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The x-ray astronomy experiment

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Abstract. One of the scientific experiments onboard *Aryabhata* was designed to detect and measure celestial x-rays in the energy range 2·5 – 155·0 keV. The payload systems comprising proportional counter and scintillation counter telescopes were intended for observations in the pointed and scan modes respectively for investigating the emission properties of celestial x-ray sources. The paper presents the details of these telescopes, their inflight performance as well as the nature of the data obtained during the first few orbits.

Keywords. X-rays; proportional counter; scintillation telescope; x-ray spectrum.

1. Introduction

Since the first discovery of strong x-ray emitting objects beyond the confines of the solar system by Giacconi *et al* (1962), several experiments have been conducted by different groups to observe the universe through this new window of the electromagnetic spectrum. The bulk of the data in this field has been gathered through the US x-ray astronomy satellite, *Uhuru*, in the 2–20 keV energy range. Detailed sky survey using proportional counter relescopes onboard this satellite (launched on 12 December 1970), has enabled the generation of a series of x-ray catalogues, the latest of which lists 168 galactic and extra-galactic objects as x-ray emitters (Giacconi *et al* 1974). Figure 1 shows the *Uhuru* sky-based on the latest catalogue. Besides the detailed mapping, these observations have also revealed the spectral nature as well as the peculiar properties of some of the individual sources. The association of x-ray sources with members of binary systems as in the case of Cyg X-1 and Her X-1, where the x-ray star itself is hypothesised to be a highly condensed object such as a black hole or a neutron star, is an important aspect of the study of x-ray astronomy The associated time variation effects have also been investigated revealing the existence of intensity changes with time scales of seconds, minutes, hours, days and even months (Giacconi *et al* 1973, Oda *et al* 1972, Schreier *et al* 1971, Agarwal *et al* 1972, Nakagawa *et al* 1973, Frontera and Fulgini 1975, Rao *et al* 1976a). Such time variation studies besides throwing light on the extent of the emitting regions also serve to make unambiguous identification of these sources through correlated observations at optical and radio wavelengths.

At higher energies, the data gathered so far are comparatively meagre owing to the more severe secondary background problems as well as the reduced intensity of

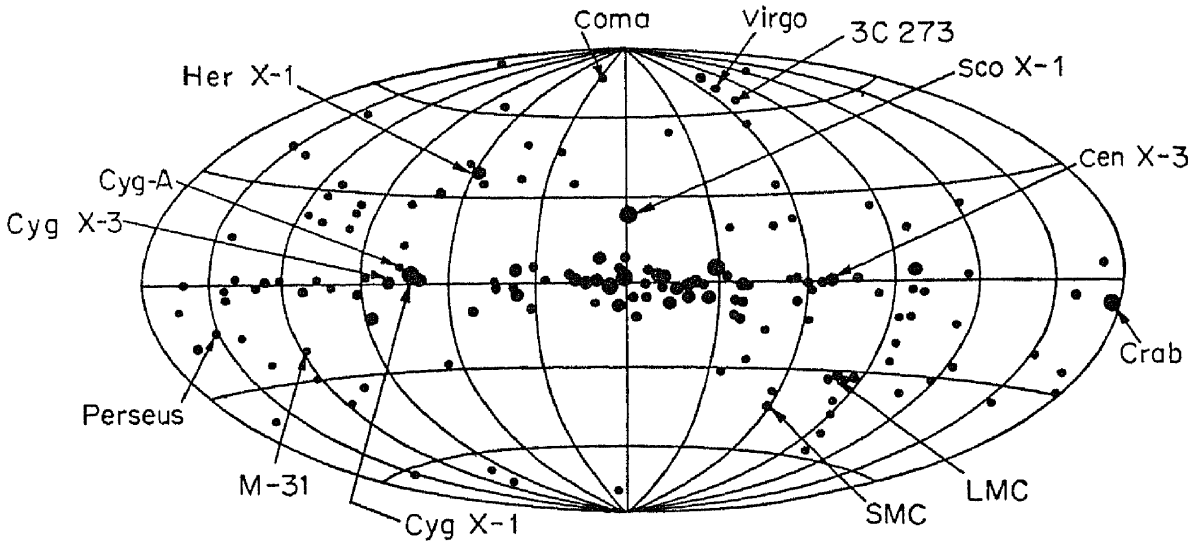

Figure 1. The x-ray sky as observed by *Uhuru* satellite.

x-ray emission from the sources. Some of the stronger sources such as Sco X-1 and Cyg X-1 have been observed and studied extensively by balloon borne scintillation telescopes and more recently by the OSO-7 satellite (Li and Clark 1974, Baity *et al* 1973). Again, the time variation effects were of prime interest in these investigations besides extending the information on the energy spectrum to higher energies.

