Publ. Astron. Soc. Japan **39**, 879–886 (1987)

0.65-Second Oscillation at the Peak of an X-Ray Burst from X 1608−522

Toshio MURAKAMI and Hajime INOUE

Institute of Space and Astronautical Science, 6–1 Komaba 4-chome, Meguro-ku, Tokyo 151

Kazuo MAKISHIMA

Department of Physics, Faculty of Science, University of Tokyo, Bunkyo-ku, Tokyo 113

and

Reiun HOSHI

Department of Physics, Rikkyo University, Nishi-Ikebukuro 3-chome, Toshima-ku, Tokyo 171

(Received 1987 April 20; accepted 1987 August 24)

Abstract

A 0.65-s period oscillation was detected near the peak of an X-ray burst from X 1608−522. The burst exhibits a clear photospheric expansion at the peak flux which is probably at the Eddington limit of the underlying star. The 0.65-s oscillation was seen in the contracting phase during which the flux stayed at the maximum value. An anticorrelation between counts in the low- and high-energy bands was observed during the oscillation. This can be interpreted as a radial oscillation of the envelope which was radiating at the Eddington luminosity.

Key words: Bursts; Oscillations; QPOs; X-Ray sources.

1. Introduction

During the past ten years the study of X-ray burst sources has progressed remarkably both in observation and theory (Lewin and Joss 1983; Joss and Rappaport 1984; Tanaka 1986, and references therein). In particular, it has been revealed that in some bursts their peak luminosities saturate at the Eddington limit with photospheric expansion (Tawara et al. 1984; Lewin et al. 1984; Inoue et al. 1984). The behavior of the photospheric expansion can now be well understood through studies of a neutron star envelope radiating at the Eddington luminosity (Ebisuzaki et al. 1983; Kato 1983; Sugimoto et al. 1984; Tawara et al. 1984; Paczyński and Prószyński 1986).

In a burst from X 1608−522 a 0.65-s oscillation was detected at the peak of the burst luminosity but in the contracting phase of the photosphere. The presence of oscillations in X-ray bursts has been pointed out by several authors (Hoffman et al. 1979; Sadeh et al. 1982; Tawara et al. 1982). Some theoretical works predict oscillations of an expanding atmosphere with increasing period which are driven by radiation pressure (Yahel et al. 1984) and in an envelope being in the course of thermonuclear flash at its base (Starrfield et al. 1982).

In this paper we present clear evidence of oscillations in an X-ray burst from X 1608−522 observed with the X-ray astronomy satellite Hakucho. Careful analysis of the burst data provides us with a clue that the neutron star envelope oscillates at a period of 0.65 s, whereas the total bolometric luminosity stays at a constant level. Such oscillations are not easily reconciled with theoretical predictions, since they require an oscillation of the luminosity as well as the radial pulsation. We discuss implications of the observed radial oscillation of a neutron star envelope with a radiative flux close to the Eddington limit. A possible model for the radial oscillation is also suggested.

2. Observations and Results

Hakucho monitored the region from Norma to Serpens along the galactic plane, as a part of a survey program of X-ray burst activity, from April to September in 1980. During this period, more than 100 X-ray bursts were recorded by the CMC detectors with a wider field of view of 17°4 (FWHM) and equipped with a pair of coarse modulation collimators to locate burst sources. Among these, 22 bursts were found to come from X 1608−522. The X-ray burst source X 1608−522, was in a burst active phase such as in 1979 (Murakami et al. 1980) throughout this observation period. However, the persistent X-ray flux was as low as 0.05 Crab (1–9 keV).

Among these 22 bursts from X 1608−522, an X-ray burst observed at 17h 05m 14s (UT) on April 8 showed a unique character. An oscillation in X-ray counts during the peak of the burst was observed. Analysis of this burst was performed using the data from the FMC detector which has a better signal-to-noise ratio compared to the CMC detector because of the narrower field of view of 5°8 (FWHM). The energy ranges of FMC were 1–9 keV and 9–22 keV for the low- and the high-energy channels, respectively, during these observations. More details of the instrumentation and the method of burst observations are found in Kondo et al. (1981).

