Discovery of a New X-Ray Burst/Millisecond Accreting Pulsar
HETE J1900.1-2455

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Abstract

A class of low-mass X-ray binary sources are known to be both X-ray burst sources and millisecond
pulsars at the same time. A new source of this class was discovered by High Energy Transient Explorer
2 (HETE-2) on 14 June 2005 as a source of type-I X-ray bursts, which was named HETE J1900.1-2455. Five X-ray bursts from HETE J1900.1-2455 were observed during the summer of 2005. The time resolved
spectral analysis of these bursts has revealed that their spectra are consistent with the blackbody radiation
throughout the bursts. The bursts show the indication of radius expansion. The bolometric flux remains
almost constant during the photospheric radius expansion while blackbody temperature dropped during
the same period. Assuming that the flux reached to the Eddington limit on a standard 1.4 solar mass
neutron star with a helium atmosphere, we estimate the distance to the source to be ~ 4 kpc.

Key words: stars: pulsars: individual (HETE J1900.1-2455) — stars: neutron — X-rays: bursts

1. Introduction

An X-ray burst source HETE J1900.1-2455 was discovered by High Energy Transient Explorer 2 (HETE-2) on 14 June 2005 as a source of type-I X-ray bursts, which was named HETE J1900.1-2455. Five X-ray bursts from HETE J1900.1-2455 were observed during the summer of 2005. The time resolved spectral analysis of these bursts has revealed that their spectra are consistent with the blackbody radiation throughout the bursts. The bursts show the indication of radius expansion. The bolometric flux remains almost constant during the photospheric radius expansion while blackbody temperature dropped during the same period. Assuming that the flux reached to the Eddington limit on a standard 1.4 solar mass neutron star with a helium atmosphere, we estimate the distance to the source to be ~ 4 kpc.

1.1. Introduction

An X-ray burst source HETE J1900.1-2455 was discovered by High Energy Transient Explorer 2 (HETE-2) on 14 June 2005. The position of the source was distributed through the Gamma ray bursts Coordinates Network circular (Arimoto et al. 2005) and The Astronomer’s Telegram (Vanderspek et al. 2005).

The follow-up observations were performed by the Rossi X-ray Timing Explorer (RXTE) on June 16 and 17 in 2005 with exposures of 1.14 ks and 5.46 ks respectively. An X-ray pulsar with a spin frequency of 377.3 Hz was found at R.A. = 19h00m13s, Dec. = -24°54′44″ (J2000) and this position was consistent with the HETE error circle. The flux of the pulsar was 6.6 × 10^-10 erg cm^-2 s^-1 in 2–20 keV (Morgan et al. 2005; Markwardt et al. 2005; Kaaret et al. 2006). Fox (2005) observed the field of the SXC error circle with the Robotic Palomar 60-inch Telescope with R-band and i-band from 07:27 to 07:57 UT on 18 June 2005, and detected a previously unknown object at R.A. =19h00m08s65, Dec. =-24°55′13″7 (J2000). The brightness of the counterpart is R ~ 18.4 mag.

HETE J1900.1-2455 is the seventh known accretion-powered millisecond pulsar. The sources of this class have some common properties. Their orbital periods are distributed between 40 min and 120 min (Kaaret et al. 2006), spectra above 15 keV were described by power-law models with exponential cut-off (for example Falanga et al. 2005; Falanga et al. 2005b), while low energy spectra need blackbody and/or disk blackbody components (for example Gierliński & Poutanen 2005; Juett et al. 2003). In fact, through the observation of HETE J1900.1-2455 by RXTE, power-law and blackbody spectral features are found by Kaaret et al. (2006) and a hint of high energy emission is reported by Goldoni et al. (2005). The upper panel of figure 1 shows the light curve of HETE J1900.1-
2. Observation and data analysis

2.1. Localization

The French Gamma Telescope (FREGATE), the Wide-field X-ray Monitor (WXM), and the Soft X-ray Camera (SXC) instruments on board HETE-2 detected an X-ray burst (trigger ID H3804) at 11:22 UT on 14 June 2005.

This event was localized by the ground analysis of WXM data, and refined by SXC data to a circle of with $80''$-radius centered at R.A. = $19^h06^m6.4^s$, Dec = $-24^\circ54'54.7''$ (J2000) (Arimoto et al. 2005). The Galactic coordinates of the burst is $l=00^h45^m$, $b=-12^\circ86'$. There was no known X-ray source at this position. The position of H3804 did not match any of the entry in in the globular cluster catalog (Harris 1996) either, while globular clusters sometimes host X-ray burst sources. The results of localizations by WXM and SXC are shown in figure 2. The positions of the source determined by the RXTE PCA scans (Markwardt et al. 2005) and the optical counterpart candidate (Fox 2005) are also shown in the figure.