More recently, the discovery of transient celestial phenomena at x-ray and gamma ray energies such as flares in x-ray sources (Kasturirangan *et al* 1974), the fast appearance and disappearance of new x-ray sources in a nova-like fashion (Matilsky *et al* 1972, Jerningan 1975, Eyles *et al* 1975, Rao *et al* 1969, 1971, Evans *et al* 1970, Pounds *et al* 1975, Harris *et al* 1969) and the cosmic gamma ray burst (Klebesadel *et al* 1973, Kasturirangan *et al* 1975) has added a new dimension to the investigations in x-ray astronomy.

The above considerations motivated the design of an x-ray astronomy payload that was flown on the first Indian scientific satellite *Aryabhata*. In this paper, we present a description of the payload, its testing and qualification as well as the preliminary data obtained from the first few orbits. The results of detailed analysis of the data obtained from this experiment are presented elsewhere (Kasturirangan *et al* 1976, Rao *et al* 1976).

2. Scientific objectives

The main aims of the x-ray astronomy experiment onboard *Aryabhata* were:

(i) the determination of flux and energy spectra of x-ray sources in the energy range 2·5 keV to 155 keV;

(ii) the exploration of new/transient x-ray sources with a sensitivity of 0·1 photon cm^{-2} s^{-1} in the 2·5–18·75 keV and 10^{-2} photons cm^{-2} s^{-1} in the 15·5–155 keV range;

(iii) study of the time variation in the intensity of strong x-ray sources with time scales of the order of a minute or more.

3. X-ray telescopes

The energy range of 2·5–19·75 keV was investigated using a gas proportional counter telescope. The proportional counter was filled with a mixture of argon and carbon dioxide in the ratio of 9 : 1 to a pressure of one atmosphere with an entrance window of 50 micron thick beryllium. It had a sensitive depth of 3 cm for the detection of x-rays. Charged particle-induced events were eliminated by providing an additional gas depth of 1·5 cm with an independent anode wire and setting the top anode events in anticoincidence with the bottom anode events. In addition, the pulse shape discrimination (PSD) technique was employed for minimising contamination due to non-x-ray events such as those due to gamma rays. The detector was imparted directionality by the use of a set of cylindrical collimators made out of an aluminium block. The physical configuration of the telescope is shown in figure 2.

The x-ray telescope for the higher energy range (15·5 keV to 155 keV) consisted basically of a NaI (Tl) crystal of 3·8 cm diameter and 4 mm thickness placed in a cylindrical plastic scintillator NE102A anticoincidence wall. The cylindrical graded shield of lead, tin and copper used as the internal lining for the plastic scintillator imparted the directionality to this telescope. The entire assembly was viewed from the bottom by a Dumont K-2227 photomultiplier of 5 cm cathode diameter. The charged particle-induced events were eliminated by the pulse shape discrimination technique, which separated the events in plastic having 10 ns rise-time from

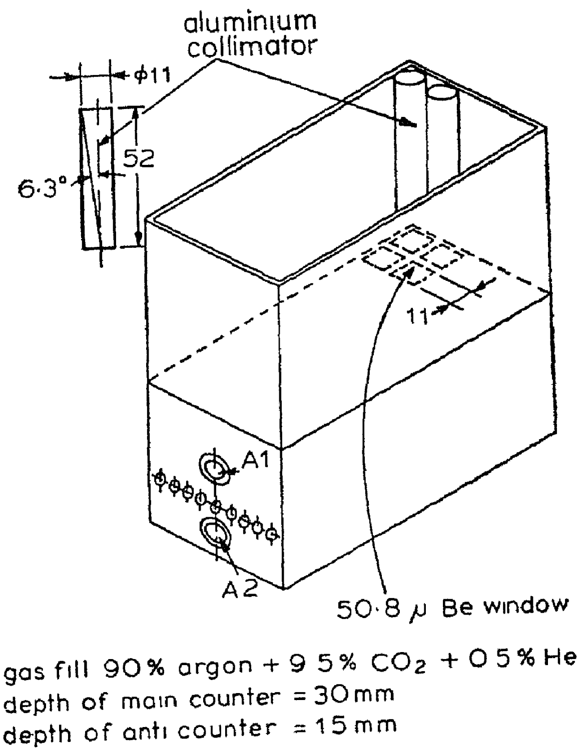

Figure 2. Physical configuration of the proportional counter telescope.

