NaSTAR OBSERVATION OF A TYPE I X-RAY BURST FROM GRS 1741.9-2853

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ABSTRACT

We report on two NuSTAR observations of GRS 1741.9-2853, a faint neutron star (NS) low-mass X-ray binary burster located 10′ away from the Galactic center. NuSTAR detected the source serendipitously as it was emerging from quiescence: its luminosity was 6 × 1033 erg s−1 on 2013 July 31 and 5 × 1033 erg s−1 in a second observation on 2013 August 3. A bright, 800 s long, H-triggered mixed H/He thermonuclear Type I burst with mild photospheric radius expansion (PRE) was present during the second observation. Assuming that the luminosity during the PRE was at the Eddington level, an H mass fraction X = 0.7 in the atmosphere, and an NS mass M = 1.4 M⊙, we determine a new lower limit on the distance for this source of 6.3 ± 0.5 kpc. Combining with previous upper limits, this places GRS 1741.9-2853 at a distance of 7 kpc. Energy independent (achromatic) variability is observed during the cooling of the NS, which could result from the disturbance of the inner accretion disk by the burst. The large dynamic range of this burst reveals a long power-law decay tail. We also detect, at a 95.6% confidence level (1.7σ), a narrow absorption line at 5.46 ± 0.10 keV during the PRE phase of the burst, reminiscent of the detection by Waki et al. We propose that the line, if real, is formed in the wind above the photosphere of the NS by a resonant transition from H-like Cr gravitationally redshifted by a factor 1 + z = 1.09, corresponding to a radius range of 29.0–41.4 km for a mass range of 1.4–2.0 M⊙.

Key words: accretion, accretion disks – nuclear reactions, nucleosynthesis, abundances – stars: neutron – X-rays: binaries – X-rays: bursts – X-rays: individual (GRS 1741.9-2853)

1. INTRODUCTION

GRS 1741.9-2853 (also called AX J1745.0-2855) is a very faint X-ray transient that was discovered by the *Granat* satellite in 1990 (Sunyaev 1990). In 1996, *Beppo-SAX* detected a series of three Type I bursts from this source, establishing that it is a neutron star (NS) low-mass X-ray binary (LMXB; Cocchi et al. 1999). Since its discovery, GRS 1741.9-2853 has been detected in outburst several times by different observatories; in 1994, 1996, 2000, 2002, 2005, 2007, 2009, 2010, and in 2013 (Sakano et al. 2002; Muno et al. 2003, 2007; Wijnands et al. 2005, 2006, 2007; Porquet et al. 2007; Chenevez et al. 2009; Degenaar et al. 2009; Trap et al. 2009; Kennea 2009; Degenaar et al. 2010, 2013b; Degenaar & Wijnands 2010; Kuulkers et al. 2013). Its typical outburst luminosity is ∼1035−36 erg s−1 (see Trap et al. 2009; Degenaar et al. 2014 for reviews of GRS 1741.9-2853 earlier and more recent outburst history). It has also been detected in quiescence by *Chandra*, with a 2–8 keV luminosity of about 1032 erg s−1 (Muno et al. 2003). Its outburst duty cycle is about 10%, with typical outburst duration of ∼10 weeks and recurrence time of ∼2 years. Its average accretion rate is of the order of 10−10 M⊙ yr−1 (Degenaar & Wijnands 2010). A distance measurement of 8 kpc was proposed by Cocchi et al. (1999), placing the source very close to the Galactic center, as it lies 10′ from Sagittarius A∗. This distance was then further refined to an upper limit of 7 kpc by Trap et al. (2009), who used *INTEGRAL*, *XMM-Newton*, and *Swift* data of the 2005 and 2007 outbursts.

GRS 1741.9-2853 is a binary system where the companion is a low-mass star (M ≤ 1 M⊙) filling its Roche lobe and pouring matter onto an accretion disk. The known LMXBs in our Galaxy are concentrated in the Galactic bulge (Grimm et al. 2002; Revnivtsev et al. 2008), and half of them are transients that increase their luminosity by several orders of magnitudes during outbursts (Liu et al. 2007). In such systems, X-ray outbursts are interpreted as an increase of the accretion rate onto the compact object (e.g., Osaki 1974). In the category of the very faint transients (2–10 keV luminosity in the 1034−36 erg s−1 range during outburst), which includes GRS 1741.9-2853, the alternation between quiescence and outburst can be described by the thermal-viscous disk instability model, where the disk spends most of its time in a cold neutral phase (quiescence), and sometimes becomes hot and ionized, triggering accretion and causing an outburst (see Lasota 2001 for a review). The source then goes back to quiescence, allowing the disk to refill until the cycle starts again. The very faint transients are not well studied, and in particular, the evolutionary scenario that leads to these very low time-averaged accretion rate systems is not clear (King & Wijnands 2006).

In many NS LMXBs, outbursts are punctuated by Type I X-ray bursts, which appear as a sudden increase of luminosity...
burst during the second observation, starting on 2013 August 3 at UT 23:03:15 (referred to as \( t_1 \) hereafter).

