Rocket Experiments on Auroral X-Rays at Syowa Station, Antarctica in 1971–1973

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ロケットによるオーロラ X 線観測

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要旨：1971～73年にかけて，昭和基地で行われたロケット実験で得られたオーロラ X 線の観測結果について概報する．観測は前後 6 回行われ，NaI シンチレーション・カウンターを使用，4 keV 以上のオーロラ X 線フラックスを観測した．その結果，X 線の空間強度分布が予想以上に早く時間変化し，また，それが，オーロラ可視光，紫外光放射の変化と良相関を有することがわかった．

Abstract: This report briefly summarizes preliminary results of a series of rocket experiments on auroral X-rays carried out at Syowa Station, Antarctica during 1971–1973. Dual sets of sounding rockets were launched each year to an altitude between 100 km and 130 km. From five of six flights in total, distinct auroral X-ray fluxes with energies above 4 keV were recorded using one or two NaI scintillation counters. These recordings revealed the existence of a rapid time variation of the spatial distribution, a good relation with visible and ultraviolet emissions, and a spectral change with time of the auroral X-rays.

1. Introduction

Since the discovery of bremsstrahlung X-rays radiated from energetic electrons precipitated into the polar atmosphere in association with auroral phenomena, a number of observations on such auroral X-rays have been performed mostly at balloon altitudes, where X-rays with energies greater than about 20 keV are usually detectable. On the other hand, very little attempt has been made at rocket altitudes, where the direct measurement of impinging electrons is rather preferential. Taking into account the practical ease of balloon flights and the relatively lower costs, no necessity for rocket observations of auroral X-rays has been recognized so far. In fact, there is little doubt that the morphology and dynamics of auroral X-rays have fairly well come to light by virtue of balloon observations

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including simultaneous flights of multiple balloons from different stations (*e. g.*, BROWN, 1966; TREFALL, 1970; KREMSER, 1973).

However, considering auroral X-ray phenomena from a standpoint of three dimensional analysis, it should be noted that observations by means of sounding rockets involve several inherent superior features as follows:

1) Since the rocket flight is normally associated with a fast spinning motion of the order of a second or less, an X-ray counter telescope mounted at a certain angle to the rocket axis is able to scan the whole sky, in principle. As a result, image formings of the auroral X-ray patterns in the sky become possible, where the experimental accuracy of the pattern thereby traced depends on various instrumental parameters, as well as on the actual strength of the X-rays and their spatial and time variations.

2) Lowering of the threshold energy detectable due to lower absorption in the thinner air gives a much better signal-to-noise ratio than at balloon altitudes.

3) Little atmospheric modification of the original energy spectrum of the precipitated electrons is expected due to a smaller degradation of the energy.

4) It is possible to measure separately each of the upward- and downward-directed X-rays radiated from the normal auroral altitude of 100 km or so (KAMIYAMA, 1966).

5) The above-mentioned features should certainly enhance the validity of direct comparisons with other auroral phenomena simultaneously occurring.

During the three year period 1971–1973, six rockets in total were launched from Syowa Station, Antarctica (69°00′S, 39°35′E) to explore the auroral X-ray features as mentioned above, as one of the Japanese Antarctic Research Expedition (JARE) programs. They were single-staged, S-210 rockets, of which, two flights were programed each year. Each rocket carried one or two NaI scintillation counters to an altitude from 110 km to 130 km. No data was obtained from one of them owing to power supply failure, but all the others succeeded in detecting remarkable auroral X-ray events. In this article we briefly describe six of the rocket experiments and report a part of the preliminary results derived from them. Details of the spatial distribution which was measured by the S-210JA-3 rocket, and further analyses of the data from the other rockets will be given elsewhere.

2. General Remarks on Experiments

The main purpose of the present series of rocket experiments on auroral X-ray observation differed somewhat from year to year. In the first year, two flights S-210JA-3 and -4 were tried for image formings of auroral X-ray patterns, similar to optical photographs usually taken by all-sky cameras on the ground. To take

X-ray pictures simultaneously from two directions upward and downward, respectively, a pair of NaI scintillation counters, which were sensitive to energies from 4 keV to 40 keV, were mounted back to back, making angles of 45° and 135° with the rocket spin axis (KODAMA and OGUTI, 1972). Unfortunately, no useful data were obtained from the second flight, because of a serious problem with the battery power supplies for the instruments, but the first one gave satisfactory results which are described in the following section.