Table 1. Specifications of the telescopes

Nature of telescope	Effective area	Nature of window	Viewing condition	Collimator	Angular response (in degrees FWHM)	Telescopic geometrical factor	Energy range (keV)
Proportional counter telescope	15·2 cm²	50 μm Be with '1/e' cut-off energy of 2·5 keV	Along the spin axis	An aluminium block with a number of cylindrical holes and with a minimum wall thickness of 2·2 mm	12·5°	0·58 cm² steradian	2·5–18·75
Scintillation counter telescope	11·3 cm²	0·285 mm Be	Across the belly band perpendicular to the spin axis	Graded shield of 0·1 cm lead, 0·3 cm tin and 0·05 cm copper	14·5°	1·1 cm² steradian	15·5–155·0

Note: FWHM=Full width half maximum

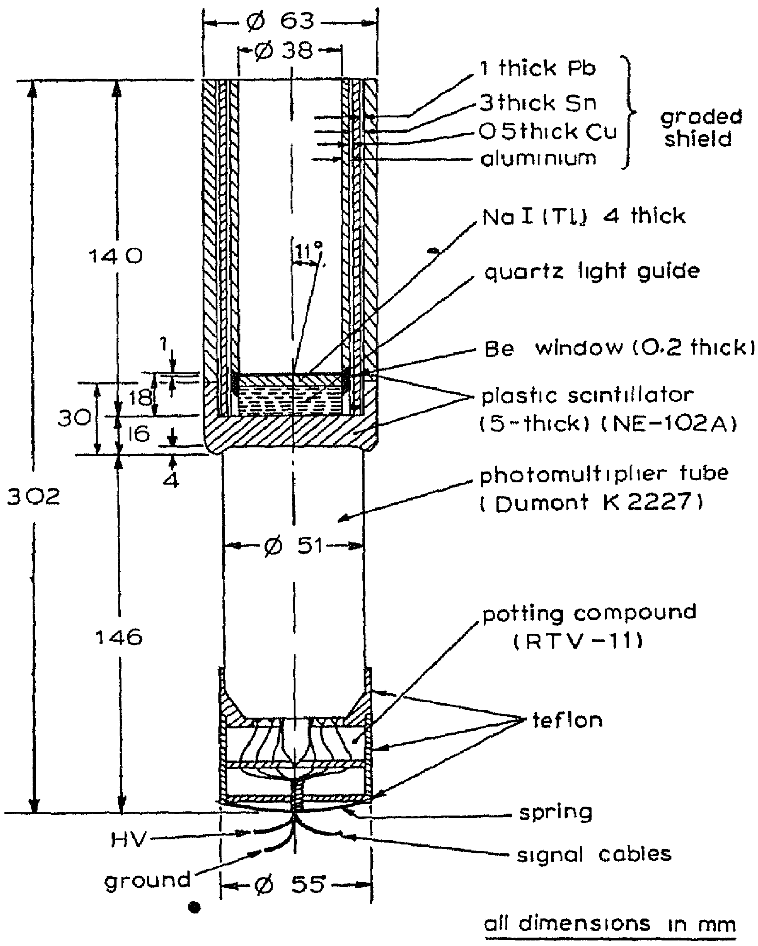

Figure 3. Physical configuration of the scintillation counter telescope

those in NaI(Tl) that had 250 ns rise-time. The physical configuration of the telescope is shown in figure 3. An identical telescope, but with the front-end shielded by a graded shield similar to the one explained above, was used for evaluating independently the internal instrumental background. The relevant specifications of the two telescopes are summarised in table 1.

4. Observational technique

The proportional counter telescope was mounted with its look direction along the spin axis of the satellite. This was to enable the detector to look at a fixed region of the celestial sphere for a long duration of time. The necessity of simultaneous correlation between the arrival time of x-rays and their associated direction was thus obviated. The scintillation telescopes were mounted with their look directions perpendicular to the spin axis in the equatorial plane of the satellite as shown in figure 4. In the spinning mode, the scintillation telescopes made a 360° scan of approximately a 20° band of the sky. In this mode, it is necessary to relate the arrival

