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ASCA Observation of the Rapid Burster in Quiescence

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Abstract

We observed the Rapid Burster in quiescence and detected a significant X-ray flux for the first time. Neither a type-I nor type-II burst was observed during the observation. The luminosity was estimated to be $(3^{+2}_{-1}) \times 10^{33}$ erg s^{-1} (2–10 keV), assuming a power-law with a photon index of 2 and a distance of 10 kpc. This luminosity is comparable to that of neutron-star transients in quiescence. If mass accretion is responsible for the X-ray emission, we can constrain the magnetic-field strength and spin period of the neutron star. A highly magnetized, rapidly rotating neutron star may be excluded.

Key words: Stars: individual (Rapid Burster) — Stars: neutron — X-rays: binaries — X-rays: sources — X-rays: transients

1. Introduction

The Rapid Burster is a unique recurrent X-ray source located in the globular cluster Liller 1 at a distance of $\sim$ 10 kpc (for a review, see Lewin et al. 1993). It is a transient source with a recurrence time of $\sim$ 6 months, and typically stays active for several weeks. When active, it can produce two types of X-ray bursts: type-I bursts, which are common to other burst sources, and type-II bursts, unique to the Rapid Burster. Type-I bursts are due to thermonuclear flashes on the surface of an accreting neutron star, while type-II bursts are the result of an accretion instability (Lewin et al. 1976). The behavior of type-II bursts is described as a relaxation oscillator; the integrated flux in a burst is roughly proportional to the time interval to the next burst. Many peculiar phenomena are associated with type-II bursts: timescale-invariant profile (Tawara et al. 1985; Rutledge et al. 1995), quasi-periodic oscillations (Tawara et al. 1982; Stella et al. 1988; Dotani et al. 1990; Rutledge et al. 1995), pre- and post-burst dips (Marshall et al. 1979; van Paradijs et al. 1979), post burst glitches (Lubin et al. 1993), etc. Although it is not known why only the Rapid Burster produces type-II bursts, it is often assumed to be due to the relatively strong magnetic field of the source (Baan 1977, 1979; Lamb et al. 1997).

In spite of all of these unique behavior, we know that the Rapid Burster harbors a neutron-star, because it produces type-I bursts. In fact, the Rapid Burster can behave like other neutron-star X-ray binaries. In 1993 August, although a strong persistent flux of X-ray was observed, no type-II bursts were found (Kunieda et al. 1984; Barr et al. 1987).

The Rapid Burster has not been detected so far in quiescence. An upper limit of 10^{34} erg s^{-1} was obtained with the Einstein observatory (Grindlay 1981). The ROSAT Sky Survey gave a comparable upper limit (Verbunt et al. 1995). In this letter, we report first on the detection of X-rays from the Rapid Burster in quiescence.

2. Observation

We observed the Rapid Burster with ASCA (Tanaka et al. 1994) from 1993 August 26, 23:15, through August 27, 15:10. The detectors aboard ASCA comprise two solid-state imaging spectrometers (SIS; Burke et al. 1994) and two gas-imaging spectrometers (GIS; Ohashi et al. 1996; Makishima et al. 1996). The SIS data were taken in the 1CCD mode, which covers a $11' \times 11'$ square field with a time resolution of 4 s. GIS covers a circular field with a radius with $25'$. The time resolution of the GIS data was increased to 61 μs while sacrificing the rise-time bits and a part of the position and energy bits of the telemetry. We obtained an effective exposure of 28 ks for SIS and 23 ks for GIS. Another burst source, 4U 1728$-$337, which is persistently bright, is located about 32′ away from the Rapid Burster. Therefore, the observation of the Rapid Burster was contaminated by stray light from 4U 1728−337 (Serlemitsos et al. 1995).

3. Analysis and Results

We detected a weak, but significant, X-ray flux with both the SIS and GIS from a source located in the sky field including the Rapid Burster. The source position deduced from the SIS data is R.A. = $17^{\rm h}33^{\rm m}19^{\rm s} \pm 7^{\rm s}$, Dec. = $-33^\circ 23' \pm 0\overset{'}{.}5$ (J2000). The GIS data, which have a poorer spatial resolution in this observation, are consistent with this result. No other source was detected in the GIS field of view. The uncertainty of the source position results from both the systematic error of the attitude determination due to the thermal distortion of the satellite structure and the statistical error. It is known that the satellite structure is distorted in response to the day/night transitions, which cause an artificial shift of the source image less than ~ 1′, approximately along the satellite Y-direction. In the case of the present observations, the shift changes primarily the right ascension of the source position. The SIS error region overlaps the HEAO-1 error box of the Rapid Burster (Doxsey et al. 1978) and includes the core of the globular cluster Liller 1 (Hertz, Grindlay 1985). Thus, the source which we detected is most probably the Rapid Burster.

