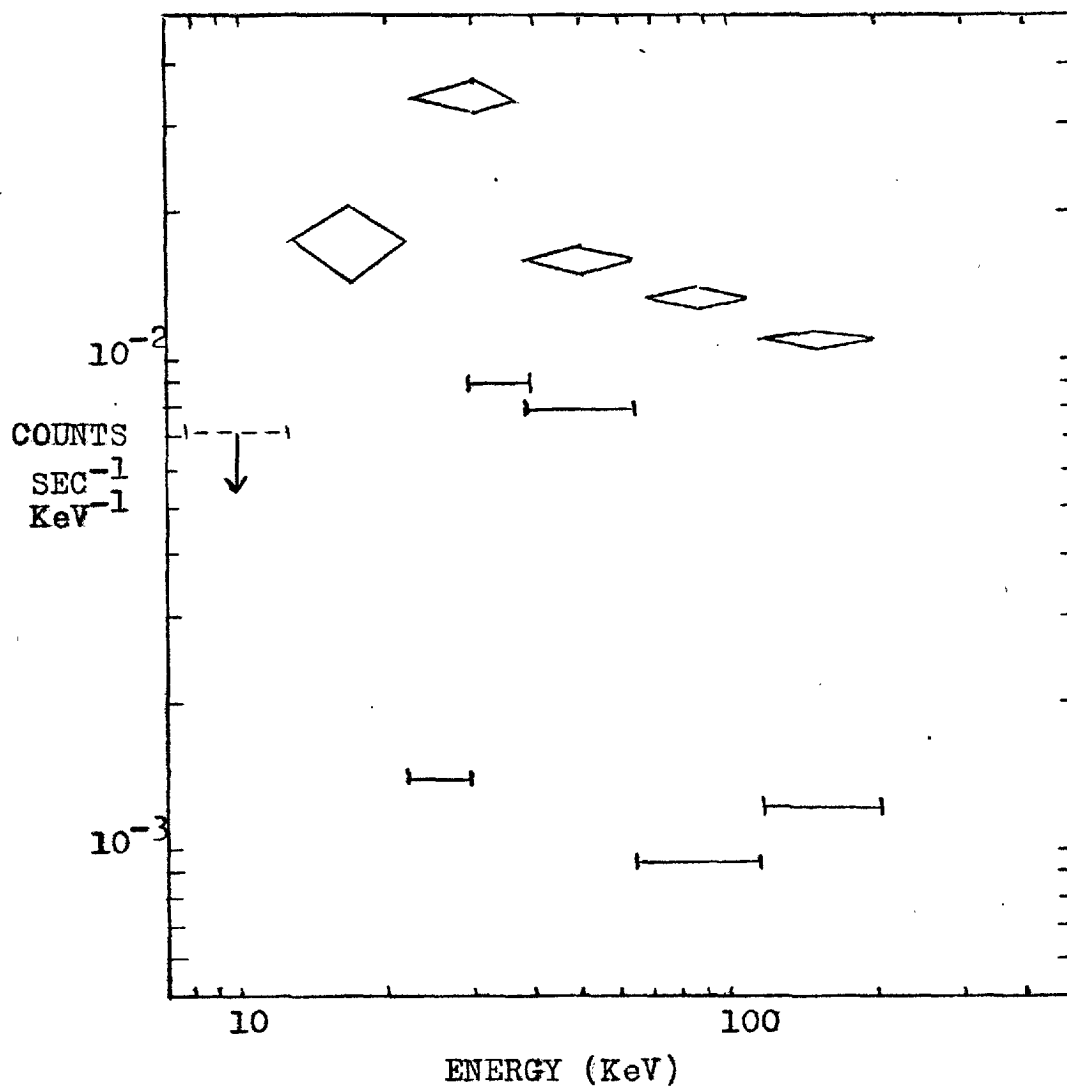
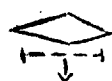


FIG.15



OSO-3 ACTIVITY CORRECTIONS
AS ESTIMATED BY SCHWARTZ
cf.



ESTIMATES BASED ON IRRADIATION RESULTS

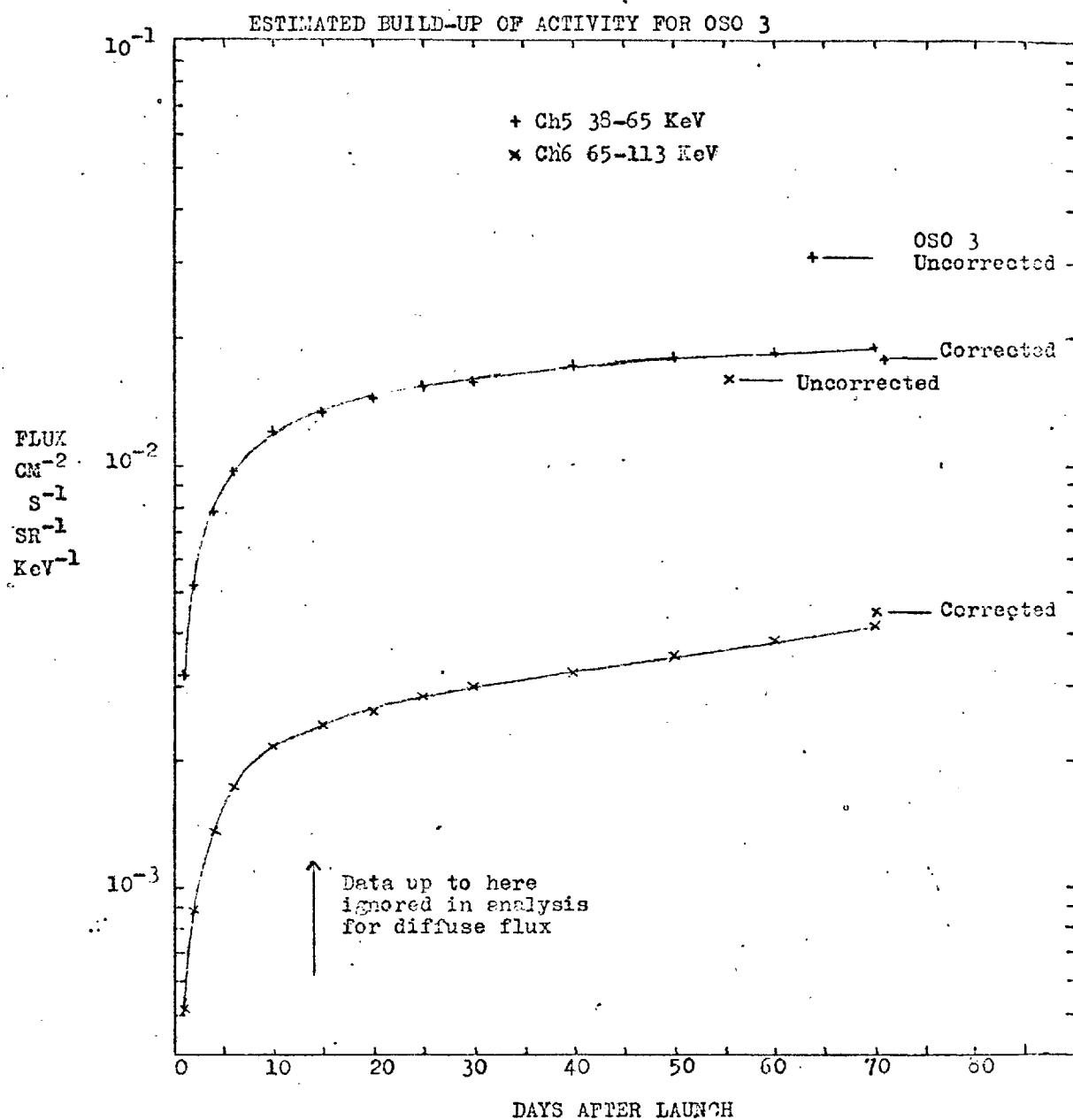


FIGURE 16. Build-up of activity for two OSO 3 channels as estimated from irradiation results.

+—etc. represent mean levels taken from the OSO 3 results (figure 17) before and after correction for the 15 hr half-life contribution by Schwartz. These levels do not refer to a specific time after launch.

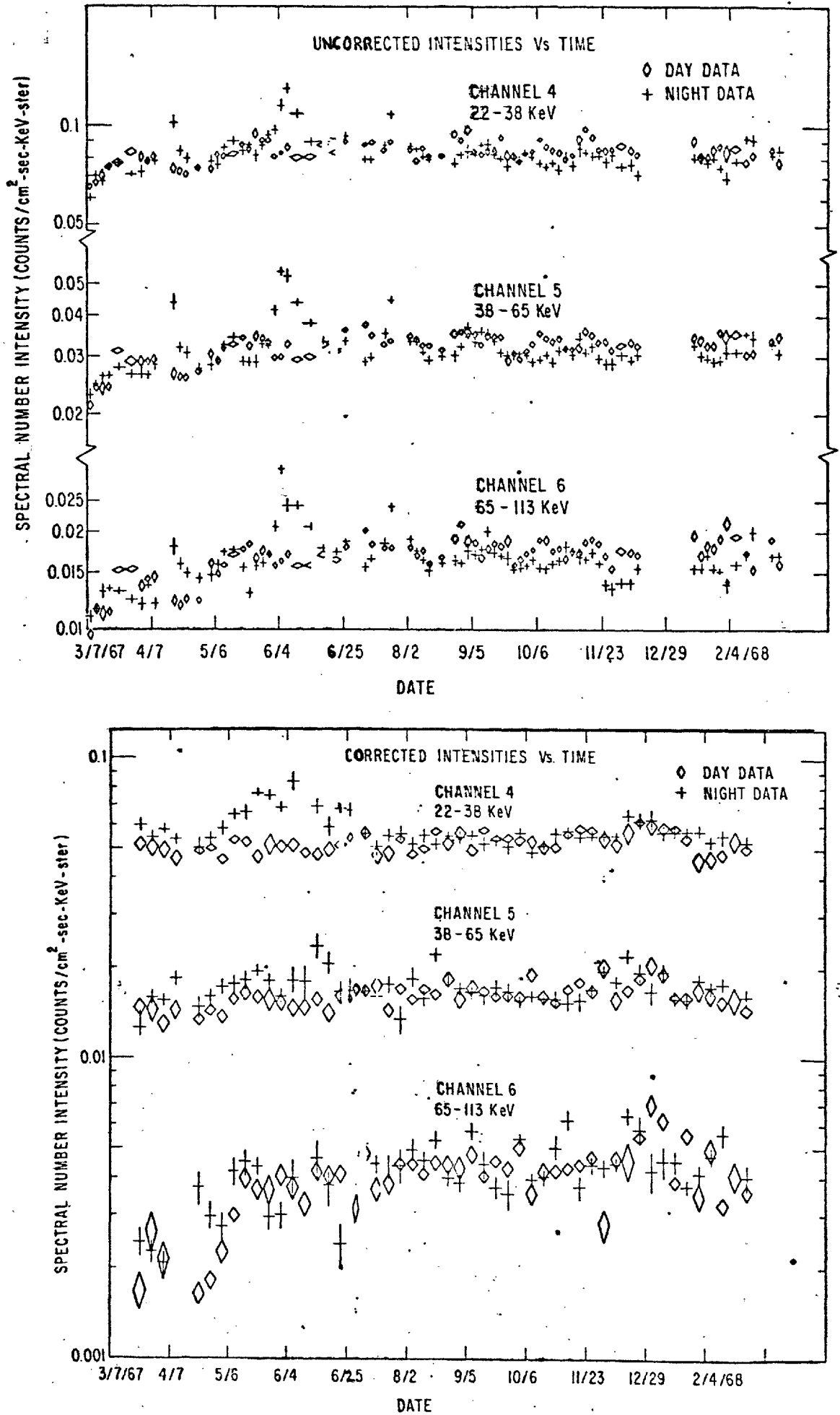


FIGURE 17: Time variations in OSO 3 rates as provided by Schwartz (1969).

peak may be thus explained, the levels in the other channels are then underestimated. This could either be due to the fact that there is a flat leakage contribution from the spacecraft or from activation of the collimator at a level comparable with spallation in the central crystal, or to the fact that in the thin NaI crystal, the high energy decays will give flat Compton peaks. This clearly illustrates the necessity for irradiation of the actual experimental packages to be employed in space.

If spallation is present at the levels predicted here, then some build-up in OSO 3 counting rates should be discernable in the data. Figure 16 shows the build-up estimated for two of the OSO 3 channels on the basis of the irradiation results, compared with OSO 3 levels before and after correction for radioactivity by Schwartz. In this case the factor four normalisation has been applied. These curves may be compared with the time variations of the corrected and uncorrected intensity provided by Schwartz in Figure 17. Time variations of about the required amplitude are indeed to be seen in the OSO 3 data. In particular the long time scale build-up of the 65 - 113 keV channel may be noted. This is probably due to the presence of a peak at 80 - 90 keV from the decays of $^{52}\text{Te}_{123}^{\text{m}}$ ($\tau_{\frac{1}{2}} = 104$ days) and $^{52}\text{Te}_{121}^{\text{m}}$ ($\tau_{\frac{1}{2}} = 154$ days) both of which have appreciable production cross-sections in both NaI and CsI (see Table 2). Schwartz interpreted these variations as due to degradation of the collimator efficiency.

3.5.3 The OSO 5 X-Ray Telescope

In this detector a thin (0.64 cm) central crystal of CsI was employed. Dennis (1970) has again used the method of subtracting rates before and after radiation belt passages in order to determine the spectrum of activation. Figure 18 presents the results of this compared with the results of normalising the irradiation results to the mass of the

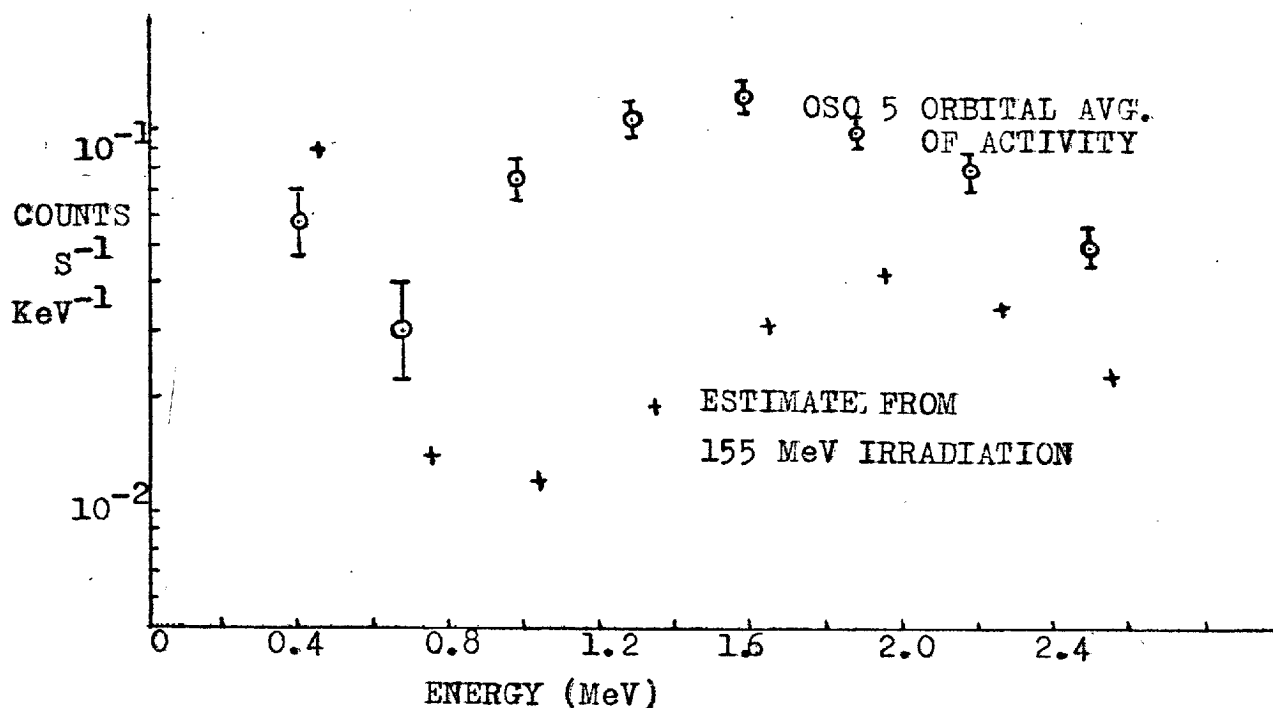


FIG. 18

OSO 5 crystal and a dosage of $6 \times 10^5 \text{ cm}^{-2}$. General agreement may be seen. Once again the crystal is much thinner than that for U.K.5 and there will be a flat contribution from higher energy decays, which give partial energy losses in the thin crystal. In addition to this there would seem to be an additional peak contributing to the OSO 5 background at around 120 keV. This could possibly indicate the production of Cs_{134}^m ($\tau_{1/2} = 15 \text{ hrs}$, γ 0.137 MeV) by neutron capture (see section 2.3). As mentioned before, a factor of four increase in the predictions matches the levels at 200 keV. This would then predict a factor four too high around 40 keV, however.

In his analysis, Dennis has identified a clear trend of build-up

in counting rates in most of the energy channels. This build-up is modulated with the period of the precession of apogee indicating the importance of the depth of penetration into the belts. Attempts have been made to fit the observed build-up curves (after smoothing for the above mentioned altitude effect) to a constant component plus a component which builds up with time after launch. Results of this for counts covering the range 82-254 keV are compared with predictions based on the irradiation experiments in Figure 19. The lower graph compares arbitrarily normalised experimental predictions with the estimated OSO 5 activity build-up obtained when a $\log_e t$ build-up is fitted. In this case the fit is not good and the residual constant level ($14.2 \text{ counts sec}^{-1}$) is a considerable overestimate of the diffuse flux. In the upper graph an estimate based on a $25 E^{-2.0}$ ($\text{photons cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{keV}^{-1}$) spectrum has been subtracted as the diffuse contribution and the build-up in activity then excellently fits the predictions. This clearly demonstrates the necessity of knowing the correct analytical or numerical form of the decay or build-up curves when attempting to fit data, and gives hope that the above procedure can be reversed so that known build-up or decay curves based on ground irradiation experiments can be fitted to satellite data to obtain better estimates of the diffuse flux.

3.6 IMPLICATIONS OF THESE RESULTS FOR THE ORBIT OF U.K.5

In this chapter it has been shown that the production of radioactive spallation products in the central crystals of satellite X-ray telescopes provides a good explanation of the observed background. These estimates indicate that for a 550 km altitude, 33° inclination orbit the background in the U.K.5 experiment 'F' due to this mechanism would exceed the background from diffuse cosmic X-rays by at least an order of magnitude at all times. Thus for such an orbit, no information on the isotropy or spectrum

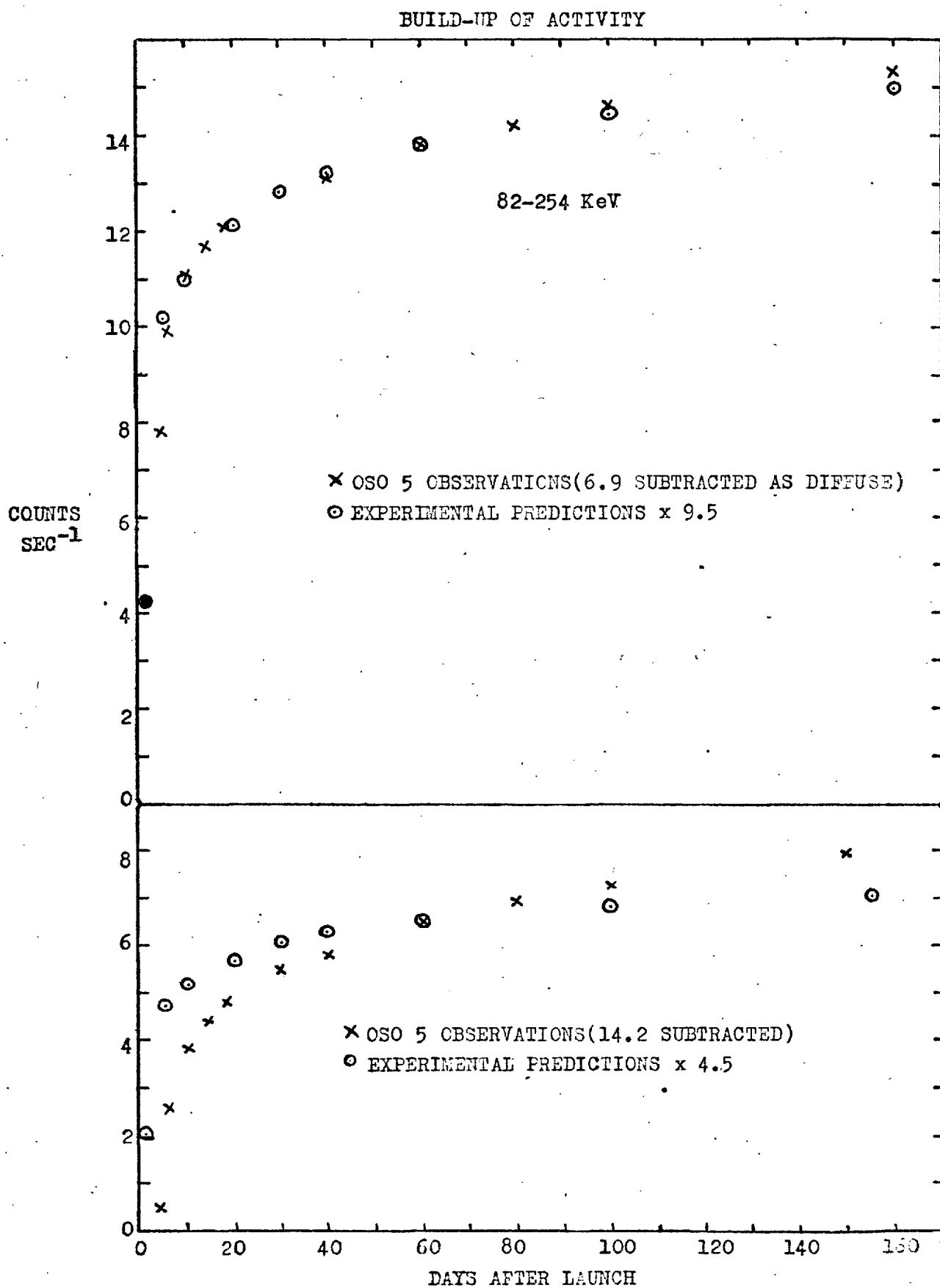


FIGURE 19: Time variations in the OSO 5 counting rate (82-254 keV channel) fitted to estimated build-up curves.

of the diffuse component can be forthcoming, and source resolution will be about a factor four down on the estimates previously made on the assumption that the diffuse component would be the dominant background (Morfill, 1971). Further emphasis is given to this point by the difficulty that has been experienced in making deductions concerning the diffuse flux from the OSO 3 and 5 experiments. From Table 3 it can be seen that these experiments both had much larger values for F (= geometric factor for diffuse photons $\div$ mass of central crystal) than the U.K.5 telescope ($F_{\text{OSO 5}} : F_{\text{OSO 3}} : F_{\text{U.K.5}} = 200 : 100 : 1$). On the spallation model ratio of diffuse counts to radioactive background counts scales directly as F .

Clearly the most satisfactory orbital situation is one in which all particle radiations are reduced as much as possible. A low altitude, equatorial orbit would seem to best satisfy this condition as in this situation penetration of the Anomaly region is reduced considerably and the contributions of primary cosmic rays and albedo neutrons are also diminished. The orbital integrations of fluxes of Lavine and Vette (1970) indicate that for a 556 km altitude orbit, the integrated trapped proton dosage is reduced by a factor 300 in an equatorial orbit compared with a 30° inclination orbit. With this reduction, the contribution to the background from inner belt protons, primary cosmic rays, and albedo neutrons will all be comparable. This factor improvement is sufficient to enable U.K.5 experiment 'F' to make useful measurements on the diffuse flux and to make previous estimates of the sensitivity valid once again. The orbital integrations of fluxes indicate that the inner belt contribution is very altitude dependent, and particularly so in equatorial orbit. For example, in equatorial orbit at 800 km altitude the dosage would exceed that for 556 km altitude at 30° inclination. It is important, therefore, that the orbit altitude should be kept as low as possible.

The importance of the build-up of radioactivity has been clearly

shown. In view of this effect it is important that experiments be switched on as early as possible in the satellite life in order that such trends can be noticed and accurate extrapolations to launch made.

CHAPTER 4. THE SHAPE OF THE DIFFUSE COSMIC X-RAY SPECTRUM

4.1 EXISTING IDEAS AND THEIR EXPERIMENTAL BASIS

In section 1.5.2, the possible cosmological significance of the isotropic sky background of X- and gamma-radiation was indicated. Figure 2 presented the existing results as interpreted by Schwartz et al. (1970). These authors fitted the OSO 3 results to a power law spectrum of index 1.7 ± 0.1 breaking at 42 ± 4 keV to become 3.0 ± 0.3 (spectrum shown by a continuous solid line in Figure 2). Such a fit left excess fluxes at $\sim \frac{1}{2}$ keV and at 1 MeV and so a spectrum due to Brecher and Morrison (1969) was fitted to give a better agreement at these extremes (spectrum shown by dash-dot line). The results of Vette et al. (1970) obtained from ERS-18 still showed a 1 MeV excess, a result which was given an interpretation in terms of proton-proton interactions or matter-antimatter annihilation at large redshifts by Stecker et al. (1969, 1971).

Evidence for a break or steepening somewhere in the region 20 to 40 keV initially came from a comparison of rocket-borne proportional counter measurements with measurements made by scintillators carried by balloons or space probe (see e.g. Boldt et al., 1969, and Bleeker and Deerenberg, 1970). Single exponent fits were made to data from a given experiment and the 'break' was usually taken to be at the intersection of the two experimental ranges (i.e. ~ 20 keV). The only experiments to have shown evidence of changes in spectral index within the range of one experiment are the OSO 3 X-ray telescope in the case of the 40 keV break and the ERS-18 scintillator crystal in the case of the 1 MeV flattening.

Chapters 2 and 3 have given a good understanding of the previously reported background problems in terms of spallation induced radioactivity.

In section 3.5.2 it was shown that correction of the OSO 3 data for a contribution from a single 15 hr half-life is inadequate. From Figure 9 it can be seen that for an omnidirectional crystal there is a significant contribution from induced activity at around 1 MeV (the UK.5 detector is essentially omnidirectional at high energies.). In the presence of a cosmic ray flux appropriate to a 2 GV rigidity cut-off, this contribution will exceed the counting rate due to a diffuse component extrapolated as a $26 E^{-2.0}$ power law spectrum. The fact that the spectrum of activity shows a peak at 36 keV and a flat portion at around 1 MeV immediately leads to suspicion about similar features reported for the diffuse flux from the OSO 3 and ERS-18 measurements. In section 4.3 extrapolation of the irradiation experiment results to these two experimental situations will be made in order to consider the reality of these features.

4.2 THEORIES OF THE DIFFUSE COMPONENT

The various astrophysical mechanisms for X- and gamma-ray production have been briefly mentioned in section 1.2. Most of these have been considered as possible mechanisms for the isotropic component, either by operation in discrete sources or in metagalactic space. As was mentioned in section 1.5.2, some evolution of sources is required to explain both the intensity and isotropy of the radiation.

Thus far considerable theoretical effort has been expended in attempting to explain the 40 keV break and 1 MeV flattening (see Review by Silk, 1970a). A brief summary is given below.

4.2.1. Inverse Compton Mechanism

Felten and Morrison (1966) suggested a mechanism involving the scattering of the 2.7 K universal black body radiation by electrons injected into metagalactic space by radio galaxies. The mean radio photon spectral

index of such galaxies is 1.7 ± 0.3 for production by the synchrotron mechanism. When these electrons escape into intergalactic space, inverse Compton losses dominate the spectrum above 100 MeV and a one-power steepening occurs leading to a half-power steepening in the photon spectrum (see section 1.2.2.). The predicted X-ray spectrum is thus 2.2 ± 0.3 . No break is predicted until the inverse Compton loss time exceeds a Hubble time corresponding to a photon energy ~ 0.1 keV. An electron density in intergalactic space of $10^{-4} \text{ eV cm}^{-3}$ is required to explain the intensity. Estimates of the electron density provided by radio galaxies fall an order of magnitude short of this value.