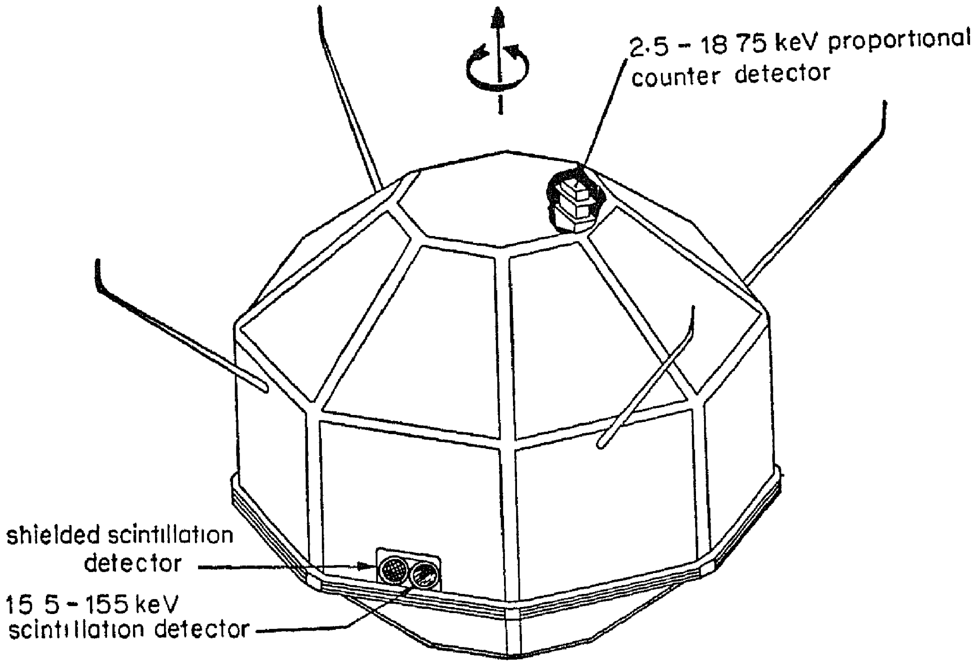

Figure 4. Location of the x-ray telescopes inside the satellite

directions of x-rays with the corresponding aspect of the satellite. Because of the fixed direction of the spin axis in inertial space, this could be realised on the identification of each x-ray event with the corresponding azimuthal direction defined in the equatorial plane of the satellite. To carry this out, the azimuthal plane was divided into 128 sectors using a set of four slit type solar sensors mounted on the equatorial plane of the satellite. The x-ray events in the energy range of interest after appropriate pulse height analysis were routed such that they corresponded to one or the other of these 128 sectors. The resulting angular width of an azimuthal bin was 2·8°.

5. Electronics

The onboard electronics for pulse amplification and processing can be classified broadly into three categories based on their functions. These were, the high-voltage DC-DC converter units that supplied the necessary voltages for the operation of the photomultipliers in the scintillation detectors as well as to the proportional detector; the analogue circuits that carried out amplification and pulse shape discrimination operations of the outputs from these detectors; and the logic circuitry used for the pulse height and direction analysis as well as the storage and interface operations with telemetry.

Figure 5 shows the block diagram of the electronic system used with the x-ray detectors. The DC-DC converters used were of the magnetic coupled multi-vibrator type and were stabilised at the output by corona discharge tubes (as for example Victoreen GV3A-1200 in the case of the scintillation counter supply). The proportional counter was supplied with + 2000 V at its anodes with respect to the body. The scintillation telescopes were supplied with +1200 V at their anodes with respect to the cathodes by a common high voltage supply.