Figure 1 shows X-ray image of the field including the Rapid Burster taken with the SIS. The diffuse emission seen in the field of view is due to stray light from 4U 1728−337. We determined the local background level around the Rapid Burster by selecting a sky region whose angular distance to 4U 1728−337 is the same as that of the Rapid Burster. Note that the contribution of particles and cosmic X-rays to the local background is negligible. It is found that the peak surface brightness of the Rapid Burster, after subtracting the local-background, is 8-times larger than the local-background fraction level. This means that the detecting the source is very significant. We calculated the source flux to be about 0.004 c $\rm s^{-1}$ (1–10 keV) for a single SIS. We also calculated the light curve with the SIS data. No X-ray burst, such as that seen in the active phase of the Rapid Burster, was observed. Because the expected count rate from the Rapid Burster in its active phase is on the order 10 c $\rm s^{-1}$, and no X-ray burst was observed, the source is conjectured to be in quiescence.

We tried to calculate the energy spectrum from the data. However, since possible fine structures in the stray-light pattern (Serlemitsos et al. 1995) produced a relatively large systematic error in the estimation of the local background level, we could not constrain the energy spectrum. If we assume a power law with a photon index of 2 with a neutral hydrogen column density of 1×10^{22} $\rm cm^{-2}$ and a distance of 10 kpc, the flux corresponds to an intrinsic luminosity of $(3^{+2}_{-1}) \times 10^{33}$ erg $\rm s^{-1}$ (2–10 keV).

We searched for coherent pulsations with the GIS data using an FFT algorithm. We could find no significant pulsations in the period range from 1 ms to 10^3 s. The upper limit (90% confidence limit) of the rms pulse fraction is about 40%.

4. Discussion

We detected a significant X-ray flux from the Rapid Burster in quiescence for the first time. The luminosity of the source was about 3×10^{33} erg $\rm s^{-1}$. We could not constrain any spectral parameters due to heavy contamination of the stray light from 4U 1728−337.

The presence of plural X-ray sources with low luminosity ($\leq 10^{33}$ erg $\rm s^{-1}$) is known in the cores of globular clusters, such as 47 Tuc (Hasinger et al. 1994), ω Cen (Johnston et al. 1994), and NGC 6399 (Cool et al. 1993). Therefore, it may be possible that some low-luminosity X-ray sources exist in the core of Liller 1 other than the Rapid Burster. Because the core radius of Liller 1 is only $3\overset{''}{.}5$ (Hertz, Grindlay 1985), ASCA cannot resolve the source spatially. If other X-ray sources were really present in Liller 1, the X-ray luminosity which we obtained should be regarded as an upper limit of the luminosity of the Rapid Burster.

The quiescent luminosity, 3×10^{33} erg $\rm s^{-1}$, is comparable to the luminosity of X-ray novae with a neutron star in quiescence. X-ray novae containing a neutron-star are often detected in the luminosity range of ~ 10^{32}–10^{33} erg $\rm s^{-1}$ according to ROSAT (van Paradijs et al. 1987; Verbunt et al. 1994) and ASCA observations (Asai et al. 1996). On the other hand, X-ray novae with a black hole in quiescence seems to be systematically dimmer than that with a neutron star (McClintock et al. 1995). The quiescent luminosity may be as low as a few 10^{30} erg $\rm s^{-1}$. Thus, as far as the luminosity is concerned, the Rapid Burster behaves like ordinary neutron-star transients in quiescence.

