1982ApJ...258..254O

THE ASTROPHYSICAL JOURNAL, **258**:254–259, 1982 July 1

PROPERTIES OF X-RAY BURSTS FROM MXB 1636−53

T. OHASHI, H. INOUE, K. KOYAMA, K. MAKISHIMA, M. MATSUOKA, T. MURAKAMI,
M. ODA, Y. OGAWARA, N. SHIBAZAKI, AND Y. TANAKA
Institute of Space and Astronautical Science, Tokyo, Japan
I. KONDO
Institute for Cosmic Ray Research, University of Tokyo
S. HAYAKAWA, H. KUNIEDA, F. MAKINO, K. MASAI, F. NAGASE, AND Y. TAWARA
Department of Astrophysics, Faculty of Science, Nagoya University
AND
S. MIYAMOTO, H. TSUNEMI, AND K. YAMASHITA
Department of Physics, Faculty of Science, Osaka University
Received 1980 December 22; accepted 1982 January 14

ABSTRACT

MXB 1636−53 was observed from *Hakucho* in four separate periods between 1979 April and July. Its persistent component was at $\sim 1 \times 10^{-9}$ ergs cm^{-2} s^{-1} in June, about half the intensity as observed by *SAS 3* in 1977 January. The X-ray bursts from MXB 1636−53 are found to exhibit a wide variety of profiles from burst to burst, and the peak flux of burst fluctuated by a factor of 6. The blackbody radius in the decay portion of the bursts is consistent to be the same for all the bursts with largely different profiles.

Subject headings: X-rays: bursts — X-rays: sources

I. INTRODUCTION

The detection of X-ray bursts from a 1 × 1° region including 2S 1636−53 was first reported by Swank *et al.* (1976). A further study of bursts from MXB 1636−53 was performed with *SAS 3* (Hoffman, Lewin, and Doty 1977).

We observed MXB 1636−53 with the *Hakucho* satellite during four separate periods between 1979 April 7 and 1979 July 30. MXB 1636−53 was continuously burst-active throughout these observational periods. Forty-two bursts were recorded in 60 days of observation.

In this paper, we present results on the properties of X-ray bursts from MXB 1636−53. The profiles of bursts from MXB 1636−53 are found to vary significantly from burst to burst, and the burst peak luminosity varied by as much as a factor of 6. A remarkable feature is the constancy of the apparent blackbody radius for the bursts from MXB 1636−53 in spite of their largely different profiles, peak luminosities, and total energies.

II. OBSERVATIONAL RESULTS

Observations of MXB 1636−53 were performed with the burst monitor consisting of the coarse and the fine modulation collimator systems (CMC and FMC) on board *Hakucho* (Kondo *et al.* 1981). We shall limit ourselves to the period between 1979 June 20 and July 4, during which MXB 1636−53 was within the field of view of the FMC system. Among 18 bursts recorded in this period, data of 16 bursts are available in two energy bands, 1–9 and 9–22 keV and are analyzed here. During this period, the persistent component of MXB 1636−53 was at a level of $\sim 1 \times 10^{-9}$ ergs cm^{-2} s^{-1} in the range 1–9 keV. Therefore, MXB 1636−53 was in its low-luminosity state during this observation.

Figure 1 shows the profiles of the fifteen bursts in the two energy bands of the FMC-2, displayed in the order of occurrence. One burst of poor statistical quality recorded during the passage of a high background region is excluded. Each burst has been corrected for the aspect and the background. The spectral softening in the decay portion characteristic of type I bursts (Hoffman, Marshall, and Lewin 1978) is evident. As Figure 1 clearly demonstrates, the bursts from MXB 1636−53 exhibit a wide variety of profiles with apparently no preferential occurrence of a specific type of profile. The burst profile can change drastically from burst to burst. This feature is most obvious in the Figures 1*f* through 1*i*. These four bursts of quite different profiles were recorded within one day. There are, however, some bursts which look quite similar to each other. For instance, the bursts shown in Figures 1*a*, 1*c*, 1*g*, and 1*j* have an almost identical profile. They are characterized by a fast rise ($\lesssim 2$ s), a fast fall (*e*-folding decay time ~ 3 s), and also by a comparatively high peak intensity.