a. *Period of Oscillations*

The raw counting rate histograms of the burst (not corrected for aspect) on April 8 are shown in figure 1 with a time resolution of 0.75 s in two energy bands. The higher energy band shows a double peaked structure. Figure 2 shows the first 18 s of this X-ray burst with a fine time resolution of 0.1875 s. We notice an oscillation in counts at the peak of the X-ray burst. In order to quantify this variability and to investigate the possibility of coherent periodicity, we carried out a Fourier power spectrum analysis for the data indicated by the arrow in figure 2. We prewhitened the data by subtracting the DC component. We see in the power spectrum shown in figure 3, a clear peak at a period 0.67 s. A chi-square test, by folding the data in the

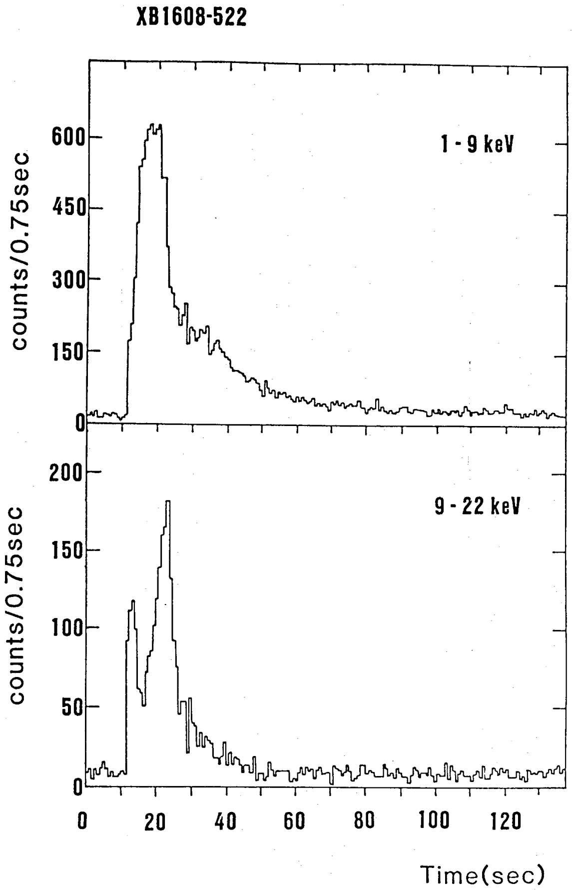

Fig. 1. The raw counting rate histograms (not corrected for the aspect) of the burst from X 1608−522 observed on April 8 with 0.75-s time binning. The upper and lower panels are counting rates for the energy bands of 1–9 and 9–22 keV, respectively.

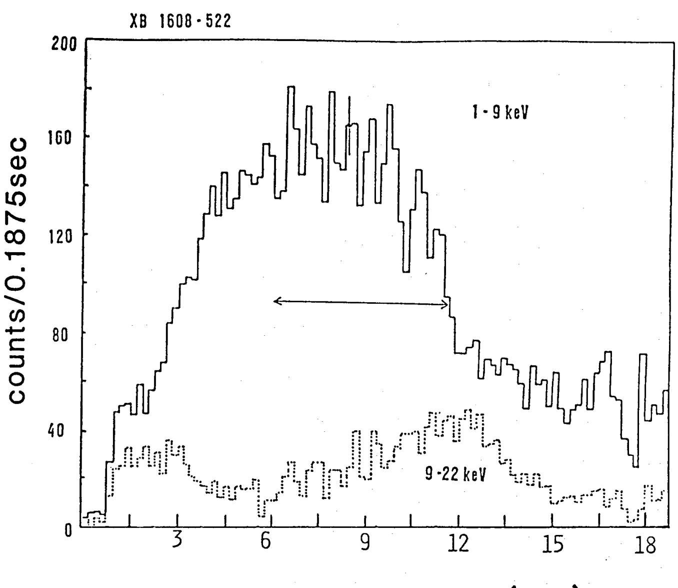

Fig. 2. The raw counting rate histograms of the first 18 s of figure 1 with a fine resolution of 0.1875 s. The oscillations around the peak of the burst are clearly seen. The horizontal arrow shown in the figure indicates the data interval used for the Fourier analysis shown in figure 3 and for the two-color diagram in figure 6.

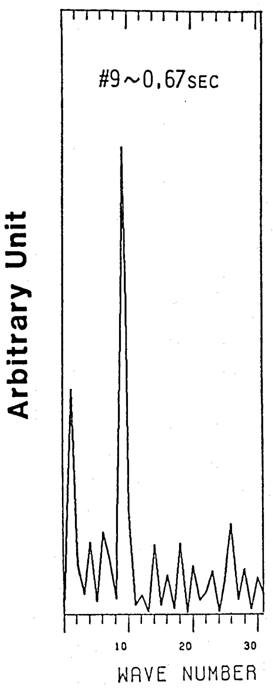

Fig. 3. The Fourier power spectrum of the 6-s interval of data shown by the arrow in figure 2. The wavenumber 9 corresponds to 0.67 s in period. The data were prewhitened by subtracting a DC component before Fourier analysis.