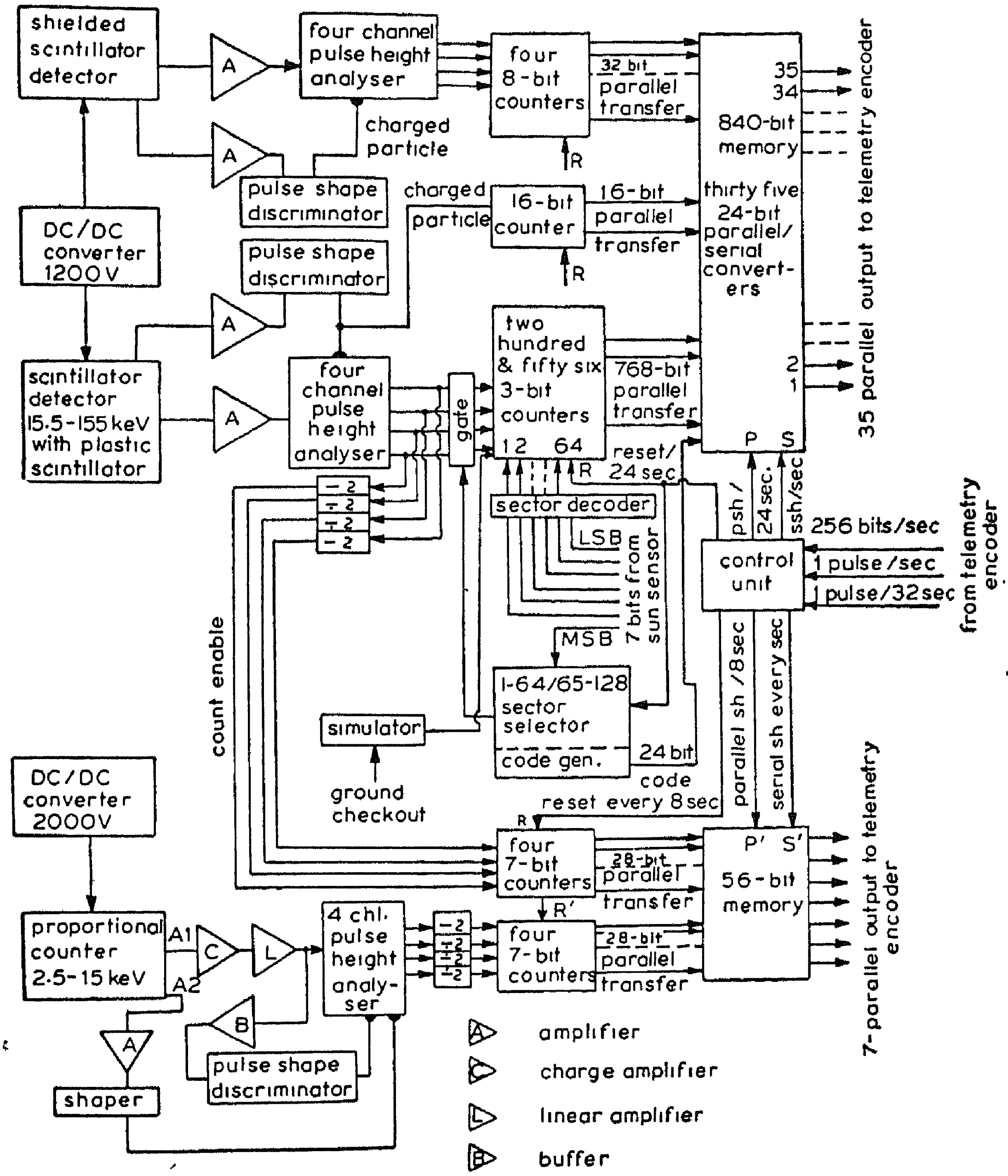

Figure 5. Block diagram of the onboard electronics system used for the experiment

As for the analogue electronics, in the case of proportional counter telescope, the output pulses from the first anode were fed to a charge integrating amplifier for impedance transformation and nominal amplification. The pulses were further amplified with a linear amplifier for subsequent pulse height discrimination. The pulses corresponding to the energy interval 2·5–18·75 keV were sorted into 4 energy bins using five comparators which gave a 6 μs pulse if the input exceeded the threshold. The output of the lowest level discriminator was used to strobe the output from other discriminators to eliminate the occurrence of any spurious output due to the finite rise time of the input pulse resulting in the earlier triggering of a low level discriminator compared to an upper one. The charged particle induced effects were reduced by generating a logic pulse corresponding to the output of the second anode after necessary amplification and using it for inhibiting the strobe pulse. Similarly, non-x-ray events were separated by pulse shape discrimination of the amplified pulses from the first anode and using them for inhibiting the strobe pulse. To realise this effectively, sufficient delay was provided before strobing, by building into the lowest level discriminator drive a 1 μs delay circuit which, in turn, drove the 4 μs strobe generator. The outputs of the four channels so obtained were stored in 7-bit counters for subsequent processing by telemetry.

In the case of the unshielded telescope, the anode output pulses corresponding to energy losses in the 15·5–155 keV range in NaI(Tl) were analysed into 4 energy channels after suitable amplification by a charge integrating amplifier and appropriate strobing. The charged particle induced events were eliminated by pulse shape discrimination of the pulses tapped from the last dynode by which the pulses corresponding to the plastic anticoincidence shield were identified. The threshold for the plastic anticoincidence was set at a level compatible with the lowest detection threshold for the NaI(Tl) crystal. The output of the four channels were routed through suitable gates to 64 3-bit counters each of which corresponded to a particular sector. The 64 sector information for one half of the 360° azimuthal band of the 7-bit output was obtained by decoding the 6-bit output from solar sensors (excluding the most significant bit (MSB)). The MSB was used for the immediate identification between the two halves of the 180° band of sky that the telescope was looking at for each observation cycle of 24 s as will be described later. The anticoincidence events from the pulse shape discrimination circuit were separately monitored by storing them in a 16-bit memory system. The shielded telescope electronics also used the same logic except that no sector information was derived. Therefore, each of the four channel outputs was separately stored in 8-bit counters.

Onboard data handling was accomplished as follows: the rates corresponding to the proportional counter and the unshielded scintillation counter telescopes, each of four channels and equivalent to a total of 56 bits of information (eight 7-bit counters), were transferred into a parallel-to-serial shift register at 8 s intervals and read out in 8 s by telemetry. Five main frame words per second were allotted to handle the information from the scintillation telescopes. This information stored in the counters was shifted once in 24 s to the parallel-to-serial shift registers which served as buffer memory for the duration of the read out. These telescopes between them represented 816 bits of information, corresponding to 768 bits of the directional and pulse height data of unshielded telescopes, 16 bits of the plastic anticoincidence shield events and 32 bits corresponding to the four channel pulse height counts of the shielded telescope.

The telemetry system read out all the above information in a 24 s cycle at 35 bits/s which, for the allotted 5 words, amounted to 840 bits. The 24 remaining bits were used for the identification of the experiment cycle. The resulting counting capabilities obtained were 35 counts per second per channel for the 15·5–155 keV x-ray events of the unshielded telescope; 10 6 counts per second per channel for the background fromthe shielded telescope and 2500 counts/second for the plastic antishield events.

