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Spectral Evolution of Type II Bursts from the Rapid Burster

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Abstract

The Rapid Burster (MXB1730–335) was observed from the X-ray astronomy satellite Tenma in August 1983 and July 1984. The spectra of both type I and type II bursts are well described by blackbody spectra with a slight excess above 10 keV. The emission region of type II bursts at the peak is found to be significantly larger than that of type I bursts, suggesting the presence of an optically-thick emission region larger than the neutron star. The spectral evolution associated with the time-scale invariant profile in the decay of most type II bursts is studied. Although most of the variation in X-ray flux within a type II burst is attributed to variation in the emission area, the temperature is also found to be variable. The variation in the color temperature of type II bursts is also time scale invariant. These observational results suggest the presence of a regulation mechanism for the accretion process, in addition to the reservoir required from the E-Δt relation. A possible picture of the generation mechanism of the type II bursts is discussed based on these observations.

Key words: X-ray bursts; X-ray sources; X-ray spectra.

1. Introduction

The Rapid Burster (MXB1730–335) was discovered in March 1976 by Lewin et al. (1976). When this source is burst active, it produces rapidly repetitive bursts [named type II bursts by Hoffman et al. (1978)], which is the characteristics of this unique source. The Rapid Burster also produces "type I bursts" similar to those produced by other bursters.

On the basis of energetics, the energy source of type II bursts is considered to be accretion, while the type I bursts are certainly caused by the thermonuclear flash of the accreted matter on the neutron star surface.

There are various modes of activities (Marshall et al. 1979; Inoue et al. 1980; Kunieda et al. 1984b) in which a variety of burst profiles has been seen, including long bursts with flat tops. During a certain period in 1983, the Rapid Burster lost its uniqueness from the other X-ray bursters, and only type I bursts were observed with rather strong persistent emission (Kunieda et al. 1984a; Barr et al. 1987). Quasi-periodic oscillations have been observed during bursts (Tawara et al. 1982) and in the persistent flux between bursts (Stella et al. 1988). Some regularities have been discovered among type II bursts. The integrated energy contained in a type II burst is proportional to the waiting time to the next burst ["E-Δt relation", Lewin et al. (1976)]. The structure in the time profile of type II burst is timescale invariant (Tawara et al. 1985).

The energy spectra of both type I and type II bursts from the Rapid Burster are consistent with blackbody radiation. The radius of the emission region of a type I burst is 9 km while that of a type II burst is 16 km at the burst peak, and decreases during the decay phase (Marshall et al. 1979). A variety of spectral temperature and emission area of flat-topped bursts was also studied (Kunieda et al. 1984b).

In this paper we present an analysis of the energy spectra of X-ray bursts, both type I and type II, from the Rapid Burster. Both types of bursts exhibit similar spectra, though the time evolution is completely different. Type II bursts exhibit a very complex time variation in energy spectra within a burst. The change in the energy spectra along with the timescale-invariant profile is found. We discuss the physical condition of the underlying neutron star on the basis of these analyses. Detailed descriptions and systematic analyses are given in Kawai (1985).

2. Observations

The activity of the Rapid Burster was observed by Tenma twice, in August 1983 and in July 1984. A detailed observational log is presented in Kunieda et al. (1984a) for the observations during 1983, in which the Rapid Burster was observed from 31 July to 6 August and from 11 August to 21 August with Tenma, and during the period from 10 August to 5 September with Hakucho. In this paper we deal with only data taken by Tenma.

The 1984 observations of the Rapid Burster were made from 2 July to 9 July by Tenma, with an effective coverage of about 33 hours. The number of bursts observed during this period was about 600. During the first two days of these observations, the Rapid Burster was observed only at the edge of the field of view because Tenma

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was pointed toward XB1715–321, an X-ray burster 3.3° away from the Rapid Burster. Nevertheless, we detected bursts with long flat-tops during this period. Tenma was then pointed to the Rapid Burster on 4 July (we continued the observations until 9 July, when the Rapid Burster was still actively producing repetitive bursts).

On this occasion we sometimes lost appreciable amounts of stored data because of trouble with the tracking system. For these reasons, we had poor coverage during July 1984. In addition, we could not obtain data with good spectral resolution from half of the SPC counters due to hardware problems, resulting in only half the effective area for spectral analysis compared to the observations during 1983. Most data were taken in a mode with high spectral resolution, while some were taken in a mode with high time resolution (0.125 s), at the expense of spectral resolution.

For all the Tenma observations, another X-ray burster X1728–34 ("the slow burster") was always in the field of view. It is therefore difficult to estimate the steady emission of the Rapid Burster. Sources of X-ray bursts, however, are rather easy to distinguish. For most cases we can safely determine the source of the observed X-ray bursts by the morphology, spectral hardness, and the position determined by the RMC (rotating modulation collimator). The energy spectrum of each burst was studied using the observed steady emission adjacent to the burst as background.

3. Activity History

3.1. August 1983

The activity during August 1983 can be divided into three periods: (a) August 5–16, (b) August 17–19, and (c) August 20–31. Period (a) is characterized by a quasi-periodic occurrence of type I bursts and an intense persistent component. No type II burst was detected during this period, and most probably no type II burst has yet been produced. During period (b), we detected type II bursts exclusively of long duration, while type I bursts continued to occur with a similar frequency as in the period (a). Period (c) is the time span through which the rapidly repetitive type II bursts were continually generated, while type I bursts were detected less frequently than the previous periods. These activities are described in more detail by Kunieda et al.(1984a).

3.2. July 1984

With respect to the mode of activity, we may divide the total period into two: (a) July 2–5, and (b) July 6–9. During period (a), relatively long bursts with durations between 40 sec and 5 min were observed. Whereas, during period (b), a mixed train of short spiky bursts and large flat-topped bursts was as observed.

Several type I bursts were detected from the Rapid Burster during period (b). In addition to these clear type I bursts, we found several bursts which show spectral softening, but have a significantly lower peak flux than typical type I bursts from the Rapid Burster.

On July 2 and 3, six bursts of duration of 1–5 min were detected. A train of somewhat shorter bursts with durations of between 40 s and 2 min spaced by 150–960 s was observed from July 4 through 5.

During period (b) from July 6 through 9, the Rapid Burster was active in a distinctly different mode from that in August 1983, producing a mixture of type II bursts of various sizes, from small spiky bursts to large flat-topped bursts. The durations of the bursts spanned the range from 4 to 220 s. This mode of activity is essentially the same as Mode I designated by Marshall et al. (1979). The peak luminosity of flat-topped bursts, ranging 200–400 mCrab, was found to be much larger than that for those in August 1983, and similar to those we observed in August 1979 from Hakucho (Inoue et al. 1980; Kunieda et al. 1984b). The decay part of the type II bursts in this time displays a complex structure of time-scale invariant profile very similar to those in the 1983 observations (Tawara et al. 1985).