The data was processed by the NuSTAR Data Analysis Software (NuSTARDAS) v1.3.0, which is distributed with HEA-SOFT v6.15, and uses the calibration files v20131007. Spectra and light curves were extracted using the “nuproducts” FTOOL from the focal plane modules A and B (FPMA and FPMB). Our extraction region is centered on \( \alpha_2000 = 17^h45^m2^s47, \delta_2000 = -28^\circ54'54"79 \), which is consistent within typical NuSTAR astrometric uncertainty (\( \lesssim 10'' \)) to the position reported in Munro et al. (2003). A circular extraction region of 120'' radius was used for the study of the burst, and a 60'' radius was used for the study of the outburst.

We performed the spectral analysis with the Interactive Spectral Interpretation System (ISIS; Houck & Denicola 2000), using Verner et al. (1996) atomic cross sections and Wilms et al. (2000) abundances for the interstellar absorption. We used \( \chi^2 \) statistics to evaluate the quality of the fit of the different spectral models. We analyzed the data over the range 3–30 keV as both the outburst and the burst spectra cut off sharply above 30 keV.

The spectral binning is identical for each spectrum presented in this paper: spectra of FPMA and FPMB were combined, and the spectral bins were grouped to reach at least 50 source + background counts and 3\( \sigma \) signal-to-noise significance in each group. The study of the outburst uses a different region from the same detector chip as background (identical time), and the study of the burst uses the same region as used for source extraction, but taking times preceding the burst as background.

3. LIGHT-CURVE ANALYSIS

The light curves were corrected for dead time (which reaches 45% at the peak of the burst), finite extraction region, and vignetting effects. Figure 1 shows the 3–30 keV light curves of the two observations. The first observation (hereafter referred to as O1) shows a continuous flux rise, revealing the beginning of the outburst (Degenaar et al. 2014). In the second observation (right panel), five periods are distinguished: the “low” level outburst at the beginning of the observation (O2), the rise (O3), the pre-burst (O4), the burst, and post-burst (O5).

Figure 2 shows a close-up view of the burst with finer bins. The burst rise, peak, and early decay is well described by a fast rise exponential decay (FRED) function, with a plateau inserted at the peak:

\[
\begin{align*}
    f(t) &= \begin{cases} 
    \exp \left( -\frac{t}{\tau_R} - \frac{t}{\tau_D} \right) & 0 < t \leq t_{peak} \\
    \exp \left( -2 \sqrt{\frac{t}{\tau_D}} \right) & t_{peak} < t \leq t_{peak} + t_{plateau} \\
    \exp \left( -\frac{\tau_R}{t - t_{plateau}} - \frac{t - t_{plateau}}{\tau_D} \right) & t > t_{peak} + t_{plateau}
    \end{cases}
\end{align*}
\]

with \( t_{peak} = \sqrt{\tau_R \tau_D} \), the time to reach the peak luminosity, \( \tau_R \) and \( \tau_D \) the characteristic rise and decay times, respectively, and \( t_{plateau} \) the duration of the plateau. Binning the light curve to 0.5 s bins, the best fit to the data returns a rise time of 4.2 s (time to reach 90% of the peak value), \( t_{plateau} = 18 \) s, and an e-folding time of 20.6 s (time to decrease by a factor \( e^1 \approx 2.72 \)). The burst lasts over 800 s (NuSTAR did not catch the end of the decay because of an Earth occultation), and its decay is unusual with variability between 48 s and 95 s into the burst. The hardness ratio remains constant within errors during these variations, which is similar to the energy-independent (i.e., achromatic) late-time variability observed by in’t Zand et al. (2011).
At 95 s, the flux increases by a factor of three to four and is then followed by a smooth decay that is not well fit by an exponential curve. Figure 3 shows that, instead, it is better described by a power law, as expected in burst tails when nuclear reactions no longer take place (in’t Zand et al. 2014 and references therein). Fitting to the burst tail (110–900 s) a function defined as
\[
f(t) = C_0 \left( \frac{t - t_s}{t_0 - t_s} \right)^{-\alpha}
\] (2)
and setting the time of the first point in the fit \( t_0 = 110 \) s (\( C_0 \) is the count rate at \( t_0 \), and \( t_s \) is the time of the burst onset), we find a decay index \( \alpha = 2.25 \pm 0.03 \). As noticed by in’t Zand et al. (2014), \( \alpha \) is strongly correlated with \( t_s \); however, we estimate that the error on \( t_s \) cannot exceed \( \pm 0.2 \) s, which leads to a systematic error on \( \alpha \) lower than \( \pm 0.002 \). Despite some variability, the interval from 75 s to 95 s seems to match with the extrapolation of the exponential decay. Another noticeable fact is that the two cooling curves do not intersect. These results are discussed in Section 6.
Figure 4. Spectra of the outburst phases with their best-fit model and the decomposition of the model into the blackbody component and the power-law component (high-energy tails). The left panel shows the spectrum of phases O1 (black plus signs, and model breakdown in purple), and O2 (red crosses, and model breakdown in orange). The right panel shows phases O4 (black plus signs, and model breakdown in purple) and O5 (red crosses, and model breakdown in orange). Each spectrum is the combination of data from modules A and B. The data points are shown with 1σ error bars, and the solid lines show the best-fit model. The lower panels show the deviation from the model in units of standard deviation.

