X-RAY BURSTING NEUTRON STARS

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ABSTRACT. The maximum peak luminosity of the X-ray bursts from a burster is most likely interpreted as the Eddington luminosity of a helium-rich envelope surrounding a neutron star. If this interpretation is true, we can obtain a relation between the mass and the radius of the neutron star in terms of the maximum effective temperature of bursts. On the other hand, the most naive understanding of the origin of the 4.1 keV absorption line often detected in X-ray burst spectra gives us another relation of the neutron star mass with its radius. By solving two simultaneous equations, we can determine the values of the mass and the radius of the neutron star, respectively. However, the result is critical to every neutron star model currently considered.

The persistent emissions from X-ray bursters are also discussed.

1. MASS AND RADIUS OF X-RAY BURSTING NEUTRON STARS

1.1. Luminosity saturation of bursts at the Eddington luminosity

Figure 1 shows the peak flux distribution of bursts from X1636-53 observed from Hakucho (Ohashi et al. 1982) and Tenma (Inoue et al. 1984) as a function of the integrated flux. This figure indicates the presence of an upper limit in the peak flux of bursts from the burster. The peak flux values of eight bursts reaching the upper limit in Fig.1 are the same within errors. After fitting a blackbody spectrum to the time-resolved spectra of the bursts, it is found that the bursts with the maximum peak flux all exhibit a flat top at the same maximum level accompanying a rapid radius change (Inoue et al. 1984). The time variation of energy flux versus apparent radius during the first 6.5 sec of a burst with the maximum peak flux is shown in Fig.2. The apparent radius quickly increases to 20-30 km during the burst rise and returns to about 10 km within a few seconds (assuming 10 kpc distance). These observed features strongly suggest that the peak luminosity of X-ray bursts from a X-ray burster is the Eddington luminosity.

When the huge nuclear energy is released in a very short time, the excess energy flux above the Eddington luminosity is converted into

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kinetic energy of the ambient matter. This results in envelope expansion while the luminosity is kept at the Eddington luminosity. This is qualitatively consistent with the radius change seen during the flux peak. However, as seen from Fig.2, the luminosity has not reached the Eddington luminosity during the envelope expansion. Sugimoto et al.(1984) suggested that since the Eddington luminosity of the hydrogen-rich envelope at the neutron star surface is lower than that of the inner helium-rich envelope, the hydrogen-rich envelope is ejected before the flux reaches its maximum. Furthermore, they pointed out an existence of a gap in the peak flux distribution by a factor 1.7 as indicated in Fig.1, which value corresponds to the difference in the Eddington luminosity of neutron stars having helium or hydrogen-rich envelopes. Thus, the observed maximum flux is consistently interpreted as due to the Eddington luminosity of the helium-rich envelope after the surface hydrogen-rich envelope has been lost.

1.2. Maximum effective temperature at the Eddington luminosity

If the maximum peak luminosity is indeed the Eddington luminosity at the neutron star surface, the maximum effective temperature, $T_{e,Max}$, at the Eddington luminosity relates to the mass, M, and the radius, R, of the neutron star as

$$\sigma T_{e,Max}{}^4 = cGM(1-(2GM/c^2R))^{3/2}/\kappa_e R^2, \tag{1}$$

where σ the Stephan-Boltzman constant, c the velocity of light, G the gravitational constant and κ_e the opacity for electron scattering (e.g. Goldmann 1979). Figure 3 shows the mass and radius relations, calculated with Eq.1, in terms of two values of the maximum effective temper-

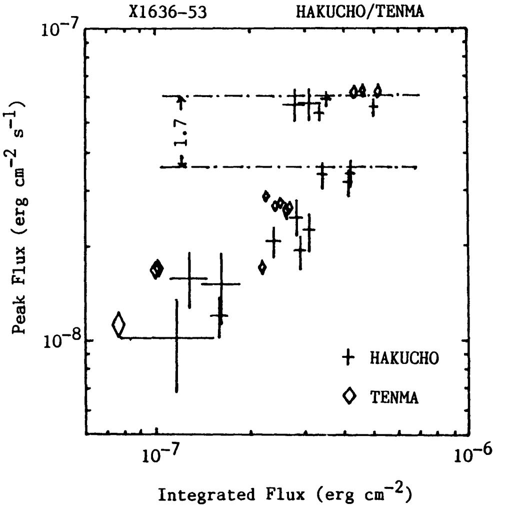

Fig.1 Peak flux distribution of X-ray bursts from X1636-53 as a function of the integrated flux.