Another alternative considered by Bergamini (1967) is inverse Compton scattering in extended extragalactic radio sources. Once again the spectrum will be 2.2 ± 0.3 . A cosmological increase in energy density of the 2.7 K radiation is required in order that the inverse Compton loss should exceed the synchrotron loss by a sufficient margin that the extragalactic radio background is not exceeded. This possibility is considered further in section 4.6.

In order to explain the 40 keV break in the spectrum, Brecher and Morrison (1969) suggested that the metagalactic electrons might originate in normal galaxies, which often show a half-power break in radio spectral index between 500 and 1500 MHz. If this break is considered to be characteristic of the electron sources and to persist on injection into the intergalactic medium, then taking the mean galactic field strength as 4×10^{-6} gauss implies a break in the photon spectrum between 12 keV and 80 keV. By considering the dispersion in spectral indices these authors produced a spectrum which showed a rise at 0.25 keV and a flattening at 1 MeV (see figure 2). The intensity of the radiation can be explained only if electrons have a leakage time from galaxies of $\sim 10^5$ years, which is considerably shorter than the value of 10^7 years required by cosmic ray

isotropy measurements.

4.2.2 Thermal Bremsstrahlung

It seems not unreasonable that there should be an intergalactic gas. Assuming there is an amount of matter in this form equal to that composing the galaxies a particle density of $\sim 10^{-7} \text{ cm}^{-3}$ is to be expected. The critical density for closure of the universe is somewhat higher at $7 \times 10^{-6} \text{ cm}^{-3}$. From the lack of Ly- α absorption observed in a quasistellar object located at $z = 2$, it follows that such a medium must be highly ionised so that there exists the possibility of thermal emission. Fitting the observations at 0.25 keV and 1 keV gives a temperature of $\sim 10^6 \text{ K}$. Steady state cosmologists have predicted temperatures as high as 10^9 K for such a medium.

4.2.3 Non-Thermal Electron Bremsstrahlung

Bremsstrahlung of cosmic ray electrons in the intergalactic medium is capable of producing photons in the required energy range. In this case features are to be expected in the X-ray spectrum as the various energy loss mechanisms for electrons become important. At low energies ionisation losses are important and in the medium energy range losses due to adiabatic expansion of the universe dominate until at high energies inverse Compton losses become significant. Various models have been considered by Silk (1970b) involving either burst injection at various red shifts or also a continuous injection of electrons. Some combination of burst and continuous injection spectra would be required to explain the features at 40 keV and 1 MeV. The energy requirements of this mechanism are not too severe, only $10^{-3} \text{ eV cm}^{-3}$ of low energy electrons being required at the present epoch if injection took place at $z \sim 3$.

4.2.4 Non-Thermal Proton Bremsstrahlung

It has been suggested that low energy cosmic rays provide the most probable mechanism for heating of the intergalactic gas. If this is the case there will also be some low efficiency for bremsstrahlung of low energy cosmic rays on the thermal electrons. The difficulty here is the large density of cosmic rays required and the large amount of thermal radiation that must also be produced. In fact to avoid excessive thermal radiation, injection at $z \sim 30$ is required. A flattening of the X-ray spectrum at low energies could occur when cosmic rays are stopped by ionisation loss. For example a break in the proton spectrum at ~ 30 MeV would produce a photon break at ~ 15 keV. A break at this energy implies a density for the intergalactic medium of at least $2 \times 10^{-5} \text{ cm}^{-3}$. At this density, excessive thermal emission is avoided only by invoking injection at $z \sim 30$.

4.2.5 Proton-Proton Interactions

The contribution of gamma-rays resulting from the decay of π^0 -mesons produced by p-p collisions of cosmic rays on the intergalactic gas has been extensively considered by Stecker (1969). In the meson rest frame two 70 MeV gamma-rays are produced and so a broad spectrum results peaked on this energy. Stecker has considered the importance of evolutionary effects on this mechanism. In earlier epochs, cosmic ray production and the intergalactic gas density would be enhanced and the π^0 -meson decay spectrum would be red-shifted to lower energies. This author found that some possibility existed for explaining the flat spectrum at 1 MeV observed by ERS-18 and the 100 MeV point obtained by Clark et al. (1968) if a model was used involving a continuous injection of cosmic rays commencing at $z = 100$. Such a model would require for the present epoch, gas densities of 10^{-5} to 10^{-7} cm^{-3} , with corresponding intergalactic cosmic ray densities

10^{-5} to 10^{-3} of their galactic value. Initial cosmic ray injection at more recent epochs would produce a 'shoulder' in the diffuse gamma-ray flux at higher energies. Although showing the required general features, the $z = 100$ spectrum when superposed on a power law (exponent 2.3) or a Brecher-Morrison spectrum was unable to give an exact fit to the ERS-18 data.

4.2.6 Matter-Antimatter Annihilation

If significant quantities of matter and antimatter were in contact at early epochs of the universe, then there could well be a significant contribution from the red-shifted photons resulting from the decay of π^0 -mesons produced by annihilation. Model spectra have been produced by Stecker et al. (1971), who show that a flattening in the spectrum at 1 MeV could result from annihilation at $z = 100$. These authors point out the importance of obtaining an accurate gamma-ray spectrum in the range 1 - 100 MeV in order to distinguish the mechanisms 4.2.5 and 4.2.6 and to determine the epochs at which they began to operate.

4.3 CRITICISM OF THE SPECTRAL FEATURES IN THE LIGHT OF THE SPALLATION

RESULTS.

4.3.1 The OSO 3 Results and the 40 keV Break

In section 3.5.2, considerable attention has already been given to comparing background estimates based on the results of irradiation experiments on CsI with Schwartz's analysis of the OSO 3 data. It was shown that spallation must be a major contribution to the background and that this offered a convincing explanation of the peak in the background estimates of Schwartz at 22-38 keV and of the variations with time of the counting rates. Two major possibilities then exist to explain the background; the radioactive background is spallation in the central crystal either with or without a flat leakage spectrum due to gamma-rays from the

15 hr. decay of Na_{24} produced through the spacecraft.

No theoretical estimates of the magnitude and shape of this leakage spectrum have been made. However, it can be seen that the leakage spectrum would need to be at the 10^{-2} flux level in figure 15 with spallation providing the 22 - 38 keV peak in order to explain the overall shape and flux levels. The method of analysis applied by Schwartz would then remove the leakage contribution and some of the short half-life spallation contribution but would ignore the level built-up in the first two weeks due to half-lives of several days. As can be seen from figures 16 and 17, most of the build-up occurs in the first two weeks and this will go unnoticed as a spurious contribution to the diffuse flux. Figure 21 shows the minimum activity in any one day built-up after two weeks, compared with the OSO 3 results before and after correction for the 15 hr contribution and for the contribution of scintillating electrons. An additional correction of the order of this built-up activity level could well apply to the data. For NaI, which was used in OSO 3, the peak lies almost entirely in the 22 - 38 keV channel so that such an additional correction could well remove the necessity for a break at 40 keV.

If there is no such leakage flux, the differences in the spectra of figure 15 could imply that the Schwartz analysis has overestimated the corrections for the energy channels above 65 keV, thus producing a false spectral break. However, a more likely explanation of the difference would be the contribution of partial energy losses from higher energy decays in the thinner OSO 3 crystal. In this case the decay curves that should have been fitted to the data and then applied as corrections would be those of figure 14 (after two weeks), rather than a 15 hr half-life. Estimates have shown that the difference in the correction factors obtained in the two cases would be about 20%. With this degree of uncertainty in

the very considerable corrections that have been applied to the data (shown in Figure 21) no deductions as to the existence of a spectral break can be considered reliable.

4.3.2 The ERS-18 Results and the 1 MeV Flattening

ERS-18 sampled cosmic gamma-rays when far removed from the earth in its highly eccentric orbit. The $31.5 \text{ cm}^2 \times 7.65 \text{ cm}$ NaI crystal was thus subject to the full interplanetary flux of cosmic rays, plus whatever dosage it might receive from the radiation belts at perigee and launch, which puts the measurements in need of approximately the same correction as those from the space probe Ranger 3 (Metzger et al., 1964). Data from ERS-18 was averaged over the first sixty days, whilst that for Ranger 3 was taken for the first two days of flight.

An attempt has been made to estimate the contribution of cosmic ray induced activity using the results of the irradiation experiments described in Chapter 2. For simplicity the cosmic ray flux level was taken as constant at $3.0 \text{ cm}^{-2} \text{ s}^{-1}$ for energies greater than 40 MeV, as measured by the Vela satellite for the same period as the ERS-18 experiment. In this case the radioactivity contribution is simply the area under the normalised decay curve as described in section 3.4. Taking the mean cosmic ray path length in the crystal as 7 cm, the fraction of cosmic rays undergoing interactions in the crystal was calculated to be 0.17. The number of spallation interactions per second is then $3 \times 0.17 \times \text{O.G.F.}$ (O.G.F. = omnidirectional geometrical factor). Thus if the area under the experimental decay curve is A for N interactions, the decay rate built-up will be interpreted as a photon flux of

$$\frac{3 \times 0.17 \times \text{O.G.F.}}{N} \times A \times \frac{1}{4\pi \times \text{O.G.F.}} = \frac{0.51 A}{4\pi N} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

The build-up estimated in this way is shown for a 150 - 250 keV channel in Figure 20. Vette et al. in their analysis of ERS-18 data considered a cosmic ray contribution as unlikely because of the apparent lack of correlation of counting rates with cosmic ray time variations. The lack of correlation could well have been due to the presence of a significant phase factor due to isotopes of $\tau_{1/2} > 1$ day. Better correlation would be expected however for the higher energy channels (> 1 MeV) in which build-up to equilibrium is almost immediate on account of the short half-lives of the β^+ decays. Some observable build-up of counting rates is to be expected for the low energy channels. There is indeed some evidence for this in the ERS-18, 200 - 400 keV channel (Pieper, private communication).

In Figure 21, the calculated built-up levels after 60 days for energy channels between 100 keV and 4 MeV are compared with the ERS-18 measures of the flux. The irradiation experimental data does not extend beyond 4 MeV but the trend of the spectrum and the fact that few β^+ decays exist with energies in excess of 4 MeV both indicate a negligible correction for spallation above 4 MeV. Apart from the 4 - 6 MeV channel, spallation would seem capable of removing most of the flattening. In the light of recent similar experiments carried on the Apollo 15 and 16 spacecraft, it is now accepted that the 4 - 6 MeV channel was in error due to some other defect (Metzger, private communication). These recent experiments still show the spallation produced hump at 1 to 3 MeV.

A major source of error in corrections estimated in this way is in the extrapolation of the decay curves back to zero of time ($10 \mu s$ in practice, as this is the anticoincidence time of the charged particle shield). The possibility exists that many isotopes with half-lives in the range $10 \mu s < \tau_{1/2} < 10 s$ could have been missed. Some of these could be light evaporation fragments which on decay could yield energies in excess of 4 MeV.

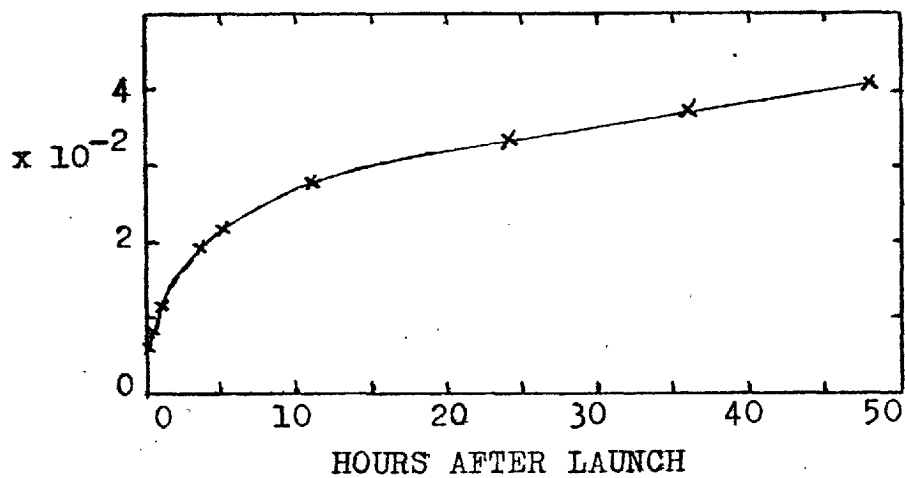
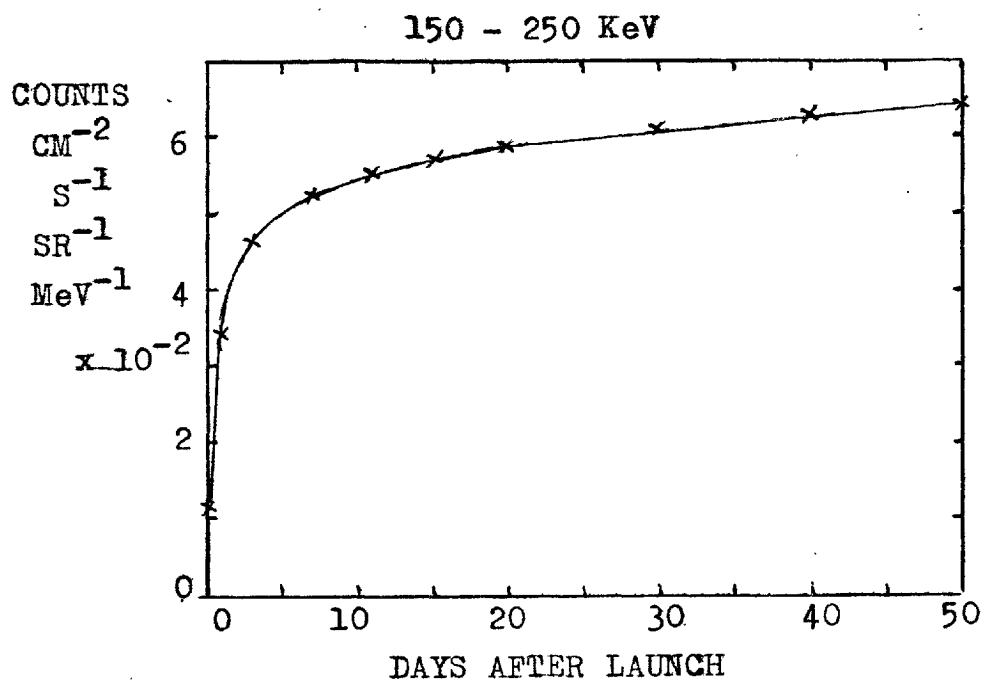
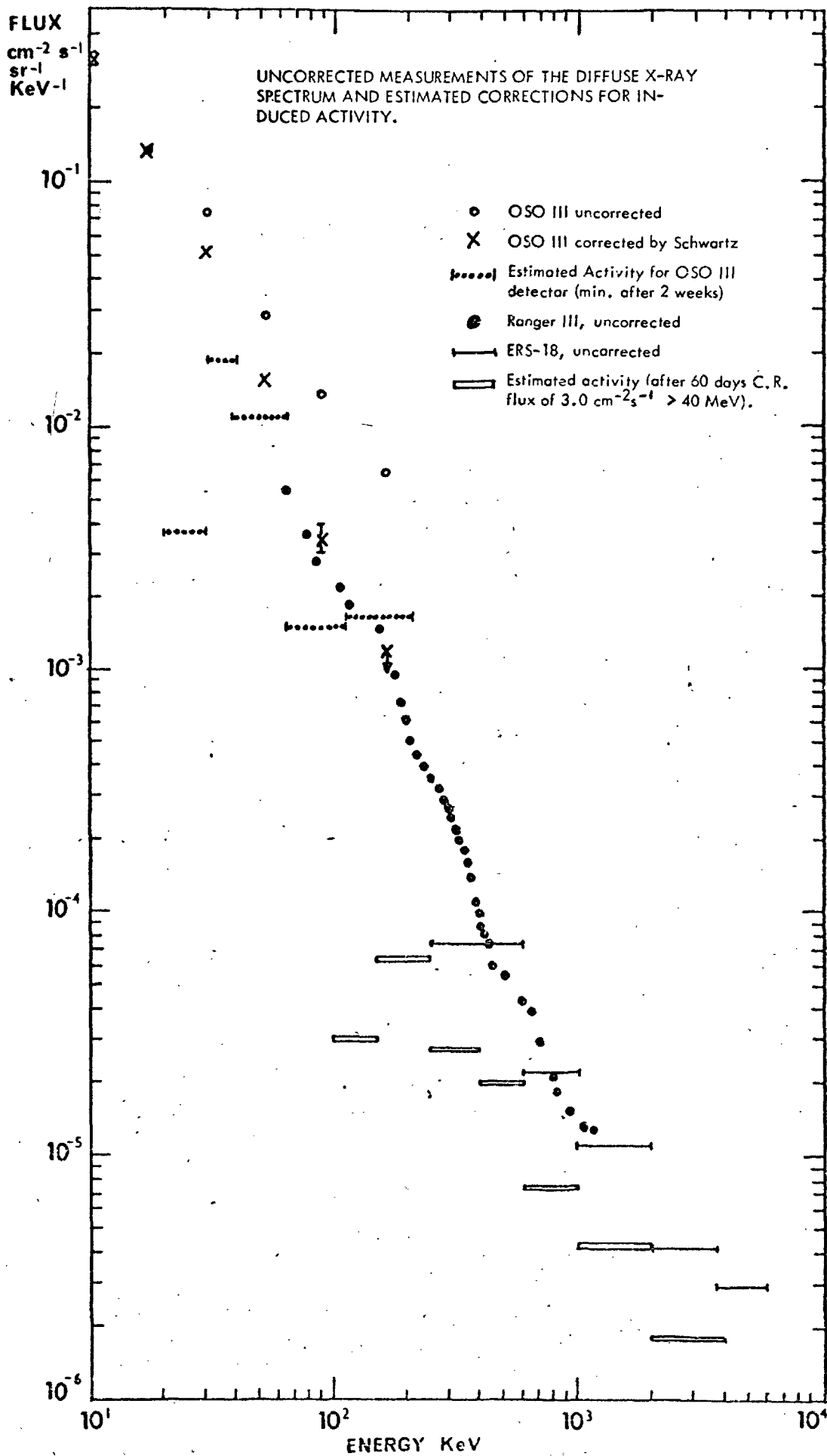


FIG. 20

FIGURE 20: Estimated build-up of activity for ERS-18, Ranger 3 detectors in an interplanetary space situation.

FIGURE 21



Further irradiation experiments will be required in which the radioactivity in equilibrium with an irradiating beam of protons can be measured.

4.3.3 Consideration of the Latest Situation

Measures of the diffuse X-ray flux over the entire spectrum are subject to considerable systematic errors both from subtraction of other backgrounds and from unfolding the photon spectrum from the pulse-height spectrum via the detector response functions. The manner in which such corrections have been applied or ignored probably explains the disparity in the results obtained so far.

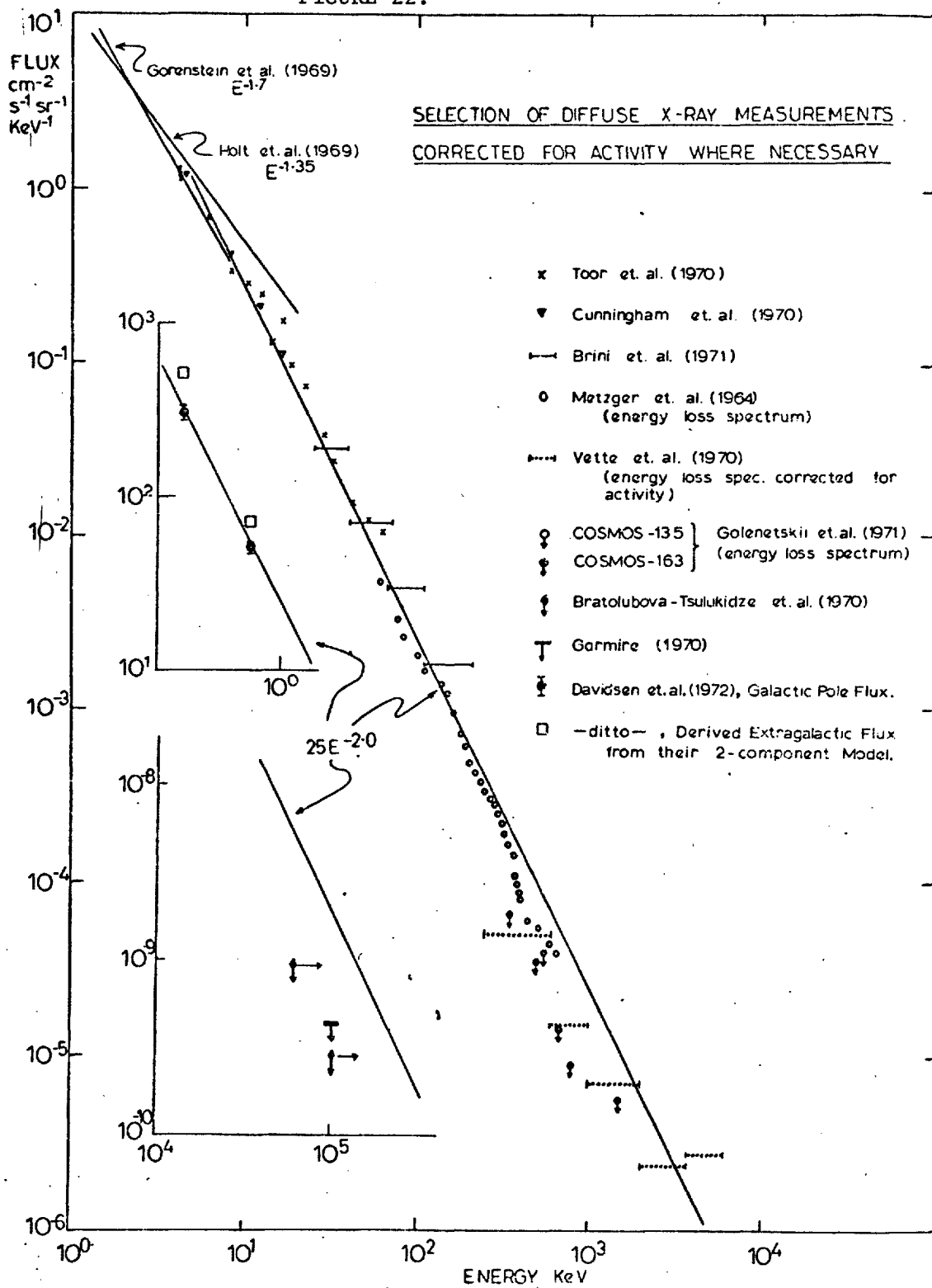
Rocket borne proportional counters have yielded spectral indices between 1.4 and 1.8 for the energy range 1 - 20 keV. Early balloon flights yielded a spectral index of ~ 2.3 above 20 keV, as did the Ranger 3 experiment for the energy range 70 keV - 1 MeV. Comparison of these results led to the conclusion that there must be a spectral break of about one power in the region of 20 keV. Results from the OSO 3 telescope were claimed to show evidence of this break at 40 keV, within the range of a single instrument.

As explained in section 4.3.2, it now seems likely that the break measured by OSO 3 was a result of inadequate allowance for radioactive background, and at the least that the experimental points should have much larger error bars so that no definitive statement on a break in this range can be made. This once again returns the situation to one of comparing different detectors. Improved corrections to balloon-borne detectors (Kasturirangan and Rao, 1972), involving allowance for Compton scattering in the atmosphere, now yield a flatter spectral index of 2.0. As pointed out by Trombka (1970), the Ranger 3 spectrum would appear flatter when unfolded through the detector response. From a rocket borne scintillator

experiment, Brini (1971) has deduced an $E^{-1.95}$ spectrum for the range 20 - 200 keV with no evidence of a break within the range. This experiment used a shielded control detector to estimate other backgrounds.

As described in section 4.3.2, subtracting the spallation contribution would seem capable of removing the break claimed by the ERS-18 experiment. Golenetskii et al. (1971) in analysing results from the Cosmos satellites, the orbits of which lie within the magnetosphere, have obtained considerably lower limits for the gamma-ray flux in the region of 1 MeV than the ERS-18 measurements, once the atmospheric contribution had been estimated (results were taken before passage through the South Atlantic Anomaly). These results lie on an extrapolation of an $E^{-2.3}$ spectrum but according to the authors would yield more like $E^{-2.0}$ on unfolding. Figure 22 presents a selection of rocket, satellite and space probe scintillator measurements covering the range 4 keV to 6 MeV. Only those results not subject to considerable radioactive contamination have been included, with the exception of the ERS-18 data from which the activity estimates of Figure 21 have been subtracted. In the low energy region there are the results of Toor et al. (1970), which cover the range 4 - 70 keV using a rocket borne scintillator with shutter to allow for background, and of Cunningham et al. (1970) covering the range 2.6 - 19 keV with a satellite borne scintillator also provided with a shutter. These yield spectra of $17.1 E^{-1.8}$ and $21 E^{-1.86}$ respectively. Results above 200 keV still require unfolding through the detector response. A line representing a $25 E^{-2.0}$ spectrum has been marked on for comparison and extrapolated to compare with the few available high energy gamma-ray upper limits and some soft X-ray measurements. On the basis of purely scintillator measurements there would seem to be good case for a single spectral index representation over the range 1 keV - 10 MeV with some hope of fitting results

FIGURE 22.



at 0.25 keV and 100 MeV. This leaves the possibility that the lower slope measured by proportional counters is a result of the different type of response function of these instruments. The proportional counter measurements of Holt et al. (1969) and Gorenstein et al. (1969) have been included on Figure 22 for comparison.

At the weakest, it can be argued that any change of slope is much less than one power and in view of the low statistical significance of the points at the high energy end of the proportional counter range could occur at energies considerably lower than 20 keV.

Future experiments should aim to overlap the experimental ranges of the two types of instrument and should employ suitable pre-flight comparisons using laboratory X-ray spectra.

4.4 ASTROPHYSICAL IMPLICATIONS OF A SINGLE EXPONENT SPECTRUM

A single exponent fit over the range 0.3 keV - 100 MeV, or at least one in which there are no marked or abrupt slope changes, would favour a single source mechanism.

Marked changes of slope are intrinsic to all the bremsstrahlung mechanisms. For example thermal bremsstrahlung yields a spectrum which falls off rapidly above 10 keV for reasonable temperatures of 10^6 to 10^7 K, and a power law extending to 10 MeV or beyond would be difficult to explain. Non thermal bremsstrahlung of cosmic ray electrons is more likely to give gamma-rays, but as mentioned in section 4.2.3, features will occur where the various energy loss mechanisms become important. From the table of numerical values given by Silk (1970b) it would appear that to lower the break in the spectrum due to ionisation to below 50 keV would require a density for the intergalactic medium of less than 10^{-7} cm^{-3} together with burst injection of electrons at $z > 10$. Furthermore it would

appear that a change of slope of at least 1.5 is to be expected. Thus it seems very difficult to reconcile this mechanism with the interpretation of the observations given in section 4.3. In the case of proton bremsstrahlung some of the difficulties involving the high density ($2 \times 10^{-5} \text{ cm}^{-3}$) of the intergalactic medium (and consequent high temperature and excessive thermal emission) required to give a break at above 15 keV by ionisation are eased by a single exponent spectrum. An evolutionary cosmology with increasing injection strength with z and a cosmic ray energy density approaching the galactic value is still required however.

The absence of a marked step in the spectrum at 1 MeV implies that proton-proton or matter-antimatter interactions at $z = 100$ probably do not contribute. If there is a contribution from such mechanisms it must become important at higher gamma-ray energies and result from processes occurring at more recent epochs than $z = 100$.