Table 1

<table>
<thead>
<tr>
<th>Outburst Phase</th>
<th>$k_B T$ (keV)</th>
<th>$\Gamma$</th>
<th>$F_{2-10}^a$</th>
<th>$F_v^b$</th>
<th>$L_v^c$</th>
<th>$f$</th>
<th>$\dot{m}_f$</th>
<th>$\dot{m}_{\text{Edd}}$</th>
<th>$M_{\text{d}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>O1</td>
<td>1.74$^{+0.66}_{-0.30}$</td>
<td>1.27$^{+0.31}_{-0.40}$</td>
<td>0.184$^{+0.075}_{-0.184}$</td>
<td>0.98$^{+0.144}_{-0.145}$</td>
<td>0.579$^{+0.084}_{-0.085}$</td>
<td>32.4</td>
<td>3.6 $\times$ 10$^{-4}$</td>
<td>0.64</td>
<td></td>
</tr>
<tr>
<td>O2</td>
<td>1.35 $\pm$ 0.05</td>
<td>1.50$^{+0.73}_{-0.97}$</td>
<td>3.01$^{+0.13}_{-0.12}$</td>
<td>5.2$^{+0.42}_{-0.40}$</td>
<td>3.06$^{+0.25}_{0.23}$</td>
<td>171</td>
<td>1.9 $\times$ 10$^{-3}$</td>
<td>3.4</td>
<td></td>
</tr>
<tr>
<td>O4</td>
<td>1.46 $\pm$ 0.03</td>
<td>1.69$^{+0.72}_{-0.97}$</td>
<td>5.58 $\pm$ 0.18</td>
<td>8.04$^{+0.38}_{-0.35}$</td>
<td>4.71$^{+0.22}_{-0.21}$</td>
<td>264</td>
<td>3.0 $\times$ 10$^{-3}$</td>
<td>5.3</td>
<td></td>
</tr>
<tr>
<td>O5</td>
<td>1.39 $\pm$ 0.04</td>
<td>1.57$^{+0.98}_{-1.49}$</td>
<td>6.16$^{+0.22}_{-0.23}$</td>
<td>9.14$^{+0.52}_{-0.48}$</td>
<td>5.36$^{+0.30}_{-0.29}$</td>
<td>300</td>
<td>3.4 $\times$ 10$^{-3}$</td>
<td>6.0</td>
<td></td>
</tr>
</tbody>
</table>

Notes.

$^a$ Unabsorbed 2–10 keV flux in units of 10$^{-11}$ erg cm$^{-2}$ s$^{-1}$.

$^b$ Unabsorbed bolometric flux (evaluated over the 0.1–100 keV energy range) in units of 10$^{-11}$ erg cm$^{-2}$ s$^{-1}$.

$^c$ Unabsorbed bolometric luminosity assuming a distance of 7 kpc in units of 10$^{35}$ erg s$^{-1}$.

$^d$ Accretion rate per unit area in g cm$^{-2}$ s$^{-1}$ determined with Equation (3).

$^e$ Accretion rate per unit area normalized by the Eddington accretion rate $\dot{m}_{\text{Edd}} = 8.8 \times 10^4$ g cm$^{-2}$ s$^{-1}$ (assuming $M = 1.4 M_\odot$ and $R = 10$ km).

$^f$ Global accretion rate in units of $10^{-11}$ $M_\odot$ yr$^{-1}$, assuming an NS radius of 10 km.

4. OUTBURST

We fit the four different phases of outburst identified in Section 3 (first observation, and low level, pre-burst and post-burst in the second observation: O1, O2, O4, O5, respectively) with an absorbed blackbody + power-law model (TBabs × (bbody + powerlaw)) with tied column density. This model is physically interpreted as the thermal emission of the disk and the NS surface (in the present case, these two components are indistinguishable and are thus modeled with a single blackbody) in addition to the non-thermal emission from a corona (Compton scattering of thermal photons by hot electrons). We obtain good agreement between the model and the data with a $\chi^2 / \nu = 1.15$ ($461$ dof), yielding a column density $N_H = 8.3^{+1.3}_{-1.5} \times 10^{22}$ cm$^{-2}$ (Figure 4). The blackbody temperatures and power-law photon indices are presented in Table 1, along with the corresponding bolometric fluxes, luminosities, and derived accretion rates.