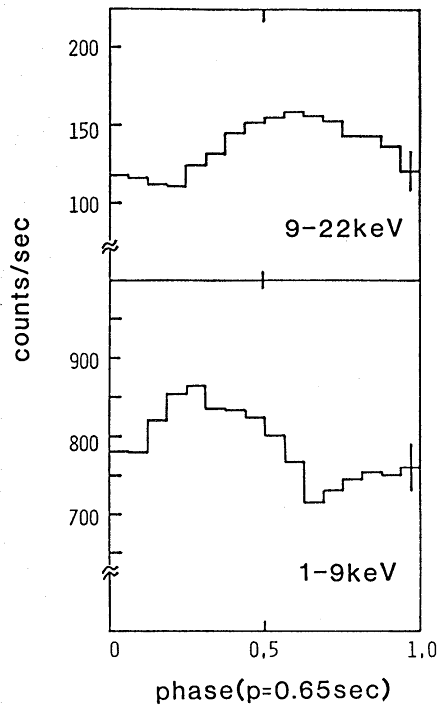

Fig. 4. The folded light curves of the raw counts with the period of 0.65 s in two energy bands. The phase lag of about 1/2 period between the low- and the high-energy bands is clear. The time resolution of observations is coarser than the phase binning, so that these folded light curves may be smeared.

low-energy band, also yields 0.65±0.03 s (FWHM) as the most likely period, with a reduced chi-square value of 3.2 (d.o.f.=7). The light curves in two energy bands folded with the 0.65-s period are plotted in figure 4 for the same data. There was no significant periodicity in any other portion of the data, including the steady X-ray component, except in the contracting phase indicated by the arrow in figure 2. Note that the time resolution of the observation is coarser than the phase binning of figure 4, so that these folded light curves may be smeared.

b. Temperature and Flux

Using the light curves in two energy bands shown in figure 2 and assuming a blackbody spectrum from a spherical surface (Swank et al. 1977; Hoffman et al. 1979), we calculated the bolometric flux, the blackbody temperature, and the radius for the burst. The results are shown in figure 5. The hydrogen column density used in this analysis is 1.8×10^{22} $N_{\rm H}$ cm^{-2} which was derived from an analysis of X-ray bursts from the same source observed by the Tenma satellite (Nakamura et al. 1988). Figure 5 shows a clear photospheric expansion as the luminosity approaches the maximum value.

The oscillation is noticeable only in the relatively slow contracting phase of the

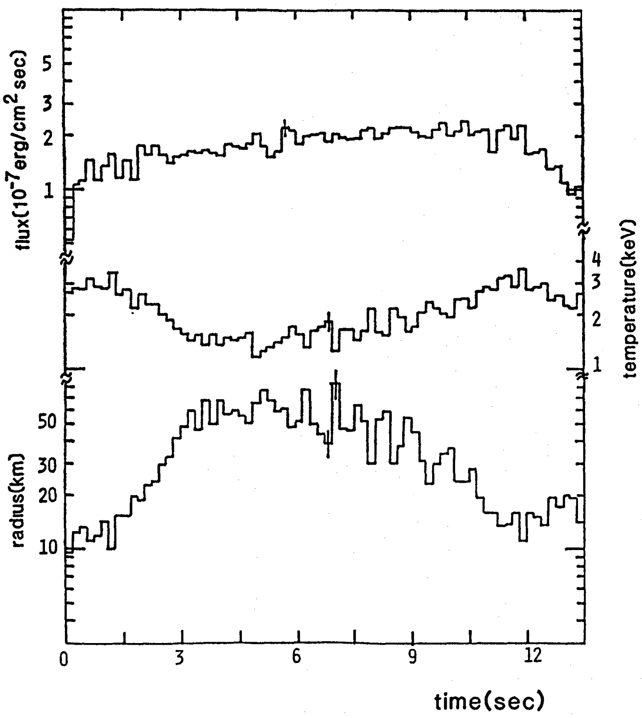

Fig. 5. Assuming a blackbody spectrum and a spherical emission, the bolometric flux, the blackbody temperature, and the radius for an assumed distance of 10 kpc are shown with 0.1875-s time bins. During the contraction phase of the burst, the radial oscillation is distinct.