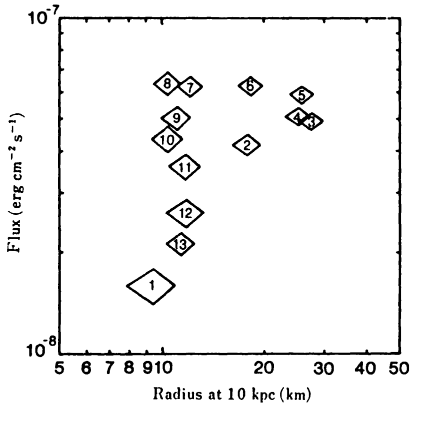

Fig.2 The time variation of flux versus apparent radius during the first 6.5 sec of a burst with the maximum peak flux. Numbers in the diamonds indicate time sequences with 0.5 sec interval.

ature. However, the observed maximum color temperature at the Eddington luminosity is as high as about 3 keV (see Fig.5, as an example), which indicates too small a mass of the neutron star. Then, it was pointed out that the color temperature can be higher than the effective temperature for the radiation from an atmosphere in which the electron scattering opacity is dominant (e.g., van Paradijs 1982).

In order to obtain the quantitative relationship between color temperature and effective temperature, London et al.(1984) and Ebisuzaki and Nomoto (1985) solved the multi-frequency diffusion problem of photons in a neutron star atmosphere. The result from Ebisuzaki and Nomoto (1985) is shown in the temperature and luminosity diagram (identical to the Herzsprung - Russel diagram) in Fig.4. We can see that the color temperature (solid line) is substantially higher than the effective temperature (dashed line). Since the theoretical curve is a function of the maximum effective temperature at the Eddington luminosity, $T_{e,Max}$, we can now determine the value of $T_{e,Max}$ by fitting the curve to the data points on the color temperature and the luminosity plane.

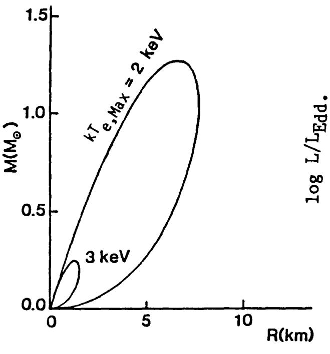

Fig.3 Mass-radius relations for two values of maximum effective temperature.

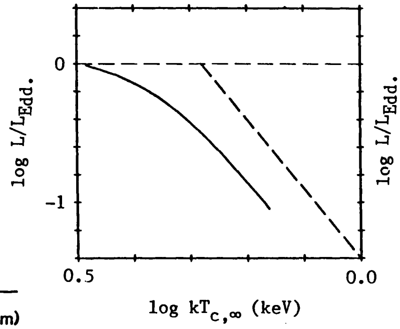

Fig.4 Relation of color temp. to effective temp. as a function of luminosity.

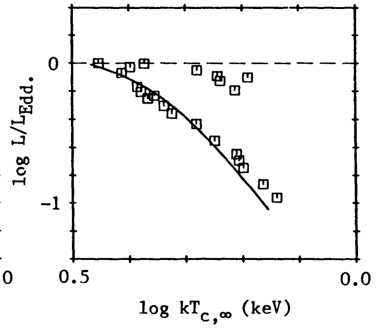

Fig.5 An example of the fitting of the theoretical curve to the data.