The column density that we find is low compared to previous studies. For instance, Muno et al. (2003) found $N_H = (9.7 \pm 0.2) \times 10^{22}$ cm$^{-2}$ using 2–7 keV data from Chandra, Trap et al. (2009) found $N_H = (11.9 \pm 0.2) \times 10^{22}$ cm$^{-2}$ using 2–8 keV data from XMM-Newton, and Degenaar & Wijnands (2010) found $N_H = (14.0 \pm 0.7) \times 10^{22}$ cm$^{-2}$ using 2–10 keV data from Swift/XRT. In these works, the results were obtained using the default XSPEC cross-sections and abundances, which leads to $N_H$ values $\approx 33\%$ lower than those obtained with TBabs using Wilms et al. (2000) abundances and Vermeir et al. (1996) cross-sections (Nowak et al. 2012). However, we note that these past studies were done over smaller energy ranges and used a simple absorbed power-law model, which requires a higher column density than a blackbody to get a curved spectrum at low energies.

The strong gravitational field of the NS decreases the luminosity observed by a distant observer (noted with the subscript $\infty$) with respect to the one emitted in the local frame (subscript $\star$) by a factor $(1+z)^2$, where $1+z = (1-2GM/(Rc^2))^{-1/2}$. In this equation, $c$ is the speed of light, $M$ and $R$ are the mass and radius of the NS, and $G$ is the gravitational constant. It also affects the emitted spectrum by changing the temperature observed by a distant observer $T_{\infty} = T_{\star}(1+z)^{-1}$ (Lewin et al. 1993).
Assuming the canonical values \( M = 1.4M_\odot \) and \( R_\odot = 10 \text{ km} \), one finds \( 1 + \frac{z}{R_\odot} \approx 1.31 \). Unless specifically noted with the subscript \( * \), all physical quantities will hereafter be expressed as seen by a distant observer.

The unabsorbed bolometric luminosity can be converted into an accretion rate per unit area \( \dot{m} \) using the formula\(^{11} \)

\[
\dot{m} = 32.8 \times \left( \frac{F_b}{10^{-11} \text{erg cm}^{-2} \text{s}^{-1}} \right) \left( \frac{M}{1.4M_\odot} \right)^{-1} \left( \frac{1 + \frac{z}{1.31}}{10 \text{ km}} \right)^{-1} \left( \frac{d}{7 \text{kpc}} \right)^2 \text{g cm}^{-2} \text{s}^{-1},
\]

(3)

where \( d \) is the distance to the observer and \( F_b \) the bolometric flux seen by a distant observer.

5. TYPE I BURST

We first look at the burst spectrum divided into three phases, corresponding to the PRE (0–22.5 s, B1), the high-temperature (after the photosphere falls back onto the NS surface, commonly referred to as touch-down, 22.5–41.0 s, B2), and the beginning of the decay (41.0–72.0 s, B3), as defined in the next paragraph.

We use the O3 outburst phase (14.6 ks right before the burst) as background. The cross calibration between FPMA and FPMB is excellent, we found agreement to better than 0.2%, so we removed the normalization constant from the model. The three spectra are well fit with an absorbed blackbody (we use TBabs \( \times \) bbody) with tied column density \( \langle N_\text{H} \rangle = 1.06, 255 \text{dof, Figure 5} \). We find \( N_\text{H} = (11.3 \pm 1.5) \times 10^{22} \text{cm}^{-2} \), consistent within errors with the value found for the outburst, and blackbody temperatures of 2.11 \( \pm \) 0.04 keV, 2.65 \( \pm \) 0.06 keV, and 1.97 \( \pm \) 0.05 keV for spectra B1, B2, and B3, respectively.

Next we look at the time-resolved spectral properties of the burst. The burst is divided to yield 700 net counts (FPMA + FPMB) in each time slice, from \( t_\odot \) to \( t_\odot + 359 \text{ s} \). The top panel of Figure 6 shows the luminosity derived from the blackbody fit to the time-resolved spectra, assuming a distance to the source of 7 kpc. The middle panel of Figure 6 shows the blackbody temperature and the bottom panel shows the NS photospheric radius \( R \) inferred from the blackbody luminosity \( L \) and temperature \( T \):

\[
R = \sqrt{\frac{L}{4\pi\sigma T^4}},
\]

(4)

with \( \sigma \) being the Stephan–Boltzmann constant.

Integrating the luminosity over these 32 slices, we find that the total energy radiated is \( 9.5 \times 10^{39} \text{ erg} \) (at 7 kpc). Following Galloway et al. (2008), we calculate the burst characteristic time \( \tau = E_p/F_p \), where \( E_p \) is the fluence of the burst (i.e., the integrated bolometric burst flux) and \( F_p \) is the peak bolometric flux. With \( E_p = 1.61 \times 10^{-6} \text{ erg cm}^{-2} \) and \( F_p = 3.58 \times 10^{-8} \text{ erg cm}^{-2} \text{s}^{-1} \), we find \( \tau = 45.0 \text{ s} \). We also note the very large dynamic range of this burst, which appeared on top of weak persistent emission; the ratio of the burst peak bolometric flux to the persistent bolometric flux preceding the

\(^{11}\text{This equation assumes that the total luminosity of the system is powered by accretion (i.e., emission from the accretion disk, the corona and the NS surface), and that obscuration is negligible. This is equivalent to saying that the radiation efficiency is equal to 1.}\)
Barrière et al.