Two different mechanisms may be responsible for the X-ray emission from the Rapid Burster in quiescence. One is the rotation power of the neutron-star; the other is mass accretion from the companion star. Many models of the Rapid Burster assume the presence of a magnetic field of 10^9–10^{10} G on the surface (Baan 1977; Lamb et al. 1977; Michel 1977). Mass accretion during the active phase is expected to have spun up the neutron star to a sub-second period (Alpar et al. 1982). If the neutron star has a magnetic field, say 10^{10} G at the surface, and spins rapidly (with a period of say 10 ms), its spin-down energy-loss rate (assuming that the loss formula for magnetic dipole radiation applies) can be as large as 10^{35} erg $\rm s^{-1}$. If about 1% of the spin-down energy is

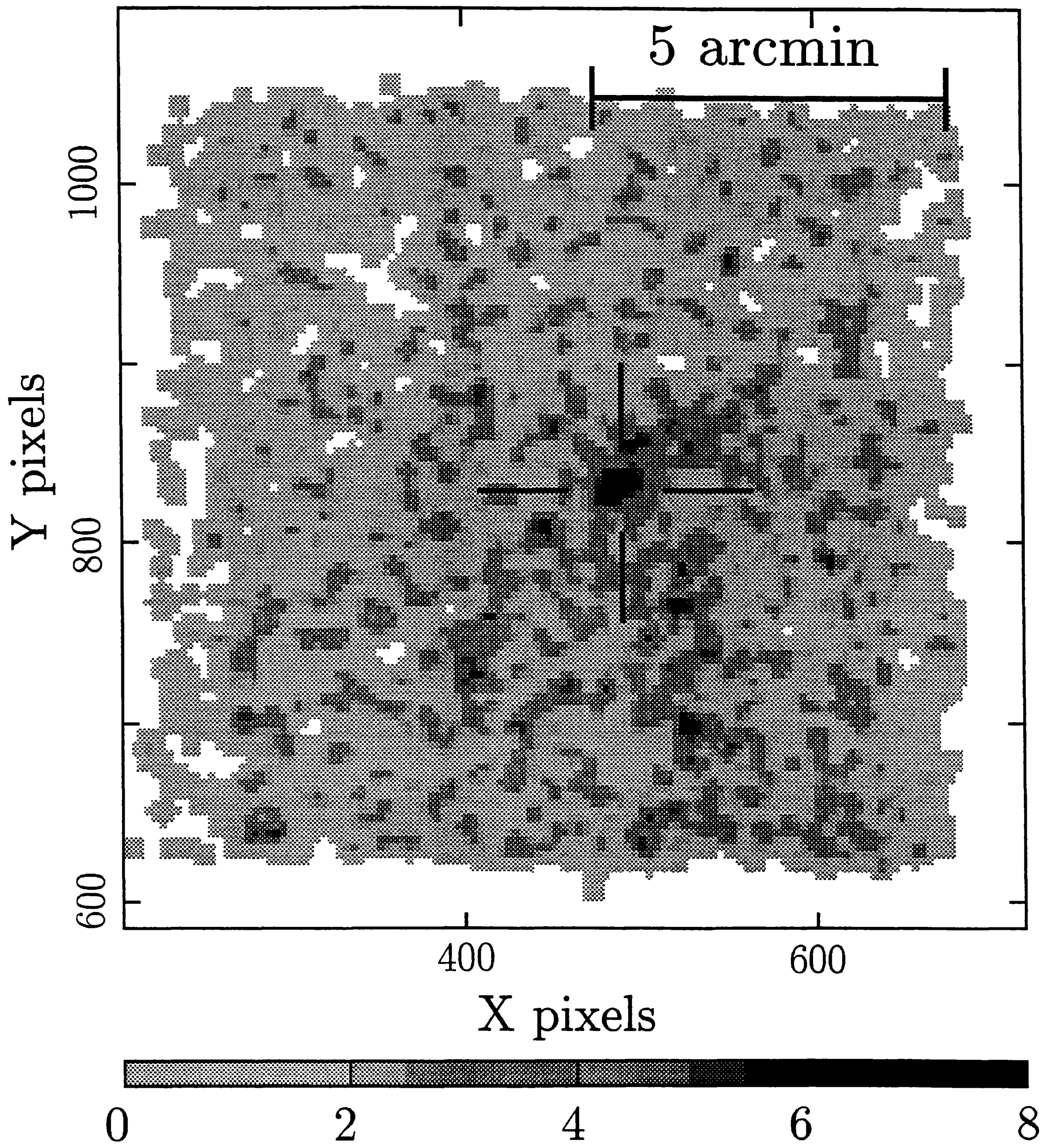

Fig. 1. SIS image of the sky field including the Rapid Burster in 2–10 keV. North is up, east to the left. The image data obtained by two SIS detectors were combined and smoothed by a Gaussian curve with $\sigma = 1.5$ pixels. The Rapid Burster is indicated by the cross. The diffuse X-ray emission is the stray light from the nearby X-ray source 4U 1728−337. The gray-scale levels are indicated in the figure in units of count $(6'')^{-2}(28\ \mathrm{ks})^{-1}$.

converted to X-rays, as is the case of the Crab pulsar, the observed X-ray flux can be explained. In this case, it would be the first observation of an LMXB which became a millisecond radio pulsar.