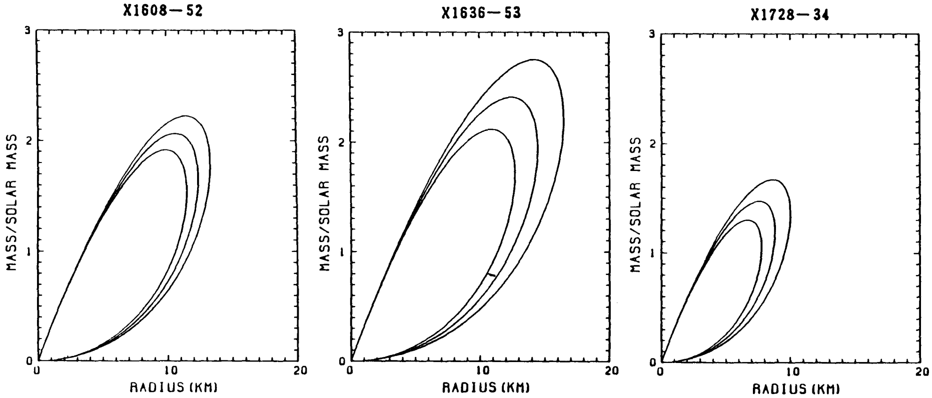

Fig.6 Preliminary results for the mass-radius relations of neutron stars in X-ray bursters; X1608-52, X1636-53 and X1728-34.

Fujimoto and Taam (1986), Ebisuzaki (1986) and Nakamura (1986) performed such fits to the data during the decay part of bursts observed from Tenma. Figure 5 shows an example from Ebisuzaki (1985). Once we have the value of $T_{e,Max}$ from the fits, we can obtain the mass-radius relation of the neutron star by using Eq.1. The preliminary results by Nakamura (1986) for three X-ray bursters; X1608-52, X1636-53 and X1728-34 are plotted in Fig.6. Outer and inner loops represent the error domain at 90% confidence limit derived from the fittings. Note that uncertainties in the theoretical calculations are not included.

1.3. Absorption lines in X-ray burst spectra

Tenma discovered significant features in X-ray burst spectra. Among sixteen bursts from X1636-53, four bursts exhibited five cases of significant dips in the spectra, whose nature was consistent with an absorption line (Waki et al. 1984). On the other hand, three bursts among seventeen bursts from X1608-52 also exhibited absorption lines in the spectra (Nakamura et al. 1986). Although Tenma detected as many as twelve bursts from X1728-34 and the data have the same statistical level as those from the above two burst sources, no significant dip was found in the X-ray burst spectra from X1728-34 (Tawara et al. 1986).

A line was observed at 5.7 keV only near the peak of a burst from X1636-53, the luminosity of which reached the Eddington luminosity. On the other hand, the line center energies in the other 7 cases are all consistent with 4.1 ± 0.1 keV, taking account of their errors. The equivalent widths of those absorption lines are about 100 to 200 eV. The observed line profile is well reproduced by the detector's responce function for a single line without significant intrinsic line width and the upper limit for the line width is about 500 eV (FWHM).

It is most likely that the absorption lines are produced by atomic processes in the atmosphere surrounding the neutron star. Then, for the plasma temperature during a burst, the helium-like ions are considered to be most abundant for the heavy element responsible for the absorption. Taking account of the possibility of the energy redshift due to the general relativistic effect on the neutron star surface, the candidate elements forming the absorption lines are those heavier than Ca for the 4.1 keV line and than V for the 5.7 keV line (Waki et al.1984).

The matter producing the absorption line may be either the products of helium burning in the bursts or the accreted matter from the companion star. The accretion rate is estimated to be 10^{16-17} g/sec, corresponding to an accumulation of matter at about 10^{3-4} electron scattering optical depth/sec over the neutron star surface. If the freshly accreted matter spreads over the neutron star surface during a burst, the most plausible element for the observed absorption would be iron which is most abundant in the accreted matter. On the other hand, when the luminosity reaches the Eddington luminosity, the surface accreted matter can be ejected by the radiation pressure and the following accretion might be hampered by the ram pressure of the ejected matter. In that case, the nuclear-burning products could be exposed on the surface. Then, the possibility of absorption by elements other than iron could not be excluded. However, the peak luminosities of a burst from X1636-

53 and three bursts from X1608-52 among the seven bursts exhibiting the 4.1 keV line are lower than the Eddington luminosity of these sources by factors 3 to 4. Matter ejection is quite unlikely for these bursts. This is in favor of the iron origin of the 4.1 keV absorption line. If so, this gives the redshift factor, $(1+z)^{-1}$, of the 4.1 keV line to be 0.61 ± 0.02.