Probably the most natural mechanism to explain a featureless spectrum is that of inverse Compton scattering of electrons from radio galaxies on the microwave background. A single exponent photon spectrum covering six decades of energy requires only that the electron spectrum should be featureless over three decades (from $\sim 100 \text{ MeV}$ to $\sim 100 \text{ GeV}$). As mentioned in section 4.2.1 a spectral index of 2.2 ± 0.3 is to be expected from observations of radio spectral indices. Whether operative in metagalactic space or in extended sources, this mechanism requires considerable evolutionary effects to explain the intensity. In this respect it is worth considering the recent suggestion of Gursky et al. (1972) that the diffuse flux could be a superposition of extragalactic sources, which, on the basis of UHURU measurements, these authors identify with Abell galactic clusters of richness class greater than or equal to 2 (Abell, 1957). These authors assign an emission flux of $10^{44} \text{ erg s}^{-1}$ to such

clusters. When such a contribution is integrated over a Hubble radius according to the source density estimates of Kiang and Saslaw (1969), the resulting intensity is a factor 100 too low to explain the observed energy flux for an E^{-2} photon spectrum extending to 50 MeV. Thus a very rapid cosmological evolution of such sources is required to explain the diffuse background. Such evolution is also required by the anisotropy limits of Schwartz et al. (1971) based on a rocket-borne proportional counter experiment. The observed isotropy requires 4×10^6 sources, whilst on a non-evolutionary model there are only 2×10^4 richness 2 clusters within our photometric radius.

Hence, although an inverse Compton mechanism would be favoured by the spectrum presented here, considerable evolution would be required to explain the intensity. If bremsstrahlung mechanisms are still to be applied, then considerable reinterpretation of the astrophysical parameters would be necessary in view of the probable lack of appreciable spectral features.

4.5 IMPLICATIONS OF THE SPALLATION RESULTS FOR FUTURE X- AND GAMMA-RAY EXPERIMENTS

4.5.1 Location of Experiments

The inadequacy of 30° inclination orbits for performing experiments on the diffuse X-ray flux has already been stressed in Chapter 3. Emphasis to this point is given in Figure 21 from which it can be seen that for an OSO 3 type detector the minimum activity level after two weeks of satellite life (when interpreted as a diffuse flux) is the same as the diffuse flux measure for the range 20 - 200 keV obtained by the Ranger 3 spacecraft. From the diagram it can be seen that the latter experiment is not subject

to a large activity correction in this range. The flatness of the spallation induced spectrum ensures that the problem will become even more severe at higher energies. Figure 21 also provides a comparison of the interplanetary space situation. In comparing the ratios between the diffuse flux (signal) and radioactive background (noise) for the various detectors, it must be remembered that different geometrical factors are being compared and consideration must be given to the 'F' factors of the instruments as defined in Chapter 3. $F(\text{OSO } 3) : F(\text{ERS-18}) = 1 : 10$, so that it can be seen that an OSO 3 style detector could be used in interplanetary space to give measurements up to ~ 200 keV. Above this energy, such directional detectors would encounter worse signal to noise problems than the Ranger 3, ERS-18 omnidirectional detectors.

For collimated instruments, the answer must certainly be to use low altitude equatorial orbits. For 550 km altitude, the orbital flux integrations of Lavine and Vette (1970) indicate a proton dosage for 0° inclination which is a factor 300 less than for 30° inclination. The integrated daily dosage from trapped protons is then $\sim 1.3 \times 10^4 \text{ cm}^{-2} > 100 \text{ MeV}$ which compares with $\sim 5000 \text{ cm}^{-2}$ cosmic rays per day for this orbit. Contributions from capture and spallation of albedo neutrons are then both of the same order as direct cosmic ray interactions (see 2.3). Reduction of orbit altitude by another 50 - 100 km would probably remove the inner-belt contribution completely and simply leave the cosmic-ray and neutron contributions. In a 30° inclined orbit, reduction of orbit altitude to 270 km would still give a daily dosage of $4.4 \times 10^4 \text{ cm}^{-2} > 100 \text{ MeV}$ for trapped radiation, and higher cosmic ray and albedo dosages than those for an equatorial orbit. The total particle dosage situation for a low altitude equatorial orbit is also down by at least a factor 15 on interplanetary space, even when the new neutron albedo estimates of Preszler et al. (1972)

are taken into account. This is exclusive of any solar flare events which can contribute an average of $\sim 10^6 \text{ cm}^{-2}$ per day $> 100 \text{ MeV}$ to a detector which is unshielded by the magnetosphere. As long as sufficiently thick active collimators are available then an equatorial orbit represents the best situation. Active shutters should be employed to act as a control for estimating other backgrounds.

If omnidirectional detectors are still to be used for diffuse flux measurements or if 'active anti-collimator' arrangements of the type suggested by Morfill and Quenby (1971) are to be employed for gamma-ray source observations, the situation is complicated by the considerable gamma-ray flux from the earth's atmosphere. From the variation of counting rate with rigidity of omnidirectional scintillator crystals carried on the low altitude Cosmos satellites, Golenetskii et al. (1971) concluded that for the 1 MeV region only 25% of the equatorial count rate was due to diffuse gamma-rays, the remainder being an atmospheric contribution. The correctness of this conclusion is indicated by the agreement of their corrected results with the corrected ERS-18 results (see Figure 22). These authors also conclude that the atmospheric spectrum is flatter ($E^{-1.5}$) than the diffuse spectrum, so that the situation is worse at higher energies. Thus omnidirectional detectors or anticollimator arrangements will be useless in measuring the diffuse flux in equatorial orbit, and in addition the background against which sources could be measured would be at least four times the diffuse background. Lightweight spacecraft in highly eccentric orbit (with no trapped particle penetration) should then be used for such detectors. Excluding solar flares, corrections for spallation will be $\sim 50\%$ in the 1 MeV region (see Figure 21), and the total background for source observation will thus be about twice the diffuse background at this energy. Above 4 MeV, radioactivity probably becomes negligible and as long as a sufficiently

light spacecraft is employed the background problem could improve.

It could be suggested, therefore, that 4 MeV represents a boundary energy below which it is best to employ active collimators in low altitude equatorial orbit and above which it is better to use anticollimator arrangements in lightweight spacecraft in highly eccentric orbit.

4.5.2 Correction of Results for Radioactive Background

Although it is to be hoped that future experiments will have reduced background problems due to improved orbital situations and also on-board estimates using active shutters, the problem of subtracting radioactive backgrounds is likely to remain relevant for some time.

Thus far counting rates have been fitted to decay laws and build-up curves which have been rather arbitrarily chosen. Typically, counting rates are least-squares fitted to expressions of the form

$$A + B f(t)$$

where A is a constant contribution of cosmic X-rays and B is a measure of the amplitude of some build-up or decay expressed by $f(t)$. Analytical expressions for $f(t)$ have been chosen simply by inspection of the data and consideration of one or two possible isotopes. The precise form chosen for $f(t)$ has a considerable influence on the values assigned to A and B and thereby on the estimate of the diffuse flux.

It is to be hoped that the procedures described in Chapters 2 and 3 for estimating the form of $f(t)$ based on ground irradiation experiments can give a considerable improvement. Encouragement can be taken from the good fit which was obtained for the OSO 5 data using this technique (see section 3.5.3). The good data coverage achieved in the 3rd irradiation experiment should prove useful in this respect, both for the future U.K.5

instrument and for existing OSO data.

The correction of omnidirectional detectors situated in interplanetary space (e.g. ERS-18 and Apollo 15) should ideally be based on irradiations of identical experimental packages using beams of protons of several GeV in energy. Three irradiations will be required to determine the complete time history of decays and hence the total activity contribution from half-lives of between $10\mu\text{s}$ and 100 days. Two of these would be of the type described in Chapter 2 for the U.K.5 crystal, but the third would require monitoring the activity in equilibrium with the irradiating beam in order to determine the contribution of very short-lived isotopes.

SECTION 2

ANALYSIS OF DATA FROM THE HIGH ENERGY PROTON
TELESCOPE, EXPERIMENT S24B, ON BOARD THE HEOS A1
SATELLITE

CHAPTER 5. THE HEOS SATELLITE AND THE S24B INSTRUMENT

5.1 SCIENTIFIC BACKGROUND

Prior to the introduction of satellites and space probes, the cosmic radiation had been studied by ground-based monitoring of the secondaries produced by interactions of the primary particles in the atmosphere. Certain monitors counted the secondary neutrons, others acted as telescopes to measure the arrival directions of secondary μ -mesons, whilst others employed coincidences between large arrays of detectors in order to detect the extensive air showers which result from very energetic primaries.

Much of the early work was expended in understanding the effects of the earth's magnetic field and of changes in the earth's atmosphere on the detector counting rates. To a first approximation the effect of the earth's magnetic field was understood in terms of the motion of the charged primary particles in a dipole field. The factor influencing the path of a charged particle in a magnetic field is its magnetic rigidity (momentum to charge ratio) and it was found that in order to penetrate the field at the equator a higher rigidity (known as the threshold rigidity) was required than for penetration over the poles. The way in which monitor counting rates decreased with decreasing magnetic latitude showed how the primary cosmic ray flux decreased with increasing rigidity. Later work included higher order terms in the expansion of the earth's field. From these studies it was possible to conclude that the solar system is subjected to a flux of energetic nuclei ranging in energy from 10^8 eV to beyond 10^{19} eV and that particles of up to 10^{11} eV are influenced by the electromagnetic conditions which exist in interplanetary space. For example, a variation in flux with sun-spot number was observed, the maximum counting rates corresponding approximately to sun-spot minimum. In addition, short-term decreases, lasting

several days, were found to follow certain solar flares for high latitude monitors (Forbush decreases), whilst for other flares an increase of counting rate gave evidence of solar-particle production up to $\sim 10^{10}$ eV. A small anisotropy in the primary flux, corresponding to a maximum counting rate at 18.00 hrs local time for a given detector, was also observed.

The introduction of satellites meant that electromagnetic conditions away from the earth could be directly monitored for the first time and that the lower energy particles could be studied. Ground-based monitors have no response to primaries of less than ~ 1 GV rigidity and in this rigidity range the effects of the earth's field are difficult to calculate. Balloon payloads are used to lower the energies observed but the use of satellite payloads has enormous advantages in the continuous monitoring available and the possibilities of measurements in positions removed from the influence of the earth's magnetic field. The disadvantages are the cost and the small detector areas.

The use of satellites and space probes soon revealed that the earth's magnetic field is confined to a region around the earth, called the magnetosphere, by a continuous flow of low density plasma from the sun. This solar wind, as it is called, is essentially ionised hydrogen gas of mean density 10 atoms per cc. and mean velocity 350 km/sec. Such a plasma has a high magnetic Reynold's number and convects with it any magnetic field in which the energy density is less than the plasma pressure (Alfvén's theorem). The sun's magnetic field is thus dragged out into interplanetary space to give a field of ~ 5 gamma at the earth (1 gamma = 10^{-5} oersted). The combination of radial wind flow and solar rotation gives a spiral structure to the interplanetary field. Following Parker (1958) the mean field is taken to have components

$$B_r = B_1 \left(\frac{r_1}{r} \right)^2$$

$$B_{\theta} = 0$$

$$B_{\phi} = B_1 \frac{r_1^2 \Omega}{Vr} \sin \phi$$

in spherical coordinates, where θ is the angle from the axis of solar rotation, ϕ is measured in the solar equatorial plane, r_1 is the distance from the sun of the point of origin of the field lines, Ω is the solar angular rotational velocity and V the solar wind speed.

Neither the solar wind flow nor the interplanetary field are steady but contain shocks, discontinuities and waves which have a considerable influence on the propagation of charged particles through the medium. In addition there exist in the wind large scale sectors, in which the mean field points alternately towards and away from the sun. Such features are swept past the earth approximately once every 27 days with the solar rotation.

The effect of the solar wind flow on the earth's field is to compress the field lines on the day side to form a magnetospheric boundary at a geocentric distance of about 10 earth radii, at which point the dipole field strength has fallen to ~ 30 gamma. At this boundary, there is first a region of disordered field and then a shock wave region where the wind flow changes from supersonic to subsonic before interplanetary space is reached. On the night side of the earth, the high latitude field lines are dragged out to great distances by the solar wind to form a geomagnetic tail which may extend for several astronomical units. Satellites have revealed the presence of trapped radiation, called the Van Allen belts, within the magnetosphere. The outer boundary to such radiation is essentially the last closed field line on the day side. This field line intersects the earth at a latitude of about 70° so that at about this latitude there is direct field line connection to interplanetary space. Such connection is probably the cause

of the aurorae seen at these latitudes.

5.2 THE HEOS SATELLITE

In order to investigate the nature of the magnetospheric boundary and to obtain complementary information on particle fluxes and electromagnetic conditions in interplanetary space a varied payload is required on a satellite which explores regions both within and well outside the magnetosphere. With this in mind the project HEOS A was initiated by ESRO in 1963. HEOS stands for Highly Eccentric Orbiting Satellite.

The 105 Kgm HEOS-A1 satellite was successfully launched by a three stage Thor-Delta rocket from Cape Kennedy on December 5th, 1968 into a highly eccentric orbit of apogee 222,300 km and perigee ~ 1800 km. The orbital inclination was 44° such as to give apogee North of the ecliptic, and the orbital period was ~ 106 hrs. Spin-axis stabilisation at about 10 rotations per minute was employed, enabling certain of the experiments to scan the equatorial plane of the satellite. A facility existed for reorientating the satellite by means of cold gas jets, and both the ecliptic and solar meridian planes were scanned at different times. The time of satellite launch ensured that useful data was obtained for the period of solar sun-spot maximum. The experiments were switched on five days after launch and at the time of writing (August 1972) intermittent data retrieval is still possible.

A total of seven different experiments were provided by six European groups. Experiment S16 provided for the release of Barium vapour near the magnetospheric boundary. Ground-based observation of the resulting ion cloud was used to give information on electric and magnetic fields and particle fluxes. The energy spectra and fluxes of protons in the range 6 - 850 MeV and of alpha particles in the range 40 - 440 MeV per nucleon were measured by experiment S72. Advantage was taken of the large apogee

of the satellite, and consequent absence of atmospheric albedo, to include experiment S79 to measure cosmic ray electrons. Data on the energy and angular distributions of solar wind protons, both in interplanetary space and in the shock region, has been provided by the combined experiment S58/S73.

A complementary set of experiments designated S24A, B, C, were provided by Imperial College, London to measure magnetic fields and the fluxes and anisotropies of both high and low energy protons. The magnetic field measurements give information on electromagnetic conditions in the vicinity of the earth whilst information on high energy galactic protons and low energy solar protons can be considered indicative of such conditions outside and inside the earth's orbit respectively.

Experiment S24A comprised a 3-axis Schonstadt fluxgate magnetometer designed to give information on the geometry and strength of the interplanetary magnetic field, on the magnitude of irregularities of the scale required to influence the particles measured by 'B' and 'C', and on the magnetic character of shock fronts and disturbances. The magnetometer was located on a boom at 2m from the satellite centre with a fourth sensor located 75 cm closer in order to estimate any satellite contribution to the measured field. A range of ± 64 gamma, at a sensitivity of 0.5 gamma per digitisation step, was available on each axis. In normal operation a vector was sampled once every 48 secs, but there were two other modes of operation available utilising a core memory to give more detailed information on interesting disturbed regions. A description of the instrument and a detailed analysis of interplanetary field data has been given by Sear (1971).

Analysis of data from the high energy proton telescope, S24B, forms the subject matter of this section and a full description of this instrument is given below.

Experiment S24C was a four element range-energy telescope designed

to give information on the time variations and anisotropies of solar protons for four energy channels between 0.8 and 20 MeV and to monitor alpha-particles in the range 3.5 to 35 MeV. Two identical telescopes were used, one pointed in the anti-spin axis direction to monitor time variations, and the other scanning radially, the counts being routed into eight sectors by sun-gate pulses. Each of the counters comprised $\sim 100 \mu$ thickness of Silicon surface barrier semi-conductor with varying thickness of Aluminium interposed between them. The viewing cone of the detector had a half-angle of $\sim 9.5^\circ$. Useful data has been obtained for protons in the energy range 1 - 13 MeV and many solar flare events have been analysed in detail (see e.g. Balogh and Hynds, 1970, where a fuller description of the detector is given).

5.3 THE HIGH ENERGY PROTON TELESCOPE - EXPT. S24B

5.3.1 Scientific Aims

Experiment S24B was designed to measure any anisotropies in the flux of cosmic ray protons of energy greater than ~ 360 MeV. The apparatus was intended to cope with the high fluxes present during certain solar flares and with the small anisotropy ($\sim 0.4\%$) of galactic cosmic-rays. Data from solar flares could be used in conjunction with data from the other HEOS experiments to give a better understanding of the propagation of particles from sun to earth, whilst the quiet-time data could give information on the anisotropies of galactic cosmic rays, particularly at the lower energy portion of the spectrum where ground-based detectors have little response. When used in conjunction with the magnetic field data, this information could yield a better understanding of the modulating effect of the solar cavity on the galactic radiation and hence an improved knowledge of the galactic spectrum could be obtained.

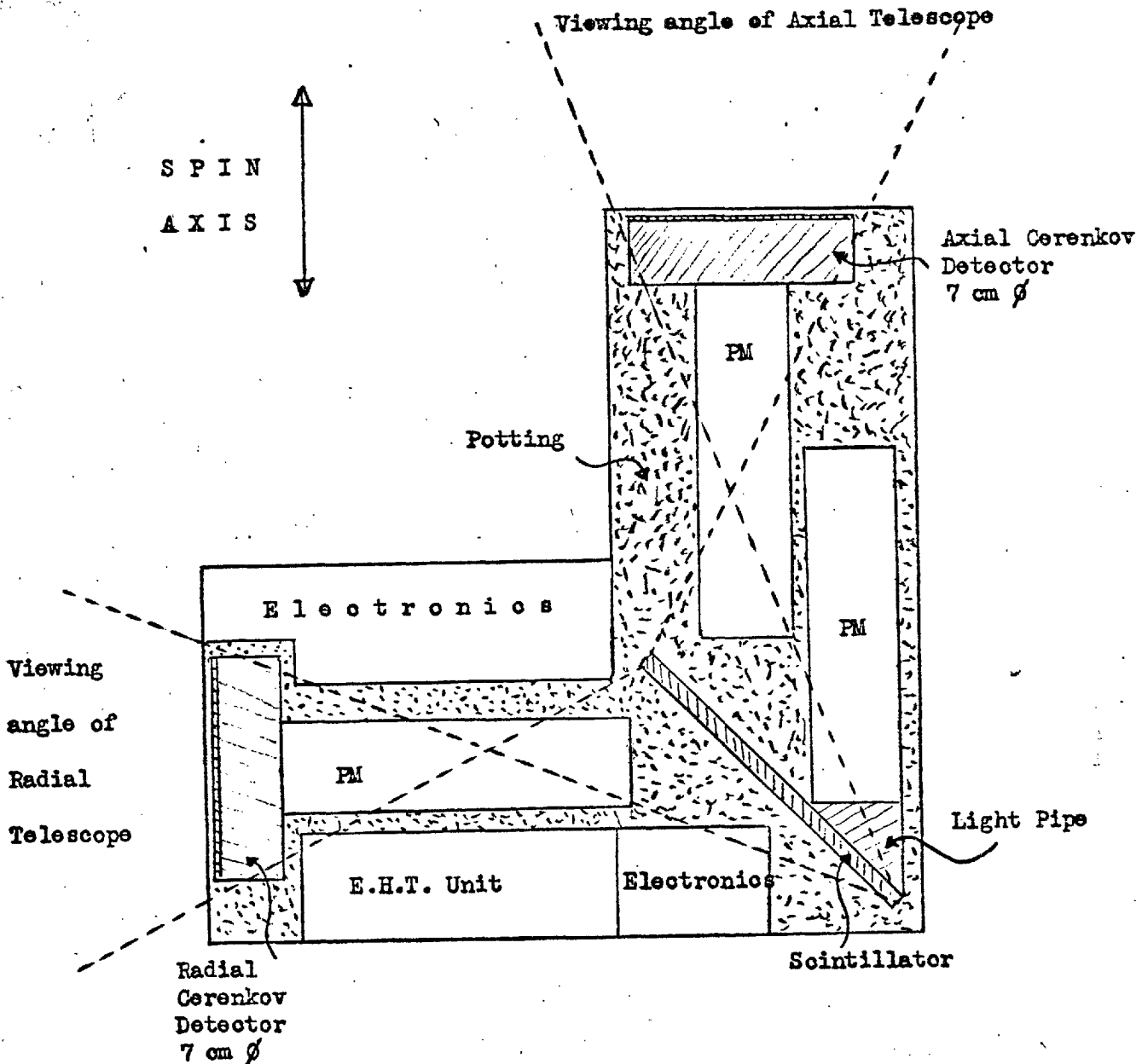


Figure 23: S24B High Energy Particle Telescope

5.3.2 The Telescope

The arrangement of the telescope elements is shown in Figure 23. Two unidirectional telescopes are used, one pointing along the spin-axis in the opposite sense to the spin vector and the other radially outwards at right angles to the spin-axis. A $\frac{1}{4}$ " thickness slab of NE102A plastic scintillator serves as a common element and is viewed through a light pipe

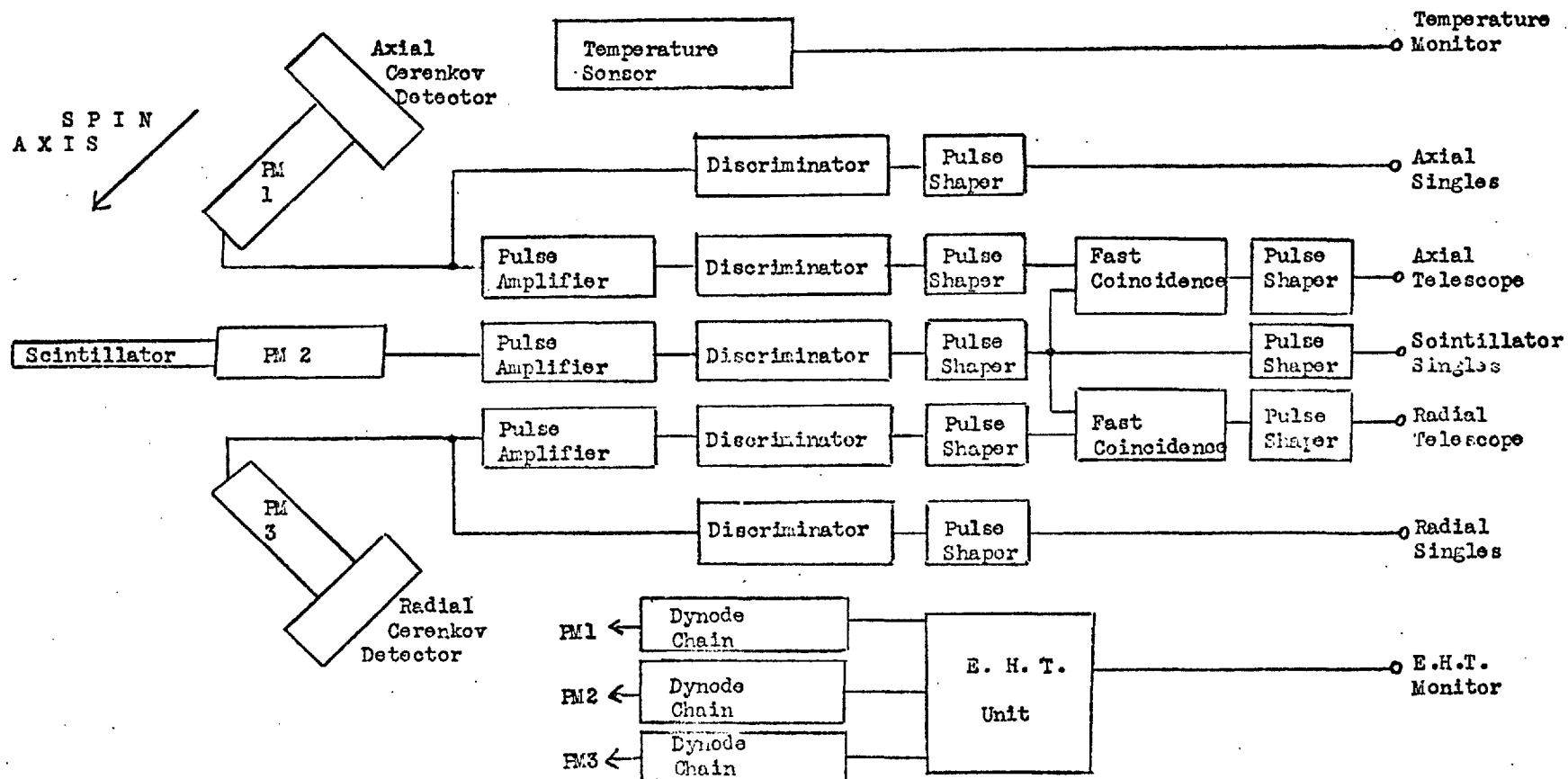
by a 1" photomultiplier (PM). This element is sensitive to all ionising radiations which can penetrate the solar panels of the spacecraft and the thin Aluminium box which houses the telescope. The shielding over part of the solid angle is $\sim 1 \text{ gm.cm}^{-2}$ which sets a threshold for the scintillator of $\sim 30 \text{ MeV}$ for protons and $\sim 1 \text{ MeV}$ for electrons. Telescope opening angles of $\sim 40^\circ$ (full angle) are defined by two perspex discs (7 cm diameter, 1.8 cm thickness), which act as Cerenkov radiators when the particle velocity (v) exceeds the phase velocity of light in the medium. A refractive index of 1.49 for perspex defines the telescope threshold energy for protons at 330 MeV. Such radiation is emitted in a cone of half-angle $\theta = \cos^{-1} \frac{v}{c}$ about the forward direction of the particle. The front faces of the perspex elements have thin discs of blackened perspex attached so that the light emitted from particles travelling in the reverse direction is absorbed rather than reflected into the 1" quartz faced photomultipliers which view the discs. This gives the telescope its directional property, although there is still some efficiency for the detection of backward-moving particles (see section 5.3.3.).

The sensor logic is illustrated in Figure 24. A coincidence between a scintillator and Cerenkov pulse (within 80 nsecs Coincidence time) defines a telescope event. The counting rates of each telescope element (singles rates) are sampled periodically as are measures of the temperature and E.H.T. voltage.

5.3.3 Telescope Geometric Factor

The geometric factor of the telescope was estimated both from numerical calculations and the pre-flight response to cosmic ray μ -mesons in the laboratory. Most cosmic ray fluxes measured by the telescope are very isotropic and it is possible to relate the instrument counting rate C counts s^{-1} to the flux F particles $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ by $C = GF$, where the

FIGURE 24: S24B Sensor Logic Diagram.



geometric factor, G , is given by

$$G = \iint_{s \Omega} \mathcal{E}(x,y,z,\theta,\phi) ds d\Omega$$

where s is the detector surface area, Ω the solid angle available to it and $\mathcal{E}(x,y,z,\theta,\phi)$ gives the detection efficiency for the arrival of a particle at a point (x,y,z) from a direction (θ,ϕ) . The detection efficiency for both forward and backward moving particles must be considered. Here the integration is simplified by taking

$$G = (\mathcal{E}_{\text{forward}} + \mathcal{E}_{\text{backward}}) \iint ds d\Omega$$

where $\mathcal{E}_{\text{forward}}$, $\mathcal{E}_{\text{backward}}$ are spatially averaged efficiencies.

The value of the integral $\iint ds d\Omega$ was evaluated numerically to be $6.3 \text{ cm}^2 \text{sr}$. Observation of the vertical μ -meson flux in the laboratory gave a value for $\mathcal{E}_{\text{forward}}$ of 90% (taking the vertical, sea level μ -meson flux in London to be $0.0009 \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$).