The next two rockets, S-210JA-9 and -10, were launched to search for a possible relation between the auroral X-rays and the associated ultraviolet emissions. The same type of X-ray counter as in the previous flights was used together with an ultraviolet detector which was sensitive to radiation having wavelengths between 1100 and 1360 Å (TOHMATSU *et al.*, 1974). Both detectors were mounted so as to look in a direction parallel to the rocket axis. No account for scanning the sky was taken due to geometrical limitation. In the last two flights, measurements

Table 1. List of rocket experiments for auroral X-rays

Rocket No.	JARE-12		JARE-13		JARE-14	
	S-210JA-3	S-210JA-4	S-210JA-9	S-210JA-10	S-210JA-16	S-210JA-17
Date	July 22, 1971	June 24, 1971	May 14, 1972	May 16, 1972	February 15, 1973	April 23, 1973
Time (45° EMT)	0052:01	0405:00	0213:00	0202:00	0245:00	0254:20
Max. altitude	131.4 km	130 km	129.3 km	115.4 km	102.5 km	124.6 km
Flight time	5m40s	5m46s	5m41s	5m28s	5m00s	5m34s
Associated P. I.*	AUV, HOR, GA	AUV, HOR, GA	NEL, AUV, GA	NEL, AUV GA	NEL, TEL GA	NEL, TEL, GA
Spin frequency	1.27 Hz	~1 Hz	1.69 Hz	1.19 Hz	1.19 Hz	1.05 Hz
Number of counters	2	2	1	1	1	1
Energy range	4–40 keV	4–40 keV	4–40 keV	4–40 keV	Ch. 1. 4–8 keV	Ch. 1. 4–8 keV
					Ch. 2. 8–16 keV	Ch. 2. 8–16 keV
					Ch. 3. 16–32 keV	Ch. 3. 16–32 keV
					Ch. 4. 32–64 keV	Ch. 4. 32–64 keV
Mounting angle	45°, 135°	45°, 135°	0°	0°	30°	30°
Collimator	Grid	Grid	Grid	Grid	Honey-comb	Honey-comb
Solid angle	19°40′ (26°50′)	19°40′ (26°50′)	19°40′ (26°50′)	19°40′ (26°50′)	9°38′	9°38′
Peak flux	3200/s		1200/s	900/s	800/s (Ch. 1)	3500/s (Ch. 1)

* AUV: Auroral Ultra-Violet, HOR: Horizon Senser, GA: Geomagnetic Aspect, NEL: Electron Density, TEL: Electron Temperature

were made in each of four channels having different energy ranges to deduce the differential energy spectrum and also to make a sky survey as a function of energy.

The X-ray detector used throughout all the above experiments was of the same type except the collimator and the energy discriminator and consisted of a sodium iodide crystal (1 inch in diameter × 2 mm in thickness) along with a photomultiplier tube RCA 2060. Hence, the auroral X-ray intensities recorded actually can be compared in absolute between at least two experiments in the same year. Also, the background flux due to cosmic rays was found to be about 20 counts/s at altitudes above 60 km, regardless of the year. Specifications of all six experiments are summarized in Table 1, where the spin frequency denoted is that determined from the actual periodic variations of auroral X-ray intensities observed.

3. Experiments in JARE-12

As already described, one of the two flights, S-210JA-3, recorded a distinct auroral event showing a magnitude of the order of 100 times the background flux. However, phenomenological and instrumental circumstances unfavorable for the main purpose of image formings of auroral X-ray patterns occurred. One was that the brightest band of aurora was moving rapidly in the horizontal direction after passing through the zenith when the rocket reached the auroral altitude. Another was an unexpected large precession motion of the rocket with a half-cone

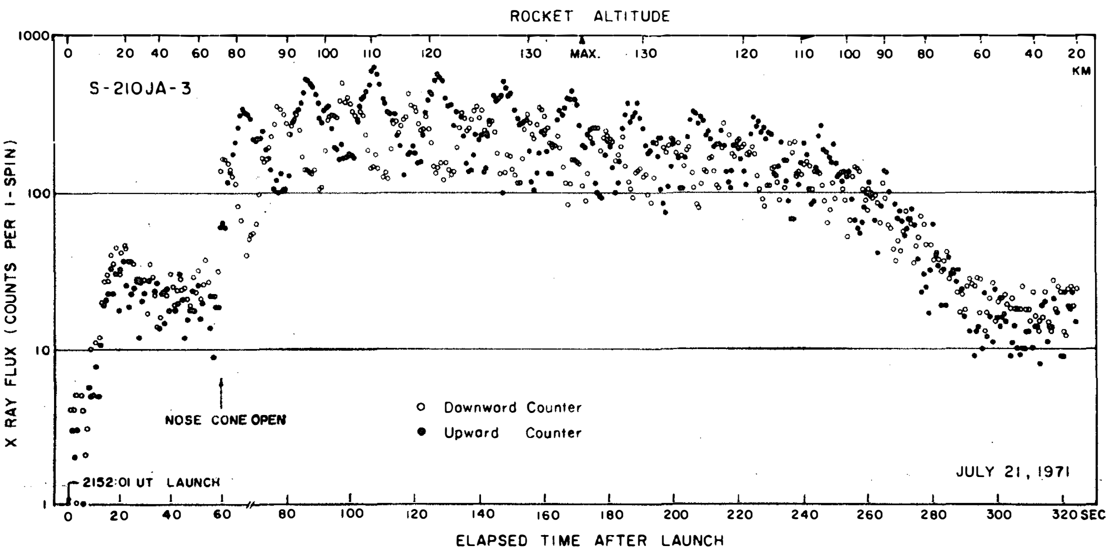

Fig. 1. Time profiles of X-ray intensities measured aboard the S-210JA-3 rocket, where counts per spin cycle are plotted. Open and solid circles correspond to the upward- and the downward-directed detectors, respectively.