6. Detector calibration, test and evaluation

The calibration of the detector systems involved the accurate determination of the energy settings for the discriminators and evaluation of their resolution characteristics. Standard radioactive sources such as ^{55}Fe (5·9 keV), ^{109}Cd (22 KeV and 88 keV), ^{241}Am (59·6 keV) and ^{57}Co (122 keV) were used for the evaluation of the resolution characteristics. The typical resolution values so derived were 19% for the 5·9 keV x-rays of ^{55}Fe in the case of proportional counter and 42% for the 59 keV x-rays from ^{241}Am for the scintillation detector. The measurements were made with a standard pulse generator to evaluate the energy thresholds. The energy settings for the detectors as evaluated are summarised in table 2.

To qualify the payload system for the environmental conditions of the launch and orbital phases, different tests were carried out on the payload, the details of which are summarised in table 3.

7. Performance of the payload in orbit

The payload was launched onboard *Aryabhata* on 19 April 1975 into a near circular orbit of 600 km at an inclination of 51°. Preliminary evaluation of the data obtained from the first few orbits showed that the payload system was functioning normally. However, after the 42nd orbit, the experiment was switched off because of a malfunction in one of the supply lines that resulted in the absence of +9V supply to the experiment. Besides, the satellite was spin-stabilised by ground command only in the 52nd orbit, with the result that the data obtained from the x-ray experiment were for the situation when the satellite was tumbling. However, it has been possible to evaluate the attitude of the satellite as a function of time using the data from the onboard magnetometers and digital sun sensors.

Table 2. Summary of the energy settings for the detectors

Detector	Channel I	Channel II	Channel III	Channel IV
Proportional counter telescope (keV)	2·5–5·4	5·4–9·8	9·8–13·8	13·8–18·85
Unshielded scintillation telescope (keV)	15·5–31·0	31·0–54·25	54·25–93·0	93·0–155·0
Shielded scintillation telescope	25 0–50·0	50·0–87 5	87·5–150 0	150·0–250·0

Table 3. Various tests carried out on the x-ray astronomy payload

S.No.	Type of test	Specification
1	Hot and cold soak test	—10°C to +50°C for 6 hr at the temperature extremes
2.	Vibration test	5 g between 30-60 Hz for 5 min along X and Y axis
3.	Shock test	20 g for 10 ms 20 times
4.	Thermovacuum test	+50°C at 10^{-5} torr for 24 hr −10°C at 10^{-5} torr for 24 hr