Inversion of the detector in this μ -meson flux gave the ratio $\mathcal{E}_{\text{forward}} : \mathcal{E}_{\text{backward}}$ as 4 : 1. The value of G was therefore taken as

$$(0.90 + 0.225) \iint ds d\Omega$$

$$= 7 \text{ cm}^2 \text{sr}, \text{ to within the accuracy of these calculations } (\sim 10\%).$$

The correction required for backward particles is then of the form

$$R(K) = \frac{4 \times R(K) - R(K \pm 4)}{3}$$

for a division of radial count rate into eight equal sectors ($K = 1, 8$) in which the count rates are $R(K)$. This correction leaves the average of

the radial sectors unaltered as the forward and backward efficiency terms are already included in the geometric factor.

This correction should remain valid for the location of the experiment on the satellite as the additional shielding in the reverse cone amounts to only $\sim 3 \text{ gm.cm}^{-2}$.

5.3.4 Detector Efficiency as a Function of Energy

The above efficiency estimate was made for highly relativistic μ -mesons. The variation of detector efficiency with proton energy was estimated from the theoretical Cerenkov light output curve and the light collection efficiency as estimated from the counting rate vs gain curve for sea level μ -mesons.

Figure 25 gives the result of this calculation, showing the half-

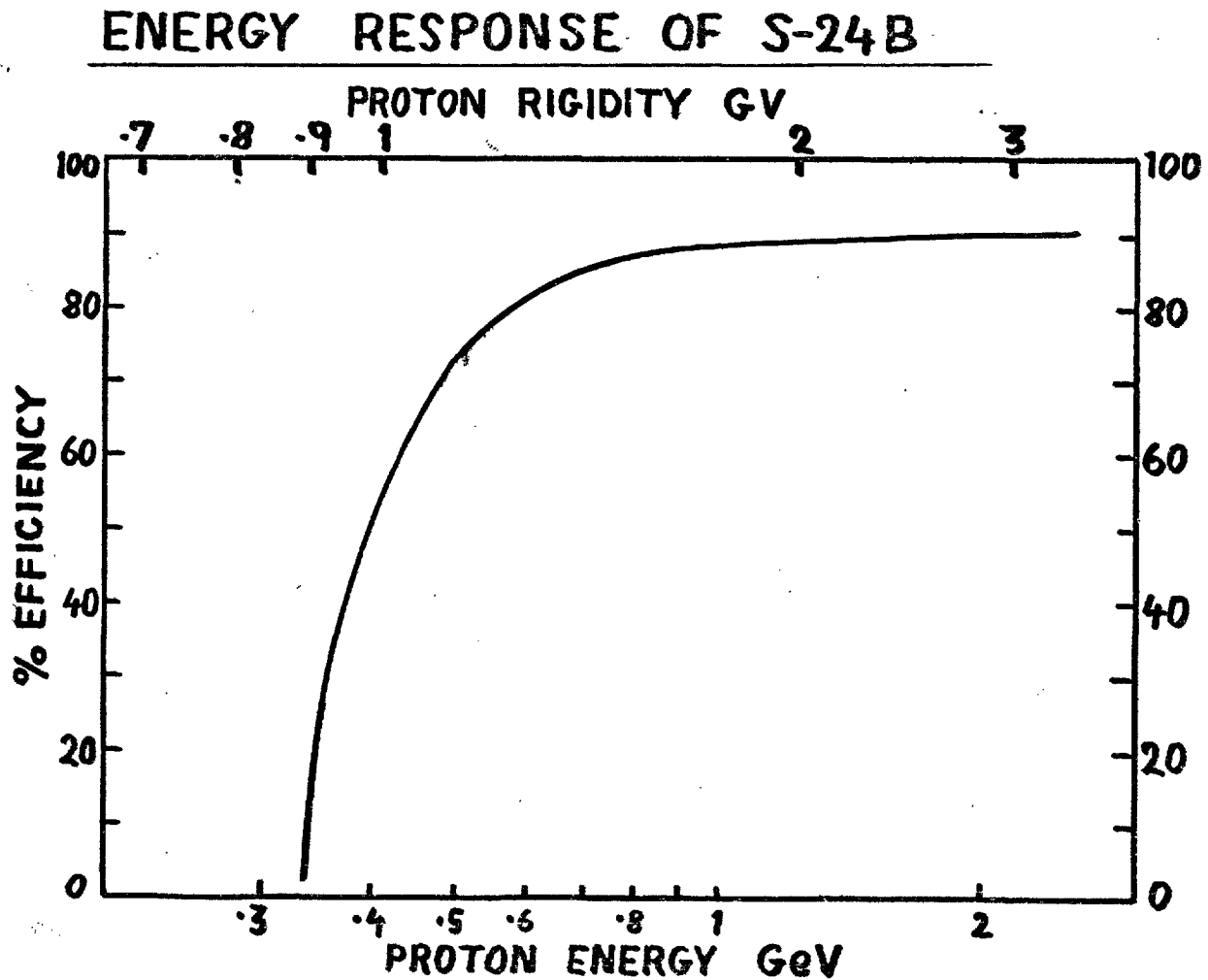


FIG. 25

maximum level to be at 380 MeV.

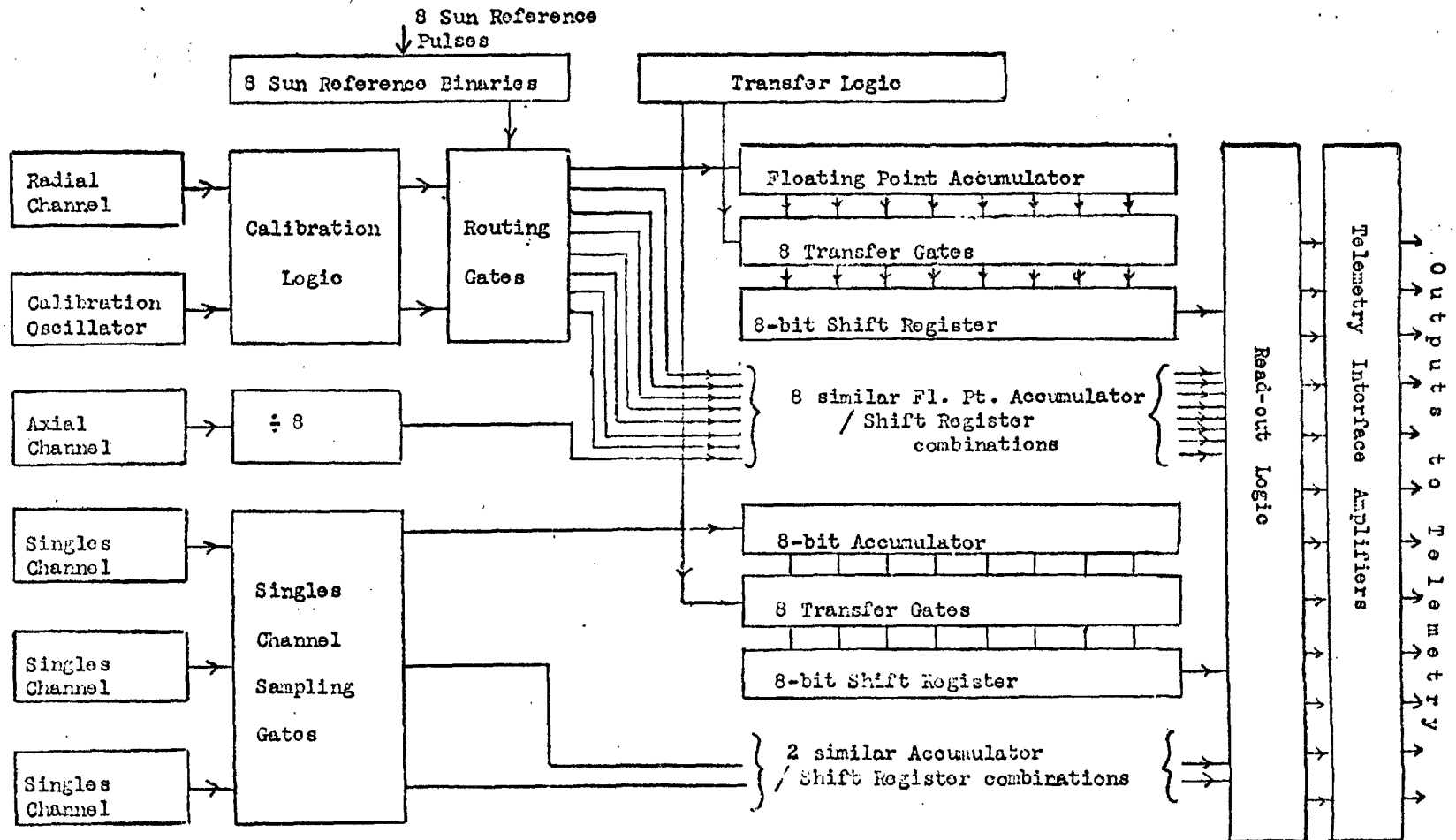
5.3.5 Geometric Factor of Scintillator Singles

As the counting rate sampled from the scintillator element is sometimes used as a monitor of the flux of low energy particles, it is useful to have an estimate of the geometric factor. For an isotropic flux of particles which can penetrate the spacecraft material, the omnidirectional geometric factor of such a square slab is simply $A/4$ where A is the total surface area. In this case $A/4$ works out to be 43 cm^2 . As mentioned in section 5.3.1 the energy threshold is set by the minimum path length of material shielding the scintillator. A significant portion of the scintillator surface has a larger amount of shielding from the body of the spacecraft ($\sim 3 \text{ gm.cm}^{-2}$ cf 1 gm.cm^{-2} minimum shielding). Thus the proton energy threshold for certain directions is raised to 60 MeV and greater. Hence while 43 cm^2 is probably a reasonable estimate of the omnidirectional geometric factor for galactic cosmic rays, the effective value for soft solar flare protons could be reduced by about a factor of two. The agreement between flux levels estimated from the scintillator singles and the telescope (see figure 28) for non solar flare periods gives confidence in the former estimate.

5.3.6 Data Handling

The data handling logic is illustrated in Figure 26. As the radial telescope scans the satellite equator with each spin, the counts are routed into eight accumulators by routing gates opened by eight sun reference signals spaced at 45° intervals. These signals are provided by eight photo-diodes which view the sun through slits. The nomenclature for these sun gate pulses, their positioning relative to the telescope, and the sectors into which the counts are divided are illustrated in Figure 27. Knowledge of the direction of the satellite spin axis enables determination

FIGURE 26: S24B Data Handling Block Diagram.



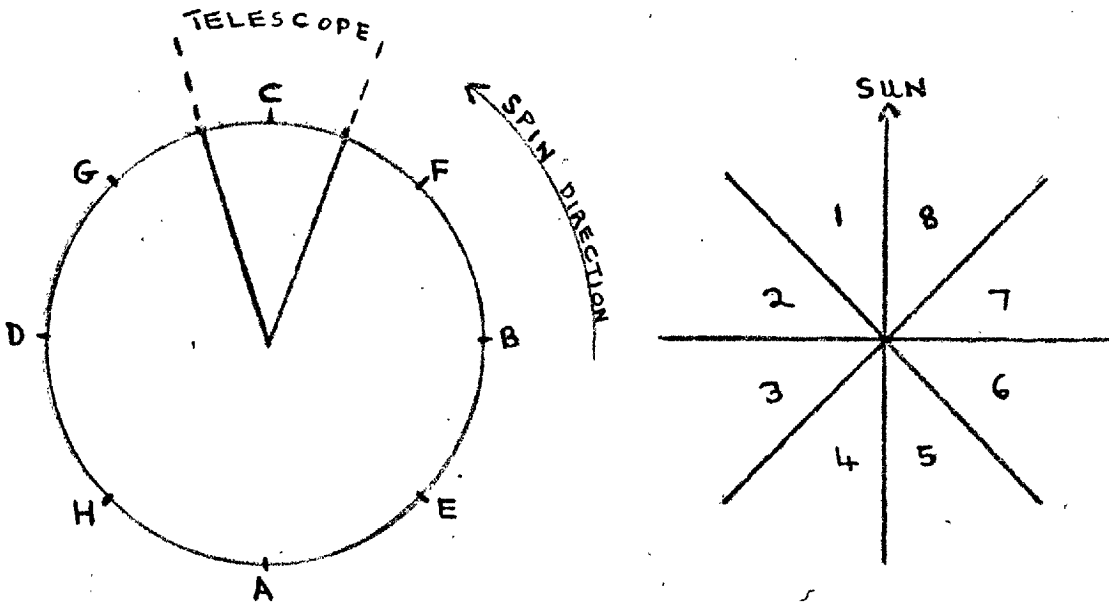


FIGURE 27: LOCATION OF SOLAR SENSORS AND SECTOR DEFINITION

of the solar ecliptic coordinates scanned by each sector.

"Floating-point" accumulators are used to accommodate the wide range of counting rates that occur during solar flares. Each such accumulator comprises a 6-bit accumulator, a 2-bit index and a 2-bit, 4-bit, or 6-bit prescaler. The 2-bit index controls the prescaler so that every time a count enters the index a new scaling factor is switched in. The counts in the index (0, 1, 2 or 3) thus measure the scaling factor to be applied (1, 4, 16, 64). Because the prescalers are reset after each read-out an average remainder must always be added in to take account of the counts left behind. The error involved is always less than the Poisson error in the number of counts. If n is the index, and m the 6-bit number, the number of counts N is given by

$n = 0$	$N = m$
$n = 1$	$N = 4m + 64 + \frac{3}{2}$

$$n = 2$$

$$N = 16m + 64 + 256 + \frac{15}{2}$$

$$n = 3$$

$$N = 64m + 64 + 256 + 1024 + \frac{63}{2}$$

For quiet-time data, $n = 0$.

Counts from the axial channel are scaled by a factor 8 before entering a floating point accumulator in order to make the counting rate comparable to the average in the radial channels.

Once every second telemetry frame (i.e. 48 secs), the transfer logic generates a pulse such that the next triggering of sun gate 'C' transfers the contents of each 6-bit accumulator and 2-bit index into 8-bit shift registers and in so doing resets the floating point accumulators for a new cycle. Here the numbers are stored until they are read out serially to telemetry by the read-out logic at the appropriate point in the telemetry format. Each telemetry format contains 16 frames (i.e. 384 secs). This arrangement ensures that each sector is sampled for the same whole number of spins so that anisotropies are readily interpreted from the data. Because the spin period is not synchronised with the telemetry but varies between about 5 and 7 secs over the satellite history, each frame of numbers is not collected for the same time. In general the sequence of collection times is a linear array of 7 or 8 spin periods, which over several formats average out to 48 secs. Averages over at least ten formats or an hour's data have been used so that ideally the error from this source should be zero. There are, however, some data gaps due to the calibration sequence or loss of telemetry synchronisation which can bias the collection time. Worst case estimates of this effect using trial data have shown the resulting errors to be less than the statistical errors. It should be noted that this error can occur only in the time variations and not in the spatial anisotropy.

Because quiet-time anisotropies are very small, it is necessary to obtain an accurate calibration of the sun reference signals. In

addition to initial errors in alignment, changes may occur in flight due to variations in the solar aspect angle and unequal expansion of the spacecraft surface, and so an in-flight calibration is employed. Once in each telemetry format, immediately after a transfer pulse, the calibration logic closes the gate to the radial channels and opens the gate to a calibration oscillator for one satellite spin. Normal operation resumes after the next transfer pulse. The calibration pulses by-pass the prescaler and are collected as an ordinary 8-bit number. The number of calibration counts collected in each channel is ~ 150 and the ratio of counts gives the ratio of collecting times for each channel. Averaging over several hours' data soon gives the requisite calibration accuracy.

The singles channels feed into ordinary 8-bit accumulators and are each sampled for $\frac{2}{3}$ secs once every telemetry format. In order to achieve a larger dynamic range a dead-time of ~ 3 msec is deliberately introduced into the singles counting rates. In the case of the Cerenkov elements the bias level for the singles sampling is higher than for the coincidence gate in order to exclude photomultiplier noise.

5.3.7 Additional Experimental Corrections and Failures.

As well as the correction for backward-moving particles and the calibration procedure already described, several experimental effects occurred which required additional corrections or else rejection of data.

i) Additional Calibration Pulses in Channel 1.

If the calibration gate is opened during an oscillator pulse an erroneous pulse is recorded in channel 1 (normally a count is registered only for each 'leading edge'). This effect was well understood and tested before flight. Both measurement of the pulse width to interpulse ratio, and testing of the calibration system by supplying equally spaced simulated sun gate pulses, showed that such erroneous pulses occur in 50% ($\pm 5\%$) of

the calibrations. Thus subtraction of half a count per calibration sequence from the calibration total for channel 1 gives a corrected calibration factor which is good to ± 0.05 in 150. The error involved in this ($\sim 0.03\%$) is negligible.

ii) Floating Point Accumulator for Channel 6.

For most of 1968-69, the prescalers in the floating point accumulator for channel 6 failed to work so that this channel could not count above 64. This effect showed up clearly as channel 6 fixed on 64 whilst counts in the other channels were in excess. For such cases, which occur only during solar flares and in radiation belt passages, channel 6 was taken as the average of channels 5 and 7. The effect remedied itself in early 1970.

Data for quiet-time periods is not affected by this fault.

iii) Failure of Sun Gate Pulses

After February 1970, sun gate pulses 'A' and 'C' were subject to intermittent failure. Sun gate 'C' is used to transfer the telescope data to telemetry so that for periods of failure there is only singles data from experiment S24B. The absence of pulse 'A' means that channel 4 is not shut and so accumulates the sum of counts from all the radial channels whilst channel 5 is never opened and accumulates zero counts. For periods of total failure of 'A' the sum of true counts in channels 4 and 5 can be determined by subtracting the sum of the other channels from the measured radial total in channel 4. However, inspection of the data shows the failure of 'A' to be intermittent on most days after April, 1970, so that it is difficult to make any deductions concerning the anisotropy from data obtained after this date.

iv) Chance Coincidences

When counting rates in the Cerenkov and scintillator elements are

high, the possibility exists of chance coincidences contributing to the telescope rate. If the counting rates are n_1 and n_2 counts sec^{-1} respectively, and the coincidence time is τ secs, then the rate of chance coincidences $N \text{ sec}^{-1}$ is given by

$$N = 2 n_1 n_2 \tau$$

From pre-launch tests, τ was determined to be 80 nsecs. If n_1 and n_2 are known, an estimate may be made of the chance coincidence contribution. The scintillator singles rate, n_2 , is sampled directly once per format. However, during intense solar flares the large dead-time in this sample renders the value unreliable. The Cerenkov singles are sampled at a higher threshold than that employed in the coincidence gate in order to eliminate noise. An estimate of the noise contribution is required in order to determine n_1 . Pre-launch tests gave the following measures of the noise:

Telescope Element	Noise Rate (counts sec^{-1})	
	Singles Sampling Threshold	Coincidence Threshold
NE102A Scintillator	6.0	6.0
Axial Cerenkov Disc	0.08	40
Radial Cerenkov Disc	2.8	265

Estimates show the μ -meson contribution to these rates to be of the order of the Axial Singles rate.

In addition, n_1 will contain particle produced counts due to pulses falling between the two thresholds. During solar flares the large increase in Cerenkov singles relative to the telescope rate suggests an important contribution from scintillation in the photomultiplier face which could add a large number of counts to n_1 . An upper limit for this effect may be set by scaling the scintillator singles rate by the ratio

Area of photomultiplier face : area of scintillator slab (~ 0.06).

Investigation shows that for quiet-time data and the less intense solar flares, noise is the dominant contribution to n_1 , whilst for events in which large numbers of low energy protons (> 30 MeV) are produced, the scintillation in the photomultiplier face dominates. The telescope is thus rendered useless during intense solar flare events.

The effects of chance coincidences on solar flare data and quiet-time data are considered in Chapters 7 and 8 respectively.

5.3.8 Analysis of Data.

Data from all the HEOS experiments, together with satellite housekeeping information, was telemetered at 12 bits sec^{-1} to receiving stations at Radu in Belgium and Fairbanks, Alaska. These stations were able to see the satellite continuously whilst its altitude was above 50,000 km. A certain amount of data obtained close to satellite perigee was lost.

The data was collected at the European Space Operations Centre (ESOC) at Darmstadt, Germany where data tapes were prepared for each experiment. 'Quick-look' samples of each days data were also distributed to maintain a check on the operation of experiments. Tapes containing data for the S24 experiments were received at Imperial College where chronologically ordered tapes were generated for each 30 days of data.

Programs were written to extract and process the data for the S24B experiment. Averages over each day were generated for both telescope and scintillator singles counting rates. Daily totals were collected on cards so that several days' data could be summed. For periods of solar flares, averages were computed for each subframe and for each hour of data. Many data selection criteria and correction routines were written into these programs. The nature and order of these processes were as follows.

i) Elimination of Errors in Telemetry Synchronisation.

At the start of each frame of data the satellite data handling system generates a code of 'synch words'. If these are not identically regenerated in the ground data, then either a loss of telemetry synchronisation or noisy data is indicated and the following data should be rejected. The programs tested each set of three synch words against the known code and generated a synch loss flag if there was any error. A frame of data was rejected if either the preceding or the following synch loss flags showed an error. If five or more frames in each telemetry format of sixteen frames were rejected, then the entire format was excluded.

Loss of telemetry synchronisation led typically to rejection of about 12% of data.

ii) Floating Point Conversion

Each floating point word of 6-bits with a 2-bit index was read from tape as an 8-bit word. The programs computed the index value and then the true number using the formulae of section 5.3.6.

iii) Channel Six Correction

During periods of channel six floating point failure, an average of channels five and seven was assigned whenever the registered value was 64.

iv) Rejection of Spurious Data

Inspection of raw data has shown the presence of occasional spurious numbers in the data due to bit errors in telemetry even when no loss of synchronisation is registered. The effect of such data was minimised by setting certain limitations on the permitted data values. In all cases, frames containing a zero were rejected. This also eliminates any frames for which there is total failure of sun gates 'A' or 'C'. In the case of the daily averages an upper limit of 20 counts per channel per frame was set (average value is ~ 7). This has the effect of cutting off the peak values during flares, but these averages were only used to show the

occurrence of such events, whilst hourly averages were taken to give their intensity. For flare events this upper limit was waived and data was rejected whenever the ratio of counts in successive channels was greater than three or less than one third. This restriction was removed during highly anisotropic events.

Limits of 127 and 170 were applied to the calibration data (mean ~ 150). These cover the widest variation in the satellite spin period.

The amount of data rejected by these means was of the order of 2%.

v) Rejection of Perigee Data.

In order to reject any contribution to the daily averages from trapped radiation and to minimise the effect of the earth's magnetosphere on the observations, all data for the daily averages was rejected when the satellite was at a geocentric distance of less than twenty earth radii. The satellite spends most time near to apogee at thirty-five earth radii, so that not too much data is lost in this way ($\sim 12\%$ in fact).

For the hourly averages of solar flare data, all possible data was examined. Contributions from trapped radiation were clearly indicated by the low satellite altitude accompanied by a sudden increase in counting rate.

vi) Correction for Unequal Sun Gate Sectors

For each daily average of counting rates, average calibration rates were computed. The channel 1 calibration totals had $\frac{1}{2}$ count per frame subtracted (see 5.3.7(i)). Then if the average of the eight calibration values $CAL(I)$ is $ACAL$ and the measured rates are $MR(I)$, the corrected rates $CR(I)$ are simply given by

$$CR(I) = MR(I) \times \frac{ACAL}{CAL(I)}, \quad I = 1, 8$$

Daily averages were corrected according to this formula. Such

corrections are of the order of 1% and for one day's data are accurate to $\sim 0.02\%$. This error is negligible compared with the Poisson error in the counting rates. Solar flare data was corrected according to such calibration factors found by averaging over several days data covering the time period concerned. Such corrections are very small compared with the Poisson errors.

A normalisation factor was generated for the axial telescope (channel 9) such as to make the mean quiet-time rates equal for both telescopes. This correction, which essentially normalises the geometric factors, amounts to a 3% increase in the axial rate.

vii) Correction for Backward-moving Particles

Following the sector calibrations, the contribution of backward particles was corrected according to the formula given in section 5.3.5.

viii) Dead-time Correction of Scintillator Singles

The singles rates were corrected for dead-time according to the standard formula

$$N = \frac{n}{1 - n\tau}$$

where N is the true count rate, n the observed count rate, and τ the dead-time per count. The value of τ drifted slightly throughout the satellite history and was estimated periodically from the maximum count rate ($n_{\max}$) observed at perigee. Then $\tau = \frac{1}{n_{\max}}$ ($n_{\max} \sim 271$ per $\frac{2}{3}$ secs in this case).

Spurious data in the daily singles averages was minimised by eliminating values of n greater than 78.

5.3.9 Harmonic Analysis of Data

It is conventional to examine cosmic ray anisotropies by analysing

the angular distribution of the intensity into a harmonic series. In experiments such as S24B, counts are routed into a number of sectors as a radial pointing telescope scans the equatorial plane of the satellite during each spin. By Fourier's theorem the angular distribution of intensity, $I(\theta)$ can be described by the infinite series

$$I(\theta) = I_0 \left[1 + \sum_{K=1}^{\infty} a_K \cos(K\theta) + b_K \sin(K\theta) \right]$$

$$\text{and } a_K = \frac{1}{\pi I_0} \int_0^{2\pi} I(\theta) \cos(K\theta) d\theta ; b_K = \frac{1}{\pi I_0} \int_0^{2\pi} I(\theta) \sin(K\theta) d\theta \dots 5.3.9.A$$

In many applications, the 1st harmonic ($K=1$) dominates and the anisotropy is defined to have an amplitude δ % and phase ϕ such that

$$I(\theta) = I_0 \left[1 + \frac{\delta}{100} \cos(\theta - \phi) \right]$$

$$\text{and } \delta = \sqrt{a_1^2 + b_1^2} ; \phi = \tan^{-1} (b_1/a_1) \dots 5.3.9.B$$

It is important to note that as defined here, ϕ represents the spatial direction in which the detector must point in order to view the maximum intensity. Any net cosmic ray streaming is in the direction opposite to this.

Equations 5.3.9.A give the results of analysing a continuous distribution function, $I(\theta)$. In S24B, $I(\theta)$ is sampled at r equidistant intervals ($\theta_1 \dots \theta_r$) and the counting rate is averaged over each sector of width $\frac{2\pi}{r}$ so that

$$\bar{I}(\theta_\sigma) = \frac{r}{2\pi} \int_{\theta_\sigma - \frac{\pi}{r}}^{\theta_\sigma + \frac{\pi}{r}} I(\theta) d\theta \dots 5.3.9.C$$

It can be shown (see e.g. Chapman and Bartels, Vol.II, Chapter 16),

that a least squares fit of such samples to a distribution such as 5.3.9 gives harmonic coefficients

$$a_K^* = \frac{2}{rI_0} \sum_{\sigma=1}^r \bar{I}(\theta_{\sigma}) \cos(K\theta_{\sigma}); \quad b_K^* = \frac{2}{rI_0} \sum_{\sigma=1}^r I(\theta_{\sigma}) \sin(K\theta_{\sigma})$$

...5.3.9.D

Substituting for $\bar{I}(\theta_{\sigma})$ from 5.3.9.A and C relates the coefficients via expressions of the type

$$a_1^* = \frac{r}{\pi} \sin\left(\frac{\pi}{r}\right) \left[a_1 + \sum_{n=1}^{\infty} \left(\frac{a_{mr-1}}{mr+1} - \frac{a_{mr+1}}{mr+1} \right) \right]$$

$$b_1^* = \frac{r}{\pi} \sin\left(\frac{\pi}{r}\right) \left[b_1 + \sum_{n=1}^{\infty} \left(\frac{b_{mr-1}}{mr-1} + \frac{b_{mr+1}}{mr+1} \right) \right]$$

(see Balogh, 1971)

...5.3.9.E

It can be shown that in general the true harmonic coefficients a_K, b_K can be obtained from the harmonic coefficients a_K^*, b_K^* obtained from the equidistant samples via 5.3.9.C, provided that harmonics of order $(r-K)$ and higher do not contribute appreciably to the distribution. The function $\frac{r}{K\pi} \sin\left(\frac{K\pi}{r}\right)$ represents the smoothing effect of averaging over a sector. It is apparent that both the effect of smoothing and of higher harmonics will be small if $K \ll r$. For S24B, $r = 8$ and this condition is satisfied for the first two harmonics.

