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X-Ray Astronomy Program in Japan

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1. Introduction

One of the great achievements in the short history of X-ray astronomy is to have established the real existence of neutron star rather than just a theoretical conception. Pursuing this extreme astronomical body and its environment will undoubtedly continue to produce important science through this decade and beyond.

We have been operating the Hakucho satellite for over two years. It is amusing as well as amazing to find that this 96 kg satellite with limited capabilities gives us plenty of interesting results and significant questions concerning neutron stars. These questions in fact constitute the basis for our planning of the future program. I would, therefore, like to illustrate some of the problems that emerged from the Hakucho observations and are to be understood by future investigations.

2. X-ray pulsars

Among many X-ray pulsars, we have conducted so far most extended observation of Vela X-1. Vela X-1 is a slow pulsator with the approximate pulsation period of 283 sec and the binary period of 8.97 days. Fig. 1 shows the history of the pulsation period variation. It is clear that the neutron star had been spinning up until 1979, consistent with the picture of acceleration by the accretion torque (e.g. Rappaport and Joss 1981). Hakucho observations revealed two remarkable features. i) The spin period started to slow down since 1979 and this trend continues (Nagase et al. 1981). The average $\dot{P} / P \simeq 3.5 \times 10^{-4}\ \mathrm{yr}^{-1}$ for the period 1979 - 1981. ii) An up-down fluctuation of the spin period with a time scale of the order of the orbital period is significantly resolved for the first time (Nagase 1981). $\dot{P} / P$ of this fluctuation ranges over $(-3 \sim +4) \times 10^{-3}\ \mathrm{yr}^{-1}$, an order of magnitude larger than that for the long-term variation. The observed long-term slowing down is not readily explained. There has been no significant

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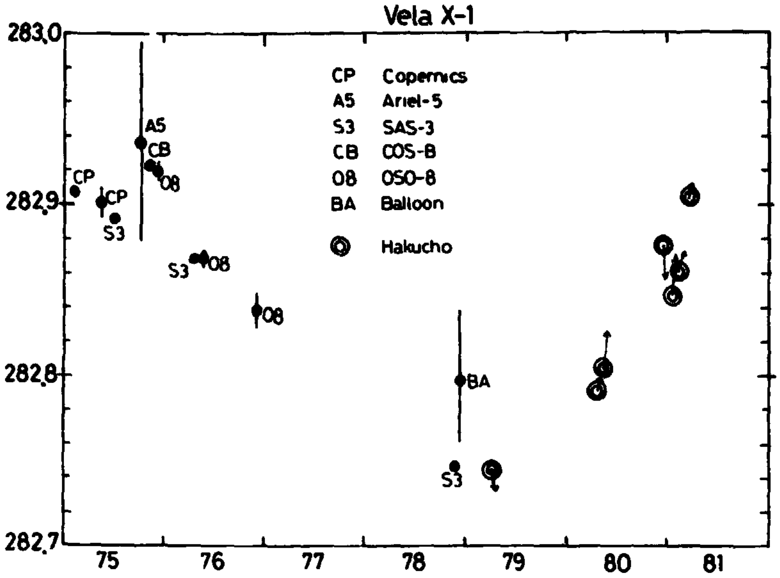

Fig.1 Histroy of the pulsation period of Vela X-1

change in the average X-ray luminosity through past several years. Would this be due to the change of the direction of accretion flow with respect to the spin vector of the neutron star? An entirely different idea suggested by Makishima is that the secular variation of the pulsation period might due to the Doppler effect by the orbital motion of the Vela X-1 binary around an unseen third body with a period of the order 10 years. If it were so, the mass of the third body would then be roughly 100 $M_\odot$, hence implying a giant black hole. It is worth noting that a similar slowing down of the neutron star revolution is also observed for GX 301-2 (Kelley, Rappaport and Petre, 1980).

The short-term up-down fluctuation of the pulsation period poses an intriguing question. If the fluctuation is of an external origin, the direction of the accretion flow may change rather quickly. If it is of an internal origin, this may be due to the coupling and decoupling between the crust and the superfluid interior such as proposed by Lamb, Pines and Shaham (1978).