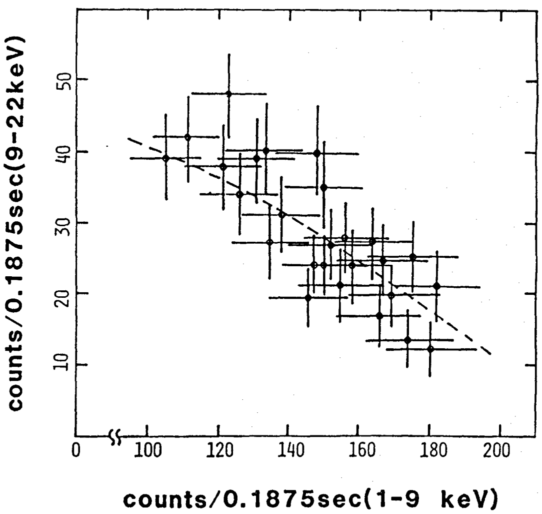

Fig. 6. Counts between low- and high-energy bands with a time resolution of 0.1875 s plotted in the two color diagram for the data indicated by the arrow in figure 2. The dashed line in the figure indicates a relation expected when a spherical blackbody changes its radius while keeping a constant luminosity.

envelope, while the luminosity is still near the peak level. As found from figure 4, the relative phases of the oscillations in the two energy bands seem to be shifted by about half a period. This is better seen in figure 6, which is a correlation plot between high-energy channel counts vs. low-energy channel counts, with 0.1875-s time resolution. A clear anticorrelation is seen in this figure. The cross product $\langle (x-\langle x\rangle) \times (y-\langle y\rangle)\rangle$ is calculated to be -154.6 (counts/bin)^2, while the standard deviation expected from the Poisson distribution is 38.3 (counts/bin)^2. Hence, the anticorrelation is significant at about a 4σ level. The dashed curve in figure 6 indicates the relation between the counts in the two energy bands expected when a spherical blackbody changes its radius while keeping a constant luminosity. This analysis implies that the observed oscillation is consistent with radial oscillation of a spherical envelope radiating with a constant luminosity. In fact, the result of the blackbody analysis in figure 5 is also indicative of a radial oscillation with a relatively large and constant amplitude.

3. Discussion

The burst discussed here shows a clear photospheric expansion. The peak flux is almost the same within the uncertainties as the highest peak flux of burst from X 1608−522 observed with Tenma (Nakamura et al. 1988). The overall changes in the temperature and the radius during the peak of the luminosity are also very similar to those bursts having the highest peak flux observed from X 1608−522 with Tenma (Nakamura et al. 1988). Thus, we conclude that the peak flux of this burst is at the Eddington limit of the underlying neutron star. Using the Eddington luminosity, we can estimate the distance to this X-ray source to be about 3.5 kpc.

We have detected a 0.65-s oscillation during the period when the flux is almost at the Eddington limit. Figures 5 and 6 are consistent with an oscillation of a blackbody radiating with constant luminosity. These facts suggest a radial oscillation of the envelope with a 0.65-s periodicity during the contracting phase of an envelope radiating at the Eddington luminosity.

In the current theory, X-ray bursts are due to thermonuclear flashes at the base of the accreted matter on the neutron star surface. In large bursts the released nuclear energy is deposited in the accreted matter (envelope) as internal energy, since the luminosity saturates at the Eddington limit. Hence the envelope expands appreciably. In such an envelope, the ratio of specific heats, γ, is close to 4/3. It is known that a supermassive star with $\gamma \sim 4/3$ is dynamically unstable due to a general relativistic effect (Chandrasekhar 1964); this implies a similar instability at a certain evolutionary stage of the expanding envelope.