Time-resolved blackbody spectral fit of the burst, assuming a distance of 7 kpc to the source, and keeping the column density fixed to $1.3 \times 10^{23}$ cm$^{-2}$.

Panel (a) shows the bolometric blackbody luminosity. Panel (b) shows the blackbody temperature, and panel (c) shows the neutron star photospheric radius inferred from the blackbody flux and temperature. Panel (d) shows the reduced $\chi^2$ of each fit. All quantities are as seen by a distant observer. The green vertical lines define the three time intervals B1, B2, and B3 used in Figure 5.

We first performed a sanity check using a much smaller region of 60$''$ radius, which makes it less sensitive to background variations. The line was still visible with this reduced extraction region. Next, we determine the significance using the XSPEC (Arnaud 1996) script simftest$^{12}$ with 5000 trials (constraining the line centroid in the 5.26–5.66 keV range, and the line width to be <0.5 keV), we found that the probability for the absorption line to be required by the data is 98.5% (equivalent to 2.4$\sigma$, as it is a one-sided distribution). This test was performed with the model $\text{constant} \times \text{TBabs} \times (\text{BBody} + \text{Gauss})$ jointly fit to FPMA and FPMB spectra over the 3–15 keV range, with $N_H$ fixed to $1.3 \times 10^{23}$ cm$^{-2}$. The spectra are rebinned to at least 25 counts and 3$\sigma$ per bin (the former condition insures a bin significance higher than 5$\sigma$ in the 5–6 keV range), as shown in Figure 7. Accounting for the fact that we found the line in one of three sub-spectra (spectra B1, B2, B3), the significance of the line drops to 95.6% (1.7$\sigma$).

5.2. Search for Oscillations

In 1996 April and July, Strohmayer et al. (1997) reported strong detection of oscillations at a frequency of 589 Hz during three bursts observed with RXTE coming from a direction close to GRS 1741.9-2853. The strongest oscillations were detected during the brightest of the three bursts with a fraction$^{13}$ of $(8.4 \pm 1.4\%)$ during the peak and $(18.4 \pm 2.8\%)$ during the decay, and were seen only above 8 keV. These bursts were tentatively attributed to MXB 1743–29 (an LMXB 24$'$ away from GRS 1741.9-2853), with the 99% confidence region excluding the position of GRS 1741.9-2853. In 1996 August–September, Cocchi et al. (1999) observed the Galactic center with BeppoSAX and detected three bursts from GRS 1741.9-2853, determining that it is a transient LMXB. Galloway et al. (2008) made the association between GRS 1741.9-2853 and the oscillations detected by Strohmayer et al. (1997) because these bursting episodes happened only a few months apart, and had similar characteristics.

We ran a combination of timing analysis procedures in order to look for coherent pulsations in the NuSTAR data set. One difficulty with NuSTAR timing is dead time: each event is followed by a dead time of $\approx 2.5$ ms (Harrison et al. 2013). At high count rates, such as those reached during the burst in our observation, dead time affects the frequency response of the FPMs, producing a “wavy” pattern in the power density spectrum (PDS; van der Klis 1989; Zhang et al. 1995), which affects heavily our detection limits for pulsations.

We first analyzed the burst light curve with a running-window epoch folding (Leahy et al. 1983) around 589 Hz. We used $^{12}$ simftest is a script that generates fake spectra based on the model without the component under investigation, and then fit to them the model with and without the component. The difference in fit statistics is recorded for each trial and is then compared to the difference obtained with the actual data set. If a significant number of trials return a difference in fit statistics larger than that obtained with the real data set, we conclude that the component under investigation is not required by the data, as the spectral feature likely results from a statistical fluctuation.

$^{13}$ Defined as the amplitude of the sinusoid divided by the constant count rate below the oscillations.
The value of \( \tau = 45.0 \) s that we determined in Section 5 puts this burst in the category of the long and unusual ones for this source, most of its “regular” bursts having \( \tau \sim 10 \) s (Galloway et al. 2008). This is not to be confused with super-bursts lasting longer than 1 hr, which results from the slow burning of C (e.g., Strohmayer & Brown 2002), nor with intermediate bursts lasting \( \sim 30 \) minutes, thought to arise from the burning of a thick layer of pure He (e.g., in’t Zand et al. 2005).

GRS 1741.9-2853 is known to produce both pure He and mixed H/He bursts (Trap et al. 2009). The accretion rate increased during our two observations to reach 0.003 \( \dot{m}_{\text{Edd}} \) before the burst, well below the critical value \( \dot{m}_C = 0.01 \dot{m}_{\text{Edd}} \) for which there is no stable burning of the freshly accreted H, nor of the He, assuming solar CNO abundance (\( Z_{\text{CNO}} \); Fujimoto et al. 1981; Bildsten 1998; Narayan & Heyl 2003). We note that \( \dot{m}_C \) is proportional to \( Z_{\text{CNO}}^{1/2} \), i.e., only weakly dependent on our assumption of solar abundance (see Equation (36) in Bildsten 1998). Peng et al. (2007) show that once a sufficient column density is reached, unstable H burning can trigger the burning of a thick He layer that formed by sedimentation for \( \dot{m} \lesssim 0.003 \dot{m}_{\text{Edd}} \), resulting in a powerful long burst. This matches well with what we observed; Hydrogen burning is \( \beta \)-limited, which slows down the reaction compared to helium burning, hence creating a longer burst. However, the burst would have been much weaker if only H had burned. Thus, based on the relatively long duration of the burst and on the low accretion rate preceding the burst, we conclude that we observed an H-triggered, mixed H/He burst.