The example of Vela X-1 demonstrates that we can learn a lot about inside and outside neutron stars by accurately monitoring the behavior of X-ray pulsars.

3. X-ray bursters

X-ray burst is another outstanding phenomenon that neutron star exhibits. As a matter of fact, one of the main emphasis of Hakucho was placed on the observations of X-ray bursts. Distribution of burst sources including those we found in the general direction of the galactic center is shown in Fig. 2. A distinct clustering towards the galactic center is evident. This distribution by itself suggests the Pop. II nature of burst sources, which is strongly enhanced by the fact that nearly half as many burst sources are associated with globular clusters.

Of particular importance of bursts is that one can in principle measure the radius of the neutron star. Owing much to the SAS-3 group (Lewin and Joss 1981), it is by now established that the "black-body" radius is conserved during the burst decay and of the order 10 km. We estimated the "black-body" radii for several

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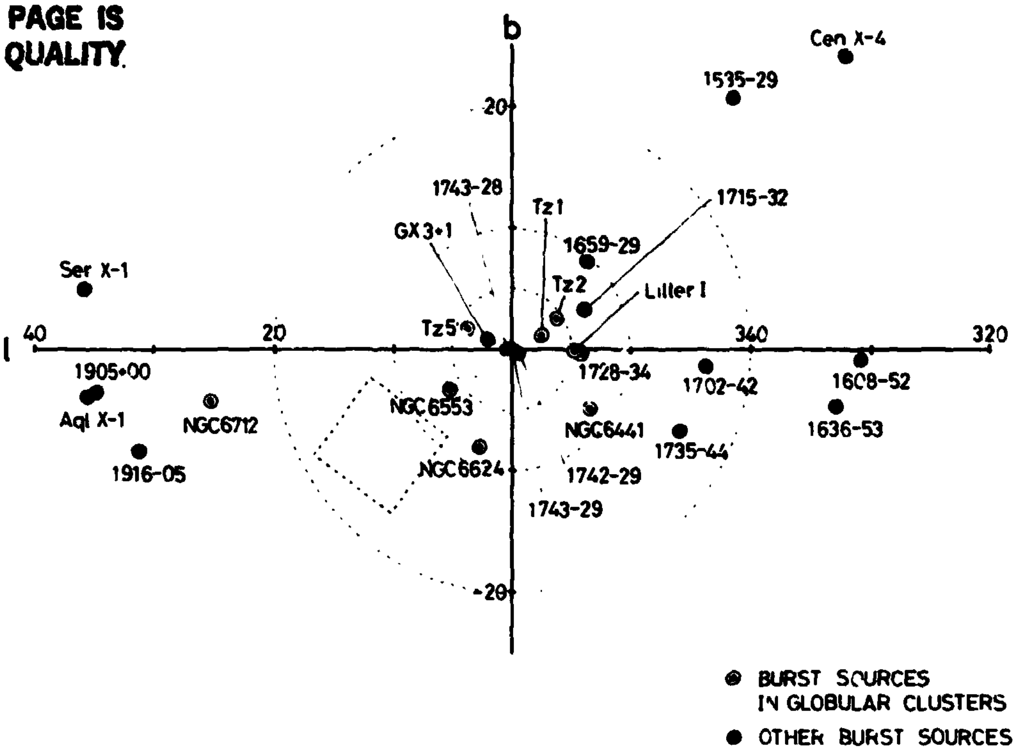

Fig.2 Distribution of burst sources around the galactic center

burst sources, including three globular cluster sources, that are most probably near the galactic center. They all come close to 10 km within 20%, implying that they are about the same size. I must caution, however, that it is too early to take this number as the actual neutron star radius for this requires correct interpretation of the burst spectrum which is yet the theme of further investigations. Nevertheless, it is very important that we have means to measure the neutron star radius in our hands. While, X-ray pulsars enable us to measure the mass of neutron stars.