The most naive understanding is that this absorption line is produced in the atmosphere surrounding the neutron star. Then, the atmosphere is considered to be geometrically thin, since the effect of the radiation pressure is negligible when the 4.1 keV line is observed. Thus, this redshift would represent the general relativistic effect on the neutron star, and we have an equation for the mass-radius relation of the neutron star as

$$\left(1 - (2GM/c^2R) \right)^{1/2} = 0.61 \pm 0.02 \ . \tag{2}$$

1.4. Mass and radius of X-ray bursting neutron stars

Now that we have had two independent equations; Eqs.1 and 2, for the mass-radius relation of the neutron star, we can determine each of the values of the mass and the radius. The results are shown on the mass-radius plane in Fig.7 for two X-ray bursters; X1608-52 and X1636-53. The mass and radius values are suggested to be about 2 M_o and about 10 km, respectively, for both of the two neutron stars.

However, these results have a serious consequence. The obtained values for the mass and the radius are critical to every neutron star model currently considered (Baym and Pethick 1979, and references therein; see also Alcock, 1987).

Fujimoto (1984) proposed a model to avoid the difficulty of the too stiff neutron star. He considered the boundary layer between the neutron star and the accretion disk as the line formation region. Since

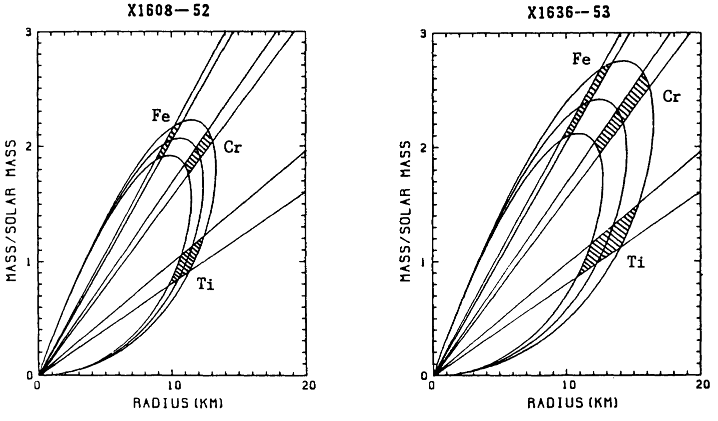

Fig.7 Mass-radius domains satisfying Eqs.1 and 2 simultaneously, for two X-ray bursters; X1608-52 and X1636-53. Results in the cases that the 4.1 keV line is originated from Fe XXV, Cr XXIII and Ti XXI are shown respectively.

the boundary layer is expected to rotate very rapidly with the accretion disk, the transverse Doppler effect due to this rotation is important in evaluating the redshift as well as the general relativistic effect. He calculated the redshift factor expected from the boundary layer, and the mass-radius relation obtained gives a good agreement with some neutron star models. However, this model has a serious difficulty.

The rotation of the line producing matter causes not only the shift of the line center energy but also the broadening of the line profile. In order to accomodate the rotational broadening with the observed upper limit for the intrinsic line width, the inclination angle of the line of sight to the rotaion axis of the line producing matter should be smaller than about 15°. However, the possibility for the line of sight to be within such a small cone is very small. Hence, it seems difficult for this model to explain the Tenma observations that among three bursters whose burst spectra were extensively searched for dip features, two sources exhibited the 4.1 keV line.

If there exists some unknown mechanism for mixing the nuclear burning products with the accreted matter, Cr or Ti are still possible candidates for the line producing element. If so, the corresponding values of mass and radius of the neutron star agree with some neutron star models (see Fig.7). A possible mechanism may be a continuous shear mixing of the rotating accreted matter with the neutron star atmosphere at the boundary layer between the accretion disk and the neutron star surface (Fujimoto et al. 1986; Hanawa 1986). Further study on this mechanism is expected.