The conclusion that this burst was H-rich is now used to calculate the corresponding Eddington luminosity, allowing us to determine a distance for GRS 1741.9-2853. In the case of a PRE burst, the peak flux \( F_{pk} \) corresponds to the Eddington luminosity \( L_{\text{Edd}} \), and the distance \( d \) of the object is simply given by

\[
d = \left( \frac{L_{\text{Edd}}}{4\pi F_{pk}} \right)^{1/2}.
\]

The Eddington luminosity, as seen by a distant observer, is given by (Lewin et al. 1993)

\[
L_{\text{Edd}} = \frac{4\pi cG M_{\text{NS}}}{\kappa} (1 + z)^{-1},
\]

where \( \kappa \) is the electron scattering opacity during the expansion phase. In the case where the scattering electrons become relativistic, the opacity can be approximated by \( \kappa = 0.2 \times (1 + X)[1 + (kT/39.2 \text{ keV})^{1/2}] \) cm\(^2\) g\(^{-1}\), where \( X \) is the hydrogen mass fraction in the photosphere (Lewin et al. 1993). Following the assumption that we observed a H-rich burst, we use \( X = 0.7 \) (corresponding to solar composition) and find \( L_{\text{Edd}} = 1.7 \times 10^{38} \) erg s\(^{-1}\). In the time-resolved spectral analysis of the burst, we found that the brightest slice has a bolometric flux \( F_{pk} = 3.58^{+0.29}_{-0.24} \times 10^{-9} \) erg cm\(^{-2}\) s\(^{-1}\), which leads to a distance of 6.3 ± 0.5 kpc. Table 2 summarizes the distances that have been found in past studies for this source, and shows the dependency of the distance on the Eddington luminosity. The present peak flux is consistent with the brightest bursts that have been observed for this source in the past. Our distance measurement is consistent with the lower range that had been established by Cocchi et al. (1999), Galloway et al. (2008), and Trap et al. (2009).

The largest source of uncertainty in this calculation is the hydrogen mass fraction \( X \) chosen for the NS atmosphere in the Eddington luminosity calculation, where any \( X \) value lower...
Table 2
Distance for GRS 1741.9-2853 from This Study Compared to Past Work

<table>
<thead>
<tr>
<th>Reference</th>
<th>$F_{pk}$ (10$^{-8}$ erg cm$^{-2}$ s$^{-1}$)</th>
<th>$d$ (kpc) $L_{edd}$ ($X = 0$, 0.7)</th>
<th>$d$ (kpc) $L_{edd}$ ($X = 0$)</th>
<th>$d$ (kpc) $L_{edd}$ (Kuulkers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cocchi et al. (1999)</td>
<td>3.26 ± 0.26</td>
<td>*6.65 ± 0.53</td>
<td>8.67 ± 0.69</td>
<td>9.87 ± 0.79</td>
</tr>
<tr>
<td>Galloway et al. (2008)</td>
<td>3.80 ± 1.0</td>
<td>*6.16 ± 1.6</td>
<td>8.03 ± 2.1</td>
<td>9.14 ± 2.4</td>
</tr>
<tr>
<td>Trap et al. (2009)</td>
<td>5.5 ± 0.7</td>
<td>&lt;5.13 ± 0.65</td>
<td>&lt;6.68 ± 0.85</td>
<td>&lt;7.60 ± 0.97</td>
</tr>
<tr>
<td>This work</td>
<td>3.58 ± 0.29</td>
<td>*6.35 ± 0.51</td>
<td>8.27 ± 0.66</td>
<td>9.42 ± 0.75</td>
</tr>
</tbody>
</table>

Notes. The second column shows the burst peak bolometric flux that the different studies used for their distance measurement. The three rightmost columns show the distance they obtained for different values of the Eddington luminosity: 1.7 × 10$^{38}$ erg s$^{-1}$ for $X = 0$, 2.9 × 10$^{38}$ erg s$^{-1}$ for $X = 0$, and (3.79 ± 0.15) × 10$^{38}$ erg s$^{-1}$ as determined empirically by Kuulkers et al. (2003). The stars indicate which value of the Eddington luminosity was favored in each study.

than 0.7 would place the source further (Table 2). Uncertainty on the distance also comes from the NS mass; for instance, considering $M = 2 M_\odot$ leads to a distance 9.2% larger. Given these uncertainties, our distance of 6.3 ± 0.5 kpc should be regarded as a lower limit, consistent with the value of $d = 7$ kpc that we have been using throughout this paper. Our measurement of the column density toward GRS 1741.9-2853 ($N_H$ = 1.66 ± 0.61 × 10$^{23}$ cm$^{-2}$) is consistent with the source being closer than the Galactic center (NustAR measured $N_H = 1.66_{-0.61}^{+0.70} \times 10^{23}$ cm$^{-2}$ to the Galactic center during flares from Sagittarius A*; Barrière et al. (2014)).