We have sofar learned that every individual burst source can produce a variety of bursts in the time profile, peak luminosity and total energy. The thermonuclear flash model provided a persuasive picture of the burst phenomenon. There are, however, several observational facts that challenge theoretical interpretations.

i) Successive bursts at a very short interval

We observed three such events; 10 min. for 1608-52 (Murakami et al. 1980), 8 min. for Terzan 5 source (see Fig. 3), and 8 min. for MXB 1636-53. The SAS-3 group observed three bursts in such short succession from a galactic-center source (Lewin et al. 1976). Such an interval is definitely too short to replenish the required nuclear fuel by the mass accretion. The nuclear fuel ought to be hidden somewhere on the neutron star surface, but where? and how? are the big questions.

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ii) Possible supercritical luminosity

A puzzling result was obtained from examination of the burst peak luminosities (Inoue et al. 1981). The peak luminosity distributions for five burst sources near the galactic center are shown in Fig. 4. If the distance to the galactic center is taken to be 10 kpc, the largest peak luminosity observed for each source largely exceeds the Eddington limit for a 1.4 $M_\odot$ neutron star. This conclusion remains valid unless the galactic center distance is much smaller than 7 kpc.

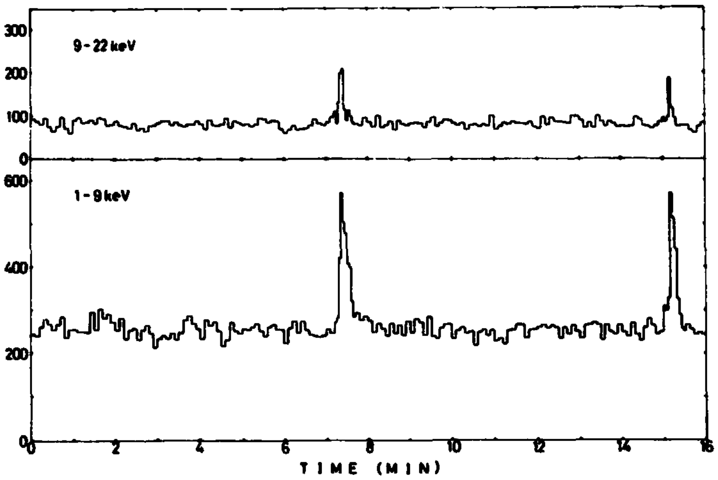

Fig.3 X-ray bursts at 8 min. interval from Terzan 5.

The same can be concluded for a Terzan 2 burst (Grindlay et al. 1980) and for the bursts from NGC 6624 (Clark et al. 1976), the distance to the latter being pretty well estimated.

One might think that the critical luminosity can be exceeded by blowing off the neutron star atmosphere. However, the observational result indicates that the "black-body" radius remains constant from the burst peak through the decay, excluding the expanding photosphere. Strong magnetic field can reduce the Thomson cross section, thereby increase the critical luminosity. This effect is significant only if the field is of the order or greater than 10^{12} Gauss. Why then does the distinct difference in the behavior and the spectral hardness between X-ray pulsars and X-ray bursters exist?

We assess a great significance upon this problem of possible supercritical luminosity. There may very well be physics intrinsic to the superdense photons.

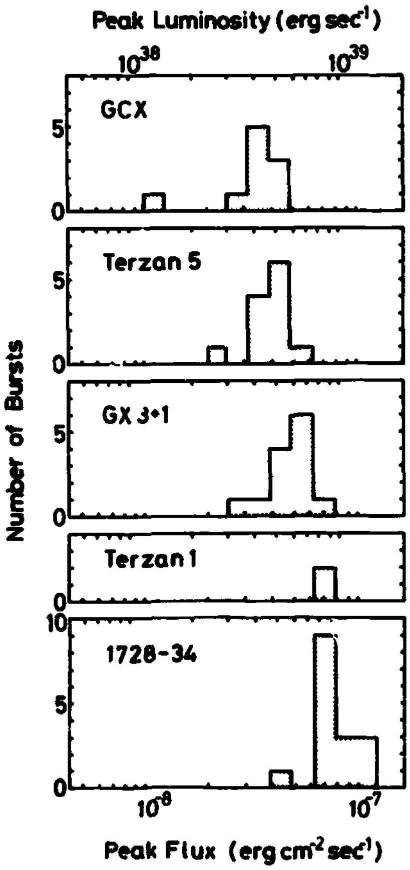

Fig.4 Distributions of burst peak luminosities for five sources near the galactic center.