2. PERSISTENT EMISSIONS FROM X-RAY BURST SOURCES

2.1. Spectral hardening with intensity-decrease at the dim phase

Figure 8 shows the change of the spectral hardness associated with the change of the luminosity of an X-ray burst source; X1608-52, observed from Tenma, together with those of three bright low-mass binary X-ray sources; Sco X-1, GX349+2 and GX5-1. The burst activity of X1608-52 in the period of the Tenma observation is also shown in Fig.8 in terms of α-value, which is the ratio of the averaged persistent flux to the averaged burst flux. The larger value of α corresponds to the lower activity of bursts. The steep increase of α-value with the increase of luminosity and the similarity in the luminosity-spectral hardness relation between X1608-52 at the bright phase and the other three sources suggest that the three bright low-mass binary X-ray sources are probably potential X-ray burst sources, although no X-ray burst has been detected from them.

When the luminosity is in the range from 5×10^{36} to 10^{37} erg/sec, the hardness increases as the luminosity decreases, as seen in Fig.8. The change of the spectrum with the luminosity decrease is more clearly seen from Fig.9. As the luminosity goes down, the high energy tail becomes more pronounced and consequently the whole spectrum approaches a power-law spectrum. This demonstrates that the spectrum of a X-ray burst source can undergo a dramatic change from a thermal type spectrum

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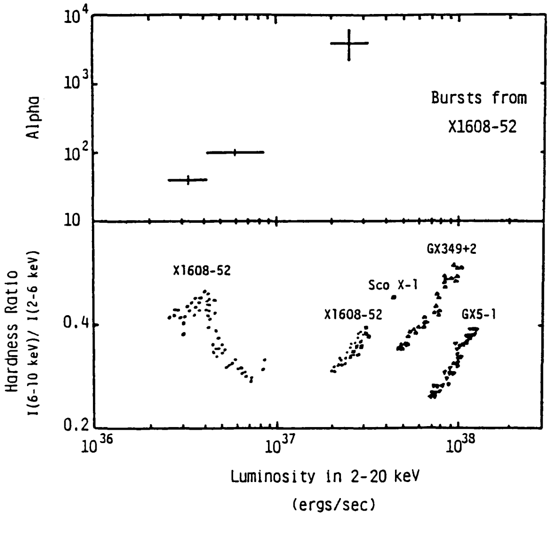
to a power-law type spectrum depending on the accretion rate.

After the detailed spectral analysis, Mitsuda and Tanaka (1986) showed that the spectral hardening with the luminosity decrease can be interpreted as due to the increase in the degree of the Comptonization for blackbody photons from the neutron star surface by hot electrons surrounding the neutron star. This may indicate that an optically thin hot region surrounding the neutron star extends when the accretion rate is reduced. The change in the accretion flow near the neutron star will be interpreted as being due to a transition in the accretion disk between an optically thick/geometrically thin state and an optically thin/geometrically thick state, depending on the accretion rate (Inoue and Hoshi 1986).

2.2. Spectral hardening with intensity-increase at the bright phase

Contrary to the above phase, X-ray burst sources exhibit a positive correlation of the spectral hardness with the luminosity, when the luminosity is as bright as 10^{37-38} erg/sec. This behaviour was investigated in detail for the four bright low-mass binary X-ray sources in Fig.8 by Mitsuda et al.(1984).

These sources exhibit intensity variations of a factor of two to three on time scales of the order of an hour. Mitsuda et al.(1984) compared the spectra when the intensity was high with those in adjacent periods of lower intensity. They found that the difference between high- and low-intensity spectra is always expressed very well by a single blackbody spectrum with kT of approximately 2 KeV for all sources examined. Furthermore, the blackbody temperature is found to be fixed



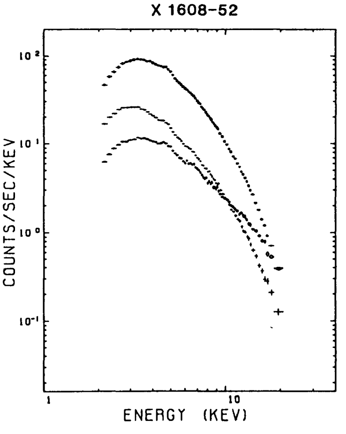


Fig.9 Change of spectrum of X1608-52.