Transient achromatic variability is observed between 48 s and 75 s into the burst. The variability is mostly on top of the exponential decay trend, but we can see at 52 s and 54.5 s that the flux goes below the decay trend, suggesting that transient obscuration is taking place. It is hard to determine if the interval between 75 s and 95 s belongs to the exponential decay trend, or if it is part of the power-law decay with obscuration (Figure 3). The latter option might be more physical, as it is hard to explain why the flux would have suddenly risen by a factor three to four while transitioning from exponential to power-law cooling. However, the fact that the two curves do not intersect could be an indication that re-heating of the NS took place during the episode of variability.

GRS 1741.9-2853 already displayed such late-time variability, as visible in bursts No. 3 and possibly 4 observed by INTEGRAL JEM-X (although the features were not discussed; Trap et al. 2009), in’t Zand et al. (2011) suggest that this variability is caused by clouds of electrons in thermal balance with the radiation field scattering the NS thermal emission (Thomson scattering). The clouds are orbiting the NS and alternatively obscure our line of sight and reflect the NS radiation toward us. The presence of these clouds could be explained by the re-organization of the accretion disk that had been disrupted by the burst. To our knowledge, this phenomenon has been reported in only six bursts from other systems, all showing super-expansion, where the photosphere is lifted up to thousands of km off the NS surface (van Paradijs et al. 1990; Strohmayer & Brown 2002; Molkov et al. 2005; in’t Zand et al. 2005, 2011; Degenaar et al. 2013a). It is interesting that the present burst shows similar behavior, although the photosphere has been merely lifted to a few tens of kilometers. Assuming that the two troughs at 52 s and 54.5 s are the signature of a cloud in a Keplerian orbit of period $P = 2.5$ s, their elevation above the NS surface would be $(P^2GM/4\pi^2)^{1/3} \approx 3 \times 10^3$ km (for $M = 1.4 M_\odot$), well beyond the photosphere. Thus, if this variability was indeed the sign of a disturbed inner accretion disk, it would have been caused only by the action of the Eddington flux and the resulting X-ray heating (e.g., Ballantyne & Everett 2005). The fact that late time variability is rare could then be explained by the viewing angle, where only high inclination systems would show this phenomenon. We note however, that GRS 1741.9-2853 is not an eclipsing or dipping system, which limits the validity of this explanation.

The high dynamic range of this burst allows the observation of a long power-law decay tail, starting around $t = 110$ s after the variability ceased. This is consistent with a pure radiative cooling without any additional production of heat. We find a power-law index of 2.25, which indicates that photons contributed significantly to the heat capacity (in’t Zand et al. 2014).

Oscillations at 589 Hz had been tentatively associated to GRS 1741.9-2853 (Section 5.2). Despite NustAR’s ability to measure oscillation frequency up to $\approx 1$ kHz (over short periods of time; Bachetti et al. 2014), we did not detect oscillations in the burst nor in the outburst. However, our upper limits are not constraining, being always above the pulsed fraction measured by Strohmayer et al. (1997). In addition, it has been proposed that oscillations appear mostly in He burning runaways (Cumming & Bildsten 2000; Narayan & Cooper 2007), which was not the case here, and it is known that they are not detected consistently even in He bursts from sources known to produce pulsed emission. So we cannot confirm nor repudiate the association of the 589 Hz pulsation with GRS 1741.9-2853.

The spectrum of the PRE phase shows weak evidence of an absorption line at 5.46 ± 0.10 keV (95.6% confidence level). Although this is only marginal detection, the importance of these features makes it worthwhile to consider its interpretation. One additional motivation for this is that there is a precedent: a line at 5.7 ± 0.25 keV was detected in the rise and PRE phase of a bright burst from 4U 1636-536 observed with Tenma a.k.a. Astro-B (Waki et al. 1984). Although this detection was clear (>99.5% confidence level), no similar line was ever observed subsequently in any source.