A significant "persistent" emission was observed to appear after large type II bursts during period (b). When the enhancement was observed, it started to grow a few tens of seconds after the end of a large burst, and underwent a broad maximum ($\approx$100 mCrab) around the mid-point to the onset of the next burst. This enhanced persistent component then gradually declined to disappear a few tens of seconds before the next burst rises. Similar phenomena have been reported by van Paradijs et al. (1979), Tawara (1980) and Stella et al. (1988). We found that the enhanced emission sometimes exhibited a significant structure on a time scale of 30 seconds. It is, however, important to mention that this enhancement did not always occur, even if the interval to the next burst was long enough. When an enhancement is not significantly observed, the persistent component is not detectable with the RMC (i.e. less than 20 mCrab).

4. Energy Spectra

4.1. Model Fitting

(i) Type I bursts

Since a single burst is statistically insufficient for investigating spectral detail, we constructed integrated spectra by taking the following procedure for bursts with similar profile and time evolution. First, we assumed that the spectrum at a given time is always expressed by a blackbody spectrum, and determined the blackbody temperature in each time bin for individual bursts. Then, the data for those time bins that give the same blackbody temperature were combined in order to obtain a spectrum with good statistics. An example of so constructed spectrum from seven type I bursts of the Rapid Burster is shown in figure 1a for kT=2.0 keV. Indeed, this spectrum is best fitted to a blackbody spectrum of 2 keV with an absorption column of 3×10^{22} H atoms cm^{-2}, except for a slight excess above 10 keV. In this way, we confirmed at other temperatures as well that the spectrum during a type I burst is expressed by a blackbody spectrum. For comparison, the spectrum of bursts from X1636–53 at 2 keV is also shown in figure 1b.

Once the blackbody temperature is determined, the apparent blackbody radius is obtained. The evolution of the temperature and radius through the burst decay is discussed in subsection 4.2.

(ii) Type II bursts

It was previously known, though qualitatively, that the spectrum of type II bursts is consistent with the blackbody spectrum (Marshall et al. 1979). We have confirmed that the spectrum of type II bursts is best fitted to a blackbody, compared to other simple models such as thermal bremsstrahlung and power-law. We processed the

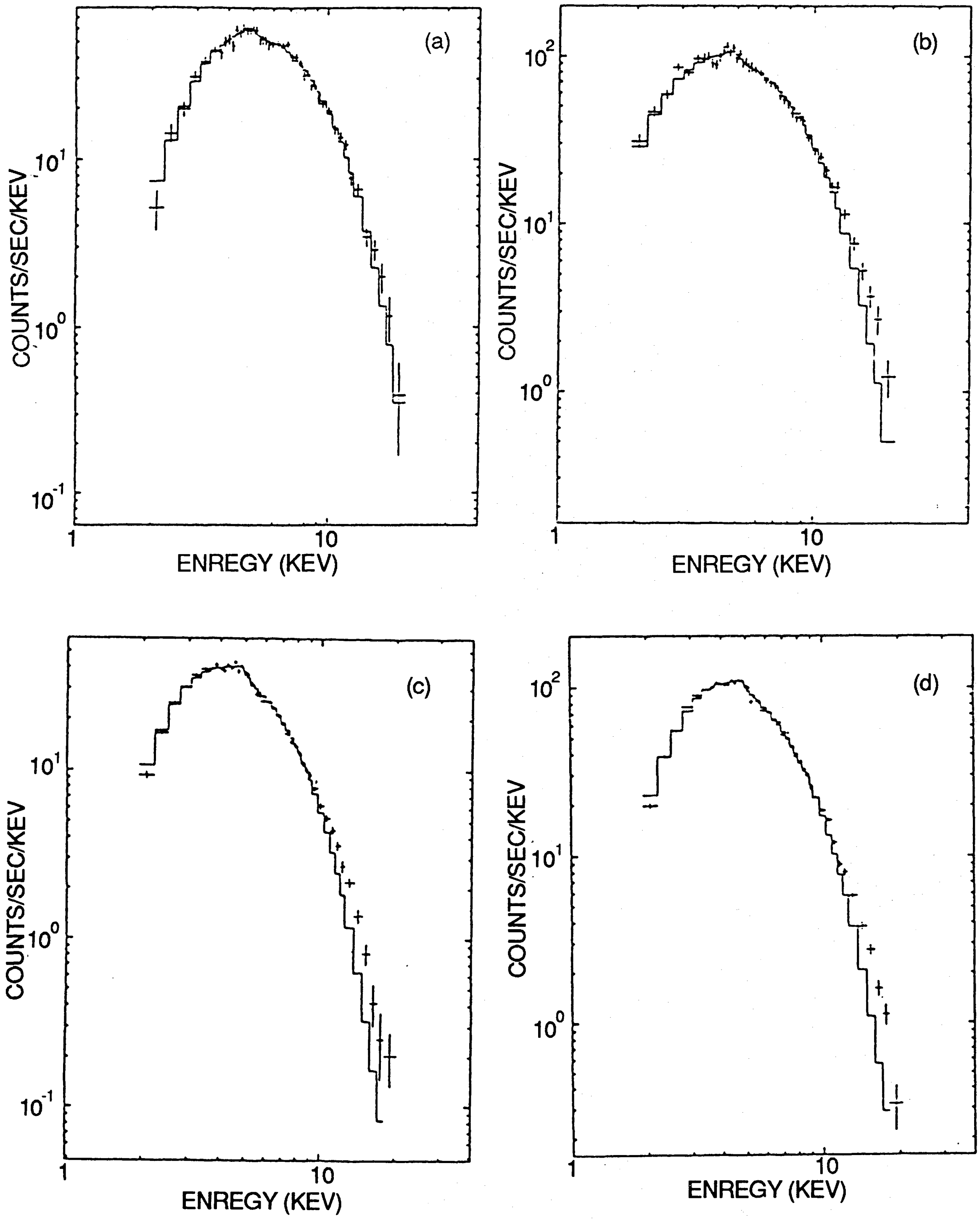


Fig. 1. (to be continued)