angle of 85° (KODAMA and OGUTI, 1974). As a result, each of two counters aboard the rocket looked at the same auroral arc not from an upward or a downward direction but almost horizontally, and scanned over all azimuthal directions once every precession cycle 20.5 s. Fig. 1 shows the time profiles of the auroral X-ray intensities recorded by each of two counters during the entire flight. It is evident that the X-ray fluxes suddenly enhanced just when the nose cone of the rocket opened and thereafter they gradually decreased with an exponential time decay constant of -t/152 s taking into account the altitude dependence appearing below 110 km.

In addition, periodic intensity variations due to the large precession motion are predominant, and these are precisely out of phase with each other since the two counters faced in opposite directions. Since there were 26 spin periods during each precession cycle, the scanning motion of both counters was along a cycloid over a circular zone having a width of 90° containing the horizon. This peculiar motion of the rocket gives an azimuthal distribution of X-rays integrated along the line of sight. An example of such distributions traced using 1/20-s counts of the data from the upward-directed counter alone is illustrated in Fig. 2. This data is from the altitude range between 113 km and 124 km, with respect to polar

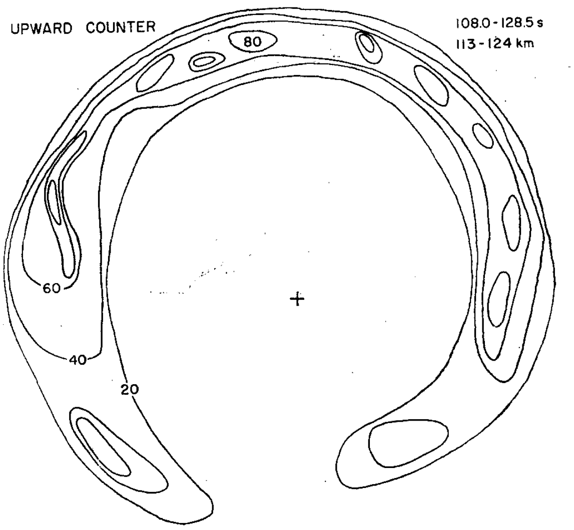

Fig. 2. An example of all-sky contour maps of X-ray intensity taken by a S-210JA-3 rocket during a precession cycle. Attached figures give counts per 1/20 s. A gap appeared below in the whole circle is almost in the geomagnetic south direction. A cross mark in the center indicates the direction of the rocket precession axis, being 16° from the zenith.

co-ordinates in which the center points to the direction of the precession axis inclined 16°SW from the zenith. It is clearly seen from the figure that the spatial distribution of auroral X-rays was not uniform but strongly dependent on the azimuth of the spin axis. Also, there were a number of patch-like irregularities suggesting a possible fine structure of the distribution.