2.2. Data analysis

In addition to the first burst on 14 June, HETE-2/WXM detected four more X-ray bursts from the source on 17 June, 27 June, 7 July, and 21 July in 2005. The burst on 14 June and 7 July were triggered events while the others were untriggered. For the second burst on 17 June the information of accurate spacecraft attitude was not available, because the optical camera system had been turned off about 100 seconds before the burst. The source position of the burst was found to be 0.6 degree off HETE J1900.1-2455 if the attitude information of 100 seconds before the burst was used. We consider, however, that HETE J1900.1-2455 is still the most likely source of this burst, as it is possible that the spacecraft attitude drifted 0.6 degree in 100 seconds, and there are no known X-ray sources within comparable distances. The time of the all events and their incident angles are summarized in Table 1. We note that the burst on 21 July was also detected by RXTE (Galloway et al. 2005).

The WXM is sensitive to photons in 2–25 keV energy range. Figure 3 shows the operation status (on or off) of WXM around the burst time. As shown in the figure, the observation efficiency of WXM is approximately 50%. We use data of WXM for temporal and spectral analysis. Table 1 contains availability of the TAG data, which consist of time tagged photons with 32 energy bins. The time resolution of the TAG data is precise enough (<1 msec) to extract spectra of arbitrary time interval. For the untriggered events (2nd and 3rd bursts), TAG data are not available. So we use the PHA data, time-integrated 32-channel spectra with 4.915 sec time resolution for the spectral analyses. There are occasional dropouts of the TAG data. Therefore, we use the TH data, time history in four energy bands with 1.229 sec time resolution for the timing analyses in all bursts in order to avoid the effects of the dropouts of the TAG data.

2.2.1. Temporal Properties

Figure 4 show the TH light curve of all five bursts in 2–5, 5–10, 10–17, and 17–25 keV. We can see the the double peak structures in the 10–17 keV bands. This features may be explained by an X-ray burst with moderate photospheric expansion at the Eddington luminosity.

We calculated the duration $T_90$, which is a standard indicator of the burst duration applied to gamma-ray bursts. In Table 2, we summarized the $T_90$ duration of each burst in each energy band. In the first four bursts, the $T_90$ durations are about 30 sec, while the last burst has longer $T_90$, about 80 sec.

2.2.2. Spectral Analysis

We performed the time resolved spectral analysis for the bursts. First, we divided the bursts into several time
Fig. 1. The light curve of HETE J1900.1-2455 observed by RXTE/ASM (upper panel), and the observation time coverage of HETE-2/WXM, where the time intervals when HETE J1900.1-2455 was in the HETE-2/WXM field of view are shown with dots (lower panel). The time of the first burst detected by HETE-2 is shown with the vertical dotted line, which coincides with the time of the sudden brightening. The ASM light curve and the WXM coverage in 2005 are enlarged in the insets with the time of the bursts shown with arrows.

Table 1. The observation log of the five bursts observed by HETE-2. The burst date and time, HETE burst ID, incident angle on WXM, and availability of TAG data are summarized in the table. \( \theta_x \) and \( \theta_y \) are the projection angles measured from the vertical direction onto the XZ and YZ plane of the detector coordinate system.

| Burst No. | date (MJD) | time (UT) | burst ID | \((\theta_x, \theta_y)\) [deg] | TAG data |
|-----------|------------|-----------|---------|-------------------------------|----------|
| 1         | 14 Jun. (53535) | 11:21:50 | 3804 | (4.24, −8.63) | yes      |
| 2         | 17 Jun. (53538) | 21:49:10 | 11663 | (3.64, −6.00) | no       |
| 3         | 27 Jun. (53548) | 13:54:10 | 11662 | (−0.82, 3.04) | no       |
| 4         | 7 Jul. (53558)  | 13:09:22 | 3858  | (18.37, 3.58) | yes      |
| 5         | 21 Jul. (53572) | 23:00:32 | 11640 | (14.83, 11.48) | yes      |

Table 2. Observed \( T_{90} \) durations of each burst/energy band are summarized. These durations are calculated using TH data in order to avoid the effects of the TAG data dropouts.