In Figure 2, the integrated energy flux of each burst is plotted against its peak energy flux. The energy flux is calculated on the assumption of a blackbody spectrum with no interstellar absorption, based on the *SAS 3* results by Hoffman, Lewin, and Doty (1977). They found that the spectrum for the MXB 1636−53 bursts was in good agreement with a blackbody spectrum and $N_H = (0 \pm 1) \times 10^{22}$ cm^{-2}. The blackbody temperature

1982ApJ...258..254O

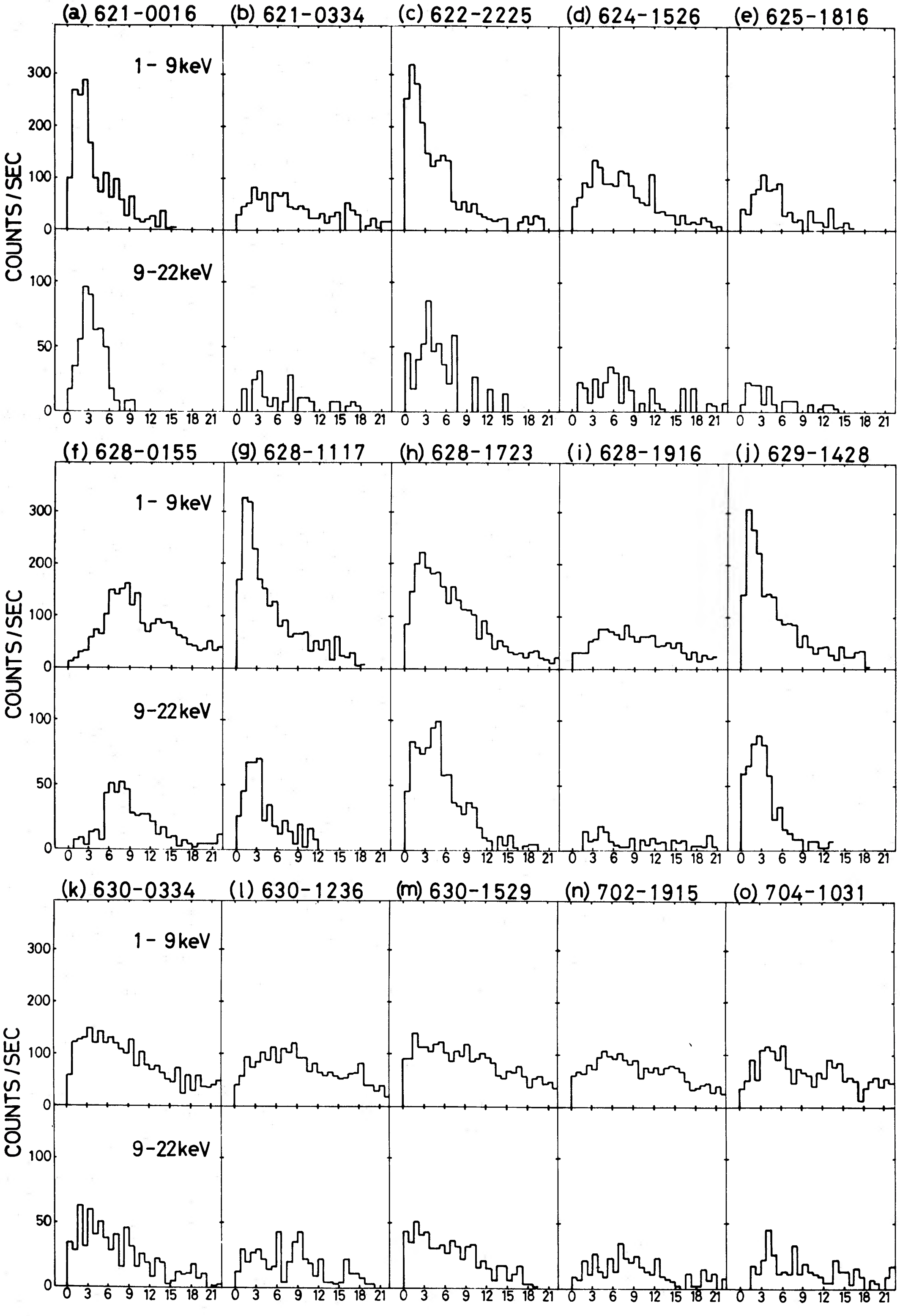

FIG. 1.—Profiles of X-ray bursts from MXB 1636−53 shown in two energy bands, 1–9 and 9–22 keV, of FMC-2. Counting rates are corrected for the aspect and the background. The number above each diagram denotes the occurrence time of burst, e.g., 621-0016 indicates 1979 June 21, 0 hr 16 min UT.