If the energy source of X-ray emission is mass accretion, there are two different ways to supply the matter: through accretion disk or by the stellar wind. If the companion star fills its Roche-lobe, it is expected that an accretion disk is also present in quiescence. The mass-transfer rate from the secondary into the disk may be very small, or the rate at which mass is transferred through the disk could be very low. The rate at which mass is fed into the disk from the companion might be much larger than the mass-transfer rate through the disk as is the case for A0620−00 (McClintock et al. 1995). On the other hand, the companion star may have a moderately strong stellar wind, as is the case for a giant, part of which is accreted onto the neutron star during the quiescent phase. In the latter case, it might be possible to consider the mass accretion on to the magnetosphere, rather than the neutron star surface, as the source of X-ray emission (van Paradijs et al. 1989; King, Cominsky 1994). However, the expected luminosity of magnetospheric accretion is relatively large for the probable parameters of LMXB, only an order of magnitude smaller than the luminosity of neutron-star accretion (Corbet 1996). The quiescent luminosity of the Rapid Burster which we obtained is 10^{-3}–10^{-4} of the average luminosity in the active phase. Thus, magnetospheric accretion may not work for the Rapid Burster in quiescent; hereafter we consider only neutron-star accretion. The accreting matter, regardless of disk accretion or wind accretion, would be channeled to the magnetic poles. The reason for this is that the Alfvén radius in quiescence, which is estimated as $r_{\rm A} \sim 1 \times 10^8 L_{33}^{-2/7} B_9^{4/7}$ cm for a neutron star of mass of 1.4 $M_\odot$ and a radius of 10 km, where L_{33} is the X-ray luminosity in units of 10^{33} erg s^{-1} and B_9 the surface magnetic field in unit of 10^9 G, is much larger than the neutron-star radius ($\sim 10^6$ cm). This means that the neutron-star works as an accretion-powered pulsar in the quiescent phase.

The rotational velocity of the magnetic field at the boundary layer must be smaller than the Kepler velocity to keep the mass accretion continuing. We can constrain the rotation period and the magnetic field of the neutron star under this condition. Assuming a neutron star of mass of 1.4 $M_\odot$ and having a radius of 10 km, the following constraint can be obtained:

$$\log P_1 - \frac{6}{7}\log B_9 > -0.5 - \frac{3}{7}\log L_{33} + \frac{3}{2}\log f_1, \qquad (1)$$

where P_1 is the spin period of the neutron star in unit of second and f_1 is the ratio of the boundary layer radius to the Alfvén radius: $f_1 \simeq 1$ for spherical accretion and $f_1 \simeq 0.5$ for disk accretion. According to this constraint, a neutron star whose surface magnetic field is 10^9 G, for example, should have a spin period longer than ~ 0.2 s (~ 0.07 s) for spherical (disk) accretion. A highly magnetized rapidly rotating neutron star can therefore be rejected. Therefore, if mass accretion were responsible for the X-ray emission from the neutron star in quiescence, it would mean either: (1) that the magnetic field of the neutron star is very low or (2) that the rotation period is very long. The former possibility was suggested by Hanawa et al. (1989) and Kawai et al. (1990) to explain the type-II burst activity of the Rapid Burster. According to the recycled scenario of millisecond radio pulsars (Bhattacharya, van den Heuvel 1991), LMXBs are generally expected to have a rapid spin of the order of a millisecond. Such a short spin period may be incompatible with the large magnetic field (10^9–10^{10} G) hypothesized in the magnetosphere models of the Rapid Burster.