Fig.8 Dependency of alpha on the 2-20 keV luminosity of X1608-52 (upper panel), and those of hardness ratio on the luminosity of four low-mass binary X-ray sources (lower panel). (Assumed distances are 4.4, 6, 6, and 1 kpc for X1608-52, GX349+2, GX5-1 and Sco X-1, respectively.)

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for a given source. Thus, the hardening of the spectrum can be interpreted as due to an intensity increase in this blackbody component.

By subtracting the 2-keV blackbody component from the observed spectra, Mitsuda et al.(1984) decomposed the observed spectrum into two spectral components; the "2-keV blackbody" component and a softer component. Following theoretical considerations about the accretion disk around a weakly magnetized neutron star (e.g., Hoshi 1984), Mitsuda et al.(1984) interpreted the softer component as the emission from an optically thick accretion disk around the neutron star and the 2 keV component as that from the neutron star surface, since the decomposed spectrum of the softer component is found to be well expressed by that expected from an optically-thick accretion disk.

Figure 10 shows the intensities of the two components of GX5-1 as a function of time (Mitsuda et al.1984). We clearly see that the 2-keV blackbody component is highly variable. While the flux of the 2-keV blackbody component varies widely, the blackbody temperature remains constant. This implies that the emitting area on the neutron star surface changes with flux. This may be understood in terms of the local Eddington limit. If the radiation flux per unit area of the neutron star surface reaches the local Eddington limit, the temperature cannot increase further. For more energy to be radiated, the surface area of the emission will have to increase. In fact, the temperature 2 keV is close to the maximum effective temperature determined from Eq.1.

However, a question is why this maximum temperature 2 keV is lower than the maximum temperature of X-ray burst emission. As discussed before, the maximum temperature of X-ray bursts goes up to about 3 keV and is interpreted also as due to the local Eddington limit at the neutron star surface. This question will be solved if we take account of the following two factors. One factor is the difference in the hydrogen abundance of the atmosphere from which the flux comes out. The Eddington limit of X-ray burst is probably that in helium rich envelope, while the matter emitting the persistent emission has cosmic element abundances. This gives a factor of about 1.7 for the difference between the two Eddington limits. Another factor will come from the transverse Doppler Effect due to the rotation of accreted matter in the boundary

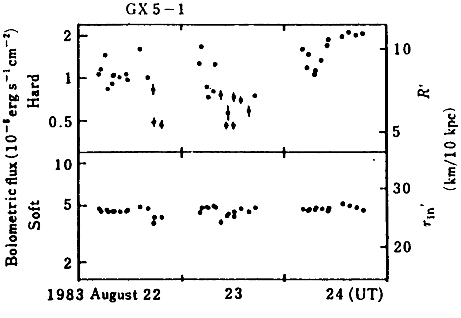

Fig.10 Flux histories of the two components from GX5-1.

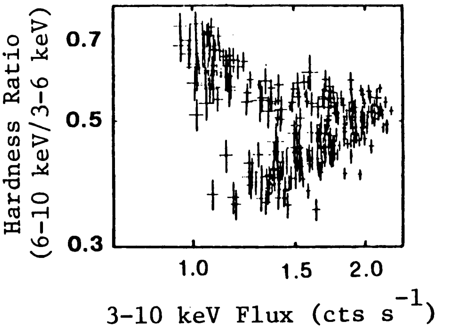

Fig.11 Dependency of hardness ratio on flux of GX5-1 observed from Hakucho.

layer between the accretion disk and the neutron star surface. This will make the observed temperature of persistent emission from the boundary layer lower than that of the X-ray burst emission, even if the two temperatures are the same at the neutron star surface.