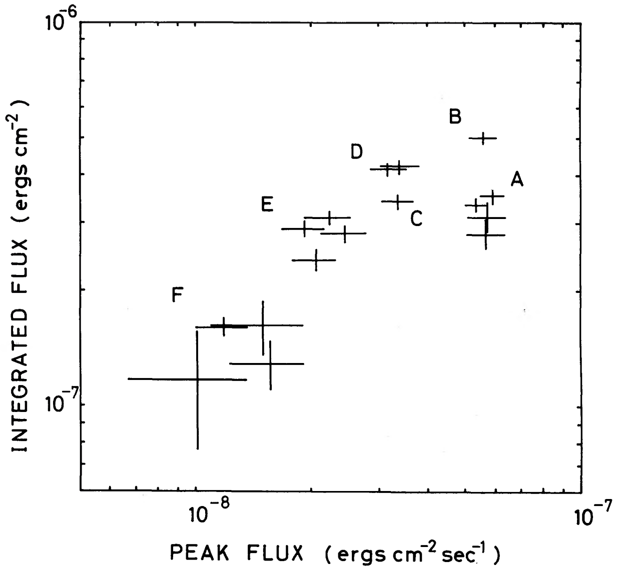

FIG. 2.—Integrated flux vs. peak flux for 16 bursts recorded in 1979 June 20–July 4 with FMC-2. Constituents of six groups are indicated.

and the bolometric correction factor are determined from the measured counting rates in two energy bands. The effect of the uncertainty in the interstellar absorption on the calculated energy flux is negligible. The observed variation of the peak flux is about a factor of 6, whereas the integrated flux varies by about a factor of 4. While a gross positive correlation is evident between the integrated flux and the peak flux, the scatter is too large to show any significant relationship.

For further investigation of the burst properties, we subdivided the fifteen bursts shown in Figure 1 into six groups in such a way that bursts in a group have a similar profile as indicated in Figure 2. A composite profile is produced for the groups which comprise two or more bursts. The constituents of these groups and their characteristics are tabulated in Table 1. The energy flux, blackbody temperature, and the blackbody radius of the emitting region as a function of time are shown for each burst or burst composite in Figure 3. The blackbody radius r is determined from the equation $F = (r/D)^2 \sigma T_b^4$, where F is the energy flux, D the distance, σ the Stephan–Boltzmann constant, and T_b the blackbody temperature, respectively. The errors on the radius are 1 sigma, taking into account the uncertainty in the blackbody temperature. The effect of the amount of interstellar absorption on the calculated blackbody radius was evaluated, and it is found that an addition of $N_H = 1 \times 10^{22}$ cm^{-2} increases the radius by about 5% both at the peak and the decay of burst.

The apparent blackbody radius for group A shows a hump in the burst peak. For the other burst group, there is no significant change in the calculated radius during the burst time evolution.

A χ^2 test shows that the blackbody radius remains constant in the decay portion of the burst for all groups with better than 90% confidence. The values of $\chi^2_{\min}$ per degree of freedom and the best-fit radii with associated uncertainties are given in Table 1. However, if one includes the peak of burst, the hypothesis of a constant blackbody radius is rejected for group A, due obviously to the presence of a hump at the burst peak. On the other hand, there exists no significant change in the blackbody radius throughout the burst for groups B–F with 90% confidence.

The best-fit radii in the decay portions of burst for groups A–F are all consistent with a constant value. As a matter of fact, another χ^2 test reveals that a single blackbody radius fits all the bursts in groups A–F with more than 90% confidence. We therefore conclude that the apparent blackbody radius, at least in the decay portion of the bursts, is consistent with being a constant independent of the burst peak luminosity and profile. The best-fit blackbody radius and its uncertainty for 90% confidence are (9.5 ± 1.0) (D/10 kpc) km.