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iii) The rapid burster

The rapid bursts from MXB 1730-335 are interpreted by Lewin et al. (1976) as due to the chopped accretion flow caused by a certain instability. Fortunately, we met its remarkable behavior in August 1979 (Inoue et al. 1980). By then, the rapid burster produced a long train of bursts with trapezoidal shape. The length of the flat top of these trapezoidal bursts ranged from half a minutes to over 10 minutes. The famous linear relation between the burst size and the time to the next burst still holds for these bursts, implying a reservoir of the capacity in excess of 10^{21} g of matter.

As can be seen in Fig. 5, an important result is that, during th flat top of a trapezoidal burst, the luminosity as well as temperature are kept constant. Hence, the emitting area is also constant. This seems to indicate that the trapezoidat burst itself represents a stationary state. Another stationary state exists, which corresponds to the low level ($\sim$ 1/10 the burst peak) persistent emission that appears between two bursts. We, therefore, revise the picture of the rapid burster that it undergoes rapid switchings between the high and low states rather than a single shot of matter onto the neutron star. However, the mechanisms of the reservoir, switching and controlling the mass flow are key questions to be answered by future study.

In two of the trapezoidal bursts, clear oscillations were discovered. As shown in Fig. 6, the power spectrum for each exhibits a prominent spike at about 0.5 sec. The oscillation does not appear as due to the neutron star revolution, since the observed spikes show a structure and are slightly but significantly different from each other. The origin of this oscillation is unknown.

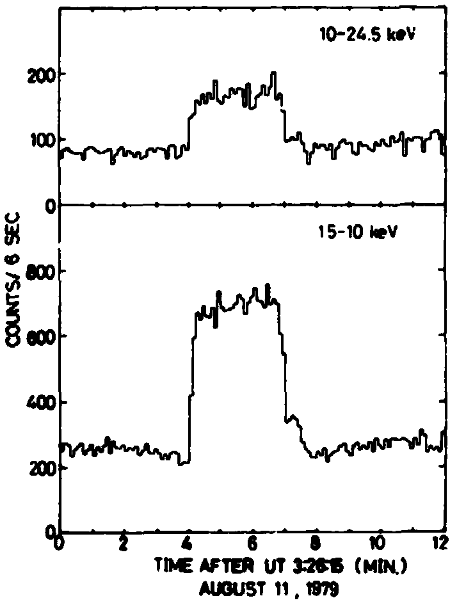

Fig.5 Example of the trapezoidal burst from the rapid burster.

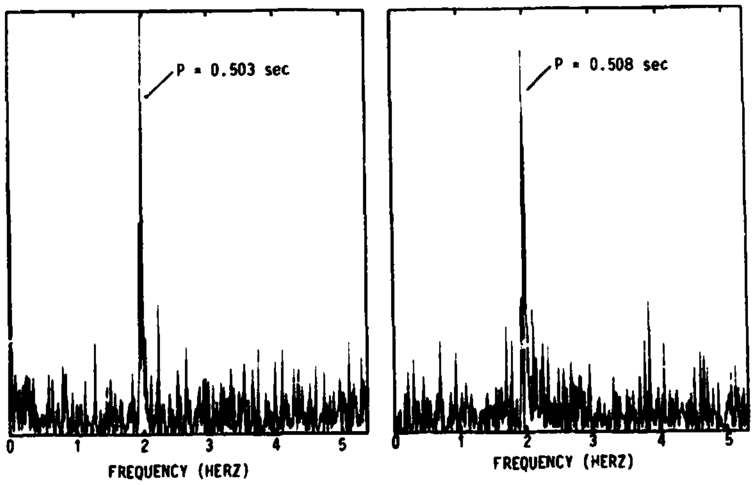

Fig.6 Power spectra for two trapezoidal bursts, for which a prominent spike is seen.