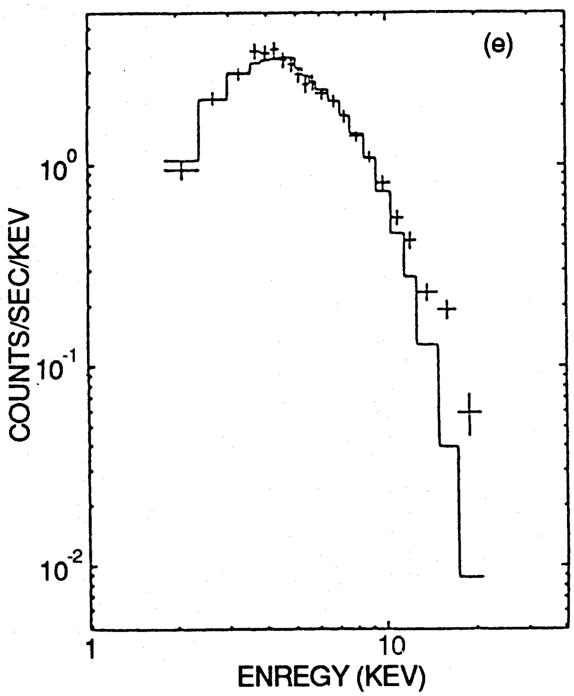


Fig. 1. Pulse height spectra of X-ray bursts: (a) integration of the sections with kT=2.0 keV of the type I bursts from the Rapid Burster, (b) peak of a burst from X1636–536 for comparison, (c) integration of seven long bursts with a fast rise in 1983 from the Rapid Burster, (d) integration of the short type II bursts in 1983 from the Rapid Burster, (e) integrated pulse-height spectrum of the enhanced persistent emission after large bursts from the Rapid Burster. The observed data points are plotted with crosses. The best-fit blackbody model spetra determined from the data in the energy range 2–10 keV are convolved with the detector response function, and plotted with step functions.

spectrum of type II bursts, likewise, as in the case of type I bursts. The flat-topped bursts bursts during August 1983 have very similar temperatures to each other on the flat tops. We simply added eight of those bursts for which the temperature on the top was equal within 0.1 keV, and examined the resultant spectrum (figure 1c). As a result, the fit to a blackbody spectrum was found to be acceptable if the energy range is limited to below 10 keV. The best-fit blackbody temperature is 1.5 keV with an absorption column of $\approx 10^{22}$ H atoms cm^{-2}, which is consistent with that of type I bursts when the systematic errors with the window thickness is considered. In the same energy range a thermal bremsstrahlung spectrum also gives an acceptable fit. However, a significantly larger absorption column, 6×10^{22} H atoms cm^{-2}, than that determined for type I bursts is required. We, therefore, consider that a blackbody spectrum is most probable.

The spectra of the shorter bursts observed during period (c) of August 1983 activity were obtained from a composite of many bursts by adding data bins for which the temperature was equal (within 0.1 keV). As a whole, the spectrum in the energy 1–10 keV is reasonably well fitted to a blackbody spectrum of kT=1.6 keV near the burst peak with an absorption column of 2×10^{22} H atoms cm^{-2}, as shown for example in figure 1d.

In both of the above spectra the major deviation from a blackbody spectrum is a significant excess above 10 keV, which is most likely to be produced by Comptonization. A similar deviation in the spectra ("high-energy tail") is found in type I bursts from X1608–52 when its persistent X-ray flux is low; this high-energy tail is explained in terms of Comptonization of blackbody photons from the neutron star surface by hot electrons in the surrounding optically thin region (Nakamura et al. 1989). For type II bursts from the Rapid Burster, Comptonization by the electrons in the accretion flow is also proposed as being a possible process in forming a high-energy tail, (Hirotani et al. 1990). Both of the Comptonization models grossly explain the high-energy tail of type II bursts, and the shapes of the best-fit models were very similar to each other. In these models the spectral shape in the energy range below 10 keV is not modified from the original blackbody spectra largely. Our discussion in the following part, though based on simple blackbody models, is not greatly affected by considering the high-energy tail.

(iii) Persistent component

During period (a) of August 1983 activity, the Rapid Burster was persistently bright. However, since another bright source, X1728–34, was in the same field of view of SPC-A and B, an unambiguous separation of these two sources is difficult. We performed an analysis with the RMC, and obtained a broad band spectrum of persistent emission from the Rapid Burster. Qualitatively, the resultant spectrum is much harder than that of X1728–34.

On the other hand, a good quality spectrum was obtained for enhanced emission after large bursts observed during July 1984. We picked on up time intervals where a significant enhancement occurred, and subtracted the data between bursts containing little enhancement. The latter consisted of data between short bursts as well as in the beginning and end of enhancement. We constructed spectra of the enhancement for several different intervals in this way. After testing that they all are consistent to be equal except for the absolute intensity, all of them were added together so as to obtain a good statistical quality. The resultant spectrum is shown in figure 1e. We then performed fittings of this spectrum to a standard three-parameter model spectra; blackbody spectrum, thin thermal bremsstrahlung spectrum, and power-law. None of them satisfactorily fit the observed spectrum. However, by limiting the fit to the energy range below 8 keV, a blackbody spectrum with kT=1.7 keV and an absorption column of 3×10^{22} H atoms cm^{-2} give the best fit. Thin thermal bremsstrahlung spectrum requires an absorption column of 6×10^{22} H atoms cm^{-2} in order to obtain an acceptable fit, which is too large to be consistent with that for type I bursts. We, therefore, consider that the spectrum of the persistent component is of blackbody nature with a pronounced hard excess above 8 keV.

In summary, the spectrum of the Rapid Burster, whether it is for burst or persistent component, can be expressed by a blackbody spectrum with kT=1.5–2.0 keV, as long as the absorption column is assumed to be constant.