We notice the presence of a flat peak in the luminosity. This feature is more pronounced for the bursts with higher peak luminosities as seen in the top diagrams of

TABLE 1

PROPERTIES OF BURST COMPOSITES

Group	Constituents[a]	Peak Flux[b] (10^{-8} ergs cm^{-2} s^{-1})	Integrated Flux (10^{-7} ergs cm^{-2})	*e*-Folding Decay[c] (s)	Duration[d] (s)	χ_r^2 [e]	Blackbody Radius at $D = 10$ kpc (km)
A	(a), (c), (g), (j)	5.7 ± 0.3	3.2 ± 0.1	~3	5.6 ± 0.3	0.26	9.3 ± 1.3
B	(h)	5.6 ± 0.5	5.0 ± 0.2	~5	8.9 ± 0.9	0.65	9.4 ± 1.2
C	(f)	3.4 ± 0.3	3.4 ± 0.1	~7	10.0 ± 0.9	1.10	9.8 ± 1.1
D	(k), (m)	3.3 ± 0.3	4.2 ± 0.1	~11	12.7 ± 1.2	0.69	9.1 ± 1.1
E	(d), (l), (n), (o)	2.2 ± 0.1	2.8 ± 0.1	~11	12.7 ± 0.7	1.39	9.8 ± 1.0
F	(b), (e), (i)	1.4 ± 0.2	1.5 ± 0.1	~10	10.7 ± 1.7	0.49	9.2 ± 1.5

[a] See Fig. 1.

[b] Peak flux is obtained by averaging the energy flux over 2.3 s at the peak.

[c] *e*-folding decay time denotes the approximate decay constant of the energy flux.

[d] Duration is defined by the integrated flux divided by the peak flux.

[e] χ_r^2 is the minimum χ^2-value per degrees of freedom (see text).

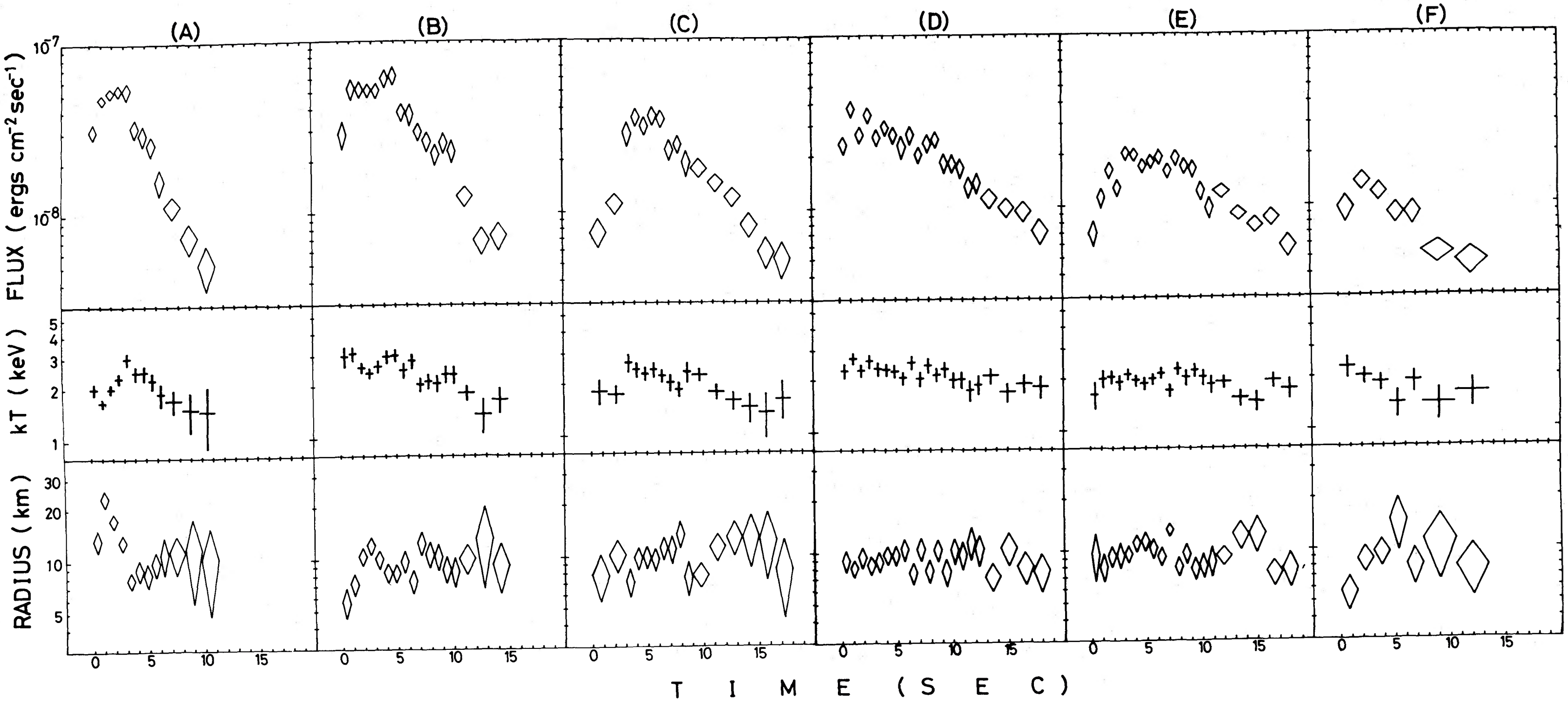

FIG. 3.—Bolometric energy flux, "blackbody" temperature, and "blackbody" radius at a distance 10 kpc plotted as a function of time for six groups of bursts or burst composites.