References

Alpar M.A., Cheng A.F., Ruderman M.A., Shaham J. 1982, Nature 300, 728

Asai K., Dotani T., Mitsuda K., Hoshi R., Vaughan B., Tanaka Y., Inoue H. 1996, PASJ 48, 257

Baan W.A. 1977, ApJ 214, 245

Baan W.A. 1979, ApJ 227, 987

Barr P., White N.E., Harberl F., Stella L., Pollard G., Gottwald M., Parmar A.N. 1987, A&A 176, 69

Bhattacharya D., van den Heuvel E.P.J. 1991, Phy. Rep. 203, 1

Burke B.E., Mountain R.W., Daniels P.J., Cooper M.J., Dolat V.S. 1994, IEEE Trans. Nuclear Science 41, 375

Cool A.M., Grindlay J.E., Krockenberger M., Bailyn C.D. 1993, ApJL 410, L103

Corbet R.H.D. 1996, ApJL 457, L31

Dotani T., Mitsuda K., Inoue H., Tanaka Y., Kawai N., Tawara Y., Makishima K., van Paradijs J. et al. 1990, ApJ 350, 395

Doxsey R., Bradt H., Johnston M., Gursky H., Schwartz D. A., Schwarz J. 1978, ApJL 221, L53

Grindlay J.E. 1981, in X-ray Astronomy with the Einstein Satellite, ed R. Giacconi (Reidel, Dordrecht) p79

Hanawa T., Hirotani K., Kawai N. 1989, ApJ 336, 920

Hasinger G., Johnston H.M., Verbunt F. 1994, A&A 288, 466

Hertz P., Grindlay J.E. 1985, ApJ 298, 95

Johnston H.M., Verbunt F., Hasinger G. 1994, A&A 289, 763

Kawai N., Matsuoka M., Inoue H., Ogawara Y., Tanaka Y., Kunieda H., Tawara Y. 1990, PASJ 42, 115

King A., Cominsky L. 1994, ApJ 435, 411

Kunieda H., Tawara Y., Hayakawa S., Nagase F., Inoue H., Kawai N., Makino F., Makishima K. et al. 1984, PASJ 36, 807

Lamb F.K., Fabian A.C., Pringle J.E., Lamb D.Q. 1977, ApJ 217, 197

Lewin W.H.G., Doty J., Clark G.W., Rappaport S.A., Bradt H.V.D., Doxsey R., Hearn D.R., Jernigan J.G. et al. 1976, ApJL 207, L95

Lewin W.H.G., van Paradijs J., Taam R.E. 1993, Space Sci. Rev. 62, 223

Lubin L.M., Lewin W.H.G., Rutledge R.E., van Paradijs J., van der Klis M. 1993, MNRAS 261, 149

Makishima K., Tashiro M., Ebisawa K., Ezawa H., Fukazawa Y., Gunji S., Hirayama M., Idesawa E. et al. 1996, PASJ 48, 171

Marshall H.L., Ulmer M.P., Hoffman J.A., Doty J., Lewin W.H.G. 1979, ApJ 227, 555

McClintock J.E., Horne K., Remillard R.A. 1995, ApJ 442, 358

Michel F.C. 1977, ApJ 216, 838

Ohashi T., Ebisawa K., Fukazawa Y., Hiyoshi K., Horii M., Ikebe Y., Ikeda H., Inoue H. et al. 1996, PASJ 48, 157

Rutledge R.E., Lubin L.M., Lewin W.H.G., Vaughan B., van Paradijis J., van der Klis M. 1995, MNRAS 277, 523

Serlemitsos P.J., Jalota L., Soong Y., Kunieda H., Tawara Y., Tsusaka Y., Suzuki H., Sakima Y. et al. 1995, PASJ 47, 105

Stella L., Haberl F., Lewin W.H.G., Parmar A.N., van Paradijs J., White N.E. 1988, ApJ 324, 379

Tanaka Y., Inoue H., Holt S.S. 1994, PASJ 46, L37

Tawara Y., Hayakawa S., Kunieda H., Makino F., Nagase F. 1982, Nature 299, 38

Tawara Y., Kawai N., Tanaka Y., Inoue H., Kunieda H., Ogawara Y. 1985, Nature 318, 545

van Paradijs J., Cominsky L., Lewin W.H.G. 1979, MNRAS 189, 387

van Paradijs J., Kraakman H., van Amerongen S. 1989, A&A 79, 205

van Paradijs J., Verbunt F., Shafer R.A., Arnaud K.A. 1987, A&A 182, 47

Verbunt F., Belloni T., Johnston H.M., van der Klis M., Lewin W.H.G. 1994, A&A 285, 903

Verbunt F., Bunk W., Hasinger G., Johnston H.M. 1995, A&A 300, 732