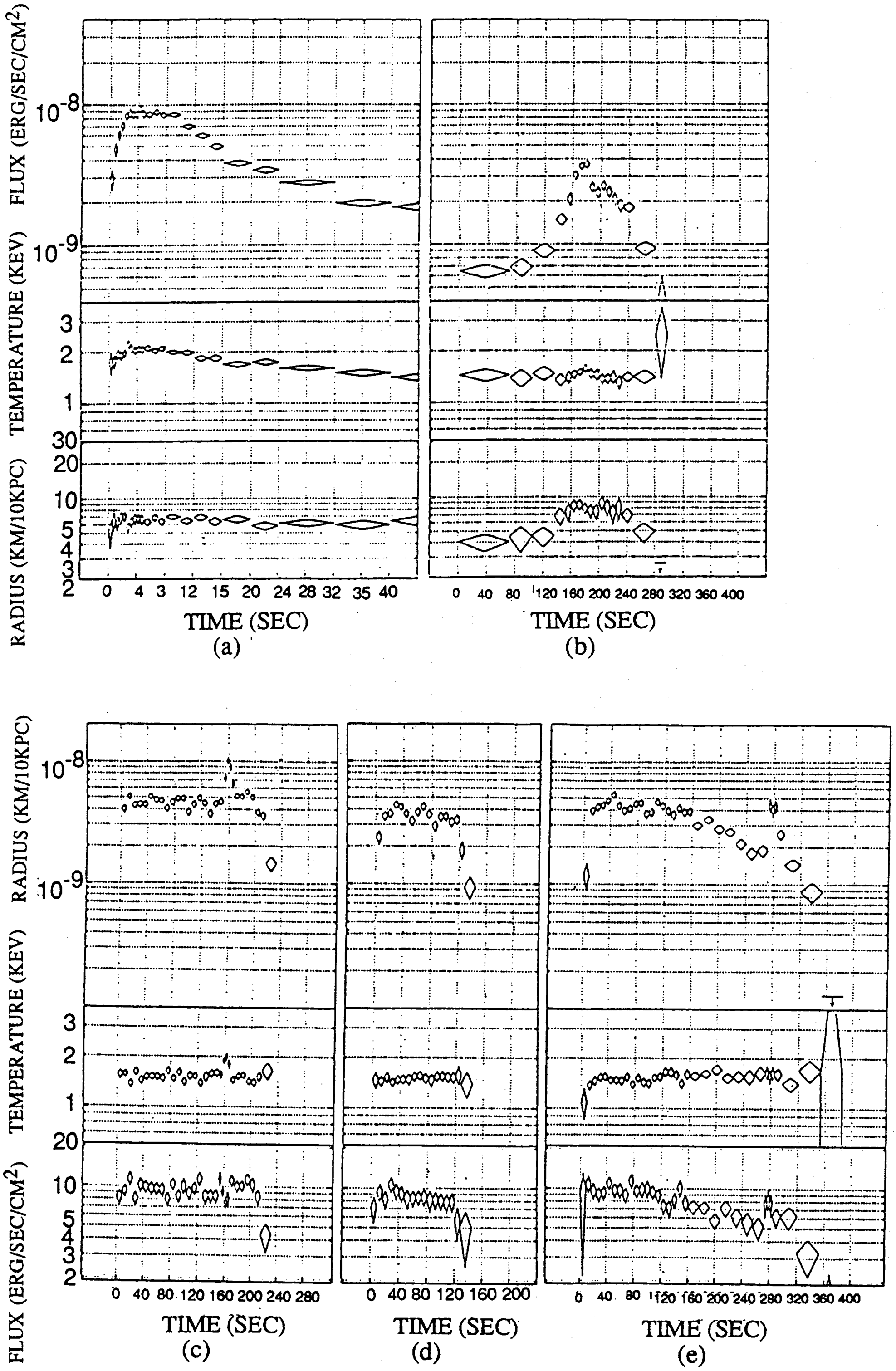
4.2. Time Evolution of Blackbody Parameters

A complete set of pulse-height spectrum is obtained every half second for the high bit rate mode and every two seconds for the low bit rate mode. Each spectrum obtained is fitted to a Planckian distribution. Absorption by a hydrogen column of

3×10^{22} H atoms cm^{-2} is included, as determined for type I bursts in the preceding section. Sometimes in the fittings, a smaller column density, 2×10^{22} H atoms cm^{-2}, is preferred. This much difference in the absorption column, however, does not influence the result of the following analysis. The bolometric energy flux is calculated from the observed total photon number flux and the spectral temperature. If we assume a spherically symmetric emission, the normalization factor is proportional to the surface area of the blackbody emitter, and the apparent blackbody radius at the assumed distance of 10 kpc is directly obtained. It is, however, important to note that the so-obtained radius is the apparent blackbody radius, which differs from the local blackbody radius for two reasons. The first is the fact that the measured blackbody temperature is the color temperature, not the effective temperature. The second reason is that the gravitational effect is not taken into account.

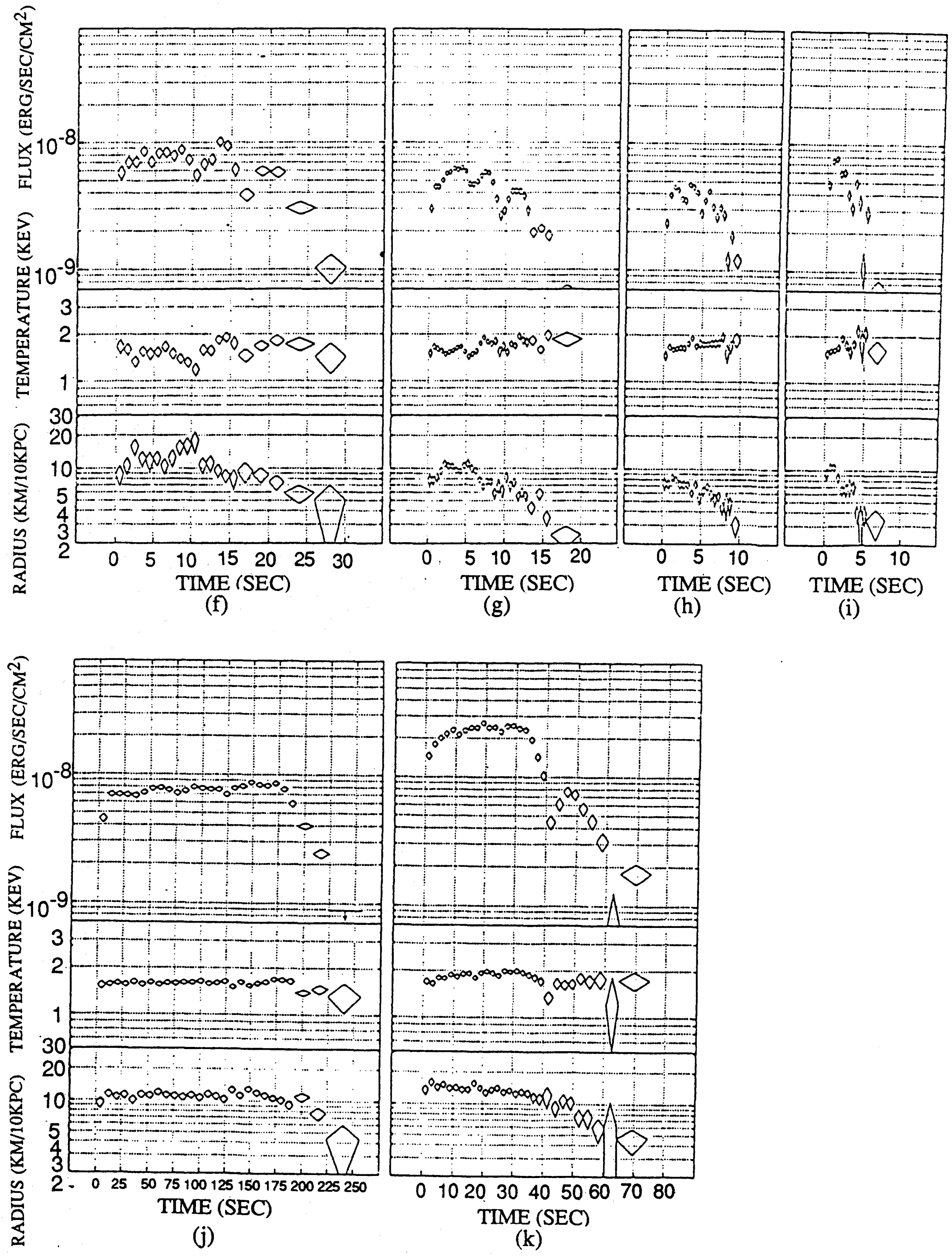
Time variations of bolometric flux, blackbody temperature, and apparent blackbody radius for bursts of various profiles are shown in figure 2. The uncertainty for each parameter is a 90% confidence limit for a single parameter (Lampton et al. 1976). It is clear from figure 2 that the behavior of these parameters is distinctly different between type I bursts and type II bursts. Type I bursts have a temperature $kT \approx$ 2.0 keV at their peak followed by a gradual decrease, whereas the apparent blackbody radius remains constant throughout the decay at about 7 km (figure 2a). On the other hand, the spectral evolution of type II bursts is characterized by a roughly constant temperature throughout the entire burst, while the apparent blackbody radius decreases during the burst decay (figures 2b-n). These characteristics are common to all type II bursts. In particular, the blackbody temperature is kept remarkably constant over the flat top of long bursts (figures 2c, d, j, k). In the meanwhile, the blackbody temperature and the apparent blackbody radius at the flat top vary from burst to burst. For instance, the flat-topped bursts observed in August 1983 (figures 2c-e) were of relatively low luminosity as compared to those in August 1979 (Inoue et al. 1980) and July 1984, and showed kT of 1.5–1.6 keV. Whereas the flat-topped bursts observed in July 1984 (figures 2j-k) were generally larger in peak flux and showed higher temperature and a larger apparent blackbody radius than those of the August 1983 bursts. Altogether, for the bursts observed over these two years, the blackbody temperature ranges up to 2.0 keV, and the apparent blackbody radius for the burst peak is found to vary in the range from 8 to 18 km. These results are depicted in figure 2. One very important result here is that the apparent blackbody radius for the peak of type II bursts is significantly larger than that for type I bursts ($\approx$7 km).