Application of these formulae to the corrected rates $CR(I)$ for the eight sectors ($I = 1, \dots, 8$) of S24B then gives

$$a_1 = \frac{\pi}{8 \sin(\frac{\pi}{8})} \left[\frac{1}{\sqrt{2}} (CR(2) - CR(4) - CR(6) + CR(8)) + CR(1) - CR(5) \right]$$

$$= 4 I_0$$

$$b_1 = \frac{\pi}{8\sin(\frac{\pi}{8})} \left[\frac{1}{\sqrt{2}} (CR(2) + CR(4) - CR(6) - CR(8)) + CR(3) - CR(7) \right] \div 4I_0$$

$$a_2 = \frac{\pi}{4\sin(\frac{\pi}{4})} [CR(1) - CR(3) + CR(5) - CR(7)] \div 4 I_0$$

$$b_2 = \frac{\pi}{4\sin(\frac{\pi}{4})} [CR(2) - CR(4) + CR(6) - CR(8)] \div 4 I_0$$

$$\text{where } I_0 = \frac{SR}{8} \text{ and } SR = \sum_{I=1}^8 CR(I) \quad \dots 5.3.9.F$$

From these coefficients, the amplitude and phase of the first two harmonics can be calculated via equation 5.3.9.B. These equations take account of averaging over a sector but not of the opening angle of the telescope which produces overlap of the sectors. The exact angular response function of the detector is not known but taking an extreme case of a rectangular function over a full width angle of 45° produces a correction to the first harmonic amplitude of only 8% (statistical errors are about 20%). The phases of the harmonics are referred to the centre of the 1st sector. Addition of 22.5° then refers the phase to the solar vector (see Figure 27) and reference to the satellite orientation locates the anisotropy vector in solar ecliptic coordinates.

It can be shown (see e.g. Chapman and Bartels) that harmonic analysis of a set of random numbers yields an amplitude for each harmonic equal to twice the standard deviation for the average of the set of numbers. The error, γ , in the anisotropy for each harmonic is then given by

$$\gamma = \frac{200}{\sqrt{SR}} \% \quad \dots 5.3.9.G$$

with a corresponding error, ϵ_K , in the phase given by

$$\epsilon_K = \sin^{-1} \left(\frac{\eta}{SR} \right)$$

Here SR is the total of all the numbers accumulated for the harmonic analysis.

The average quiet-time count rate is about 1 count s^{-1} for S24B, and the percentage of useful data obtained in one day averages out at $\sim 70\%$ when all forms of data loss described above are taken into account. Of this one eighth is calibration data. When these numbers are used in equation 5.3.9.G, it can be seen that the error in the anisotropy based on one day's data is $\sim 0.85\%$. This error drops to 0.3% for nine days' data and to 0.1% for 80 days. Anisotropies for quiet time data are expected to be $\sim 0.4\%$.

Although Poisson statistics set an ultimate limit on the anisotropy that can be resolved, the data may contain other errors, and error estimations based on the actual data must be employed. This will be considered in Chapter 8.

A program was written to sum the daily totals obtained on cards for any chosen grouping of days and to apply formulae 5.3.9.F and G to determine the 1st two harmonics and their errors. The program was tested on known wave form inputs. Results obtained for quiet-time anisotropies are presented in Chapter 8.

During solar flare particle events both intensities and anisotropies are increased so that there is a strong possibility of obtaining significant anisotropies from hourly averages obtained during the more intense events. An additional program was written to perform an harmonic analysis for such periods. In this case a background counting rate of cosmic radiation must be subtracted from each channel before analysing for anisotropies in the solar contribution. The error equation must then be modified to take account of this subtraction, giving

$$\eta = 200 \frac{\sqrt{SR + BKG}}{SR} \%$$

where BKG is the total number of counts from which the average background rate per channel is calculated. Anisotropies in solar flare proton events will be examined in Chapter 7.

CHAPTER 6. MODULATION OF THE COSMIC RAY INTENSITY

6.1 INTRODUCTION

The HEOS satellite was launched in December, 1968, in order to monitor conditions in interplanetary space during a period of solar sunspot maximum. Such periods have been found to recur with an eleven year cycle and to correspond to a minimum in the cosmic ray intensity. At such times a large number of solar flares occur which often result either in solar particle production or in short-term decreases in the flux of galactic cosmic rays.

Time variations in the cosmic ray intensity have been observed by ground-based detectors for some thirty-five years, and more recently observations have been extended to lower energies using balloon and spacecraft payloads. A review of such observations and the various theories has been given by Quenby (1967). The short term, or Forbush, decreases have recently been reviewed by Lockwood (1971).

Theories of cosmic-ray modulation generally invoke a model of diffusion-convection equilibrium in which galactic particles diffuse into a modulation region formed in interstellar space by the solar wind flow. Diffusion is considered to be predominantly along the direction of the spiral interplanetary magnetic field with scattering resulting from discontinuities or waves in the field. Convection results from the radial flow of these irregularities at the solar wind speed. More recent investigations have taken account of energy loss of particles due to adiabatic deceleration in the expanding solar wind. On the Jokippi model of resonant wave-particle interactions causing random pitch angle changes, the mean free path, λ , in a power spectrum of irregularities $\Pi_{\perp}(f)$ perpendicular to the mean field, B , is given by

$$\lambda = \frac{P^2}{\Pi_1(f_{\text{res}})V} \quad 6.1.A$$

for a rigidity P , solar wind speed V , where the resonant frequency f_{res} is given by

$$f_{\text{res}} = \frac{\sqrt{3} V B}{2\pi P} \quad 6.1.B$$

Thus if $\Pi_1(f) \propto \frac{1}{f^{\delta}}$, $\lambda \propto P^{\alpha}$ where $\alpha = 2 - \delta$

Solution of the Fokker-Planck equation for particle diffusion in phase space then predicts a modulation of the form

$$n(t) = n_s \exp\left\{\frac{-K(t)}{\beta P^{\alpha}}\right\} \quad 6.1.C$$

where $n(t)$ is the differential number density at rigidity P , n_s is the density outside the modulating region, $\beta = v/c$, and $K(t)$ varies over the solar cycle. Here it has been assumed that δ is not a function of radial distance from the sun. Quenby and Sear (1971) have considered the possibility that the long term modulation is caused by an overall enhancement in the power spectrum of irregularities at solar maximum. From neutron monitor observations it would seem that $\alpha = 1$ gives a good fit to the data. This ties in well with field measurements which give $\delta \sim 1$. However, more recent investigations have shown this simple theory to be inadequate. Changes in the solar wind and magnetic field parameters measured close to the earth would seem incapable of producing the observed modulation so that there exists the possibility that phenomena occurring off the ecliptic plane are important (Hedgecock et al., 1972). Also step-like changes in the modulation function have been observed and are difficult to reconcile with simple form given in 6.1.C (Stoker and

Carmichael, 1971). There is some controversy as to whether Forbush decreases satisfy the same modulation function as the long-term modulation. If so it can be hypothesised either that such decreases are an enhancement of the long-term mechanism or that the latter is a superposition of a large number of the short-term decreases. Quenby (1971) has proposed a model in which particles are swept out by a large-scale tangential discontinuity, with the subsequent recovery phase determined by a perturbation to the existing modulation due to enhanced scattering and solar wind velocity. The possibility exists that for such disturbed periods, there could be a change in the power spectrum which would alter the rigidity dependence of the recovery.

Daily averages from the S24B instrument have been obtained for the period December, 1968, to April, 1972. During this period there occurred a considerable change in the cosmic ray intensity and also a number of Forbush decreases. In this chapter such variations will be compared with data from the high latitude neutron monitor at Deep River, Ontario, in order to determine the rigidity dependence in the range 1-10 GV.

6.2 DETECTOR RESPONSE FUNCTIONS

In order to fit trial modulation functions to the data from different detectors it is necessary to know their differential response functions $\frac{\partial N}{\partial P}$ defined such that

$$N(t_o) = \int_{P_c}^{\infty} \frac{\partial N(t_o)}{\partial P} dP \quad 6.2.A$$

$$\Delta N = N(t_o) - N(t) = \int_{P_c}^{\infty} \frac{\partial N(t_o)}{\partial P} (1 - F(t, P)) dP \quad 6.2.B$$

where $N(t)$ is the counting rate of the detector,

P_c is the threshold rigidity of the detector,

$F(t,P)$ is the modulation function measured relative to time, t_0 , such that the differential flux of the primary cosmic radiation $J(P,t)$ is modulated as

$$J(P,t) = J(P,t_0) \times F(t,P)$$

It is usual to refer all modulation to cosmic ray maximum. For the purposes of this chapter, differential response functions are required for the year 1969, a period of minimum cosmic ray intensity.

6.2.1 The Deep River Neutron Monitor

The response of a neutron monitor situated at an atmospheric depth of $x \text{ gm/cm}^2$ can be represented by a specific yield function $S(P,x)$ defined such that

$$\frac{\partial N(P,x,t)}{\partial P} = J(P,t) \times S(P,x)$$

$S(P,x)$ thus represents a combined efficiency function of the detector-atmosphere system.

In practice, neutron monitor detector response functions have been calculated from latitude surveys for which counting rates have been plotted against computed values of the vertical threshold rigidity. A review of this method is given in Quenby (1967).

Mathews et al. (1971) have considered neutron monitor data for the period 1965-69 in order to compare the rigidity dependence of the long-term modulation with that of Forbush decreases. A modulation function $F(t,P)$ of the form $\exp(-\frac{K(t)}{P})$ was found to give a good fit to the long-term data with an increase in the value of $K(t)$ of 1.9 between 1965 and

1969. These authors give values for $\frac{\partial N}{\partial P}_{\min}$ appropriate to sea-level for sunspot minimum in 1965, from which values of $\frac{\partial N}{\partial P}_{\max}$ for 1969 have been calculated via

$$\frac{\partial N}{\partial P}_{\max} = \frac{\partial N}{\partial P}_{\min} \times \exp\left(-\frac{1.9}{P}\right)$$

to give the values present in Table 4. These values will be used in section 6.4 to compute the changes in the counting rate of the Deep River monitor for different modulation functions. The vertical threshold rigidity (P_c) of this detector was taken to be 1 GV.

Table 4: Differential Response Function for the Deep River Monitor for 1969.

Rigidity (GV)	$\frac{\partial N}{\partial P}_{\min}$ (1965)	$\exp\left(-\frac{1.9}{P}\right)$	$\frac{\partial N}{\partial P}_{\max}$ (1969)
1.5	0.7	0.28	0.2
2.5	2.8	0.47	1.3
3.5	3.7	0.58	2.1
4.5	4.0	0.66	2.6
5.5	4.1	0.71	2.9
6.5	4.2	0.75	3.1
7.5	4.1	0.78	3.2
8.5	3.9	0.80	3.1
9.5	3.7	0.82	3.0
10.5	3.5	0.83	2.9
11.5	3.2	0.85	2.7
12.5	2.8	0.86	2.4
≥ 13	$148 P^{-1.57}$	—	$106 P^{-1.5}$

6.2.2 The S24B Detector

In this case, $\frac{\partial N}{\partial P} = J(P) \epsilon(P)$ where $\epsilon(P)$ is the efficiency of the detector as a function of rigidity. As can be seen from section 5.3.4, $\epsilon(P)$ can be well approximated to the rectangular function,

$$\epsilon(P) = 0 \quad \text{for } P < 0.9 \text{ GV}$$

$$\epsilon(P) = 1 \quad \text{for } P \geq 0.9 \text{ GV}$$

in which case $\frac{\partial N}{\partial P}$ is simply the differential spectrum of primary cosmic rays. The error involved in using this approximation in the calculations of 6.4 has been found to be negligible. Because S24B measurements represent an integral intensity above a threshold rigidity (P_c) of 0.9 GV an independent measure of the differential primary spectrum is required. Such measurements are provided by Rygg and Earl (1971), who have carried out several balloon measurements of the primary intensity for a number of energy channels covering the range 100-730 MeV. These flights cover the ascending phase of the last solar cycle between 1965-69. Their results have been used here to interpolate the estimates of the primary spectrum at solar maximum and minimum as given by Webber (1967). The interpolated spectrum (i.e. S24B response function) is summarised in Table 5. Balloon flights for 1969 were carried out on July 11th and 18th. Estimates of the integral intensity above 0.9 GV based on this spectrum yield a value of $1600 \text{ protons m}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$, which agrees to better than 10% with the S24B integral flux estimate for this period (see Figure 28). Thus the values given in Table 5 would seem to be a reasonable estimate of the S24B response function for 1969

Table 5: Differential Response Function for S24B for 1969

Rigidity GV	$\frac{\partial N}{\partial P}$ protons $\text{m}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GV}^{-1}$
1.0	366
1.5	340
2.0	290
2.5	250
3.0	200
3.5	180
4.0	160
5.0	135
6.0	105
7.0	77
8.0	60
9.0	50
10.0	40
11.0	30
12.0	26
≥ 13	$10^4 P^{-2.4}$

6.3 VARIATIONS IN THE COSMIC RAY INTENSITY FOR DECEMBER, 1968, UNTIL APRIL, 1970.

In Figure 28, daily averages of the S24B counting rates are plotted against day number for the period of good data coverage from launch until sun gate failure at the end of April, 1970. The telescope rates are the mean of the eight radial channels, and together with the scintillator singles rates are interpreted as fluxes according to the geometric factors discussed in Chapter 5. There are data gaps for certain

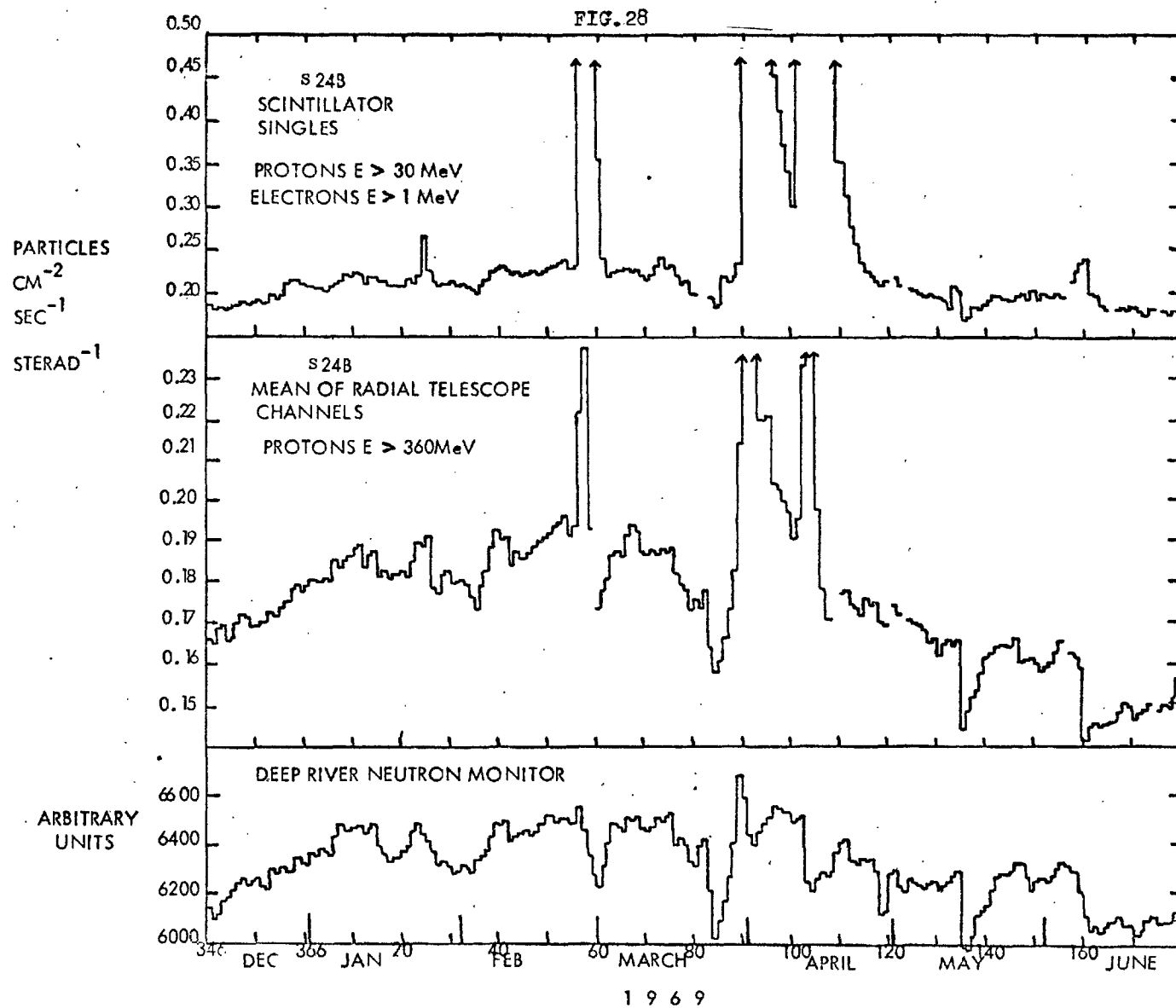
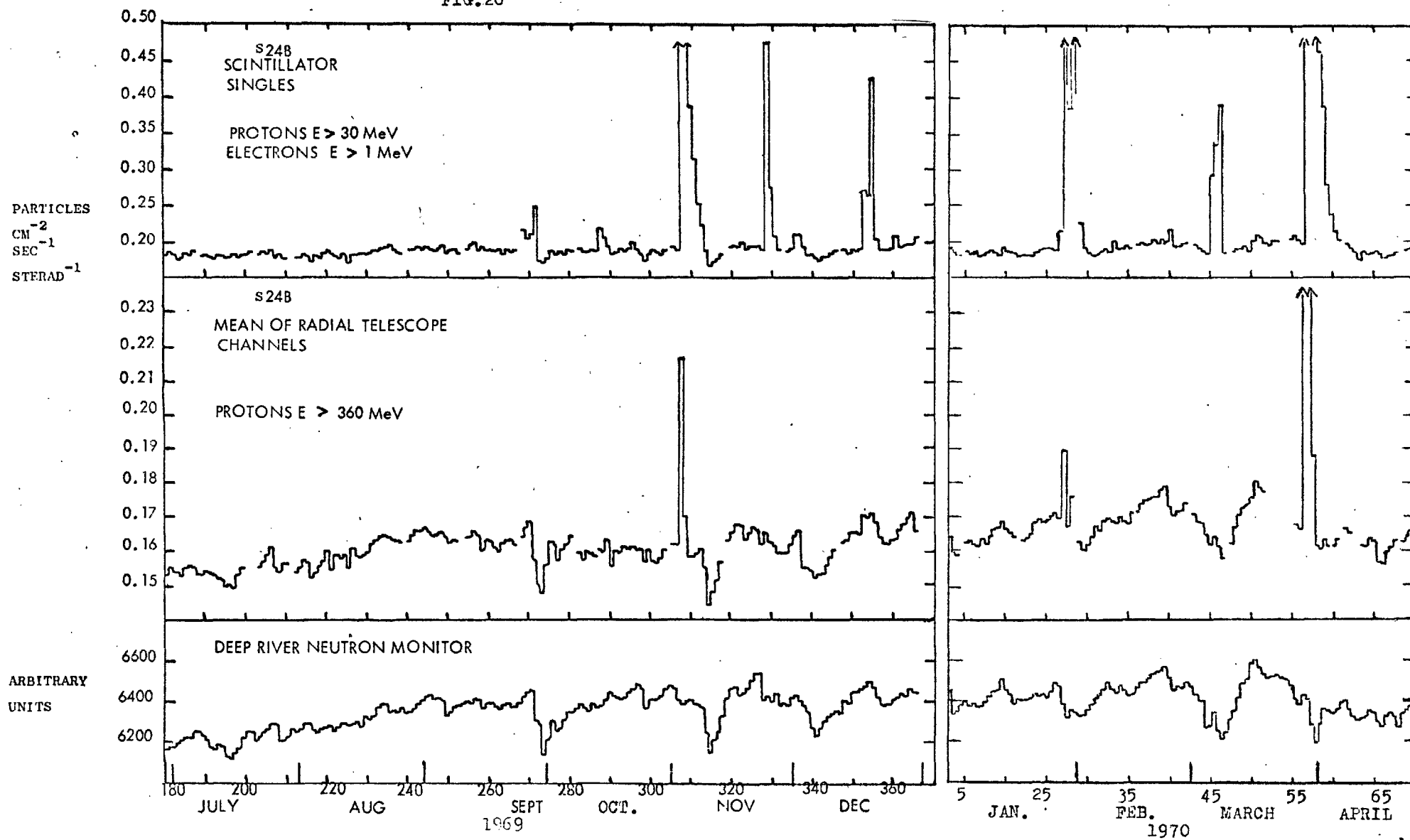


FIG. 28



of the perigee passes and also where sungate failures start to occur. Solar flux increases are merely indicated rather than the maximum intensity given. Such events will be discussed in more detail in Chapter 7. The daily averages of the high latitude neutron monitor at Deep River have been plotted for comparison after correction to 74.7 cm Hg atmospheric pressure (values taken from Steljes, 1969-70).

It can be seen that the S24B and Deep River plots follow each other closely, a decrease in one being attended by a decrease in the other. Certain flare increases shown by S24B are not discernable in the neutron monitor data, however. The reality of such events will be discussed in Chapter 7 where the problem of chance coincidences will be considered. The scintillator singles plot shows a number of flare increases not seen by the telescope because of the softness of the flare particle spectrum. A large number of decreases may be observed, some showing the classical Forbush profile of rapid decrease followed by exponential recovery (e.g. Day No. 135), whilst others have a more symmetrical profile (e.g. Day No. 26). A few of these decreases are shown by the scintillator singles (e.g. Day No. 135) but most are presumably filled in by the presence of soft solar protons (and possibly electrons).

Inspection of the neutron monitor data shows the increasing counting rates observed immediately after launch to be part of a long time-scale recovery from a Forbush decrease which took place on December 4th, 1968. Neutron monitor data for the months which follow this data (i.e. May and June, 1970) show this period to be relatively undisturbed.

It can be noted from Figure 28 that the Forbush decrease occurring on June 8th, 1969, had a very long-lived recovery and depressed the S24B intensity relative to that of Deep River for the remainder of the period of observation. This event is discussed in more detail in section 6.4.

6.4 COMPARISON OF TIME VARIATIONS IN THE S24B MEASUREMENTS WITH THOSE OF THE DEEP RIVER NEUTRON MONITOR

6.4.1 Regression Lines.

A number of plots have been made of S24B counting rates versus Deep River counting rates for different periods. Ideally it would be possible to separate the long term variation from the short-term decreases to compare the regression lines for the two cases. In fact the entire period is disturbed by a series of Forbush decreases and it is only possible to compare periods of recovery which are relatively long-lived, such as those following the events of December 4th, 1968 and June 8th, 1969, with those which are short lived, such as May 14th, 1969. In fact the major difference observed is between time variations which occur before and after the June 8th event. The possibility exists that the minimum in the cosmic ray intensity is approached by a series of Forbush decreases which are fundamental to the process. Certainly the June 8th event has a long-term effect on the modulation.

Figure 29 compares regression lines before and after the decrease of June 8th. Graphs (a) and (b) contain data prior to June 8th, 'a' giving the longer term variations whilst 'b' gives the Forbush decreases. The different periods contained are illustrated by the use of different symbols. Where the decay phases of short-term variations are plotted, they are indicated by the letter 'D'. Graphs 'c' and 'd' are similar plots for long and short-term variations respectively for the period after June 8th.

6.4.2 Theoretical Fit to the Results

An attempt has been made to fit the data given in 6.4.1, which includes all time variations observed during the S24B data coverage, to a modulation function $F(t,P)$ of the form given in equation 6.1.C. The

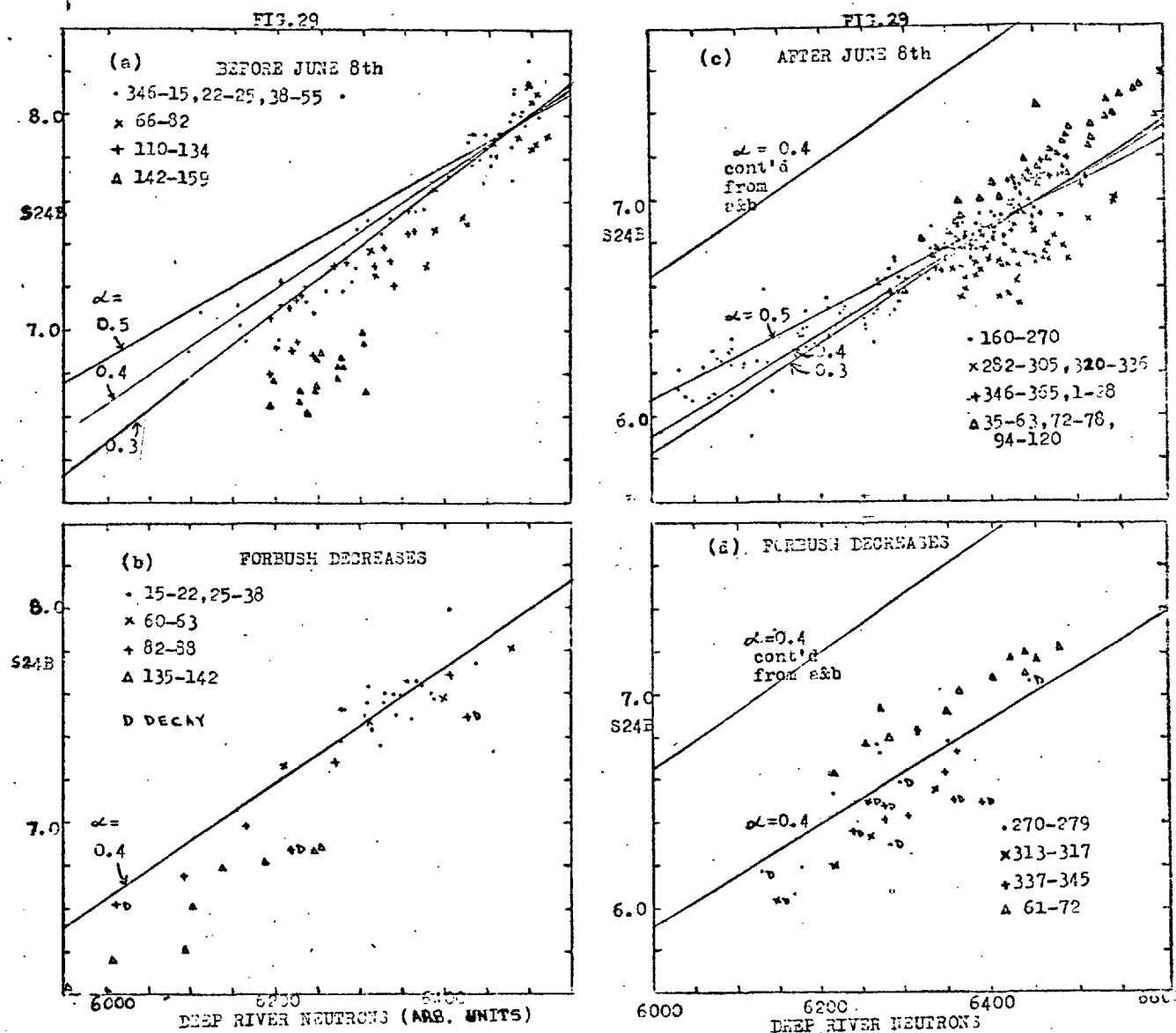


FIGURE 29. Regression lines between S24B and Deep River neutron monitor counting rates before ('a' and 'b') and after ('c' and 'd') the June 8th Forbush Decrease. 'a' and 'c' present data for the longer time scale variations, 'b' and 'd' that for Forbush decreases.

response functions given in 6.2 were used and values of the fractional decrease, $\frac{\Delta N}{N(t_0)}$, were computed according to equations 6.2.A and 6.2.B for different values of $K(t)$ and α . For a given value of α , the variation of $\frac{\Delta N}{N(t_0)}$ with $K(t)$ for the two detectors gives the theoretical regression line between them. The computer program was checked by a hand calculation for the cases $\alpha = 1.0$ and $\alpha = 0.5$. It was assumed that the modulation function was continuous until ∞ in rigidity, whereas a cut-off in the modulation somewhere in the range 80-200 GV is generally accepted. Choosing the lower limit of 80 GV as a sharp cut-off in modulation would change the shape of the regression curves for the low values of α by $\sim 10\%$. A more rigorous analysis would also compare the results of high latitude monitors and underground μ -meson telescopes and would allow for a continuous variation of α with rigidity.