Considering the fact that each of the two counters simultaneously covered a

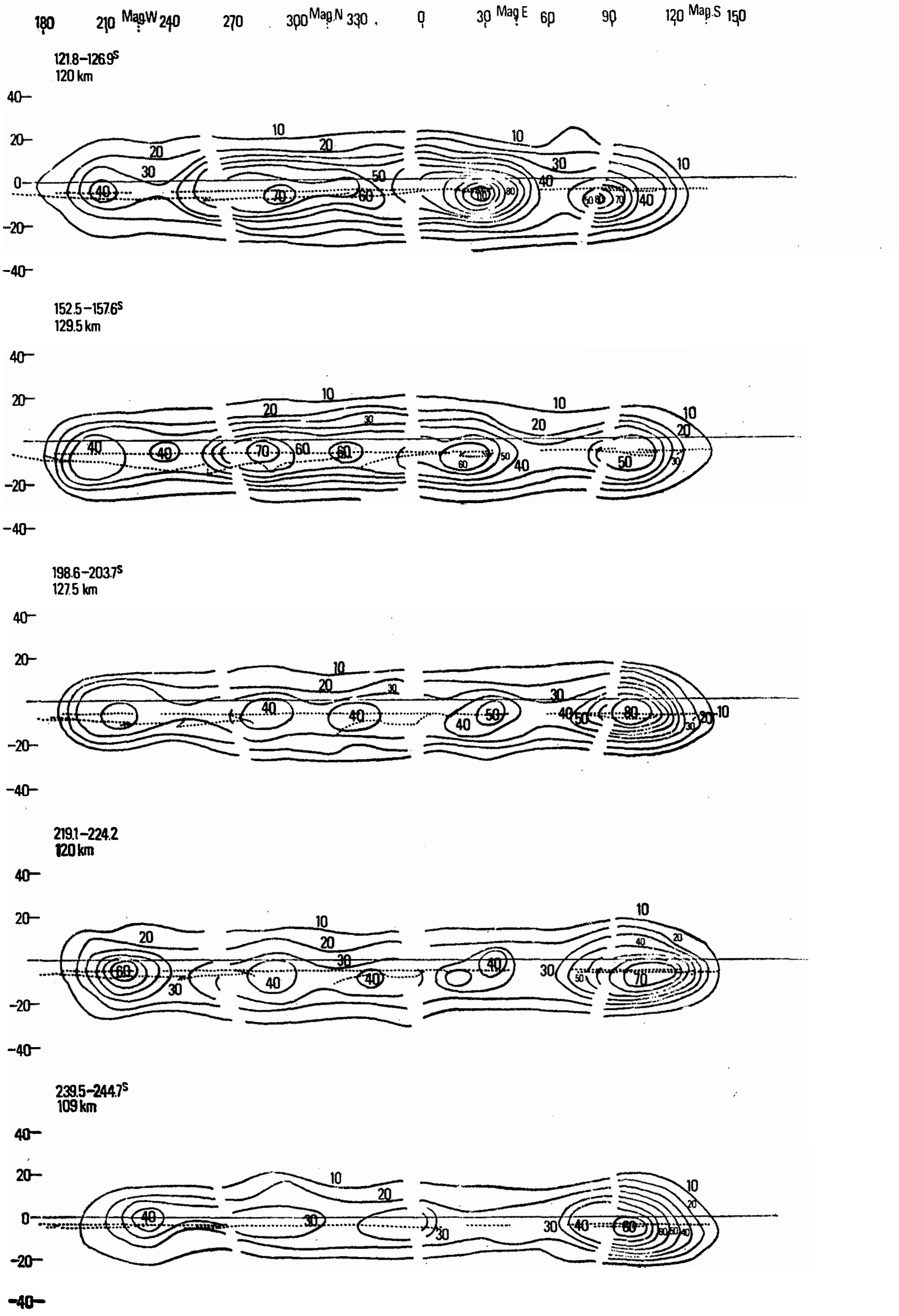

Fig. 3. Some examples of isophoto maps of X-ray fluxes viewed from an altitude between 120 km and 109 km in the descent of the S-210JA-3 rocket. Numerical units are the same as those in Fig. 2. Dotted lines indicate the location of the brightest arcs of optical aurora.

width of 90° in azimuth during one spin cycle, it took only 20.5/4 s≃5 s to finish a scan over 360° in azimuth by use of the two counters. In other words, one can trace an isophoto-map of X-rays every 5 s. Consequently, these successive maps revealed the temporal variations of the spatial distributions. In Fig. 3 is shown a sequence of the maps viewed from an altitude from 120 km to 109 km in the descent, where a horizontal line is the horizon seen from the rocket altitude. The dashed lines of the contours drawn in each diagram indicate schematically the position of the brightest aurora forms inferred from the analysis of the all-sky camera photographs taken at Syowa Station. These lines lie near the position of the maximum X-rays which existed at an elevation angle of 5° below the horizon regardless of the azimuthal angle. The distribution of X-rays is spread over a larger area than that of the optical auroras, because of the wide-angle sensitivity of the X-ray counter used here.

Since the ultraviolet detector was mounted in parallel with the rocket axis, its viewing direction crossed the above-mentioned cycloid locus only two times, when enhanced emissions were recorded (TOHMATSU *et al.*, 1974). A qualitative correlation with the X-ray enhancements was confirmed, but a direct comparison in absolute intensity between the two is still in progress.

4. Experiments in JARE-13

Two kinds of detectors for auroral X-rays and ultraviolet emissions were mounted along the rocket spin axis, so that a direct comparison in physical characters