| Burst No. | 2−5 keV | 5−10 keV | 10−17 keV | 17−25 keV |
|-----------|---------|----------|-----------|-----------|
| 1         | 27.0 ± 3.7 | 25.8 ± 10.6 | 16.0 ± 37.1 | 16.0 ± 10.0 |
| 2         | 29.5 ± 3.5 | 23.3 ± 2.1 | 23.3 ± 2.7 | 18.4 ± 8.8 |
| 3         | 23.3 ± 11.1 | 24.6 ± 7.3 | 17.2 ± 7.2 | 29.5 ± 12.7 |
| 4         | 28.3 ± 4.6 | 29.5 ± 7.2 | 28.3 ± 8.9 | 47.9 ± 30.7 |
| 5         | 73.7 ± 9.8 | 71.3 ± 7.3 | 50.4 ± 12.2 | 65.1 ± 17.3 |
Fig. 3. The operation status of WXM around the burst on 14 June, 17 June, 27 June, 7 July, and 21 July (from top to bottom). Each panel shows the status, on or off, of WXM from 30000 sec before the burst to 30000 sec after the bursts. The burst time are aligned at time=0.

intervals (see figure 4). We used the data before and/or after the burst as background data. Although these background must contain photons of the persistent emission from the source, they should be negligibly small (∼1/100) compared with burst emission and should not affect the results. There were TAG data dropouts in the time interval between 14.5 sec and 17.5 sec of the 5th burst. Therefore we did not analyze the data of this time interval. However according to the TH data, the count rates and the hardness ratios of this burst do not change much from 14.5 sec to 20.0 sec. So the spectral parameters of the time interval of data lack may be similar to that of the time interval between 17.5 sec and 20.0 sec.

We use the XSPEC version 11.3 software package for spectral fitting. We find that the blackbody model is the best fit model for the bursts. We also tried the blackbody with photo-electric absorption model. However we scarcely see the improvement in the $\chi^2$. The $N_H$ value is negligibly small.

We plotted the best fit spectral parameters with blackbody model in figure 4: blackbody temperature $kT$ in the unit of keV, the bolometric source flux $F_b$ in the unit of $10^{-7}$ ergs cm$^{-2}$ sec$^{-1}$, and the source radius in the unit of km. In order to estimate source radius, we assumed the source distance $d = 4.3$ kpc, which is estimated from the source flux and the Eddington luminosity (see section 3.1).

3. Discussion

3.1. The distance to the source

In section 2.2.2, we showed that the spectra of all time interval are consistent with blackbody emission. All the bursts have the time regions which show the drops of blackbody temperature and the rises of source radius. These features can be interpreted as photospheric expansion at the Eddington luminosity. The drop of blackbody temperature in the tail parts show cooling. All these results are consistent with Eddington-limited type-I X-ray burst.

From the spectral fitting we obtained bolometric flux $F_b$ at the peak of each burst, and summarized in table 3. The largest peak flux is that of the second burst, $1.21 \times 10^{-7}$ [ergs cm$^{-2}$ s$^{-1}$]. If it is equal to the Eddington luminosity of 1.4 solar mass neutron star ($L = 2.7 \times 10^{38}$ [ergs s$^{-1}$]), the distance $d$ is

$$d = \left( \frac{L}{4\pi F_b} \right)^{1/2} = 4.31 \text{[kpc]}.$$ (1)

3.2. The observation time and activities of the source

WXM and FREGATE on HETE-2 detected only five X-ray bursts form HETE J1900.1-2455 in 2005 although the source was in the field of view of HETE-2/WXM in every summer since 2001, as shown in the lower panel of figure 1. According to figure 1, we should have detected bursts
Fig. 4. The TH light curves of the X-ray burst HETE J1900.1-2455 in four energy bands observed by HETE-2 WXM. The upper three plots are the bursts on 14 June, 17 June, and 27 June (from left to right). The lower plots are the bursts on 7 July (left) and 21 July (right). The count rates are in the unit of counts per 1.229 sec bin. The spectral parameters of the fits to the blackbody model are also shown in the lower three panels of each plots (see section 2.2.2). The blackbody temperature $kT$ in the unit of keV, the bolometric source flux $F_b$ in the unit of $10^{-7}$ ergs sec$^{-1}$ cm$^{-2}$, and the source radius in the unit of km. The distance to the source is assumed to be 4.31 kpc to estimate the radii of the blackbody radiation. The uncertainties are 90% confidence limits.
between 2001 and 2004, if the source had been active as much as in 2005. The absence of the burst before 2005 means that the source was “turned on” some time after the summer of 2004.