The problem remains of normalising the regression lines to a certain level against which any decreases are measured. Ideally this level would be taken for the exact time for which the response functions are deduced but this accuracy is not possible. In Figure 29, the regression lines are normalised to different levels before and after June 8th. With these limitations in mind the entire data gives a reasonable fit to a modulation function of the form 6.1.C for which α lies between 0.3 and 0.5. The ratio of the fractional changes in the two detectors (S24B : Deep River) is then ~ 2.2 .

6.4.3 Discussion of these Results

The values of α required to fit the S24B - Deep River data for the period December, 1968, to April, 1970, are clearly much less than the commonly accepted value of unity for intercomparisons of neutron monitor data during the long-term modulation. For a rigidity dependence of the modulation function given by $\alpha = 0.3 - 0.5$, the 50% modulation levels (i.e. rigidity above and below which there are equal contributions

to the change in counting rate) are in the region of 3 GV for S24B and 10 GV for Deep River. The flatter rigidity dependence is then due either to the sensitivity to the lower rigidities of the S24B detector or to the fact that all time variations observed are of the short-term type. Evidence for the latter possibility comes from the work of Lockwood et al. (1972), who compare the modulation observed between 1965 and 1969 by detectors sensitive to protons of energy > 60 MeV on board Pioneers 8 and 9 with that observed by the Mt. Washington neutron monitor. These authors obtain a rigidity dependence with $\alpha = 1$ for the long-term modulation with some steepening after the June 8th event. The results presented here would then support the viewpoint that short-term variations in the cosmic ray intensity have a flatter rigidity dependence than the 11 yr variation (cf. Lockwood, 1971, vs. Mathews et al., 1971).

From Figure 29 it is clear that data obtained after the Forbush decrease of June 8th follows a different regression line to the preceeding data. The regression line fit to 'a' and 'b' is continued on 'c' to illustrate this change. Some change in the modulation may also be observed to follow the May 15th Forbush decrease. Data between these two events, whether in the recovery phase of the May 15th event or in the intervening 'quiet-time' can be seen to lie on an intermediate line. It is interesting to note that these two events are probably caused by the same corotating structure, the 25 day time lag between them comparing favourably with the 27 day solar rotation period. This new regression line is followed closely until the end of the S24B data in April, 1970. The lower slope of this line indicates the relatively greater exclusion of the lower energy particles. For the June 8th decrease the ratio between the fractional decreases of the two detectors (S24B : Deep River) is 3.1, whereas the ratio of the recovery phase increases over the minimum levels is 2.4. This event has also been detected for protons of energy greater than 60 MeV by the experiments on board

Pioneers 8 and 9 and reported by Lockwood et al., (1972). These authors note that the relative depression of the lower energy particle fluxes continues until at least August, 1970. A change of regression line over a long time scale of this sort indicates an abrupt change in the long term modulation function at the June 8th event. Clearly a function of the form of equation 6.1.C cannot then fit the data and there must be a questioning of the assumptions that α and S are independent of time and radial distance from the sun. This time lag in the recovery of the low energy particles at solar maximum could be another example of the 'hysteresis' effect which was observed at solar minimum by Balasubrahmanyam and Venkatesan (1971). These authors observed that the regression line between the IMP proton monitor (sensitive to energies > 60 MeV) and the Deep River monitor changed after solar minimum due to the longer survival of lower energy particles into the phase of increasing solar activity.

It is interesting to note the differences in the various observations of the recovery phase of the June 8th event. For the first three days after the decrease, the Pioneer 8 data shows a rapid recovery and follows the pre-decrease regression line. The recovery then flattens off and follows a new line. During this period, Pioneer 8 was positioned about 35° E of the earth. Between June 13th and September 8th, the Pioneer data recovered by 4% whilst the Mt. Washington and Kula neutron monitors increased by 6.3% and 2.4% respectively (Lockwood et al., 1972). Roelof (1971) has compared data from a balloon-borne neutron monitor with the Inuvik monitor for the same period and from the comparable recoveries in the two instruments (4.9% cf. 4.3%) concluded that the recovery phase was rigidity independent. This author claims that the mean response of the balloon-borne detector is 1-2 GV compared with 10-15 GV for the ground-based monitor. The results presented here show a 9.7% recovery in the S24B rates compared with 4.9% for Deep River. Although the S24B results would seem to be

anomalous, it is clear from the profile of the Pioneer 8 recovery that the percentage increase quoted is very dependent on the shape of the recovery and the initial level chosen. Taking June 11th and 12th as a starting point gives a recovery of more like 10%. The difference in the recovery profile of Pioneer 8 is probably due to its distance from the earth. It is also possible that the detectors analysed by Roelof have mean response energies less widely separated than assumed by that author. It is then likely that the rigidity dependence of the recovery is more like $\frac{1}{p^{0.4}}$ as determined in section 6.4.2.

6.5 ANISOTROPIES DURING FORBUSH DECREASES

In his review on Forbush decreases, Lockwood (1971) has noted that many such events show enhanced anisotropies often accompanied by a change in phase compared with the quiet-time diurnal anisotropy. This can sometimes result from a depletion of cosmic ray intensity towards the sun along the direction of the interplanetary spiral magnetic field line. Approximately one third of all events show evidence of a North-South anisotropy. In some cases the anisotropy has reached $\sim 4\%$, comparable with the magnitude of the decrease itself.

The Poisson error in the harmonic analysis of 4 days' data from the S24B experiment is $\sim 0.4\%$ and so there is the possibility of observing such marked anisotropy enhancements.

All the short-term intensity decreases observed in Figure 28 have been subjected to harmonic analysis. Where the decay phase lasted for more than one day, the decay and recovery phases have been separately analysed in addition to the data total taken over the whole event. In no case was there any significant enhancement in the amplitude of the 1st harmonic. The largest value observed was $1.1\% \pm 0.4\%$ for days number 85-88, 1969. In general the results showed no obvious differences from the scatter

in results obtained by analysis of four day quiet-time totals. The only feature of note was the more frequent occurrence of larger values for the second harmonic amplitude. The instances in which a 2nd harmonic was observed to exceed 1σ are tabulated below.

Table 6: Anisotropies during Forbush Decreases

Day Nos.	Plane of Telescope Scan	1st Harmonic		2nd Harmonic	
		Amplitude	Phase	Amplitude	Phase
1969					
15-22	Ecliptic	0.63±0.29	140°E+32°	0.31±0.29	43°E+72°
31-34	Ecliptic	0.32±0.39	-	0.44±0.39	89°E+61°
36-38	Meridian	0.32±0.39	-	0.51±0.39	67°S+49°
337-340	Meridian	0.40±0.42	-	0.78±0.42	87°S+32°
341-345	Meridian	0.88±0.40	95°N+26°	0.45±0.40	56°S+62°
1970					
61-68	Ecliptic	0.17±0.29	-	0.40±0.29	26°W+44°
70-74	Ecliptic	0.26±0.38	-	0.56±0.38	57°W+43°

Although these results are of dubious statistical significance, it is interesting to compare the phase obtained for the 2nd harmonic in the case of the meridian plane scan with the only significant 2nd harmonics obtained for the same satellite orientation during 'quiet-time' data (see Chapter 8, Table 8). Both cases are consistent with a small amount of two-way streaming directed North and South of the ecliptic. The latter of the two 'quiet-time' observations is in fact the recovery phase of the long-lived Forbush decrease of June 8th.

CHAPTER 7 HIGH ENERGY PROTONS FROM SOLAR FLARES.

7.1 INTRODUCTION

The first evidence that the sun acts as an occasional source of energetic particles was obtained from ground-based ion chambers in 1942. By 1956 a world-wide set of neutron monitors had been established, enabling the spectral characteristics of such events to be examined. The use of balloons, and later satellites, extended the range of observations to lower particle energies and increased the number of observable particle events. Measurements were also extended to include electrons and heavier nuclei.

Solar production of energetic particles has shown good correlation with flare activity in which there are marked radio and X-ray outbursts. These two characteristics are therefore used to identify the flares associated with the particle acceleration.

A wide variety of events has now been studied and there is becoming available a sufficient statistical sample that a classification of events can be made. The subject has been recently reviewed by McCracken and Rao (1970). This chapter will be concerned with events in which particles of rigidity > 1 GV (the S24B threshold) are produced. Such events are found to follow promptly after the parent flare and are generally detectable by neutron monitors.

Theories of particle events usually invoke anisotropic diffusion along magnetic flux tubes connecting to the flare region. A simplifying assumption of point-source injection in both space and time is made and the mean free path against scattering is assumed to be in power law relationship with radial distance from the sun. The scattering processes are generally assumed to be those summarised in section 6.1. An outer boundary beyond which there is catastrophic loss of particles is assumed to occur

at some distance beyond the earth's orbit. With these assumptions, several authors (e.g. Fisk and Axford, 1968; Webb and Quenby, 1972) have produced solutions of the Fokker-Planck equation describing the diffusion, convection and energy loss effects occurring in the expanding solar wind. Lower energy particles (~ 10 MeV) are found to show several phases of propagation. Early in the event there is a field-aligned anisotropy due to diffusion and this is followed by a convective phase in which the anisotropy is radially directed away from the sun. The later stages in the event show an equilibrium phase in which diffusion and convection along the field line approximately cancel leaving an anisotropy which is nearly perpendicular to the field. In the case of more energetic particles (> 300 MeV), the convection and energy loss terms are small and in general an initial field-aligned anisotropic phase is followed by isotropy.

The shape of the particle intensity vs time profile is found to be very dependent on the flare position on the sun. If the foot of the magnetic flux tube being swept past an observer lies near the flare region then connection is good and a faster rise and decay is seen than in cases where there is a wide separation. This effect was already known from the different characteristics of East and West solar hemisphere flares, but has been more clearly illustrated by observations from space probes situated at considerable azimuthal distances from the Earth. In the case of high energy particle flares this effect is shown by a greater association of observable events with Western hemisphere flares. To summarise, high energy events are characteristically associated with a visible disc flare, are of short-time duration and have an initial anisotropic phase followed by isotropy.

Studies of solar flare particle propagation thus yield important information about conditions in interplanetary space and the sun's chromo-

sphere. An accurate knowledge of these processes is also required to make extrapolations back to the point of release. If this can be done the sun represents a unique astrophysical situation in which there are a wide range of observables to which to fit any theories of particle acceleration.

Although low energy solar particle events show a good correlation with solar sunspot activity, there is a tendency for relativistic particle events to avoid periods of maximum activity. However, solar cycle 20 showed a relatively weak maximum, and in this case there were a number of high energy events observed by S24B.

7.2 SOLAR FLARES DURING 1969

The particle-producing flares occurring during 1969 have been identified by Barouch et al. (1971) who use data from the 6.7 - 25 MeV proton channel of the S72 instrument carried on board HEOS to identify particle increases. These authors conclude that for this year there were two or three well-defined regions of solar activity responsible for all the flares. In particular, the flare events of February 25th, March 30th, April 10th and November 2nd all occurred in the same region at Carrington longitude 80° . All these events were seen by the S24B telescope, but there is considerable doubt about the reality of the increases in the latter two cases (see section 7.4).

In addition it is shown that for this year, the particle propagation delay time shows a well defined pattern in solar longitude with a minimum in the region 35° - 45° W. Because this falls $\sim 20^{\circ}$ East of the foot of the Parker spiral field, Barouch et al. conclude that there existed, for at least a year, a magnetic field configuration in the active region deflecting the spiral field lines 20° East.

7.3 S24B OBSERVATIONS

Figure 28 of Chapter 6 illustrates the particle flare increases observed by the S24B telescope and scintillator elements for the period December, 1968, to April, 1970. Of the nineteen flares observed in 1969 by Barouch et al. (1971) at a proton threshold of 6.7 MeV, fifteen are shown by the scintillator singles at a threshold of 30 MeV and four by the telescope at the 360 MeV threshold. (Note that the February increase in fact consisted of three separate increases.) Of these four high energy events, only the first two are accompanied by increases in the Deep River neutron rates. It seems likely, therefore, that the apparent telescope increases of April 10th and November 2nd were due to chance coincidences, a point which receives further study in section 7.4. During the first four months of 1970, telescope increases were observed for events on January 29th and 31st and March 29th.

7.4 THE CONTRIBUTION OF CHANCE COINCIDENCES TO THE TELESCOPE COUNTING RATE DURING SOLAR FLARES.

Although no exact calculation of the chance coincidence rate may be made, the upper and lower limits of the contribution may be estimated as described in section 5.3.7(d). Table 7 summarises the estimates of this effect made for the increases observed by the S24B telescope. The minimum estimates were obtained by setting the Cerenkov rates equal to the sum of noise and sampled rate and the upper limits by taking noise plus 6% of the scintillator rate (upper limit on scintillation in photomultiplier face). In the April and November events this procedure was complicated by the large dead-time of the scintillator singles and so estimates of the flux of protons > 30 MeV obtained from Explorers 34 and 41 were used to estimate the count rate in this element. In Table 7 the estimated chance coincidence rates have been expressed as fractions

Table 7: Chance Coincidence Contribution to Counting Rates

Flare Event	Scintillator singles $n_2 s^{-1}$	Radial Cerenkov Singles $n_1 s^{-1}$		Increase in radial telescope rate s^{-1}	Estimated Chance Coincidence Rate s^{-1}		Percentage Contribution	
		Min.	Max.		Min.	Max.	Min.	Max.
1969 Feb. 25 Maximum 11.00hrs	9700	470	850	9.7	0.74	1.3	7.6	13.4
Feb. 25 Decay 18.00hrs	2570	315	420	1.3	0.13	0.17	10	13
Feb. 26 Maximum	1050	292	330	0.3	0.05		16	
Feb. 27 Maximum	2100	300	380	1.0	0.13		13	
March 30 Maximum	3600	336	481	6.7	0.19	0.27	2.8	4.0
April 10 Maximum	$\sim 6 \times 10^4$	587	~ 4000	15.3	5.9	~ 40	39	>100
Nov. 2 Maximum	$\sim 7 \times 10^4$ Probably factor 2 worse (Explorer Data)	1915	~ 4000	159	22	~ 160 Minimum values factor 2 worse	14	~ 100 probably
Nov. 2 Decay	9690	370	840	1.5	0.6	1.4	40	~ 100
1970 Jan. 29 Maximum	320	265	265	0.2	0.01		5	
Jan 31 Maximum	1310	265	343	0.4	0.06	0.08	15	20
March 29 Maximum	2700	265	430	1.6	0.12	0.20	7.5	12.5

of the increases in telescope rates over the pre-increase levels in order to test the reality of the increases. It can be seen that for the April and November events the existence of protons of energy > 360 MeV cannot be confidently established. These events are not discussed further. In all other cases there is a real increase in the flux of relativistic protons although a typical chance coincidence contribution of 10% necessitates further consideration of the effect on anisotropy measurements (see section 7.5).

It can be seen from these results that the S24B instrument has not proved to be very suitable for monitoring solar flares, particularly those events in which there are large numbers of soft protons present.

The floating-point accumulator has proved redundant as the high counting rates required to bring this into use necessarily imply a catastrophic level of chance coincidences.

Nevertheless in two events, namely Feb. 25th and March 30th, counting rates were sufficiently high and chance coincidences sufficiently low ($\sim 10\%$ and 3% respectively) that detailed analysis is rewarding. These two events are analysed below.

7.5 THE SOLAR FLARE EVENT OF FEBRUARY 25th, 1969

The particle increase of Feb. 25th has been associated with the class 2B optical flare occurring at 0900 U.T. and located on the sun at $N12^{\circ}W37^{\circ}$. Both X-rays and Type IV radio emission were observed, the former reaching maximum at 0918 U.T. On this day the HEOS satellite was near to apogee at 35 earth radii altitude and throughout the flare events was oriented so that the spin-axis lay in the ecliptic plane pointing East. The S24B radial telescope was thus set to scan the solar meridian plane.

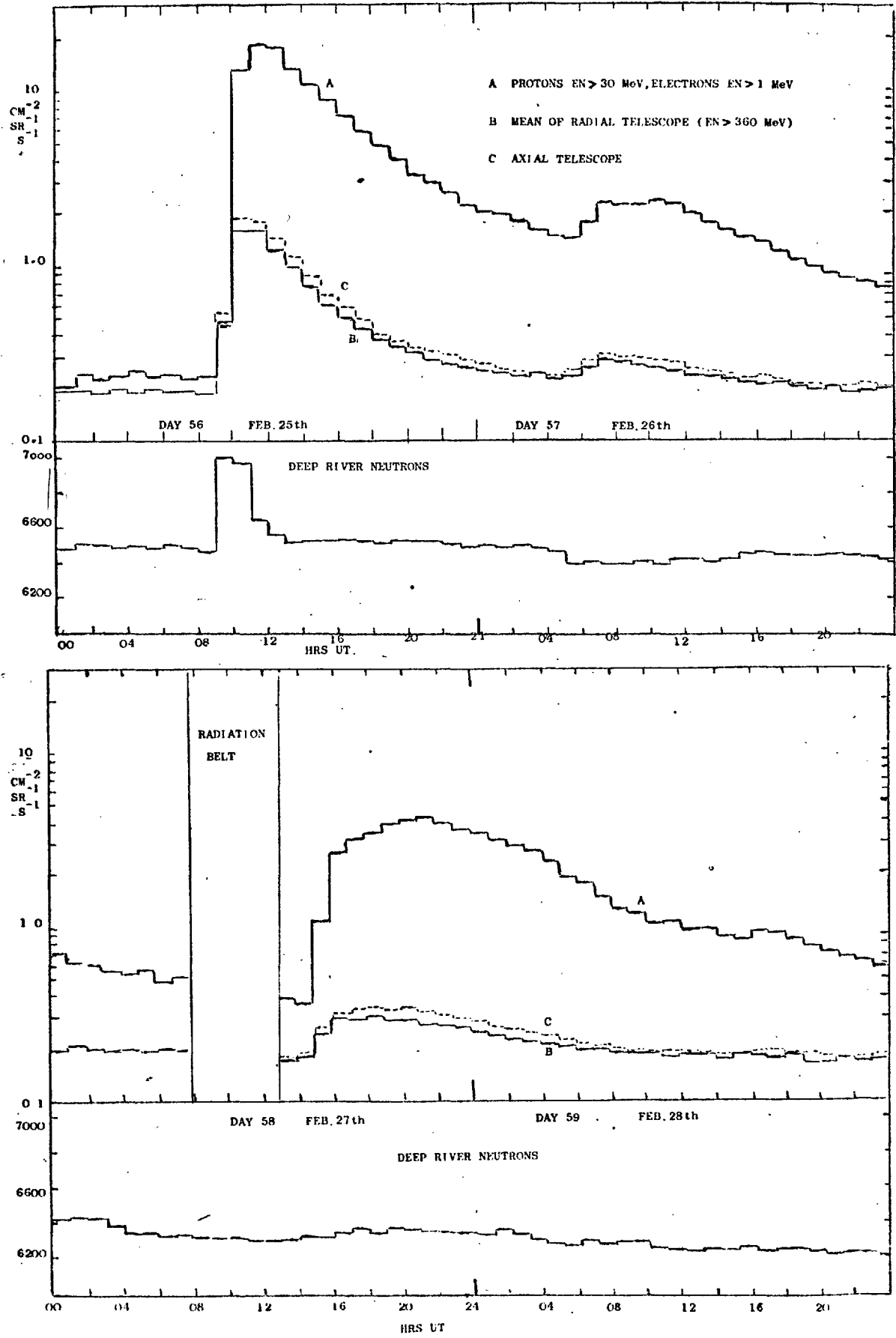
Protons of energy > 360 MeV were first detected at 0926 U.T. ($+ 3$ minutes). There are difficulties in locating the time of particle acceler-

ation and release at the sun, but it would seem that this delay is greater than the 11 min. rectilinear propagation time along the 1.3 AU Parker spiral so that some scattering must have occurred. Time profiles obtained from the S24B telescope and scintillator hourly averages are plotted in Figure 30, where comparison is made with similar averages for the Deep River Neutron Monitor. It can be seen that the decay phase of the event is interrupted by other flare increases at 0600 U.T. on Feb. 26th and 1500 U.T. on Feb. 27th and by passage of the spacecraft through the radiation belts at perigee. Section 7.4 has shown both these flare increases to be real effects. The Feb. 27th event has been identified with a class 2B flare at N13W65°. This event thus shows a longer delay time than the Feb. 25th event, as has been noted for low energy protons by Barouch et al. (1971).

All three time profiles show rapid rise times and decay (cf. the March 30th event discussed below). For the S24B telescope, the decay time to half maximum is about four hours. The shorter decay time of the higher energy particles is suggestive of a simple velocity dependent diffusion process (mean free path independent of rigidity). Plots have been made of intensities against distance travelled by the particle for different energy ranges and a reasonable match obtained, showing the rigidity independence of the scattering process (Engel et al., 1970; Masse, 1972).

Care must be taken in interpreting the scintillator results as the results from experiment S79 (Bland et al., 1970) have shown that the flux of electrons of energy > 7 MeV ^{is comparable to the} ~~exceeds~~ the proton flux (> 30 MeV) at early times. ~~Only~~ After 1200 U.T. ~~does~~ the electrons flux fall to less than ^{0.5%} 10% of the proton flux. Also the flux levels based on the geometric factor described in Chapter 5 are about half those determined by Explorer 34 for greater than 30 MeV protons. This is probably due to the energy dependence of the geometric factor as discussed earlier (section 5.3.5).

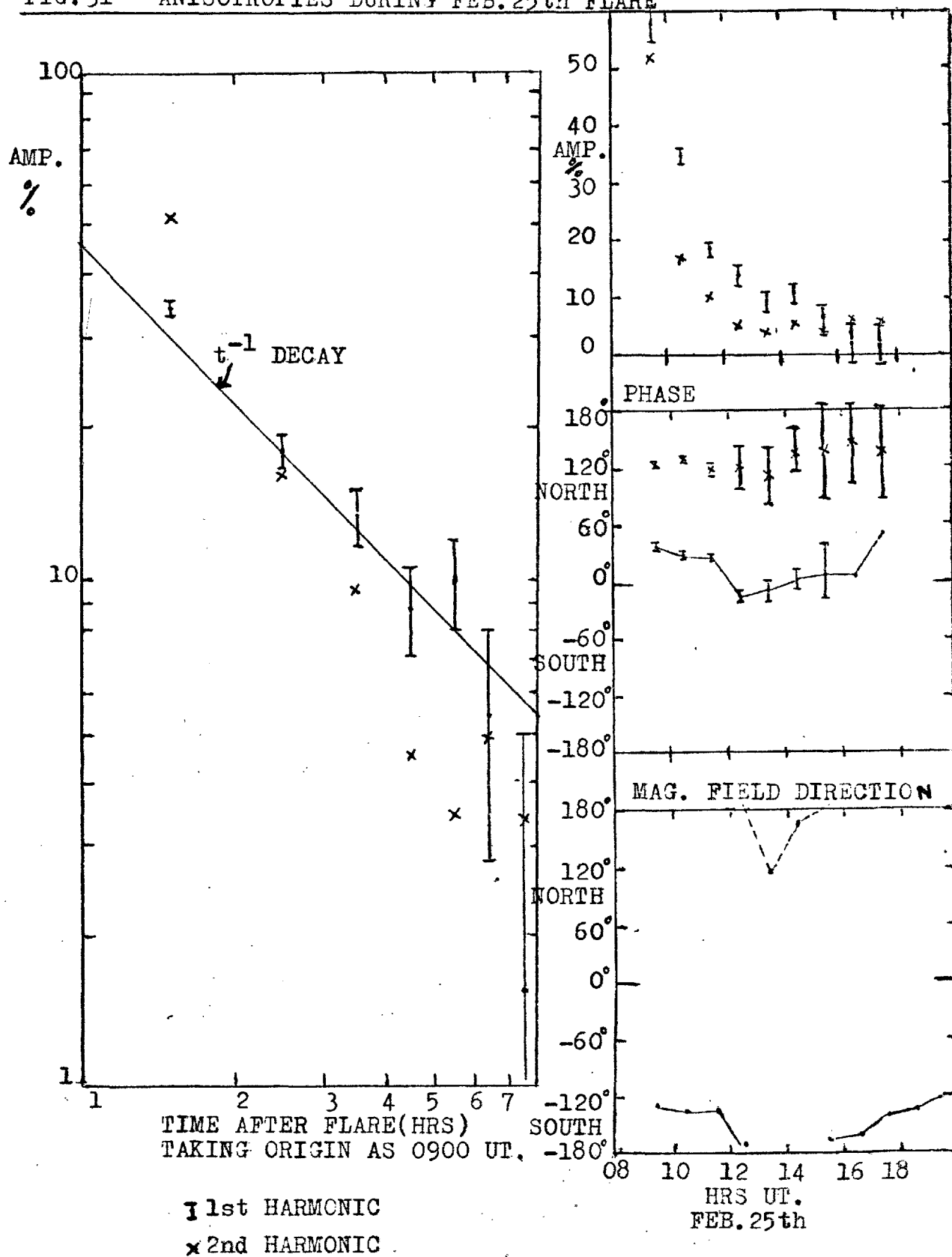
FIG 30
FEBRUARY 25th SOLAR FLARE EVENT



The difference between the axial and radial telescope rates clearly shows the anisotropy of the flux of high energy protons. Any correction for chance coincidences ($\sim 2.5\%$ for axial cf. 10% for radial telescope) would enhance this difference. Harmonic analysis has been performed on hourly averages of the radial rates in order to determine anisotropies in the meridian plane. The amplitude and phase of the first and second harmonics are plotted against time in Figure 31. The plot is terminated when the statistical errors become too great. Figure 31 shows that the decay of the anisotropy follows t^{-1} law as predicted by simple diffusion theory. It must be considered to what extent any variation in the counting rate of the scintillator element can influence anisotropy measurements via the 10% chance coincidence contribution to the telescope rate. Although the scintillator element is essentially isotropic, there will be some variation in the rate in an anisotropic low energy proton flux due to the unequal shielding of the two sides of the slab. Measurements on low energy protons obtained from the S24C experiment show anisotropies of around 50% for this event (Balogh and Hynds, 1970). Using this result together with the energy spectrum obtained from Explorer 34 implies a maximum variation in scintillator response of $\sim 13\%$ and hence a maximum contribution to the anisotropy of $\sim 1.3\%$.

Also included in Figure 31 are the directions of the meridian plane component of the hourly averages of the interplanetary magnetic field obtained from experiment S24A. It can be seen that whilst the phase of the 1st harmonic tends to follow the field direction (pointed towards the sun in a direction 60° North), the phase of the 2nd harmonic remains essentially constant at 60° South (120° North). An explanation of the considerable 2nd harmonic in the high energy proton distribution in terms of backscattering from a kink in the magnetic field has been given by Engel (1970). Inadequate allowance for the influence of backward-moving

FIG. 31 ANISOTROPIES DURING FEB. 25th FLARE



particles on the telescope rate can of course produce a 2nd harmonic but the phase would be identical with that of the 1st harmonic (see section 5.3.3). In this case there is a phase difference between the harmonics of about 90° .

The increases of Feb. 26th and 27th have been analysed for anisotropies but the counting rates were low and the statistics were insufficient to resolve a 1st harmonic.

To summarise it can be said that the February 25th event showed the usual characteristics of a high energy event in which there is a good field line connection to the flare region. Specifically there was rapid rise and decay and an early anisotropy (roughly field aligned) which decayed via a t^{-1} law to an isotropic phase.