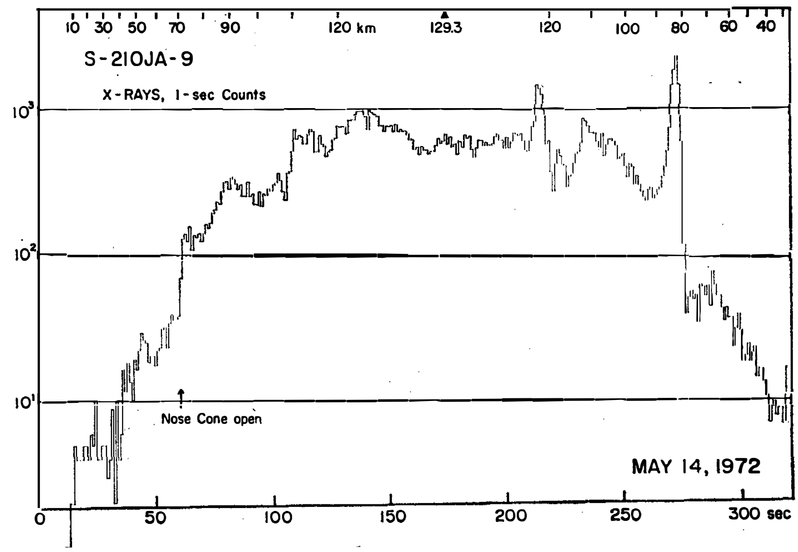

Fig. 4. The entire time profile of 1-s counts of X-rays observed aboard the S-210JA-9 rocket.

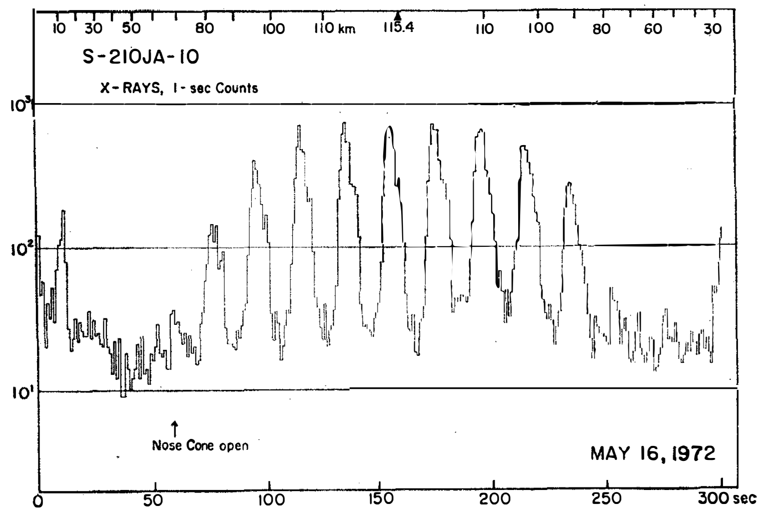

Fig. 5. The entire time profile of 1-s counts of X-rays observed aboard the S-210JA-10 rocket.

between both phenomena is easy if it appears a distinct aurora during the flight. Figs. 4 and 5 show the time profiles of X-rays in flights No. 9 and No. 10, respectively. The latter displayed periodic variations similar to that in Fig. 1, but with greater amplitude. Such a feature is obscure in flight No. 9 despite an intensity enhancement close to the peak flux observed in flight No. 10.

To examine whether or not some rapid changes are included within each of the nine distinct periodic peaks seen in Fig. 5, 0.1-s counts in place of 1-s counts are plotted every precession cycle in Fig. 6. It is obvious that there occasionally appear short period changes with frequency near 1 cycle per s, these more rapid fluctuations look like micropulsations. Since the detector always views the same auroral arcs every precession, it seems that these short term variations may be due to either the spatial movement of the arcs or to a flickering in the intensity itself.

According to actual recordings of the geomagnetic aspect senser on board, there was also a considerable difference in the precession motion between both flights. Whereas the all-sky camera photographs corresponding to the respective flight times exhibited diffuse and arc types of auroras for flights No. 9 and No. 10, respectively. Therefore, it is still open to question which of the above-mentioned two origins mainly contributes to the time profile difference between Figs. 4 and 5. On the other hand, the general feature of the time profiles as for ultraviolet emissions looks like that of X-rays (KANEDA, 1974). Detailed analyses of the data, particularly from rapid run recordings, will be tried in the near future to search for the origin of the difference between the two flights, as well as to make a comparison between the two types of emissions having different wavelengths.