In the following, we derive the stability condition for the above-mentioned envelope from energetic considerations. Since the envelope is totally supported by the hard neutron star surface, in the computation of the internal energy the integration is carried out from the neutron star surface to the surface of the envelope, in contrast to calculations for a supermassive star (where the integration is carried out from the center to the surface). This difference adds an extra term in our case, the last terms in equations (1) and (3). Here, we consider an idealized situation that the neutron star is a hard sphere on which the envelope is piled up. When the luminosity is close to the Eddington limit, the ratio of gas pressure to total pressure is small, $\beta \ll 1$ or $\gamma-(4/3)=\beta/6 \ll 1$ except for the bottom region of the envelope. Under the above assumptions and post-Newtonian approximation the total energy of the envelope is given by

$$E_{\mathrm{env}}=\left[-\left(\frac{\bar{\beta}}{4}\right)\left(\frac{R_{\mathrm{g}}}{\bar{r}}\right)+\frac{5a}{8}\left(\frac{R_{\mathrm{g}}}{\bar{r}}\right)^2-\frac{b}{2}\left(\frac{R_{\mathrm{g}}}{\bar{r}}\right)\left(\frac{R}{\bar{r}}\right)^3\left(1+\frac{R_{\mathrm{g}}}{R}\right)\right]mc^2\,, \quad (1)$$

where R_{g} and R are the Schwarzschild radius and radius of a neutron star, and $\bar{\beta}$ and $\bar{r}$ are the mean values over the envelope defined as

$$\bar{\beta}=\int\beta\, udm\Big/\int udm\,, \qquad \frac{1}{\bar{r}}=\frac{1}{\Delta m}\int\frac{dm}{r}\,. \quad (2)$$

Here, u is the specific internal energy, $\Delta m=\int dm$ is the mass of the envelope, r is the radial distance from the center of the neutron star, and a and b are structure factors of order unity which depend on the structure of the envelope. In deriving this equation we assumed $\beta \ll 1$. The envelope is dynamically unstable when $dE_{\mathrm{env}}/d\bar{r}<0$. This gives

$$\bar{\beta}<5a\left(\frac{R_{\mathrm{g}}}{\bar{r}}\right)-8b\left(\frac{R}{\bar{r}}\right)^3\left(1+\frac{R_{\mathrm{g}}}{R}\right), \quad (3)$$

where we have assumed that the structure factors a and b have weak dependences on $\bar{r}$. The existence of a hard neutron star surface stabilizes the envelope through the last terms in equations (1) and (3). When the envelope becomes unstable, it follows practically adiabatic contraction or expansion, since in our case the observed oscillation period is shorter than the duration of the burst. Thus, $\bar{\beta}$ remains almost constant during the contraction or expansion, because the entropy is a function of $\bar{\beta}$ and the logarithm of the temperature. For a constant $\bar{\beta}$, as seen from equation (3), the envelope is stabilized at large and small $\bar{r}$. The overshoot and following bounce in the stabilized state would develop into a limit cycle. However, overall changes of the structure in the contraction phase makes the limit cycle terminate when it is totally stable. This may account for the rather rapid growth and extinction of the observed oscillation. According to Ebisuzaki et al. (1983), mass from the outer envelope is lost at a rate of 10^{18} g s^{-1} in the expanding phase of the envelope. The time scale for matter to pass the unstable region may be shorter than the growth time of the instability (0.65 s). This explains why no oscillation is observed in the expanding phase of the burst. In the contracting phase, however, the rate of mass loss is so weak that the instability grows to oscillation with a fairly large amplitude. A theoretical study of the stability of the contracting envelope of a neutron star radiating at the Eddington luminosityis necessary to confirm this speculation.

Quasi-periodic oscillations (QPO) have been discovered from several bright low-mass binary X-ray sources (van der Klis et al. 1985; Lewin 1986; and references therein). Although a beat frequency model has been proposed by Alpar and Shaham (1985) and Lamb et al. (1985) [see also Lewin (1986) and references therein], the mechanism of QPOs is still open to future study. The QPOs are observed from low-mass binary X-ray sources as luminous as 10^{38} erg s^{-1} which is close to the Eddington limit of a canonical neutron star. X-ray bursts are also detected from low-mass binary X-ray sources with burst peak luminosities often close to the Eddington limit.

These similarities suggest that they may share the same mechanism. If the observed oscillations during type-I bursts from X 1608−522 are, in fact, OPQs, then this would cast serious doubt on all magnetospheric models of QPOs which rely on the interaction of accreting matter with a magnetosphere.

The authors thank S. Hayakawa of Nagoya University for helpful comments on the manuscript.