In the insets of figure 1, the time of the bursts are plotted with arrows. The figure clearly show the correspondence between persistent flux and burst activity of the source, which is the common behavior of bursts from the transient sources (e.g., Cen X-4: Matsuoka et al. 1980; Aql X-1: Koyama et al. 1981; X1608-522: Murakami et al. 1980; Nakamura et al. 1989). These observations agree with theoretical predictions that bursts occur when the persistent flux is between 0.1% and 10% of the Eddington luminosity (Lamb & Lamb 1978; Joss 1978; van Paradijs et al. 1979). In the case of HETE J1900.1-2455, assuming the peak flux of the bursts reached the Eddington luminosity, the persistent flux at the time of bursts is about 1% of the Eddington luminosity. On the other hand, the upper limit of the persistent flux in the quiescent state is an order of magnitude smaller than in the active state, which can be read from figure 1. These facts are consistent with the above theoretical expectation.

We can see the bursts occurred somewhat regularly in June and July of 2005 except the first burst. Unfortunately, the WXM did not point toward the source after early August. Therefore we do not know the regularity of the bursts after the last burst. We should note here that the instruments on HETE-2 are turned off during the half of the orbits, and observation efficiency is ∼ 50%. There may be missing burst in the time interval of regular activity.

We estimated α value (Lewin et al. 1993), which is ratio of the average persistent X-ray flux to the average flux emitted in bursts, using the information of persistent flux reported by Kaaret et al. (2006). The average persistent flux in 2−20 keV is ∼ 7 × 10^{−10} erg cm^{−2} sec^{−1} during the observation. To calculate average flux emitted in bursts \( \mathcal{F}_b \), we divided the burst fluence by the waiting time after the previous burst. Since there may be some bursts we did not observed, \( \mathcal{F}_b \) that we calculated should be lower limit. The fluence of the 2nd, 3rd, 4th, and 5th bursts are ∼ 2.0, 1.1, 0.96, and 4.1 × 10^{−6} erg cm^{−2} respectively. The waiting time of these bursts are 2.97, 8.36, 8.61, and 12.4 × 10^{5} sec. Therefore upper limits of α for these bursts are ∼ 100, 500, 700, and 200. The α for the 2nd burst is consistent with the standard α value for a pure helium atmosphere, which is ∼ 100. It is unlikely that more than three missing bursts were present between the waiting time, because the observation efficiency of WXM is roughly 0.5. Thus real α of the 3rd and 4th bursts might not be lower than 150. This α value may be slightly higher than standard value. Here we note that the estimated bolometric persistent flux may be smaller than the real value, because the persistent emissions of this type of sources have bright power-law component in addition to the blackbody emission from the neutron star surface. The harder and the brighter spectral shape makes the larger difference between estimated and real bolometric persistent flux. However, the difference may not be larger than several tens percent of the estimated flux. More precise consideration is possible in comparing the α value of HETE J1900.1-2455 with other burst sources on the \( \alpha \) and \( \gamma \) plane, where \( \gamma \) is the bolometric persistent flux normalized with the bolometric peak flux of the burst. The studies of relation between \( \alpha \) and \( \gamma \) are summarized in van Paradijs et al. (1988), and there is a trend of lower \( \alpha \) for the source with lower \( \gamma \). On the other hand, our results, log\( \alpha \) ∼ 2 and log\( \gamma \) ∼ −2, show high \( \alpha \) despite low \( \gamma \). The other accreting millisecond pulsars with type-I X-ray bursts, which are SAX J1808.4-3658 (in’t Zand et al. 1998; in’t Zand et al. 2001) and XTE J1814-338 (Strohmayer et al. 2003; Krauss et al. 2005), may show the same tendency. Therefore, high \( \alpha \) in low \( \gamma \) might be a common property of the accreting millisecond pulsar, while the confirmation with larger samples is needed.

3.3. The durations of the bursts

The 5th burst had obviously longer duration than other four bursts, and smaller α value at the same time. According to the model of hydrogen and helium flash, the burning of hydrogen together with helium makes the rise time longer and α value smaller. Since both short and long bursts have the indications of photospheric expansion, both bursts reach the Eddington limit. Generally the Eddington limit corresponding to the hydrogen-rich matter should be lower than the case of the pure helium matter. The observed peak flux are, however, almost constant or slightly higher in the longer burst. These results are not fully understood in the framework of hydrogen and helium flash model.
4. Conclusion

We discovered the new X-ray burst source HETE J1900.1-2455. We analyzed five X-ray bursts from the source. The temporal and spectral properties of the bursts are consistent with those of Eddington-limited type-I bursts. If the peak luminosity of the bursts is the Eddington luminosity of a standard 1.4 solar mass neutron star with a helium atmosphere, the distance to the source is \( \sim 4 \) kpc. The alpha values of the 3rd and 4th bursts, were estimated to be \( >150 \). Such a large value can be explained by the bright power-law component of the persistent emission. The long duration and lower \( \alpha \) value of 5th burst may indicate the hydrogen-rich composition of burst fuel. However the Eddington limit of the burst is comparable to the other bursts.

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