4. Future satellite program

So far, I have briefly covered the crucial problems that the Hakucho observations have put forward concerning neutron star and its system. Following Hakucho, we have two more approved X-ray astronomy missions, ASTRO-B and ASTRO-C. The task of these missions is to better understand the above-described problems and to explore further.

Since the time of the Hakucho launch, the capability of the satellite launch vehicle at ISAS has been steadily increasing. The present ISAS launcher, M-3S, is capable of launching a ∿ 250 kg satellite into a 500 km altitude circular orbit. New development effort has started to upgrade the launch power. The first step is M-3S II which can carry a payload over 400 kg for a 500 km orbit. The second step, M-3S III, would achieve substantial increase of the launch capability over that of M-3S II.

Fig. 7 illustrates the current mission plan at ISAS. Those with solid circles are approved missions to date, whereas those with dashed circles are yet to be approved. Main features of ASTRO-B and ASTRO-C are listed in Table I, in comparison with those of Hakucho.

ASTRO-B weighing 220 kg is due for launch in early 1983, and the flight hardware is presently under fabrication. The main instrument of ASTRO-B is gas scintillation proportional counters with the total area of about 1000 cm^2. Major increase

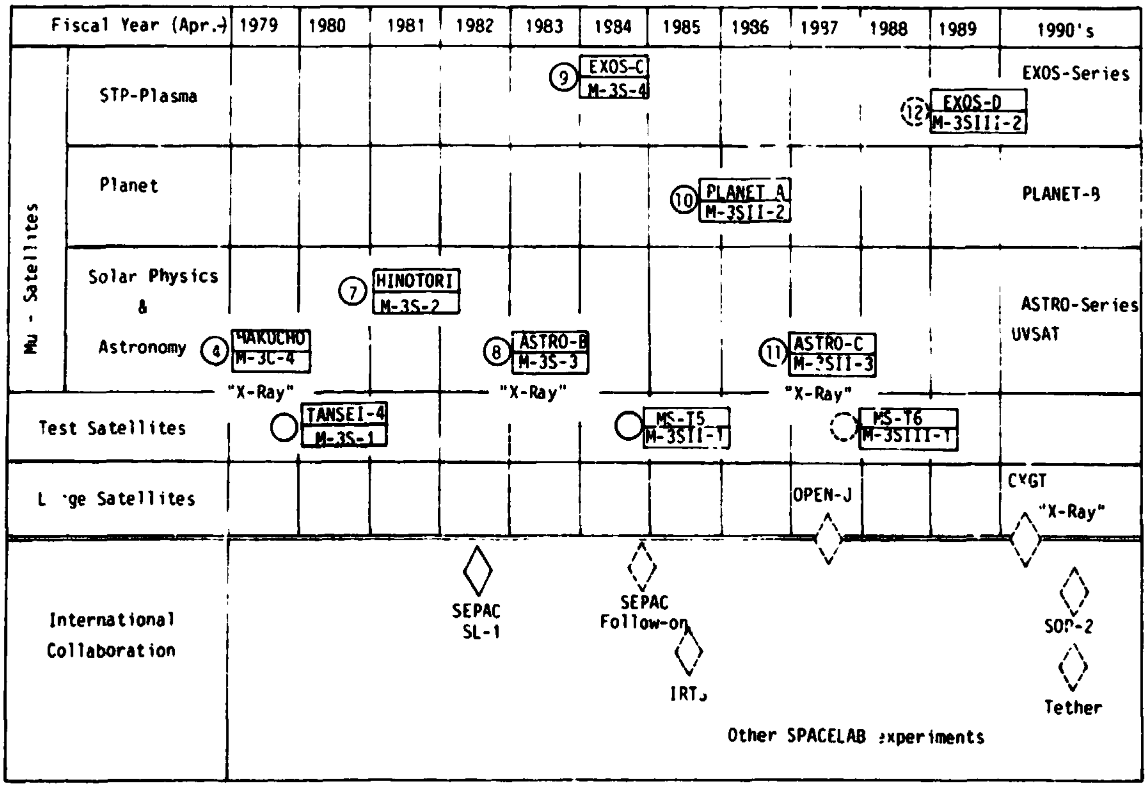

Fig.7 Current mission plan at ISAS for 10 years. The serial number of scientific satellite, mission name and launch vehicle are indicated for each.