References

Alpar, M. A., and Shaham, J. 1985, *Nature*, **316**, 239.
Chandrasekhar, S. 1964, *Astrophys. J.*, **140**, 417.
Ebisuzaki, T., Hanawa, T., Sugimoto, D. 1983, *Publ. Astron. Soc. Japan*, **35**, 17.
Hoffman, J. A., Lewin, W. H. G., Primini, F. A., Wheaton, W. A., Swank, J. H., Boldt, E. A., Holt, S. S., Serlemitsos, P. J., Share, G. H., Wood, K., Yentis, D., Evans, W. D., Matteson, J. L., Gruber, D. E., and Peterson, L. E. 1979, *Astrophys. J. Letters*, **233**, L51.
Inoue, H., Waki, I. Koyama, K., Matsuoka, M., Ohashi, T., Tanaka, Y., and Tsunemi, H. 1984, *Publ. Astron. Soc. Japan*, **36**, 831.
Joss, P. C., and Rappaport, S. A. 1984, *Ann. Rev. Astron. Astrophys.*, **22**, 537.
Kato, M. 1983, *Publ. Astron. Soc. Japan*, **35**, 33.
Kondo, I., Inoue, H., Koyama, K., Makishima, K., Matsuoka, M., Murakami, T., Oda, M., Ogawara, Y., Ohashi, T., Shibazaki, N., Tanaka, Y., Hayakawa, S., Kunieda, H., Makino, F., Masai, K., Nagase, F., Tawara, Y., Miyamoto, S., Tsunemi, H., Yamashita, K., and Yoshimori, M. 1981, *Space Sci. Instrum.*, **5**, 211.
Lamb, F. K., Shibazaki, N., Alpar, M. A., and Shaham, J. 1985, *Nature*, **317**, 681.
Lewin, W. H. G. 1986, in *The Physics of Accretion onto Compact Objects*, ed. K. O. Mason, M. G. Watson, and N. E. White (Springer-Verlag, Berlin), p. 177.
Lewin, W. H. G., and Joss, P. C. 1983, in *Accretion-driven Stellar X-ray Sources*, ed. W. H. G. Lewin and E. P. J. van den Heuvel (Cambridge University Press, Cambridge), p. 41.
Lewin, W. H. G., Vacca, W. D., and Basinska, E. M. 1984, *Astrophys. J. Letters*, **277**, L57.
Murakami, T., Inoue, H., Koyama, K., Makishima, K., Matsuoka, M., Oda, M., Ogawara, Y., Ohashi, T., Shibazaki, N., Tanaka, Y., Tawara, Y., Hayakawa, S., Kunieda, H., Makino, F., Masai, K., Nagase, F., Miyamoto, S., Tsunemi, H., Yamashita, K., and Kondo, I. 1980, *Astrophys. J. Letters*, **240**, L143.
Nakamura, N., Dotani, T., Inoue, H., Mitsuda, K., Tanaka, Y., and Matsuoka, M. 1988, submitted to *Publ. Astron. Soc. Japan.*
Paczyński, B., and Prószyński, M. 1986, *Astrophys. J.*, **302**, 519.
Sadeh, D., Byram, E. T., Chubb, T. A., Friedman, H., Hedler, R. L., Meekins, J. F., Wood, K. S., and Yentis, D. Y. 1982, *Astrophys. J.*, **257**, 214.
Starrfield, S., Kenyon, S., Sparks, W. M., and Truran, J. W. 1982, *Astrophys. J.*, **258**, 683.
Sugimoto, D., Ebisuzaki, T., and Hanawa, T. 1984, *Publ. Astron. Soc. Japan*, **36**, 839.
Swank, J. H., Becker, R. H., Boldt, E. A., Holt, S. S., Pravdo, S. H., and Serlemitsos, P. J. 1977, *Astrophys. J. Letters*, **212**, L73.
Tanaka, Y. 1986, in *The Origin and Evolution of Neutron Stars, IAU Symp. No. 125*, ed. D. J. Helfand and J.-H. Huang (Reidel, Dordrecht), p. 161.
Tawara, Y., Hayakawa, S., Kunieda, H., Makino, F., and Nagase, F. 1982, *Nature*, **299**, 38.
Tawara, Y., Hirano, T., Kii, T., Matsuoka, M., and Murakami, T. 1984, *Publ. Astron. Soc. Japan*, **36**, 861.
van der Klis, M., Jansen, F., van Paradijs, J., Lewin, W. H. G., van den Heuvel, E. P. J., Trümper, J. E., and Sztajno, M. 1985, *Nature*, **316**, 225.
Yahel, R. Z., Brinkmann, W., and Braun, A. 1984, *Astron. Astrophys.*, **139**, 359.