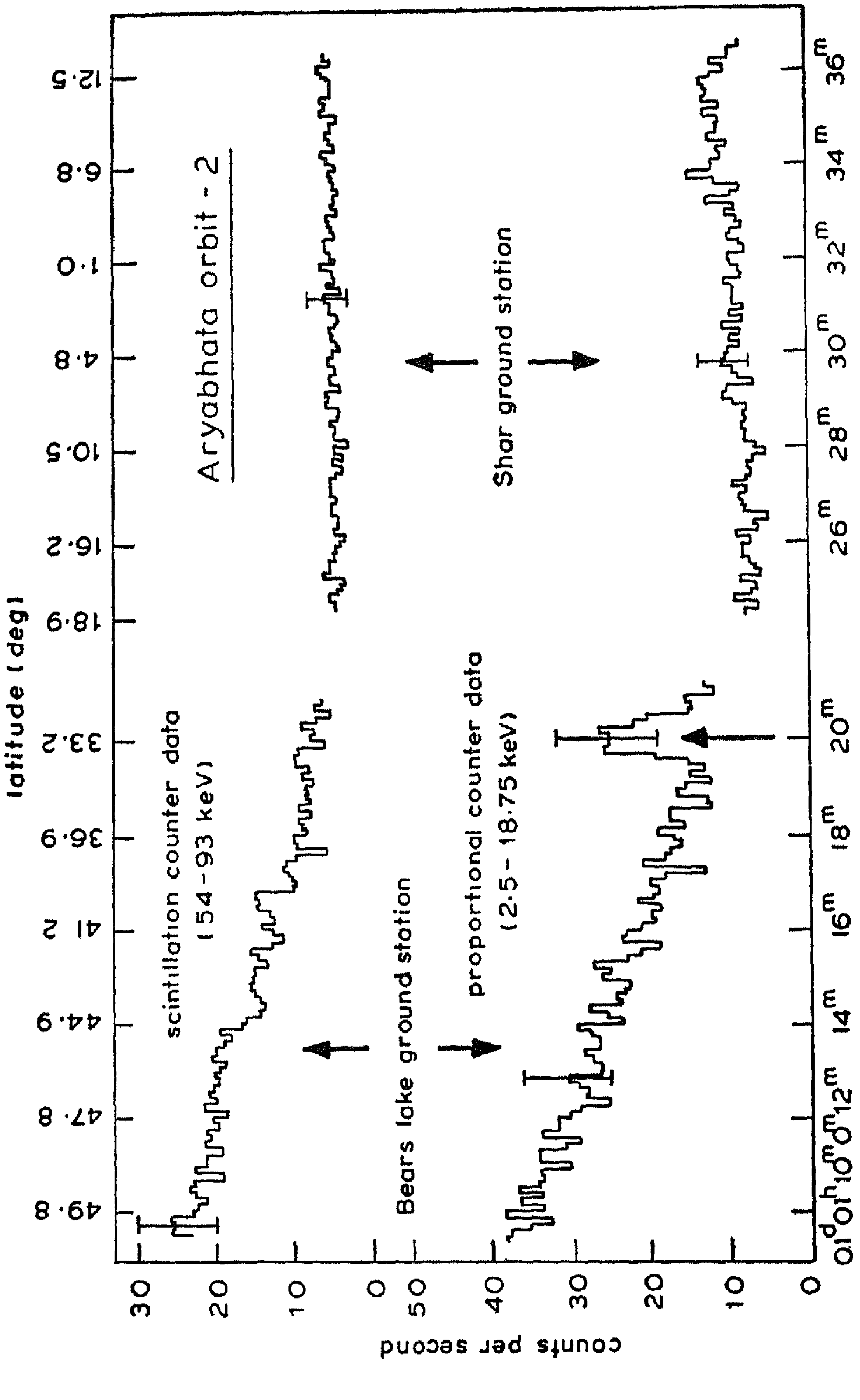

Figure 6. The counting rate profiles as registered by the two telescopes in Orbit No. 2.

Figure 6 shows typical counting rate profiles for passes over the Moscow and SHAR receiving stations for the proportional and scintillation telescopes for orbit-2. The latitude effect of the background radiation as the satellite comes from the high latitude to mid and low latitudes is clearly discernible. The peak indicated by an arrow against the proportional counter counting rate profile is due to an x-ray source as discussed a little later. The observed counting rate comes down by a factor of 4·5 in the 2·5–18·75 keV range and by a factor of 6 in the 54–93 keV range as the latitude changes from 50° to near equatorial regions.

Figure 7 shows the computed scan path of the proportional counter telescope in orbit-2 during the passage of the satellite over the ground receiving station near Moscow.

From the information on the attitude of the satellite and its correlation with the observed count rates, we concluded that in orbit No. 2, Cyg X-1 was observed by the proportional counter telescope. The spectrum derived from the observation fits with a power law distribution of the type

$$dN/dE = KE^{-\alpha} \text{ photons cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1},$$

with $K = 0{\cdot}26,\ \alpha = 0.66 \pm 0{\cdot}2.$

Cyg X-1 is now conjectured to be a member of a binary system with a 5·6 day period. It is interpreted to be the invisible companion of HD 226868 and its mass is estimated to be around seven times that of the sun (Giacconi 1975). The observed variability from various observations implies a compact source with a diameter of about 10^6 cm. Thus, the invisible object is a potential candidate for a black hole. The x-ray production could arise from the gravitational accretion of matter on to the compact object from its giant companion (Thorne and Price 1975).

Observations were also made on the galactic centre source GX 17+2 and GX 9+9 in the thirty first orbit. The spectrum of GX 17+2 can be fitted to an exponential