For the shorter type II bursts observed in August 1983, the spectral changes associated with the structure in the decay part ["time-scale invariant profile"; (Tawara et al. 1985)] were found. In figure 2f-i, the evolutions of the blackbody parameters for four different cases with respect to the characteristic time scales of the structure in the decay are shown. In all cases, one finds a gradual increase in the blackbody temperature from $kT \approx$ 1.7 keV to 1.9 keV. Furthermore, the spectral evolutions of these bursts are very similar to each other, except for the characteristic time scale. In order to study details of the spectrum and its evolution related to the structure in the decay part, we constructed a composite profile from $\approx$100 bursts by normalizing them according to their characteristic time, as shown in figure 3. The evolution of the blackbody parameters for the composite profile is shown in figure 4. A general increase



(a)
(b)
(c)
(d)
(e)

Fig. 2. (to be continued)



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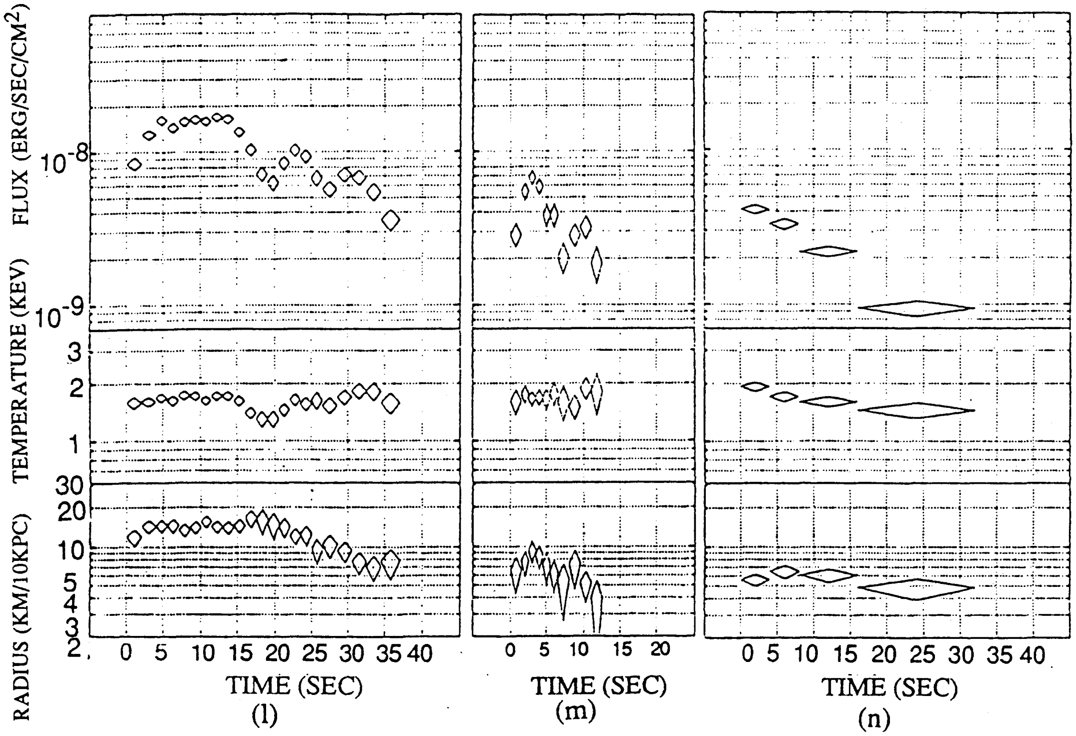

Fig. 2. Evolution of a best-fit blackbody energy flux, blackbody temperature and a blackbody radius of bursts from the Rapid Burster: (a) Composite of seven type I bursts, (b) a long triangular-shaped type II burst with a slow rise in 1983, (c) and (d) flat-topped bursts in 1983, (e) a long triangular-shaped type II burst with a fast rise and a sharp feature on top, (f), (g), (h) and (i) short type II bursts in 1983, (j) and (k) flat-topped bursts in 1984, (l) and (m) short type II bursts in 1984, (n) composite of four low-luminosity bursts.

of blackbody temperature with time is evident. In addition, blackbody temperature exhibits peaks at the luminosity humps, whereas the apparent blackbody radius seems to undergo a step-like decrease through each luminosity hump.