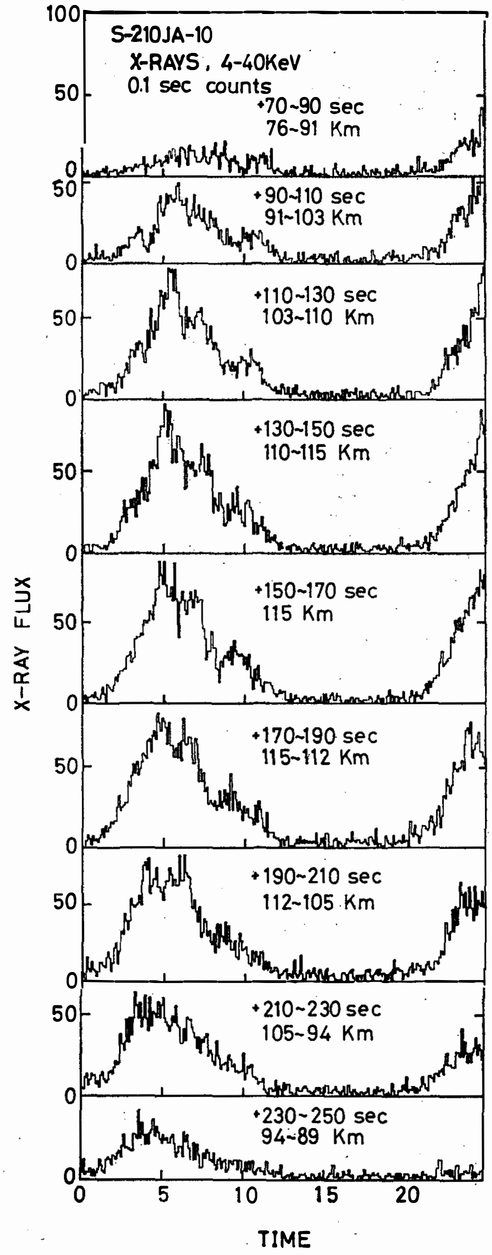

Fig. 6. A sequence of time profiles of 0.1-s counts of X-rays observed aboard the S-210JA-10 rocket. Each diagram is arranged in order of the precession cycle.

5. Experiments in JARE-14

Two rockets, Nos. 16 and 17, each carried a NaI scintillation counter with four channels of differential energy discriminators: 4–8 keV, 8–16 keV, 16–32 keV and 32–64 keV. Based on the preceding experiments, the aperture and the mounting angles of the detector were narrower than in the previous flights, in order to improve the resolving power of the viewing field. The time profiles of the X-rays observed by S-210JA-16 rocket are shown in Fig. 7, where counting rates per spin

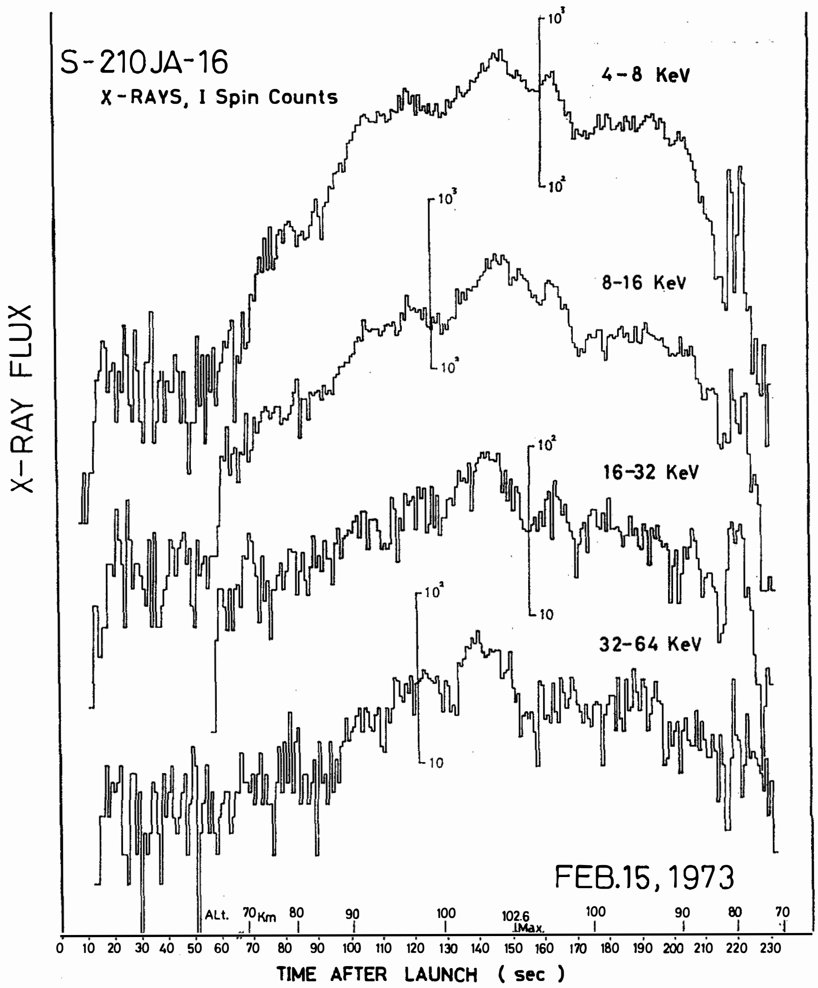

Fig. 7. Time profiles of X-ray intensities measured in four channels having different energy ranges aboard the S-210JA-16 rocket, where the X-ray counts are given every spin cycle.

are plotted for each of the four different energy ranges. Their general form is similar to that in Fig. 4, being like that for diffusive type aurora.