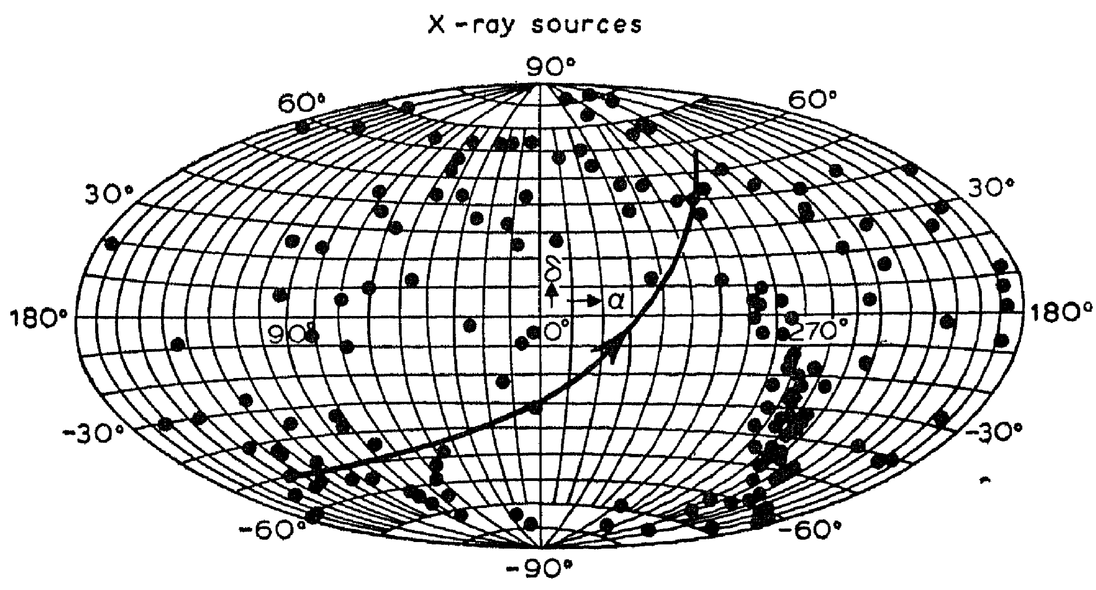

Figure 7. The scan path over the celestial sphere of the proportional counter x-ray telescope axis during Orbit No. 2.

function in the present case and yields a characteristic value of $9{\cdot}31 \pm 0{\cdot}3$ keV. The spectral distribution of GX 9+9 seems to be governed by a power law function with an exponent value of $\sim 1{\cdot}2$ and is suggestive of a non-thermal mechanism for x-ray emission.

The detailed scientific results are published elsewhere (Kasturirangan *et al* 1976, Rao *et al* 1976).

8. Conclusion

A payload designed for investigations in x-ray astronomy in the energy range of 2·5 keV to 155 keV was launched onboard the first Indian satellite *Aryabhata* on 19 April 1975. Based on the limited data available, it is deduced that the payload systems had functioned in orbit according to the expectations thereby validating the various design concepts. The detectors have recorded the fluxes from x-ray sources Cyg X-1, GX 17+2 and GX 9+9 (Kasturirangan *et al* 1976, Rao *et al* 1976).

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References

Agarwal P C 1972 *Study of cosmic x-ray sources using balloon borne detectors*. Ph. D. thesis, University of Bombay

Baity W, Ulmer M, Wheaton W and Peterson L 1973 *Nature London Phys Sci.* **245** 92

Evans W, Belin R and Conner J 1970 *Astrophys J. Lett.* **159** L57

Eyles C J, Skinner G K and Willmore A P 1975 *Nature London* **256** 628

Frontera F and Fulgini F 1975 *Astrophys. J.* **196** 597

Giacconi R, Paolini F, Gursky H and Rossi B 1962 *Phys. Rev. Lett* **9** 439

Giacconi R, Gursky H, Kellogg E, Levinson R, Schreier E and Tananbaum H 1973 *Astrophys. J.* **184** 277

Giacconi R, Murray S, Gursky H, Kellogg E, Schreier E, Matilsky T, Koch D and Tananbaum H 1974 *Astrophys J Suppl. Series* **27** 37

Giacconi R 1975 Centre for Astrophysics Preprint No. 304

Harris J, McCracken K G, Francey R and Fenton A 1967 *Nature London* **215** 38

Jernigan G 1975 No IAU Circular 2817 Aug. 13

Kasturirangan K, Rao U R, Sharma D P, Rastogi R G and Chakravarthy S 1974 *Nature London* **252** 113

Kasturirangan K, Rao U R, Sharma D P, Rastogi R G and Chakravarthy S 1975 *Indian J. Radio Space Phys.* **4** 203

Kasturirangan K, Rao U R, Sharma D P and Radha M S 1976 *Nature London* **260** 226

Klebesadel R, Strong I, Olson R 1973 *Astrophys. J. Lett* **182** L85

Li R and Clark G 1974 *Astrophys. J. Lett* **191** L33

Matilsky T, Giacconi R, Gursky H, Kellogg E and Tananbaum H 1972 *Astrophys. J. Lett.* **174** L53

Nakagawa M, Sakurai H and Kitamura T 1973 *13th Int. Cosmic Ray Conf.* Denver, USA Paper 671

Oda M, Wada M, Matsuoka M, Miyamoto S, Muranaka N and Ogawar Y 1972 *Astrophys. J. Lett* **172** L13

Pounds K A, Cooke B A, Ricketts M J, Turner M J, Peacock A and Eadie G 1975 *Astrophys Space Sci.* (to appear)

Rao U R, Chitnis E V, Prakasarao A S, Jayanthi U B 1969 *Astrophys. J. Lett.* **157** L127

Rao U R, Chitnis E V, Sharma D P, Prakasarao A S and Jayanthi U B 1971 *Nature London* **229** 248

Rao U R, Kasturirangan K, Sharma D P, Jain A K and Jayanthi U B 1976a *Astrophys. Space Sci.* **42** 193

Rao U R, Kasturirangan K, Sharma D P and Radha M S 1976b *Nature London* **260** 307

Schreier E, Gursky H, Kellogg E, Tananbaum H and Giacconi R 1971 *Astrophys. J. Lett.* **170** L21

Thorne K S and Price R H 1975 *Astrophys. J. Lett.* **195** L101