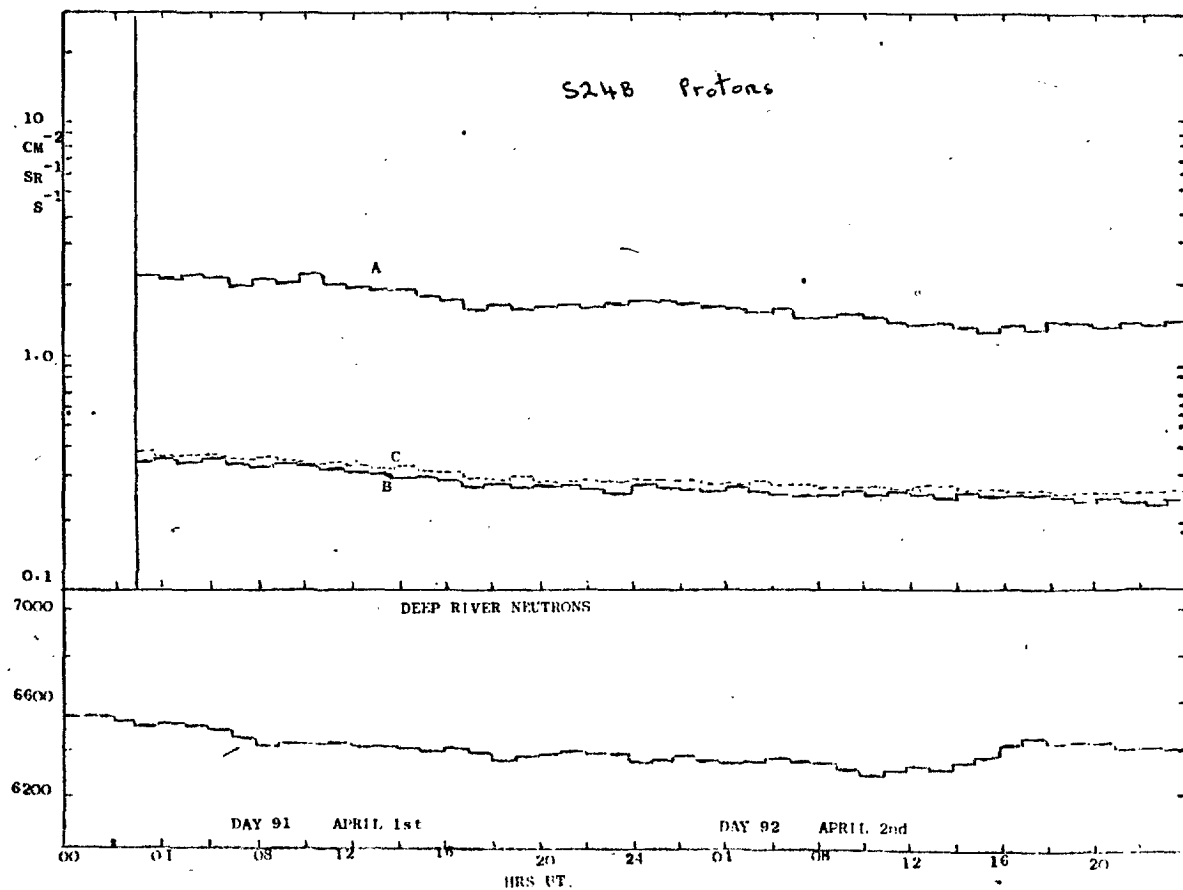
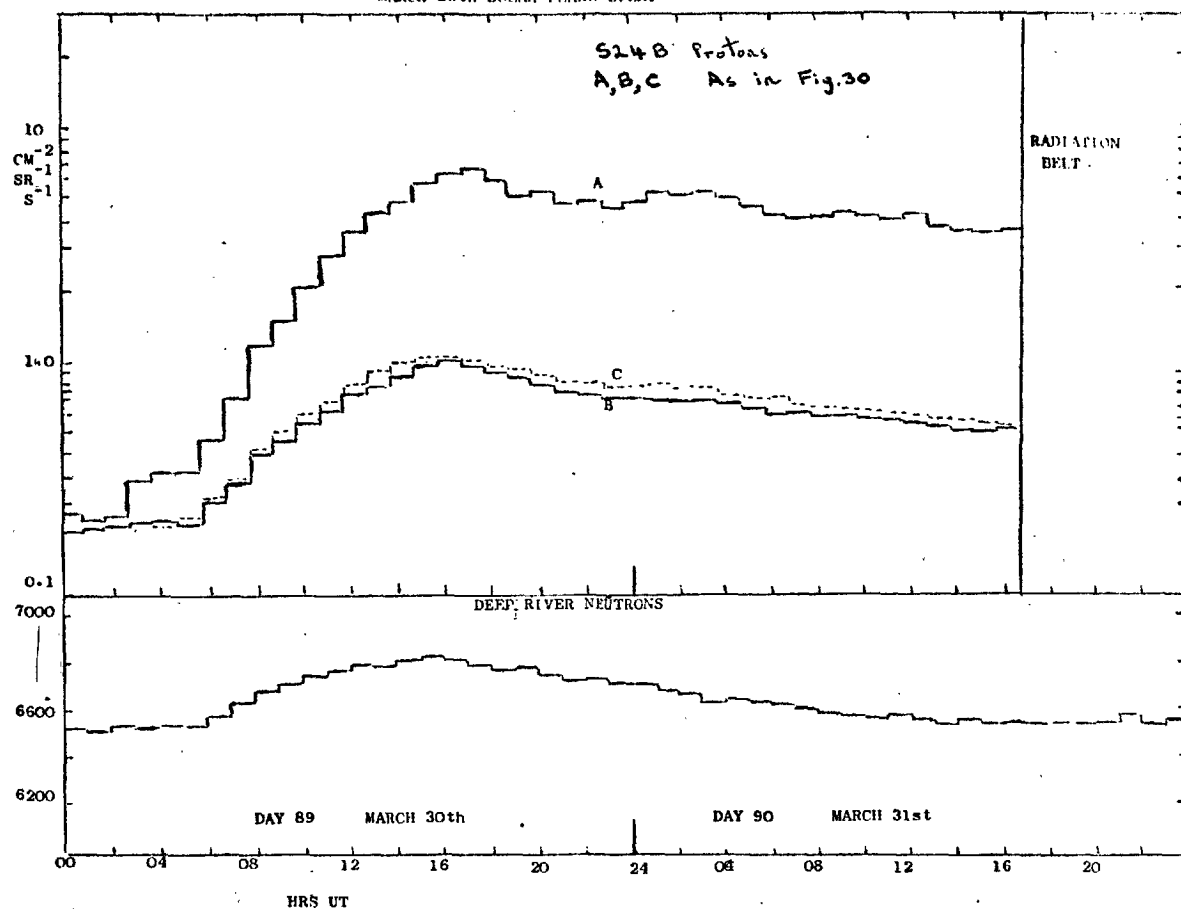
7.6 THE SOLAR FLARE EVENT OF MARCH 30th, 1969

For the March 30th event, the HEOS spacecraft was again situated near to apogee but in this case the spin-axis was oriented perpendicular to the ecliptic plane and pointed in a southerly direction. This event cannot be related to a chromospheric flare but several authors (e.g. Barouch et al.) have identified the event with radio and X-ray emission occurring at 0248 U.T. on the West limb. Extrapolating the rotation of an active region beyond the West limb locates the flare coordinates at N19° W110°. This active region was also responsible for the Feb. 25th flare (see section 7.2).

The time profiles of the particle event are presented in Figure 32 and show a marked contrast with the February event. Both rise and decay times are much more extended (decay to half maximum ~ 20 hours) and the profiles for different particle energies are almost identical. The exact onset time of such a slowly rising event is difficult to determine but there were definite increases in the scintillator and

FIG. 32

MARCH 30th SOLAR FLARE EVENT



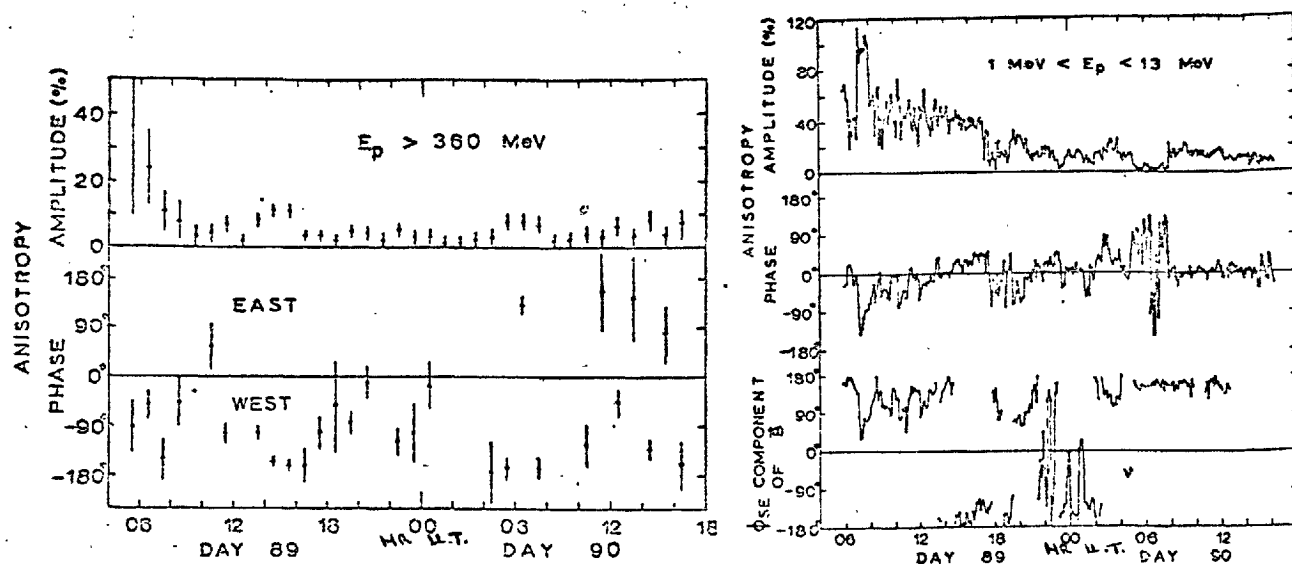


FIGURE 33. Comparison of Anisotropies observed by S24B with low energy proton and magnetic field measurements for the March 30th, 1969 event.

telescope rates at 0300 U.T. and 0400 U.T. respectively. Again there is the possibility of an electron contribution to the scintillator counting rate. The results of Bland et al. (1970) show that the flux of 7-100 MeV electrons ^{is ~10% of} rises with the proton flux > 30 MeV. Later in the event the electron flux ^{is less than 5%} varies between 50 and 80% of the proton flux.

Anisotropies in the ecliptic plane have been analysed and the results are presented in Figure 33. Comparison is made with the anisotropies of low energy protons obtained from experiment S24C and with the mean magnetic field directions obtained from experiment S24A. The contribution of chance coincidences is very small (2-3%) and may be neglected. It can be seen that the high energy protons show a high degree of isotropy throughout the event. The only significant anisotropies obtained are of the order of 7% ($\pm 2\%$) at around 0600 U.T. on March 31st when the anisotropy direction varies between 165° West and 130° East. This result is consistent

with the results of Bukata et al. (1970), who analyse neutron monitor observations and find a very small anisotropy such that the number of particles arriving from 90° to 180° East is greater than those arriving between 65° W and 25° East. The behaviour of the low energy protons is considerably different and the anisotropy shows decay from an early field-aligned phase to a convective phase.

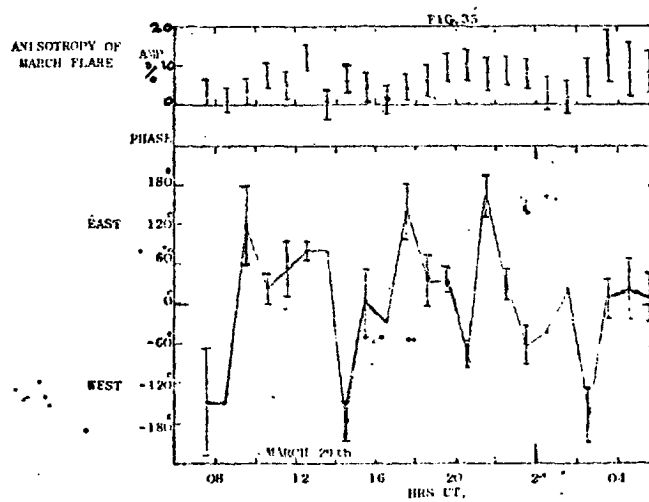
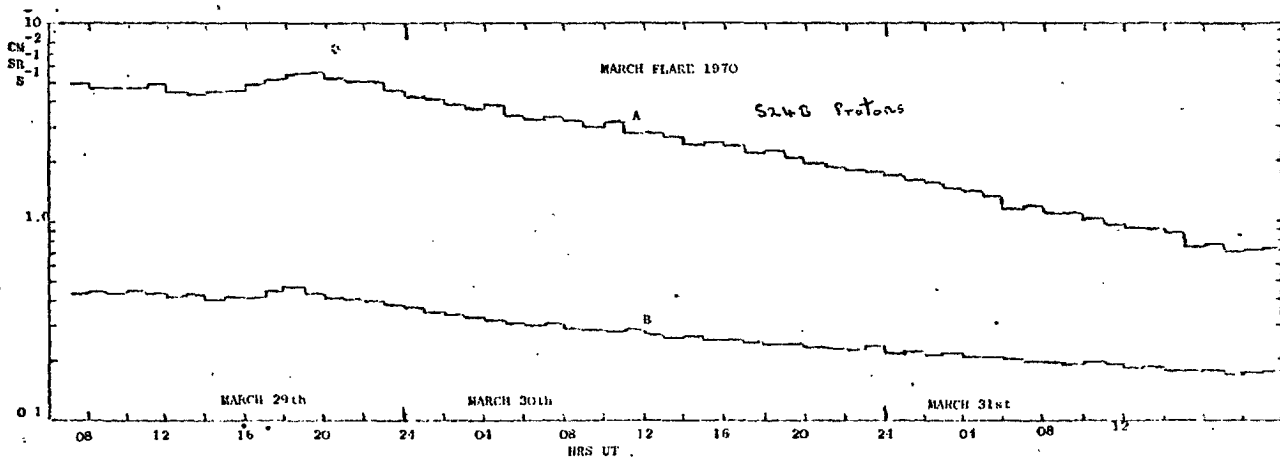
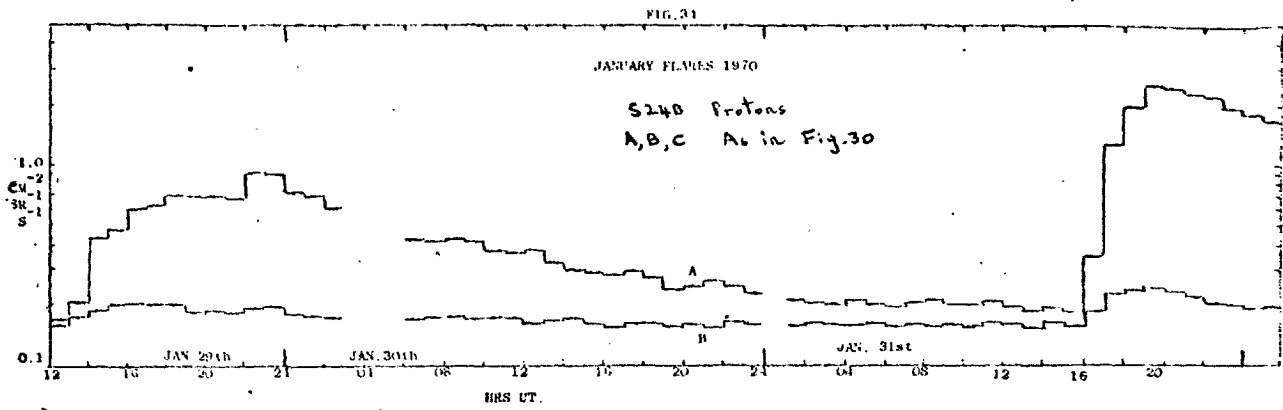
A propagation model which can explain these results has been discussed by Balogh et al. (1971). It would seem that an extended source region together with some secondary magnetic field loops is required to feed the low energy particles onto spiral field lines connecting to the earth. From the isotropy of the high energy particles it would seem that they must have undergone perpendicular diffusion from magnetic field lines to the West. The different routes taken by the different energy particles together with the corotation of the core of the particle intensity must conspire to produce the overall time behaviour which is approximately independent of particle energy. Clearly the time profiles cannot fit simple diffusion models in which there is point injection into a medium in which the diffusion coefficient varies as β , βR or βR^2 (β = relative particle velocity, R = Rigidity) as these all imply much shorter time profiles for the high energy particles compared with those of lower energy. These dependencies cover all reasonable possibilities for the parallel and perpendicular diffusion coefficients (see sections 6.1 and 8.1). Also there cannot be a continuous injection of particles as this would produce persistent anisotropy directed away from the sun for both low and high energy particles.

Finally it can be said that the March 30th event showed none of the usual characteristics of a high energy particle event, in contrast to the more typical Feb. 25th flare.

7.7 OTHER HIGH ENERGY PARTICLE FLARES OBSERVED BY EXPT. S24B

As mentioned in section 7.4, several real high energy particle increases were detected during the first four months of 1970. Time profiles for these three events are presented in Figure 34. Both the increases of Jan. 29th and Jan. 31st were very small and no anisotropies were detectable. In the case of the Jan. 29th event, the first particles were detected at 1355 U.T. (both 360 MeV and 30 MeV) and the parent flare was probably the class 1N flare, coordinates $S8^{\circ}W12^{\circ}$ occurring at 1329 U.T. For the Jan. 31st event the parent flare was possibly the class 2B event at 1525 U.T. and coordinates $S22^{\circ}W65^{\circ}$. Particles were first positively identified at 1615 U.T. Such a long time delay must render this flare identification doubtful.

Unfortunately the rise phase of the March 29th event coincided with data loss at perigee and the first data available is at 0600 U.T.. This event is interesting as it can be associated with a class 2B flare at coordinates $N13^{\circ}W36^{\circ}$ which commenced at 0010 U.T. and reached maximum at 0043 U.T. This flare location is identical with that for the Feb. 25th, 1969 event. However, in this case the decay is much more similar to that of the March 30th event, showing a long time scale (~ 20 hrs decay time) and close tracking between 30 MeV and 360 MeV protons. As can be seen from Figure 35, anisotropies in the high energy proton fluxes are small throughout the period of observation. The most significant anisotropies ($9 \pm 3\%$) occur rather late in the event and fall between $40^{\circ}E$ and $60^{\circ}W$. Clearly there was not good field line connection to the active region in this case and any type of long-lived structure (as proposed by Barouch et al., 1971) must have broken down by the time of this event.



CHAPTER 8. ANISOTROPIES IN THE QUIET-TIME COSMIC RADIATION

8.1 INTRODUCTION

Ever since the first discovery of the extraterrestrial origin of cosmic radiation in 1912, attempts have been made to detect anisotropies with a view to understanding the origins of the radiation. Although the existence of a sidereal anisotropy is still a matter of debate, ground-based monitors have established the existence of a periodicity in intensity with respect to solar time. Once the effects on counting rates of varying atmospheric pressure and temperature were understood and allowance made for the bending of particle trajectories by the earth's magnetic field, this periodicity was related to an interplanetary space anisotropy of about 0.4% in the direction 90°E of the earth-sun line (following the definition of anisotropy given in section 5.3.9). A review of current knowledge concerning this solar diurnal anisotropy is given by Pomerantz and Duggal (1971). An upper limit to the rigidity of particles which partake in this anisotropy has been set at around 100 GV, with a possible variation over the solar cycle. From ground-based observations the lower limit can only be set at somewhat less than 8 GV and satellite observations similar to experiment S24B are required to elucidate the behaviour of the lower energy particles.

Theoretical understanding of the anisotropy was largely achieved with the realisation of the spiral nature of the interplanetary field and the scattering of particles that results from noise therein. On the assumptions that particles diffuse preferentially along the magnetic field direction, and that conditions in the solar cavity are spherically symmetric, the fact that the sun is neither a source nor sink for cosmic rays demands that in the steady state situation the radial outward con-

vection of particles is exactly balanced by the radial component of diffusion resulting in a purely azimuthal component of flow. The cosmic ray gas is thus constrained to corotate with the interplanetary medium. Application of the solar rotation period of 27 days and the Compton-Getting factor for the cosmic ray spectrum then predicts an anisotropy of 0.6% for relativistic particles.

The reduction of this amplitude to the value of 0.4%, which best seems to fit the results, was explained by Parker (1967) in terms of the partial cancellation due to a cosmic ray density gradient produced perpendicular to the solar equatorial plane by the $\underline{B} \wedge \underline{V}$ electric field. The extent to which this gradient is removed by diffusion perpendicular to the magnetic field (thus allowing the anisotropy to approach the maximum theoretical value) is determined by the appropriate diffusion coefficient, $K_{\perp}$. For resonant scattering by magnetic field inhomogeneities $K_{\perp}/K_{\parallel} \sim \rho^2/\lambda^2$, where ρ is the particle Larmor radius. For large values of $K_{\perp}$ the anisotropy is again reduced, this time by the 'slipping' of particles across the field lines. Clearly for the case $K_{\perp} = K_{\parallel}$, the diffusion is isotropic and there can be no anisotropy. There is thus a maximum in the anisotropy for some intermediate value of $K_{\perp}/K_{\parallel}$. Subramanian (1971) has considered several possible corrections both in the theory, in terms of an improved rigidity dependent Compton-Getting factor, and in the comparison with experiment, and concludes that a good fit is obtainable without such considerations of $K_{\perp}/K_{\parallel}$.

Evidence for a rising symmetrical cosmic ray density gradient perpendicular to the ecliptic has come from observations of a second harmonic ($\sim 0.05\%$ at 10 GV) in cosmic ray intensity directed roughly perpendicular to the spiral field and increasing in amplitude with magnetic rigidity. Such a gradient could result from the easier access of particles via the less tightly wound field lines at high solar latitudes

or from a decrease in solar activity with increasing latitude.

Particles observed in the ecliptic plane at right angles to the magnetic field have a guiding-centre density determined by conditions one Larmor radius North or South of the ecliptic depending on the particle direction. By a similar mechanism an asymmetric gradient produces a component of streaming directed normally to the field and which changes direction according to the sector structure. Evidence for a southward directed gradient has come from a correlation of neutron monitor and meson telescope results with sector structure (Hashim and Bercovitch, 1971; Swinson, 1971). Such a gradient could result from the greater amount of solar activity observed at Northern latitudes.

Either of these gradients can result in an outward radial flow component in the ecliptic plane due to a finite value of K_1 . This effect has been studied by Quenby and Hashim (1969), who produce evidence for the occurrence of such a component during certain years (up to 0.1%). In this case cosmic ray flow patterns are set up whereby there is streaming inwards in regions of easy access and a streaming outwards in regions of difficult access. Several authors (see Pomerantz and Duggal) have produced evidence for a variable component of anisotropy along the spiral field direction which goes through one complete period (amplitude $\sim 0.15\%$) in one 20 year solar cycle. The projected contribution in 1969 would be zero.

A radial streaming component in the anisotropy can also result from energy loss in the expanding solar wind. This effect has been extensively studied by Urch and Gleeson (1972) who carry out numerical solutions of the Fokker-Planck equation for solar minimum conditions and a variety of trial galactic spectra. It is shown that whereas the cosmic ray spectrum observed at earth is almost independent of the assumed form of galactic spectrum, the variation of the radial streaming component with

particle energy is much more sensitive. Measurements of radial streaming could thus be used to demodulate the observed cosmic ray spectrum. However, the solutions presented assume spherical symmetry and ignore cosmic ray gradients and diffusion perpendicular to the ecliptic plane. Results presented in this chapter will be used to illustrate the importance of these off-ecliptic phenomena.

8.2 THE S24B OBSERVATIONS - EVIDENCE FOR RADIAL STREAMING

Quiet time data from the S24B telescope has been analysed for anisotropies for the period from launch in December, 1968, until the end of April, 1970. Periods when the counting rate was changing rapidly have been excluded from the analysis. These periods include the solar flare events discussed in Chapter 7 and the majority of the Forbush decreases analysed in Chapter 6. The long-lived recovery of the June 8th event has been included as the rate of change of counting rate was very small. Simple inspection of Figure 28 was used to select these quiet-time periods.

During this period of time three different spin-axis orientations were employed. In two of these the telescope scanned the ecliptic plane with the spin-axis directed either North or South. In the third orientation the spin-axis was pointed East and the telescope scanned the meridian plane.

The various stages in the production of the daily averages, the corrections applied and the harmonic analysis technique have been described in Chapter 5. In order to attain the degree of accuracy required to resolve any anisotropy it is necessary to add the counts over many days' data for a given satellite orientation. For this purpose the slight drift in spin-axis direction has been ignored. The maximum drift of the spin-axis during any orientation was 10° and this would have a negligible effect on the measured anisotropy to within the experimental accuracy. When data

from consecutive days was summed, the calibration data was also summed and this correction applied to the total. To obtain larger groupings of data, the totals from different periods have been added and in this case the calibration was applied to each period before summing.

Figure 36 shows the various stages in the correction of the raw data averages and the fitting of a sine curve. The data used covers the period from Day no. 357, 1969 to Day no. 34 in 1969, during which time the spin-axis pointed North.

Table 8 presents the results obtained for the 1st harmonic for the different periods covered, arranged in chronological order. The results of analysing the data totals for the entire period are also presented. For this purpose the calibrated sector totals obtained when the spin-axis was pointed North were reversed in order before addition to the data totals obtained in the Southward pointing case. In each case the error estimates are based on Poisson statistics according to the formulae given in Chapter 5. Figure 37 summarises these results in the form of harmonic diagrams for the case of ecliptic and meridian scans respectively. Again the error circles are 1σ Poisson estimates. It is convenient to resolve the anisotropy vector into radial and azimuthal streaming components and these are also presented in Table 8. In this notation the positive streaming direction is that of net cosmic ray flow. Thus positive radial and azimuthal components would imply net flow components from 90°E and from the sun.

It can be seen from Table 8 and from the harmonic diagrams that there is evidence for a component of radial streaming towards the sun of about 0.3%. There is also evidence for a corotation component from 90°E with some possibility of a variation with time over the period 1969-1970.