5. Discussion

5.1. Blackbody Radii of Type I and Type II Bursts

We have found that the radii of the emission region at the peak for type I bursts (7 km) and type II bursts (8–18 km) are significantly different from each other. This is consistent with the report by Marshall et al. (1979) who obtained blackbody radii of 9±2 km for type I bursts and 16±2 km for type II bursts at the peak. As discussed in the previous section, the activity of the Rapid Burster during the first half of the August 1983 activity, period (a), is very similar to that of the other X-ray bursters. In fact, type I bursts of the Rapid Burster have general characteristics in common with the X-ray bursts from other sources. Therefore, we assume that the current understanding of type I bursts can be applied to the Rapid Burster.

The emission region of a type I burst is considered to be the entire surface of the neutron star for two reasons. Firstly, the blackbody radii during the decay have

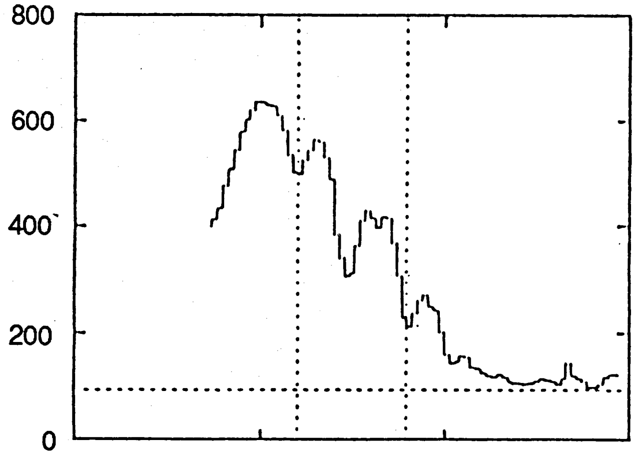

Fig. 3. Composite profile of short type II bursts used for a spectral analysis of the time-scale invariant profile. One hundred bursts were scaled by the characteristic time t_c and were anchored scaled by the structure in the decay before they were folded. The slow rise of the profile is an artifact caused in the process of folding.

been found to be same within statistical accuracies for every X-ray burst from a single source (Hoffman et al. 1977a; Hoffman et al. 1977b; Swank et al. 1977; Hoffman et al. 1979; Grindlay et al. 1980; Inoue et al. 1981; Ohashi et al. 1982). This suggests that X-ray bursts are emitted from a region rotationally symmetric with respect to the spin axis of the neutron star. Secondly, the blackbody radius of the X-ray burst is found to be constant over various sources, assuming a reasonable distance to each source (van Paradijs 1978; Inoue et al. 1981). This demonstrates that the neutron stars in those systems are similar in size to each other and that the apparent emission region is constant, regardless of geometrical conditions of individual sources (e.g. system inclination with respect to the line of sight). All of these results strongly suggest that a type I X-ray burst covers the entire surface of a neutron star. Thus, an apparent blackbody radius of 7 km for type I bursts from the Rapid Burster can be regarded as representing the neutron star radius, apart from the effects of photon dilution by electron scattering (London et al. 1986; Ebisuzaki 1987) and the general relativity on the neutron star surface.

Obviously, general relativity has no different effect for type I and type II bursts if both are phenomena on the same neutron star surface. The effect of photon dilution is not very different for the two types of bursts in changing the apparent blackbody radii either. Since type I bursts and type II bursts from the Rapid Burster have a similar luminosity and color temperature, the physical condition of the atmosphere and, hence, the dilution factor, should not be much different between them. Therefore, the larger values of the apparent blackbody radius of type II bursts must be attributed to an actually larger size of the emission region than the surface area of the neutron star, typically four times as large as that of the surface area of the neutron star.

In addition to the constraint on the size mentioned above, most of the gravitational energy released must be emitted from regions with similar temperature, since the energy spectrum of a type II burst is roughly expressed by a blackbody of a single temperature. In the following subsections, let us examine a few conceivable substances