2.3. The "horizontal branch" at the brightest phase

Hakucho observed GX5-1 for about 40 days in April to June in 1980. In most of the observational period, GX5-1 showed large intensity variations on a time scale of hours, when the spectral hardness correlated positively with the intensity as observed with Tenma ("normal branch"). However, the intensity variation on a time scale of hours occasionally disappeared, when the intensity-spectral hardness diagram reveals the "horizontal branch" as shown in Fig.11 (Mitsuda 1984). The spectral hardness increases as the intensity increases in the "normal branch". However, when the intensity reaches the brightest point, there exists an alternative branch where the spectral hardness is almost constant against the intensity variation within the same range as that of the "normal branch".

As discussed in the preceding subsection, the emission region of the 2-keV blackbody component changes its area with the intensity in the "normal branch". The projected radius of the emission region of the 2-keV blackbody component is indicated at the right hand side of Fig.10, where we find that the emitting area seems close to the whole surface of the neutron star at the brightest point. This suggests the luminosity at the brightest point to be almost the Eddington luminosity, since the 2-keV temperature is considered to be determined by the local Eddington limit on the neutron star surface. In fact, the luminosity estimated from the maximum flux of GX5-1 exceeds 10^{38} erg/sec, even if we assume the distance to be as small as 6 kpc. This value is consistent with the Eddington luminosity for about a solar mass neutron star.

These facts may suggest that the transition from the "normal branch" to the "horizontal branch" will take place when the mass accretion rate onto the neutron star exceeds the critical rate corresponding to the Eddington luminosity.

In the case of the accretion rate larger than the critical rate, the radiation pressure will prevent all of the accreted matter from reaching the neutron star surface and part of matter will be blown away. Then, if the "horizontal branch" indeed corresponds to the case of super-critical accretion, it is very interesting to note that the observed flux is smaller than the maximum flux. This may indicate the presence of the focussing of radiation into some direction unobservable by us, which accelerates the matter to form the cosmic jets. Although this suggestion is too speculative presently, the possibility will, at least, stimulate further study about the "horizontal branch".

Finally, we will give a short comment on the quasi-periodic oscillation (QPO) from GX5-1 (for recent observational results of QPOs from various sources, see van der Klis 1987; Hasinger 1987; Lewin 1987).

Van der Klis et al.(IAU Circ. No.4140) reported that the QPO from GX5-1 seems to appear mainly in the period when the source is on the "horizontal branch". If the "horizontal branch" corresponds to a state when the accretion exceeds the critical rate as discussed above, the radiation pressure will be dominant in the neutron star envelope at that state. Then, it is to be pointed out that the following evidences probably indicate the presence of the oscillation in the radiation-pressure dominated atmosphere on the neutron star surface.

High time resolution light curves near the peaks of X-ray bursts from X1728-34 (Hoffman et al.1979) and from X1608-52 (Hayakawa 1981) show the oscillatory behaviour on a time scale of about 0.5 sec during the peak. Since the peak fluxes of these two bursts are consistent with the maximum peak luminosity of the bursts from these sources, which is probably the Eddington luminosity, the oscillatory behaviour can be considered to occur in the radiation pressure dominated atmosphere. Hence, the stability of the radiation pressure dominated atmosphere on the neutron star surface will have to be studied in relation to QPOs and also to the "horizontal branch".

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DISCUSSION

A. Burrows: The neutron star masses you derive for this group of bursters are rather large. Taking these results at face value can you say why this population is comprised of neutron stars whose masses are so different from those derived for other classes of neutron stars?

H. Inoue: The high mass neutron star in the X-ray burst sources can be interpreted in terms of the increase of the mass due to the accretion. The persistent emission of X-ray burst sources requires the mass accretion rate of the order of 10^{-9} $M_\odot$/year. If the life time of the X-ray burst sources is of the order of 10^9 years, the amount of mass accreted by the neutron star during that period will be about a solar mass. Hence, the neutron star mass in X-ray burst sources can be 2 $M_\odot$ or more, even if the initial mass is 1.4 $M_\odot$ or less.

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