FIG. 36 STAGES IN DATA ANALYSIS

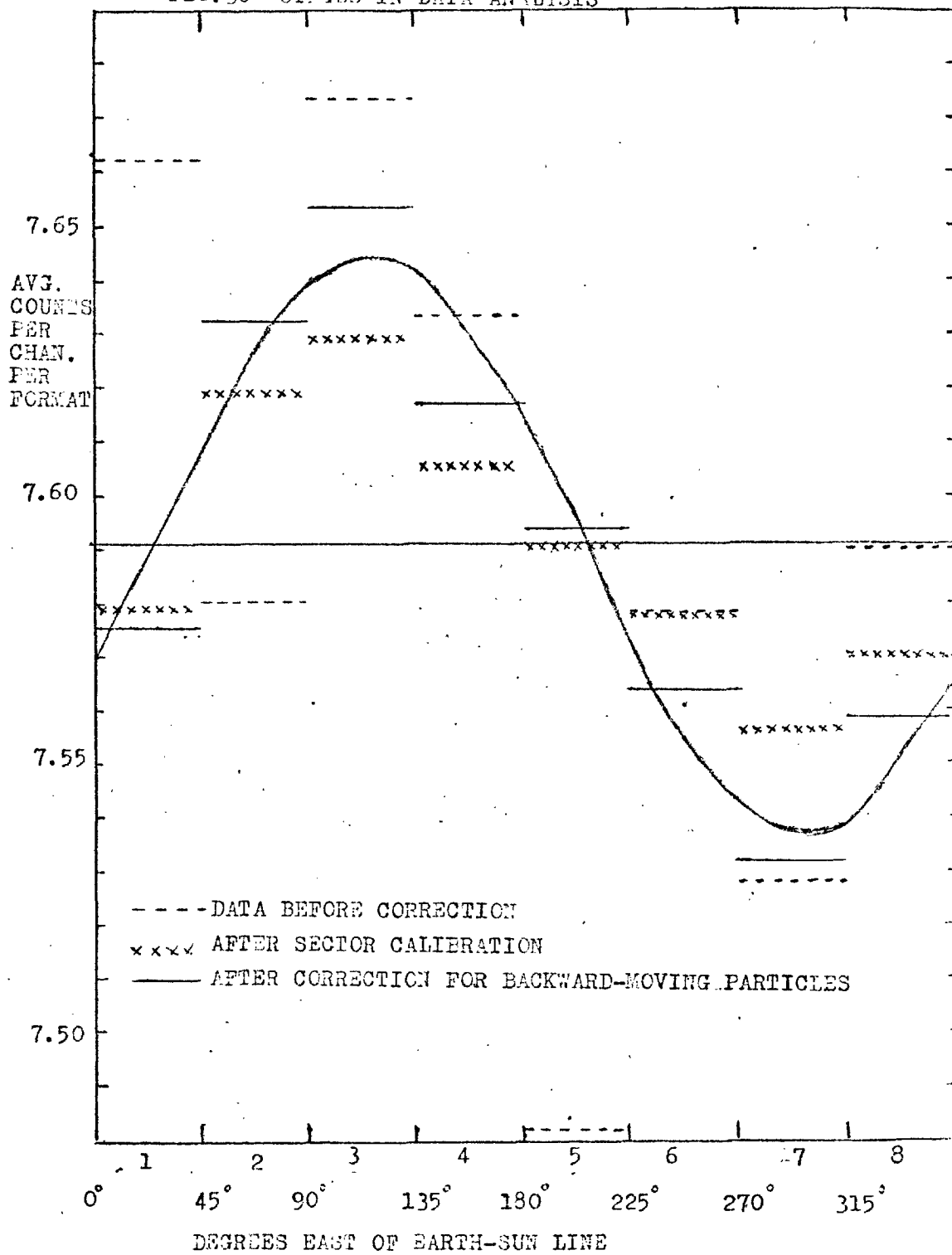


FIG. 37 HARMONIC DIAGRAMS

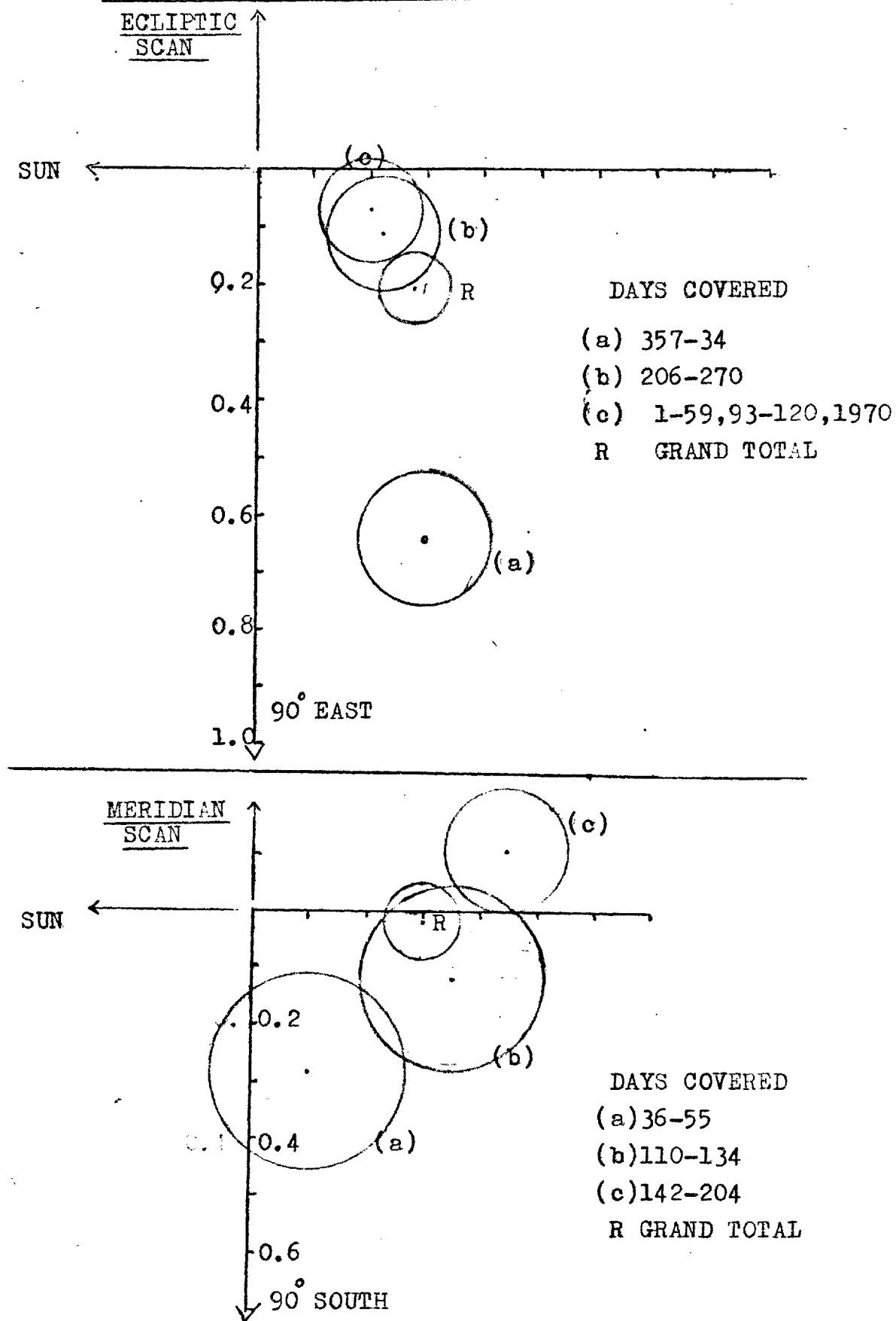


TABLE 8: Results of Harmonic Analysis

Period covered	Spin-Axis Direction	Plane of Telescope	1st Harmonic		Components of streaming	
			Amplitude%	Phase	Radial	Azimuthal
1. 1968 Day 357 to 1969 Day 34 44 Days	North	Ecliptic	0.70 <u>+0.12</u>	115°E <u>+9°</u>	-0.30	0.63
2. 1969 Day 36 to Day 55 19 Days	East	Meridian	0.28 <u>+0.17</u>	109°S <u>+37°</u>	-0.09	-
3. 1969 Day 66 to Day 81 16 Days	South	Ecliptic	0.43 <u>+0.21</u>	142°E <u>+29°</u>	-0.31	0.30
		2nd Harmonic	0.37	80°E <u>+35°</u>		
4. 1969 Day 110 to Day 134 24 Days	East	Meridian	0.37 <u>+0.16</u>	162°S <u>+25°</u>	-0.35	-
		2nd Harmonic	0.18	41°S <u>+66°</u>		
5. 1969 Day 142 to Day 204 59 Days	East	Meridian	0.45 <u>+0.11</u>	166°N <u>+14°</u>	-0.44	-
		2nd Harmonic	0.15	94°S <u>+48°</u>		
6. 1969 Day 206 to Day 270 61 Days	South	Ecliptic	0.25 <u>+0.11</u>	153°E <u>+26°</u>	-0.22	0.11
7. 1969 Day 275 to Day 302 27 Days	South	Ecliptic	0.62 <u>+0.19</u>	171°W <u>+18°</u>	-0.61	-0.10
8. 1969 Day 319 to Day 335 16 Days	East	Meridian	0.18 <u>+0.23</u>	140°S Insignificant	-0.14	-

cont'd.

Table 8, cont'd.

Period covered	Spin-Axis Direction	Plane of Telescope	1st Harmonic		Components of streamir	
			Amplitude%	Phase	Radial	Azimuthal
9. 1970 Day 1 to 1970 Day 59 46 Days	South	Ecliptic	0.21 ± 0.12	167°E $\pm 35^{\circ}$	-0.21	0.05
10. 1970 Day 93 to Day 120 24 Days	South	Ecliptic	0.24 ± 0.19	143°E $\pm 50^{\circ}$	-0.19	0.14
11. Grand Total 124 Days		Meridian	0.30 ± 0.07	177°S $\pm 14^{\circ}$	-0.30	-
12. Grand Total 218 Days		Ecliptic	0.34 ± 0.06	143°E $\pm 9^{\circ}$	-0.27	0.22

Because this result differs from the predominately corotation behaviour observed at slightly higher energies using neutron monitors, any possible errors, both statistical and experimental, will be carefully considered in section 8.3.

The harmonic analysis was continued as far as the 2nd harmonic but only in three cases was an amplitude obtained of greater than 1σ (Poisson statistics). These are included in Table 8, but are of little statistical significance.

8.3 SOURCES OF ERROR

8.3.1 Statistical Errors and Variation of the Anisotropy with Time

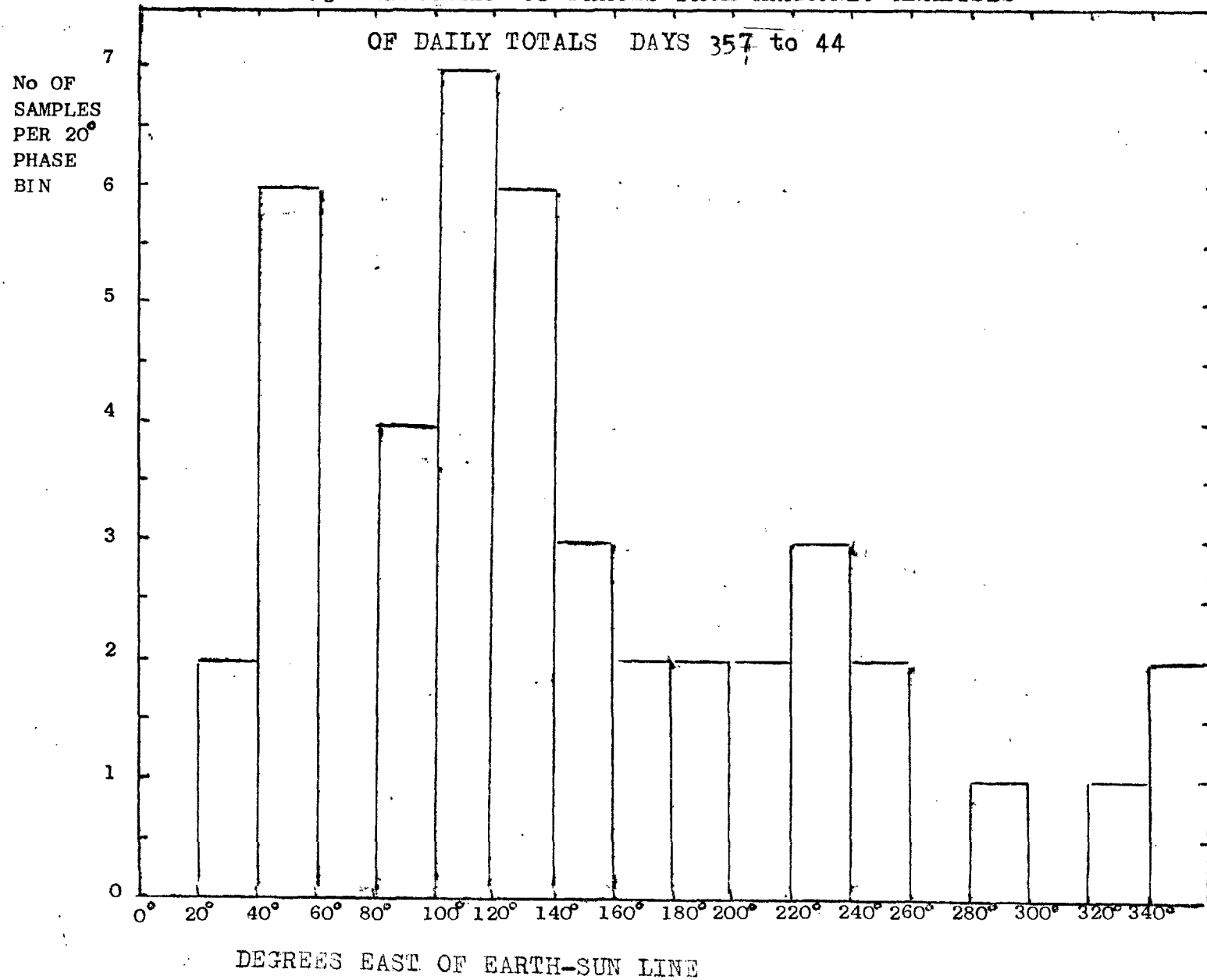
When data summed over a period of time is subjected to harmonic analysis as in section 8.2, two questions arise concerning the error in

the resultant. The first asks to what extent does the average of the data fit a sine wave model in the presence both of statistical errors and of errors in that model (which could be experimental, arising from the corrections etc.). The second asks to what extent the average describes what is taking place over any shorter time period (which can vary due to changing conditions in interplanetary space etc.). In the presence of uncertain corrections and/or poor statistics it is difficult to separate these questions.

In the case of ground based monitors where there are good statistics but uncertain corrections, the yearly average harmonic is commonly estimated from the average of daily values and its error from the spread in those values. This 'error' then contains real physical fluctuations as well as statistical and systematic (correction) errors. This method is probably unsuitable for S24B as the counting rates are relatively low and about 40 days of data are required to give as good statistics as a ground monitor. When the results are analysed on a day to day basis a wide dispersion of points is produced. However, when a histogram of phases is plotted (Figure 38) the distribution shows an encouraging maximum at the phase of the 1st harmonic obtained from the data total.

In the case of experiment S24B, the calibration factors for 40 days' data should be very accurate and it is probably more satisfactory to test the individual samples by the method of residuals, which takes account of both statistical errors and errors in the mathematical model fitted (due to errors of calibration, etc.). If the errors are purely statistical in nature, these estimates should be comparable with the Poisson error estimates. A discussion of this method is given by Sandstrom (1965) who gives formulae relating the error variances of the harmonic coefficients (σ^2) to the error variance ($\sigma_{e_k}^2$) of the residuals

FIG. 38 HISTOGRAM OF PHASES FROM HARMONIC ANALYSIS



(e_K = difference between value in Kth channel and value of the sine wave fit in that channel).

$$\sigma^2 = \frac{2}{V_c} \sigma_{e_K}^2$$

$$\begin{aligned} \sigma_{e_K}^2 &= \frac{\sum_{K=1}^{V_c} e_K^2}{(V_c - 2j - 1)} \\ &= \frac{\sum_{K=1}^{V_c} (n_K - \bar{n})^2}{2} - \frac{V_c}{2} \sum_{j=1}^j A_j^2 \end{aligned}$$

where

n_K = counting rate in channel K,

$\bar{n}$ = mean counting rate,

V_c = number of channels,

and harmonic coefficients (A_j) have been fitted up to the jth.

This method assumes that the residuals follow an approximately normal distribution and have a mean value equal to zero.

These formulae have been used to estimate the errors for the data periods given in Table 8 and the results obtained are comparable with the Poisson errors. In addition the mean values of the residuals are very small. Two examples of these three different approaches are given below, one for a short data period and the other for the complete period of data coverage.

i) From Harmonic Analysis of Totals and Poisson Error

A. Days 357(1968) - 34(1969)

$$U_r = -0.30 \pm 0.12$$

$$U_\phi = 0.63 \pm 0.12$$

B. Total Data Coverage

$$U_r = -0.30 \pm 0.07 \text{ meridian}$$

$$U_r = -0.27 \pm 0.06 \text{ ecliptic}$$

$$U_\phi = 0.20 \pm 0.06 \quad "$$

ii) From Harmonic Analysis of Totals, Error from Residuals.

A.

$$U_r = -0.30 \pm 0.08$$

$$U_\phi = 0.63 \pm 0.08$$

B.

$$U_r = -0.30 \pm 0.02 \text{ meridian}$$

$$U_r = -0.27 \pm 0.06 \text{ ecliptic}$$

$$U_\phi = 0.20 \pm 0.06 \quad "$$

iii) From Harmonic Analysis of Short Periods and Mean and Spread of Results.

A. 4 day periods

$$U_r = -0.26 \pm 0.5$$

$$U_\phi = 0.63 \pm 0.5$$

B. Periods of Table 8.

$$U_r = -0.31 \pm 0.13$$

$$U_\phi = 0.22 \pm 0.20$$

U_r = radial streaming component of anisotropy in percent

U_ϕ = azimuthal streaming component of anisotropy in percent.

These results would seem to indicate that it is statistics which limit the accuracy of the results presented and not errors in correction. The Poisson errors are then a good estimate of the errors and the degree of confidence in the results. The large errors estimated for the total data on the basis of the dispersion in the results from smaller periods is then probably in part due to real physical changes in the anisotropy vector. If the Poisson errors in the smaller data totals are accepted as reasonable error estimates, Figure 37 and Table 8 would seem to show evidence for a change in the anisotropy vector over the year. This appears to be largely due to a reduction in the azimuthal component.

8.3.2. Harmonic Analysis Technique and the Effect of Smoothing

A detailed discussion of the harmonic analysis technique has already been given in Chapter 5. The program has been tested on trial sine waves to ensure against errors.

The effect of smoothing due to averaging counts over a sector and also overlap of sectors has been shown to be less than 8% of the 1st

harmonic amplitude. This error is less than the statistical errors. Any correction for this effect would increase the amplitude. No error in phase or spurious radial streaming could be produced in this way.

8.3.3 Calibration of Sectors

It is evident from Figure 36 that the observation of a sine wave in the data is entirely dependent on the calibration factors applied to the eight sectors. However, this diagram also shows that a good sine wave is obtained, as is further evidenced by the low value of the error estimated from the residuals, thus giving confidence in the accuracy of the calibrations.

For any variation in the calibration pulse rate to systematically bias the results it would have to vary in phase with the satellite spin which changes continuously. Also any digitisation error in the calibration is guarded against by the lack of synchronisation between the spin period and telemetry sequence. Further evidence that the radial streaming cannot arise from such a bias comes from the fact that the 1st harmonic maximum occurs in different channels according to the satellite orientation. The maximum occurs in channels 3, 4, 5 respectively for spin-axis orientations North, East and South.

8.3.4 Spurious Data

A strong argument against the influence of spurious data is provided by the consistency of the radial streaming component over all the data samples. To serve as a further check certain of the data groups were re-run rejecting all data in which variations of more than 2σ from the mean occurred. Less data was obtained but no significant change in the anisotropy was observed.

8.3.5 Sun Gate Failure

There is no evidence of sun-gate 'A' failure before April, 1970 from the other S24 experiments. Any failure lasting for more than two telemetry frames would be automatically excluded by the data extraction program as there would be no counts recorded in channel 5. It is extremely unlikely that there would be intermittent failures lasting for less than two frames without at some time showing a longer failure. Further confidence that there is no such systematic bias towards a high count rate in channel 4 and low rate in channel 5 is given by the good fit of the sine waves and by the occurrence of the maximum in channels 3 and 5 for two of the satellite orientations.

8.3.6 Backward-Moving Particles

It is evident from the nature of the correction as given in section 5.3.4 and from Figure 36 that the effect is to change the amplitude of the harmonic without any alteration in phase. The application of a correction for a 25% contribution from backward-moving particles in fact increases the amplitude of the 1st harmonic by a factor of 1.7. Varying the correction between 20% and 30% would alter the amplitudes presented here by $\pm 10\%$. This is less than the statistical errors.

8.3.7 Chance Coincidences

During quiet-time data there is the possibility of chance coincidences between noise in the Cerenkov element and counts from the scintillator slab. Using the figures given in section 5.3.7(d) and the quiet-time scintillator rate implies a chance coincidence contribution to the radial telescope of $\sim 0.4\%$ for such times. The scintillator slab is very omnidirectional to high energy protons and so any anisotropy cannot make any contribution to the variation in telescope rate via this low contribution. It is possibly worth considering, however, whether any

variation in scintillator count rate due to solar protons, X-rays or light leakage could have any effect, although these would be manifest as a component of streaming away from the sun. This possibility can be easily refuted by inspection of the scintillator singles data. During any day's data the scintillator element will be sampled over a complete range of positions relative to the satellite-sun direction because of the lack of synchronisation between the telemetry and the satellite spin. The spread of scintillator singles values over any one day has been shown to give a standard deviation in accordance with that expected on the basis of Poisson statistics (i.e. $\sim 10\%$). Thus any variation in scintillator rate due to any of the reasons given above must be less than this and would contribute less than 0.04% to the measured anisotropy. Hence any further investigation of this problem, which would require determination of the scintillator position for each sample, is probably unnecessary.

8.4 PHYSICAL EXPLANATIONS

As the observed radial streaming component would not seem to be due to any obvious experimental defect, it is necessary to seek an explanation in terms of the effect of the earth's magnetosphere or conditions in interplanetary space.

8.4.1 The Effect of the Earth's Magnetosphere

Although the HEOS satellite was designed to observe conditions outside the magnetosphere, it is necessary to consider whether there could be any small effect on the observed particle anisotropies due to any shielding or reflection. A thorough investigation of this problem involving integration of particle trajectories has not been carried out but it is possible to advance arguments based on the data to show that the radial streaming is probably not due to any magnetospheric effects.

The S24B data which has been analysed for anisotropies was

obtained when the satellite was at a geocentric distance of more than 20 earth radii. At such an altitude, the satellite enters the magnetosphere only in the tail region where the field is weak. During one year the satellite apogee goes through a complete cycle of positions relative to the earth-sun line. Thus in early 1969 and early 1970 the data was predominantly obtained whilst the satellite was on the day side of the earth outside the magnetosphere, whilst during the summer of 1969 data was obtained on the night side of the earth within the magnetotail.

Inspection of Table 8 shows that the ecliptic plane scans, periods 1 and 9, took place in the former position whilst the meridian plane scans, periods 4 and 5, took place in the magnetotail. In addition, the ecliptic plane scan, period 6, was taken predominantly in the magnetotail. The other data is intermediate between these situations. It can be seen from Table 8 that a consistent value and direction for the radial streaming is obtained whether the satellite is on the night or day side of the earth, so that no simple reflection or shielding can explain the result. It can also be noted that the possibility of a time variation in the corotation component comes from comparison of period 1 with periods 9 and 10, which occur a year later when the satellite has returned to the same position relative to the magnetosphere.

8.4.2 The Influence of the Polarity of the Interplanetary Magnetic Field

It is worthwhile considering whether the radial streaming is dependent on the polarity of the magnetic field sector engulfing the earth at the time of measurement in the way discussed by Swinson (1971) for higher energy particles. This is immediately rendered unlikely by the continued observation of streaming in the same direction for all the periods in Table 8, which include many sectors.

The sector structure of the interplanetary field during 1969

has been studied by Sear (1971) using data from experiment S24A, and also by Wilcox and Colburn (1972). This epoch was characterised by two sectors per solar rotation. Quiet-time data from experiment S24B for 1969 has been divided up according to satellite orientation and interplanetary field polarity and the results are presented in Table 9.

TABLE 9: Analysis According to Sector Structure

Day Nos covered	Spin-Axis Direction	Plane of telescope Scan	Polarity of Interplanetary Field	1st Harmonic Amplitude	Phase
1968 357-358 1969 7-23	North	Ecliptic	-Ve	0.57 ± 0.18	87°E $\pm 18^{\circ}$
1968 360-366 1970 1-5, 24-32	North	Ecliptic	+Ve	0.85 ± 0.17	129°E $\pm 11^{\circ}$
36-49, 120-126, 133-134 148-164 319-329	East	Meridian	-Ve	0.37 ± 0.11	161°S $\pm 18^{\circ}$
51-55 111-118 128-132 142-146 331-335	East	Meridian	+Ve	0.28 ± 0.15	160°S $\pm 33^{\circ}$
66-76, 206-219, 260-270, 289-302	South	Ecliptic	-Ve	0.38 ± 0.13	165°E $\pm 19^{\circ}$
78-81 249-258 275-287	South	Ecliptic	+Ve	0.39 ± 0.18	159°E $\pm 27^{\circ}$

Days containing sector boundaries have been left out and the errors presented are Poisson errors as these have been confirmed as realistic by the estimations based on residuals.

It can be seen that the radial streaming towards the sun occurs regardless of the field polarity. To within the statistical errors there is no significant difference between observations made during periods of different polarity.

8.5 DISCUSSION AND CONCLUSIONS

This chapter has provided evidence for an integral radial streaming component of 0.3% ($\pm 0.07\%$) towards the sun for cosmic ray particles of rigidity greater than 1 GV. The result would not seem to be due to any obvious experimental defect or effect of the earth's magnetosphere, although in the latter case some further theoretical investigation is possibly required. There is also evidence for a corotation component in the usual sense and of amplitude between 0.1 and 0.6% with some evidence for a reduction in amplitude between early 1969 and early 1970. These phenomena show no apparent variation with the polarity of the interplanetary magnetic field.

The results of Urch and Gleeson (1972) show that under spherically symmetric conditions in the solar cavity, radial streaming towards the sun becomes of the order of 0.1% only at a particle kinetic energy less than 100 MeV. The S24B result would therefore indicate the importance of cosmic ray gradients perpendicular to the ecliptic plane and off-ecliptic phenomena on the sun and in interplanetary space. Clearly the low energy portion of the cosmic ray spectrum cannot be demodulated until such effects are understood.

Any theoretical explanation must cope with the sharp rigidity dependence of the effect, as neutron monitor results would seem to indicate a small radial streaming in the opposite sense (Quenby and Hashim, 1969). A streaming of about -0.8% in the range 1 to 3 GV and rapidly falling to zero above this rigidity would probably be sufficient

to explain the difference between the S24B and neutron monitor results.

Streaming towards the sun would indicate that the ecliptic plane is an easy access region with the cosmic ray density falling off with increasing heliolatitude. Such an effect could result from the occurrence of regions of maximum solar activity at around $\pm 20^\circ$. The different streaming direction of the higher energy particles could be due to the cosmic ray density increasing again above this latitude.

The unique nature of these results emphasises the importance of including similar experiments on future spacecraft located well outside the magnetosphere. Also there would seem to be a good case for the investigation of off-ecliptic phenomena.

ACKNOWLEDGEMENTS

Firstly I would like to thank Professor H. Elliot for allowing me to work in his group. My thanks are extended to all members of the Cosmic Ray Group for providing such a pleasant working atmosphere and for many enlightening discussions which have contributed towards this thesis.

I owe a particular debt of gratitude to my supervisor, Dr. J.J. Quenby, for his continual guidance and suggestions. Special thanks should also go to Dr. A.R. Engel for his unstinting help throughout the work and for providing the S24B experiment and the basis of the data extraction programs.

The collaboration of Dr. G.E. Morfill on the early parts of the spallation investigation is gratefully acknowledged. I would also like to thank Detlef Damaske and Geoff Carpenter of Imperial College, and Dr. I. Blair at Harwell for their help during the irradiation experiments.

Understanding of the spallation problem has been greatly enriched by the opportunity to travel and discuss results, and in this respect I am indebted to Dr. B. Dennis for his hospitality during a visit to the Goddard Space Flight Center, U.S.A. Results from OSO's 2 and 5 are reproduced with his permission. A week spent in discussion with Dr. G. Morfill and Dr. G. Pieper, by courtesy of the Max-Planck Institute in Munich, was also very valuable, as was the opportunity to attend the conference on background problems held in New Hampshire. I also thank Dr. D. Schwartz for fruitful discussions on the OSO 3 results.

The S24B results would not have been possible without the work of many people at ESRO and their contractors. The ordered data tapes were provided by Dr. R.J. Hynds and Anne Evans at Imperial College.

Throughout this work I have been supported by a Science Research Council studentship.

I am very grateful to Corri van de Stege for enduring many pages of bad handwriting to type this thesis.

Finally I am indebted to my mother and brother for their continual encouragement throughout my studies.

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