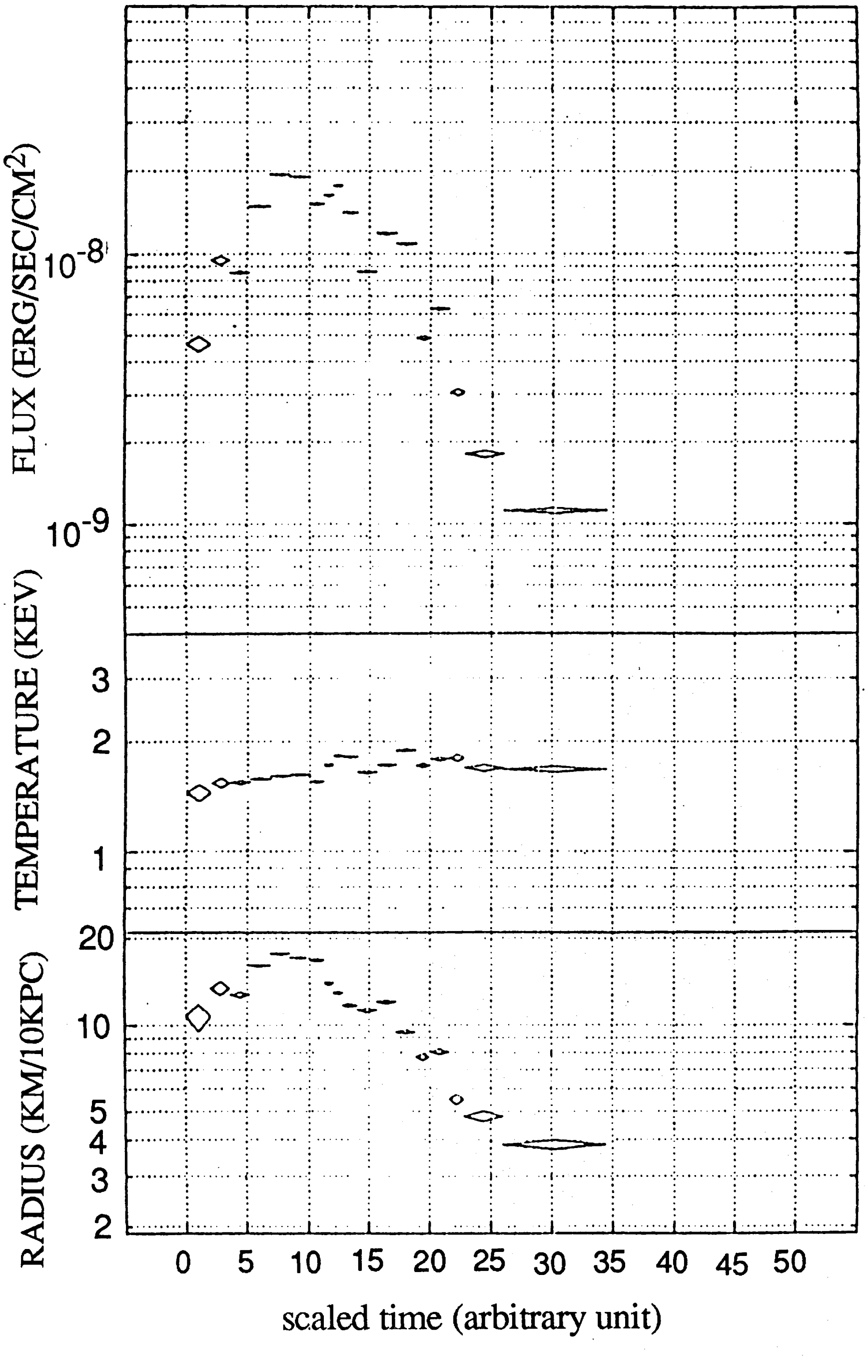

Fig. 4. Evolution of blackbody parameters of the composite spectra of short type II bursts in 1983. These Bursts are scaled by the characteristic time of the time-scale invariant profile before folding.

with different geometry, which could be the emission region of a type II burst.

5.2. Type II Burst as Reprocessed Emission

First, let us consider a case in which the gravitational energy released on the surface of a neutron star is reprocessed by a shell or cloud surrounding the neutron star. Then, we should observe the reprocessed emission as a type II burst. If a large part of the neutron star surface is heated by accretion, the reprocessing region must necessarily cover a large fraction of the neutron star, such that the neutron star surface is not visible. Otherwise a mixed spectrum consisting of two temperature components would be observed: one from a surface of higher temperature, the other from a reprocessing region with lower temperature.

This scenario imposes rather unique conditions on the emission region. First, the emission region must be present only when a type II burst occurs and must disappear when the burst is terminated. This is required from two observational results. One is the constant emission area of type I bursts with an apparent blackbody radius of 7 km, even if it occurs between type II bursts. If the reprocessor which covers the neutron star still exists during a type I burst, the type I burst, itself, would be reprocessed and would show a larger blackbody radius. The other result is the decreasing emission area observed during the decay of type II bursts. As presented in figures 2 and 4, the blackbody radius decreases as the X-ray flux diminishes, while the blackbody temperature remains roughly constant. If the reprocessor does not decrease in size during decay, the area of the emission region would remain constant and the temperature would fall as the energy production rate decreases. Thus, we need to consider that the reprocessor is formed only during a type II burst, most probably by the accreting matter, itself, which is responsible for the burst. This fact would imply that the accreting matter is supplied to the reprocessing region and this matter gradually flows down onto the neutron star surface from the reprocessor during a type II burst.

Then, the reprocessing region has to contain enough matter to be optically thick, even for the smallest type II burst. If the accreting matter is distributed in a shell with radius $\mathrm{R_s}$ of the burst emission area, the column density is expressed by

$$N_{\mathrm{H}} = M_{\mathrm{b}}/4\pi R_{\mathrm{s}}^2 m_{\mathrm{H}} = 4.8 \times 10^{27}(M_{\mathrm{b}}/10^{17}g)(R_{\mathrm{s}}/10^6\mathrm{cm})^{-2}\mathrm{cm}^{-2}. \tag{1}$$

The energy contained in the smallest burst is about 5×10^{37} erg, which corresponds to an accretion of mass of

$$M_{\mathrm{b}} = 4 \times 10^{17}(M_*/M_{\odot})^{-1}(R_*/10^6\mathrm{cm})(D/1\mathrm{kpc})^2 g, \tag{2}$$

where D is the distance to the source; M_* and R_* are the mass and the radius of the neutron star, respectively. Since $R_{\mathrm{s}} = 2 \times 10^6$ cm, we obtain $N_{\mathrm{H}} = 5 \times 10^{27}$ H atoms cm^{-2}, which is enough to form an optically-thick reprocessing region.

This reprocessing shell has to be maintained at some distance by some mechanism. As we show below, it is difficult to keep an optically thick shell against the strong gravitational field of the neutron star.

The radiation pressure is only important when the luminosity is very close to the Eddington limit, determined by the neutron star mass M and the opacity. However, the peak luminosity of a type II burst varies by a factor of four (Inoue et al. 1980). Therefore, only the brightest bursts could be close to the Eddington limit. For less luminous bursts, the radiation pressure is not effective for supporting matter surrounding the neutron star over a substantial solid angle. For the same reason, an expanded atmosphere of a neutron star, such as that observed in X-ray bursts at the

Eddington luminosity form X1636–53 (Inoue et al. 1984), cannot account for the large area of type II bursts. While expansion of the atmosphere is only possible for bursts reaching the Eddington luminosity (Sugimoto et al. 1984), we observed a variety of levels in the luminosity of type II bursts, and many type II bursts with relatively low luminosities exhibit larger emission area than type I bursts.

The gas pressure is not effective, because the thermal energy required for a nucleon to balance the gravitational force is several tens of MeV and it is orders of magnitude higher than the observed temperature of 2 keV.

The centrifugal force cannot play a major role either. The accretion disk can be geometrically thick enough to cover a large solid angle only if the thermal energy of the gas is as large as the gravitational potential, which is again several tens of MeV per nucleon. It is much higher than the observed spectral temperature.

The magnetic field, on the other hand, could support an optically thick shell. For a shell with an optical depth of τ, the gravitational force is equated to the magnetic pressure,

$$\frac{\tau m_{\mathrm{H}} G M_*}{\sigma_{\mathrm{T}} R_{\mathrm{s}}^2} = \frac{B^2}{8\pi}, \tag{3}$$

where σ_T is the Thomson cross section. Then the required magnetic field on the surface of the neutron star B_0 is given by

$$B_0 = 9.2 \times 10^7 \tau^{1/2} (M_*/M_{\odot})^{1/2} (R_{\mathrm{s}}/10^6 \mathrm{cm})^2 (R_*/10^6 \mathrm{cm})^{-3} \mathrm{gauss}. \tag{4}$$

Thus, an optically thick shell is possible with a reasonably weak ($\approx$several times 10^8 gauss) magnetic field.

A weak magnetic field is consistent with such observations as type I X-ray burst activity and lack of pulsation similar to X-ray pulsars. The lack of a soft component in the energy spectrum is also consistent with a weak magnetic field. An optically-thick accretion disk, which contributes to the soft X-ray emission of low-mass X-ray binary sources (Mitsuda et al. 1984) is disrupted by the magnetic field at some distance where the temperature is below the observation range. A weak magnetic field on the Rapid Burster is also favored by a consideration on the regulation mechanism of accretion in type II bursts (Hanawa et al. 1989).