as compared to Hakucho is made in the sensitivity as well as in the spectral resolution. ASTRO-B will consequently provide us with much better temporal and spectroscopic information about the galactic sources than we are having from Hakucho. As a significant feature, the energy resolution of the gas scintillation proportional counter which is twice that of the conventional proportional counter would enable us to study the spectral detail and in particular emission lines or absorption features.

ASTRO-C is the follow-on X-ray astronomy satellite scheduled for launch in 1986-87. The spacecraft will be approximately 400 kg in weight and 3-axis stabilized. At present, we are in the biginning of the prototype design phase. The main instrument will be low-background proportional counters with the total area of about 5000 cm^2. Gas scintillation proportional counters may well be a part of it. An all-sky monitor will also be included.

The primary mission objective of ASTRO-C is the study of the time variability. Main emphasis here is not only accurate timing analysis of the galactic sources but the scrutiny of the time variability of active galactic nuclei. Exoticism of active galactic nuclei is immense but yet little is explored. We consider that study of the time variability is of crucial importance of the physics involved in the power house problem.

We hope that the ASTRO-series missions with the improved M-launcher will

Table I. Main features of Hakucho, ASTRO-B and ASTRO-C.

	HAKUCHO	ASTRO-B	ASTRO-C
LAUNCH YEAR	1979	1983	1986-7
WEIGHT (kg)	96	220	~ 400
MAIN INSTRU.	PROP. COUNTER	G.S.P.C.	P.C. (MULTI-CELL)
EFFECTIVE AREA	6° x 6° 80 cm^2 17° x 17° 70 cm^2	3° x 3° 1000 cm^2	~ 1° x 3° ~ 5000 cm^2
SCIENTIFIC OBJECTIVES	◦ WIDE F.O.V. RMC BURST SURVEY ◦ MONITORING SEVERAL SOURCES AT A TIME ◦ SOURCE LOCATION CMC 0.5° FMC 0.05°	◦ SPECTRAL AND TEMPORAL VARIATION OF GALACTIC SOURCES ◦ $\Delta E/E \approx 10\%$ AT 6 keV POWERFUL FOR IRON LINES CYCLOTRON LINES ◦ 1-50 keV IN 128 CH / 0.5 S 32 CH / 0.125 S	◦ TIME VARIATION OF EXTRAGALACTIC & GALACTIC SOURCES ◦ 0.5 μJy SOURCES IN 10 MIN. $\gtrsim$ 300 GALAXIES ◦ SIZE OF ACTIVE GALACTIC NUCLEI ◦ STRUCTURE OF DEGENERATE STARS
AUXILIARY INSTRUEMNTS	◦ SCANNING P.C. 35 cm^2 x 2 1.7° x 37° ◦ SUB-keV X-RAY MONITOR 80 cm^2 x 2 P 80 cm^2 x 2 S	◦ 1-DIM. HADAMARD TEL. 70 cm^2 x 2 20° x 20° ◦ SCANNING P.C. 100 cm^2 x 2 ◦ 1-DIM. REFLECTOR 20 cm^2 x 2	◦ ALL SKY MONITOR $\gtrsim$ 100 μJy $\gtrsim \pi$ STERADIAN

continue through 1990's. Besides this stream, we also envisage to carry out a larger X-ray astronomy mission than the planned capability of the M-launcher. This mission was originally named the Cosmic X-ray and Gamma-ray Telescope (CXGT). Over past years, the concept of CXGT has evolved. As X-ray astrophysics advances, more and more sensitivity and spectroscopic resolution are inevitably needed. It is therefore logical to consider a focusing optics for CXGT.

Finally, I would like to mention that the government level agreement on the U.S.-Japan collaboration programs in space science including X-ray astronomy was made. We very much hope to enhance the tie through possible collaborations in this field.

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