The ratio of the count from the 4–8 keV energy range to that from the 32–64 keV range was taken as a measure of spectral indices, and plotted in Fig. 8 together with the counting rates from the lowest energy range. It is seen from the significant time variation of the ratio that the energy spectrum of X-rays is not always stable but changeable with time even in small time duration. There is, however, no significant correlation in time variations between the intensity and the ratio.

Though the data from the last flight, S-210JA-17, has not yet been fully analysed, the time profile of the X-rays from the lowest energy range alone is given in Fig. 9, in which the strongest flux of all in the present series of experi-

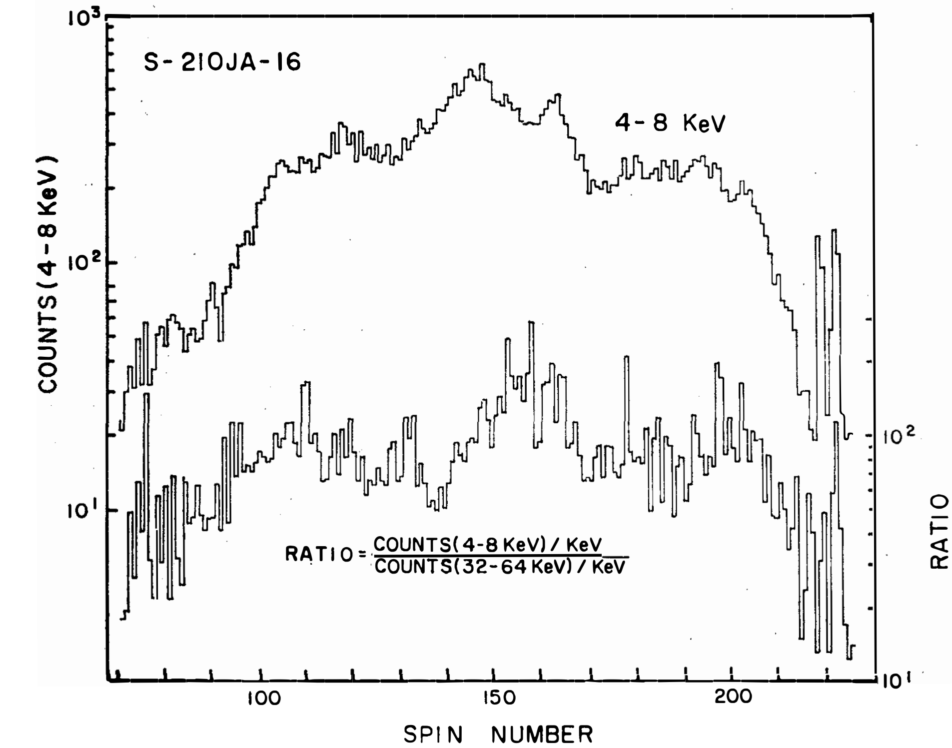

Fig. 8. Time variations of X-ray intensities in the 4–8 keV energy range and of the ratio of the counts from the 4–8 keV channel to that from the 32–64 keV channel.

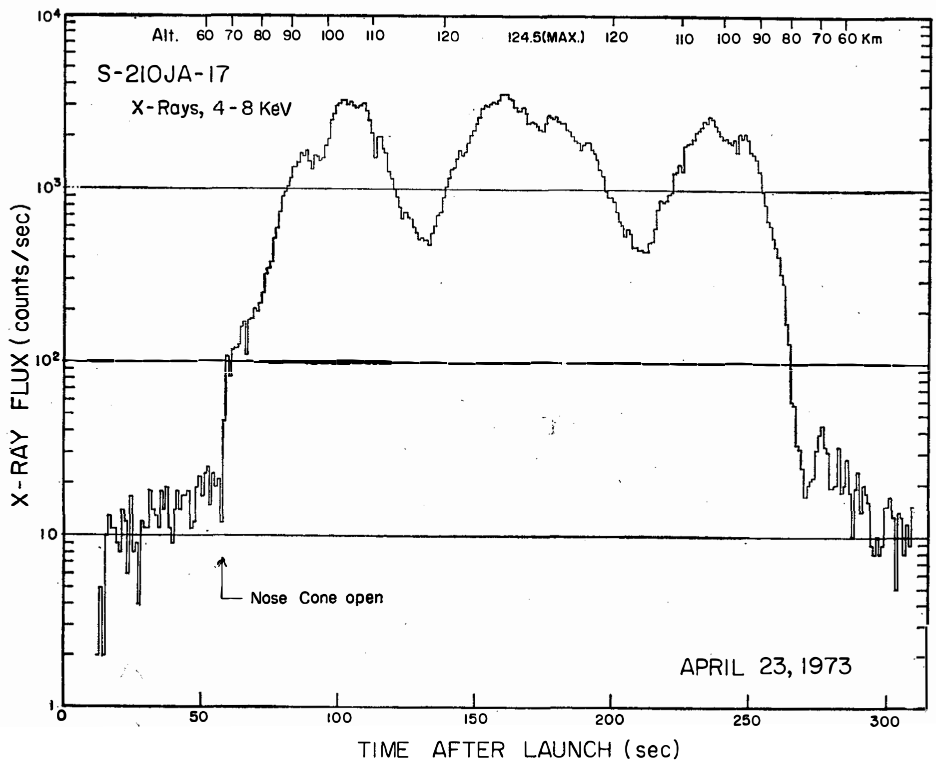

Fig. 9. The entire time profile of 1-s counts of the 4–8 keV X-rays observed aboard the S-210JA-17 rocket.