5.3. Other Geometries

In addition to the reprocess shell geometry discussed in the previous subsection, we consider an accretion column with a small base area on the neutron star as the second case, for which a large emitting area on the side will be available. In this case photons are created preferentially near the surface of the neutron star where the gravitational energy release is largest, and the photons diffuse out from the accretion column within a height comparable to the size of the base area on the neutron star. Since the resulting photons are emitted effectively at a higher temperature from a small area, compared to the neutron star surface, the radiation is not of single temperature.

In the third case when the gravitational energy is gradually released in the accretion disk, the emergent spectrum is modeled as a "multi-color" blackbody (Mitsuda et al. 1984). In order to fit the spectra of type II bursts to the "multi-color" spectra of an optically thick accretion disk, it requires much larger absorption than determined for type I bursts, and the fit is no better than the blackbody spectrum with a single color temperature. There have, however, been other attempts to predict the X-ray spectra from an accretion disk (White et al. 1988; Hanawa 1989). At this moment it is not clear which of these pictures are correct and applicable to the Rapid Burster. Until emission process and the energy spectrum of the accretion disk are well understood, we cannot dismiss this possibility of an accretion disk for the emission region of a type II burst.

5.4. Time-Scale Invariant Profile

As has already been reported by Tawara et al. (1985), the structure in the decay portion of type II bursts is time-scale invariant for the characteristic time from 0.3 to 10 sec. One simple corollary of this characteristics is that the time scale of the burst profile is determined by the total size of the burst. Whatever is the mechanism producing the profile, it must know the quantity of the accreting matter at the beginning of a burst. This is possible in two cases: i) the relaxation oscillator is responsible for both E-Δt relation (determines the size of a burst) and the time-scale invariant profile, or ii) the whole quantity of accreting matter is supplied at once from the reservoir to the region creating the burst profile.

Another characteristic of a type II burst derived from the burst time evolution is that the X-ray emission cannot be determined only by the accretion rate. There is no one-to-one relationship between the luminosity and temperature in the spectral evolution of a type II burst. The observed blackbody temperature shows an apparent peak at each hump of luminosity, while the average temperature gradually increases as the luminosity decays (figure 4). The accretion rate on to the neutron star surface, therefore, does not uniquely determine the temperature and luminosity of a burst. The lack of a unique relationship between the luminosity and the spectral hardness is common to the persistent emission from low-mass X-ray binaries (LMXRB). These sources exhibit different properties both spectral and temporal (in particular QPO), depending on the branch in the luminosity-color diagram (see e.g. Lewin et al. 1988). Observations with higher time resolution of the QPO property will be made for each step in the time evolution of a type II burst, and can be compared to the branches of the persistent emission of LMXRB. We can then address more closely the similarities and differences between steady accretion and a type II burst.

5.5. Components to Create Type II Bursts

On the basis of the above-mentioned keys found from observations, we try to clarify the necessary components to produce a type II burst in terms of function.

A reservoir connected to a steady supply of accreting matter is required in order to explain the proportionality of the burst size to the waiting time to the next burst (E-Δt relation). The reservoir must be able to contain 10^{21} g of accreting matter, corresponding to the largest single burst. The magnetosphere is not likely the reservoir, because the surface magnetic field has to be extremely strong to hold so much matter (Tawara 1980). An accretion disk is the only possible reservoir which creates the E-Δt relation. We also refer to it as the "main reservoir".

The next component which we need is the emission region of a type II burst. The requirements have already been discussed in subsection 5.2. The actual substance is not yet clear. If it is a part of an accretion disk, it should be separated from the main reservoir. In such a case, the main reservoir is always present and is located at a large distance from the neutron star, while the emission region should be the inner part of the disk located at a few radii of the neutron star, and should be present only during bursts. The energy emitted from this region is most likely reprocessed emission originating from the surface of the neutron star, since a large part of the gravitational energy is released as matter is accreted on the surface of the neutron star. If the reprocessing emission region covers only a small solid angle (as is in the case of an accretion disk), the radiation from the surface needs to be beamed in order to shine the disk effectively. If the region is a shell covering a large solid angle around the neutron star, there is not such requirement.

The third component creates the time-variable spectral features of the time-scale invariant profile. Because the spectral shape is not determined only by the accretion rate, the main reservoir cannot be this component. As discussed in subsection 5.4, the whole quantity of accreting matter is supplied to this component at once before the energy is emitted as a burst. This component is, in other words, the waiting room of the accreting matter after leaving the main reservoir.

We thus need three components to create a type II burst: a main reservoir, an emission region, and a waiting room. Unlike the main reservoir, the latter two functions can be performed by a single substance. In fact, they have similar requirements. First, both of them are located between the neutron star surface and the main reservoir. Second, they contain matter only during a type II burst. It is rather natural to assume that these two components are one thing, and it consists of accreting matter.

There has been an attempt to explain the time-scale invariant profile by an instability in the accretion disk, attributing the characteristic time scale of 0.3–10 s to that of free fall or Keplerian motion at the distance of 10^9–10^{10} cm (Hayakawa 1985). As discussed above, the spectral change of the time-scale invariant profile does not favor this picture.

The accretion rate from the waiting room onto the neutron star surface is regulated by some mechanism, since the peak flux does not vary so much from burst to burst as the size varies widely. A regulation mechanism is also required to maintain the flux level in flat-top bursts. One possible mechanism is a magnetic torque that extracts angular momentum from the matter in the waiting room (Hanawa et al. 1989). Since the cooling time of matter that releases its gravitational energy on the neutron star surface is sufficiently short, as compared to the decay time of bursts, the structure in the burst decay is interpreted to reflect the variation of mass-flow rate as a function of time. If the decay time scale was predetermined according to the burst size, which is "already known from the beginning", the same mechanism should regulate the mass-flow rate based on this time scale. An important point is that the mass-flow rate at successive times in a burst is prescribed by the total amount of matter corresponding to the burst size, and not by the amount still remaining in the waiting room at that time.

6. Conclusion

We have found that the energy spectrum of a type II burst from the Rapid Burster is described by a blackbody spectrum in the energy range below 10 keV. The emission region of a type II burst at its peak is significantly larger than that of a type I burst from the same source. This implies that the emission region is larger than the neutron star. The actual substance of the emission region is not clear. It should emit X rays with a high and relatively constant temperature, impossible for an optically thick multicolor blackbody disk. The emission region is only present during a type II burst, since no cooling is observed in its decay, and a type I burst found between type II bursts exhibits ordinary emission area, presumably of the surface of the neutron star. When the time evolution of a type II burst is studied, there is no one-to-one relationship in luminosity and spectral temperature, so the emission region is not controlled only by the instantaneous accretion rate. There should be a buffer (waiting room) between the emission region and the main reservoir which is responsible for the E-Δt relation.

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