1982ApJ...258..254O

Figure 3. Furthermore, Figure 2 shows that the measured peak fluxes of all five bursts in groups A and B agree with each other within statistical uncertainties.

III. DISCUSSION

MXB 1636 − 53 is found remarkable in the present observation in that the bursts from this source exhibit widely different profiles. The burst peak flux fluctuated by as large as a factor of 6. Similar fluctuations of the burst peak flux were reported for MXB 1735 − 44 (Lewin *et al.* 1980) and for 1608 − 522 (Murakami *et al.* 1980). The rise and the decay times of the bursts from MXB 1636 − 53 were also variable from burst to burst. The rise time spread from $\lesssim 1$ s to $\gtrsim 5$ s. The shortest decay time was about 3 s (*e*-folding time), while the longest one exceeded 10 s (see Table 1). Variation of the burst profile was also noted in 1608 − 522 but in a different manner than MXB 1636 − 53 (Murakami *et al.* 1980). This source revelaed two distinct episodes in 1979; bursts in one episode were almost all of fast rise and fast fall, whereas in the other, all bursts were of slow rise and slow fall. However, MXB 1636 − 53 is the first to show an irregular and abrupt change of the burst profile as best demonstrated by four bursts observed on June 28 (see Figs 1*f*–1*i*). This change of the burst profile is not related to the persistent flux variation, because the persistent flux remained constant through these days within the statistical uncertainties.

Hoffman, Lewin, and Doty (1977) reported that, among six bursts from MXB 1636 − 53 observed with *SAS 3*, five bursts were quite similar in profile, but one burst looked unusual. This unusual burst lacked a narrow intense peak at lower energies and was significantly smaller in total energy than others. This burst occurred only 2.7 hr after the preceding burst, much shorter than other burst intervals ranging from 9.5 hr to 12.2 hr. A similar feature was noted in the present observation. The mean burst interval in the period 1979 June 20–July 4 was about 240 min for net observation time, the shortest interval being 92 min. During the same period, there were four bursts that occurred about 100 min after a preceding burst. These four bursts were all below 2×10^{-7} ergs cm^{-2} in integrated flux (total energy), the smallest four among 16 bursts recorded in this period (see Fig. 2). The average total energy of the four bursts with ~ 100 min interval is about 1.4×10^{-7} ergs cm^{-2}, which is significantly smaller than the average for all the 16 bursts including these four, 2.8×10^{-7} ergs cm^{-2}. Due to a rather sparse and intermittent coverage of the source, it is difficult to make a detailed comparison between the burst energy and interval for each burst. However, these facts suggest that the bursts which occurred at unusually short intervals tend to be small in the burst energy.

Hoffman, Lewin, and Doty (1977) found that the apparent blackbody radius remained constant (within a factor of 2) as the blackbody temperature decreased with time. They derived the blackbody radius to be (11 ± 4) (*D*/10 kpc) km. Van Paradijs (1978) showed that the blackbody radii for 10 burst sources including MXB 1636 − 53 did not change significantly throughout the burst decay and were essentially the same for all the 10 burst sources. He obtained for MXB 1636 − 53 the blackbody radius to be (7.4 ± 1.2) km at a distance of (4.5 ± 0.4) kpc, assuming the burst peak luminosity to be equal to the Eddington limit for 1.4 $M_\odot$.

The present result for the burst MXB 1636 − 53 confirms the constancy of the blackbody radius throughout the burst decay. The blackbody radius we derived, (9.5 ± 1.0) (*D*/10 kpc) km, is consistent with the *SAS 3* results, supporting the idea that a neutron star is involved. Moreover, it is to be emphasized that the blackbody radius in the decay reveals one and the same value within statistical uncertainties for all the bursts with largely different profiles, peak luminosities, and total energies.