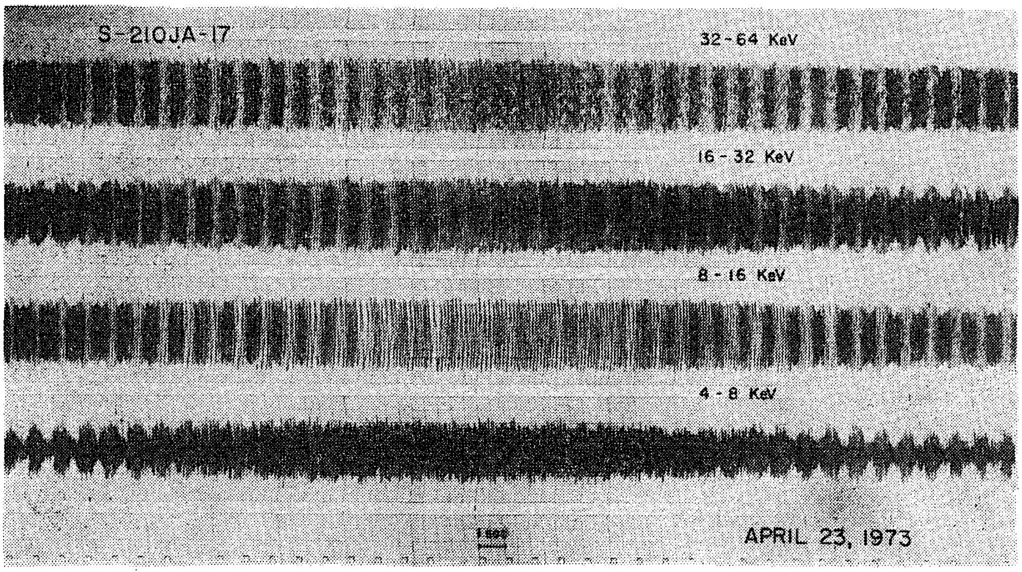

Fig. 10. Reproduction of the pen-writing recording chart of X-rays obtained in the S-210JA-17 rocket experiment. Patterns from four different energy channels are displayed, respectively. One cycle up and down in each diagram equals 32 counts of X-rays. Periodic reduction in amplitude seen from the lowest pattern are attributed to over-sensitivity of the pen-writing recorder due to very high counting rates observed.

ments was recorded accompaning with three humps possibly due to the precession motion of the rocket. From a reproduction of a part of the pen-writing recording charts, as seen in Fig. 10, each of the four patterns indicates the repetition of thick and thin bands representing the periodic variation caused by the spinning motion. Thus, it is expected that a certain spatial pattern of X-rays will be obtained as a function of energy.

6. Comments on Future Experiments

Data reduction and analysis for the entire series of rocket experiments has not yet been completed, including synthetic analyses in relation to other associated phenomena observed aboard the rocket or on the ground. However, we can point out several problems for further rocket experiments of auroral X-rays, on the basis of the experimental results obtained up to data.

First of all, it goes without saying that the purpose of the experiment should be decided with due consideration of other experimental methods such as satellite, balloon and ground level observations. Since the different methods of observations have their own advantageous features, it is of great importance to put the methods in their proper respective roles in order to make the most efficient use of the various methods. In this way, simultaneous observations complementary with each other among four methods are most useful. In other words, it is resonable to stress that the so-called stereographic measurement from different altitudes will be required with respect to various physical parameters: X-rays, optical and ultraviolet emissions, electric field, precipitating electrons and protons and so on.

One of the projects most suitable for rocket experimentation, as described earlier, is an application of the feature of the rapid scanning of the sky. Recognizing the existence of the fine structure and its rapid movement in optical auroras (OGUTI *et al*., 1974), such similar phenomena could be expected in case of X-rays too. In order to observe them a higher resolution in the angle of the X-ray detector needs to be attempted by the development of a new detector or a new way of arranging the detector, so that much higher detection efficiency can be achieved. If the rocket altitude is increased and if the rocket is stable in flight, then both the upward and downward coming X-rays can be measured, independently during the flight. The result thereby obtained will be useful in a comparison of the theoretical calculations on the altitude dependence of both components.

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