According to the current nuclear flash model of type I bursts (Joss 1979 and references therein), the peak luminosity is expected to become close to the Eddington limit, whereas the observed large fluctuation of the burst peak luminosity suggests that the Eddington limit for a spherical emission does not apply. The observed constancy of the blackbody radius in the decay portions of bursts for groups A–F does not support a nonspherical emission or an emission from a fraction of the neutron star surface for explaining the large fluctuation. Even if one includes the peak of burst, there appears no significant deviation from a constant blackbody radius throughout the bursts for groups B–F as demonstrated in Figure 3. It is most plausible that the emission of bursts is spherical involving the whole neutron star surface.

The blackbody radius for the group A undergoes an increase during the burst peak to roughly 3 times the value derived for the decay part. This effect appeared significant only for those bursts of fast rise and fast decay and with the highest peak luminosities. Swank *et al.* (1977) reported a similar effect in a long burst most probably from Terzan 2. They obtained (100^{+60}_{-20}) (*D*/10 kpc) km at the peak intensity during the first 20 s and ~ 15 (*D*/10 kpc) km for the remainder of the burst.

It is interesting to point out that a radial expansion of an outer layer may occur if a hydrogen envelope, which is of sufficiently small mass yet optically thick for electron scattering, is present above the helium burning shell. This hydrogen envelope could be driven to some radial distance from the surface by the radiation pressure of the helium shell whose Eddington luminosity is twice that for hydrogen envelope (Hayashi, Hoshi, and Sugimoto 1962). The observed increase of the blackbody radius in the burst rise for group A may be interpreted this way.

On the other hand, the energy spectrum of bursts involves some problems to be investigated. Swank, Eardley, and Serlemitsos (1979) discussed the influence of electron scattering to the blackbody spectrum. Van Paradijs *et al.* (private communication from D. Q. Lamb, 1980) deal with the modification of the spectrum in the presence of a radial temperature gradient within the neutron star envelope as well as the effect of Comptonization. In view of these problems, it may be premature to relate the apparent blackbody radius to the actual physical size, until the emission spectrum from the neutron star envelope is solved in a self-consistent manner.

REFERENCES

Hayashi, C., Hoshi, R., and Sugimoto, D. 1962, *Prog. Theor. Phys. Japan, Suppl.*, No. 22.

Hoffman, J. A., Lewin, W. H. G., and Doty, J. 1977, *Ap. J.* (*Letters*), **217**, L23.

Hoffman, J. A., Marshall, H. L., and Lewin, W. H. G. 1978, *Nature*, **271**, 630.

Joss, P. C. 1979, in *Proc. 9th Texas Symposium, Ann. NY Acad. Sci.*, **336**, 479.

Kondo, I., *et al.* 1981, *Space Sci. Instr.*, **5**, 211.

Lewin, W. H. G., Van Paradijs, J., Cominsky, L., and Holzner, S. 1980, *M.N.R.A.S.*, **193**, 15.

Murakami, T., *et al.* 1980, *Ap. J.* (*Letters*), **240**, L143.

Swank, J. H., Becker, R. H., Boldt, E. A., Holt, S. S., Pravdo, S. H., and Serlemitsos, P. J. 1977, *Ap. J.* (*Letters*), **212**, L73.

Swank, J. H., Becker, R. H., Pravdo, S. H., Saba, J. R., and Serlemitsos, P. J. 1976, *IAU Circ.*, No. 3000.

Swank, J. H., Eardley, D. and Serlemitsos, P. J. 1979, *Ap. J.* (*Letters*), submitted.

Van Paradijs, J. 1978, *Nature*, **274**, L11.

H. Inoue, K. Koyama, K. Makishima, M. Matsuoka, T. Murakami, M. Oda, Y. Ogawara, T. Ohashi, N. Shibazaki, and Y. Tanaka: Institute of Space and Astronautical Science, 4-6-1, Komaba, Meguro-ku, Tokyo 153, Japan

S. Hayakawa, H. Kunieda, F. Makino, K. Masai, F. Nagase, and Y. Tawara: Department of Astrophysics, Faculty of Science, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464, Japan

I. Kondo: Institute for Cosmic Ray Research, University of Tokyo, 3-2-1, Midori-cho, Tanashi, Tokyo 188, Japan

S. Miyamoto, H. Tsunemi, and K. Yamashita: Department of Physics, Faculty of Science, Osaka University, 1-1, Machikaneyama, Toyonaka 560, Japan