Detection of absorption lines in burst spectra are rare and have been controversial due to their lack of consistency, even within seemingly identical bursts from given sources. Here is a brief summary of the main cases. A line at 4.1 keV was detected in the Tenma spectra of non-PRE bursts from 4U 1636-536 (in 4 out of 12 bursts; Waki et al. 1984) and from 4U 1608-52 (in 3 out of 17 bursts; Nakamura et al. 1988). Another line at 4.1 keV was found by Magnier et al. (1989) with EXOSAT in a 0.5 s slice of the rise of a non-PRE burst from EXO 1747-214, although this detection is more controversial due to its short duration and large equivalent width. More recently, Cottam et al. (2002) found a set of absorption lines in the stacked spectra of 28 bursts from EXO 0748–676 observed with the Reflection Grating Spectrometer.
onboard XMM-Newton, which they interpreted as being due to transitions from Fe xxv, Fe xxvi, and O viii, all gravitationally redshifted by a factor $1 + z = 1.35$. This detection was not confirmed in subsequent observations (Cottam et al. 2008), and a 552 Hz spin was found for the NS (Galloway et al. 2010), which is incompatible with the production of narrow absorption lines at the surface of an NS (Lin et al. 2010). in’t Zand & Weinberg (2010) analyzed 32 super-expansion bursts and detected absorption edges in three cases. They interpreted them as signatures of heavy elements (synthesized during the burst) present in the atmosphere of the NS and the wind created by the burst.

If the GRS 1741.9-2853 line is real, what could its origin be? The two mechanisms that can produce absorption lines are resonant cyclotron scattering and resonant atomic level transitions. An electron cyclotron line at 5.5 keV would require a magnetic field of the order of $10^{12}$ G, which is three to four orders of magnitude higher than what is expected for Type I bursters (e.g., Bildsten 1998). Thus, we favor the resonant atomic transition interpretation.

During the PRE phase of the present burst, we observe a roughly constant color temperature of $T = 2.44 \times 10^7$ K ($k_B T = 2.1$ keV), which corresponds to a local effective temperature of $T_e \approx 23$ MK, using a correction factor of 1.4 to account for the spectral hardening from Comptonization (Madej et al. 2004), and correcting for the redshift with $1 + z = 1.31$. We assume that accretion is quenched during the PRE phase of the burst due to the radiation pressure at the Eddington level. Weinberg et al. (2006) showed that the products of nuclear burning can come to sufficiently shallow depth to be blown away by the wind and therefore be exposed to the photosphere. According to the same authors, the most likely heavy elements to be present in the photosphere and above it in the wind are Zn and Cr for a mixed H/He burst. At a temperature of $T_e \approx 23$ MK, Saha equilibrium indicates that these elements will be either fully ionized or in the H-like ionization state. The most intense transition for H-like ions is Kα.\footnote{The Kα transition is actually double, Kα₁ referring to $1s \rightarrow 2p_{3/2}$ and Kα₂ referring to $1s \rightarrow 2p_{1/2}$, with Kα₁ twice as strong as Kα₂. However, the energy difference is too small to differentiate with NuSTAR.} We see in Table 3 that if Zn was causing this absorption line, the gravitational redshift factor would be $1 + z = 1.70$, which is not reasonable during a PRE phase. However, Cr yields a factor $1 + z = 1.09$, resulting in a plausible radius range of 29.0–41.4 km for a mass range of 1.4–2.0 $M_\odot$.

Besides the obvious limitation that the line is only weakly detected, one caveat of this interpretation is that the accretion rate preceding this burst was lower than $0.01 m_{\text{edd}}$. This goes beyond the case studied by Weinberg et al. (2006); accretion rate of $\approx 0.01 m_{\text{edd}}$ resulting in a mixed H/He burst triggered by triple-α He reactions), which could result in very different nucleosynthesis products being sent in the NS atmosphere.

### 7. SUMMARY

*NuSTAR* observed GRS 1741.9-2853 twice in summer 2013 as it was entering in outburst for the first time since 2010 July. We detected a Type I burst with the second highest fluence reported for this source (burst No. 8 in Galloway et al. (2008) has 50% higher fluence). Based on the low accretion rate before the burst ($3.0 \times 10^{-3} m_{\text{edd}}$) and the long duration of the burst, which includes a 18 s plateau, we interpret it as an H-triggered mixed H/He thermonuclear explosion. The burst underwent a moderate phase of PRE, thus reaching the Eddington luminosity.

Assuming an H-rich atmosphere, we derive a new constraint on the source distance, $6.3 \pm 0.5$ kpc. However, given the fact that this value relies on highly uncertain parameters, such as the hydrogen mass fraction in the atmosphere, and the NS mass, we consider it more conservative to use the distance of 7 kpc, in agreement with past works.

The low persistent emission allows a power-law decay to be revealed in the burst tail. The transition from the exponential to the power-law decay is affected by strong variability above and below the decay trend. To our knowledge, it is the first time that this phenomenon is reported in a moderate PRE burst. The current model involving clouds of electrons created as the inner accretion disk reorganizes itself after having been disturbed by the burst is hard to reconcile with the fact that this late time variability is rare.

We searched for pulsations during the burst and the outburst, but found none. However our upper limits on the pulsed fraction around 589 Hz (between 17% and 25%) during the peak and the decay of the burst are not constraining as they are above the strongest pulsed fraction reported by Strohmayer et al. (1997).

A line at $5.46 \pm 0.10$ keV is weakly detected during the PRE phase of the burst. Assuming that the line is real, we speculate that it is due to the Kα resonance absorption line of H-like Cr ions, which is a product of the nuclear reactions, based on the work of Weinberg et al. (2006). Unfortunately, given that the line is observed while the atmosphere is lifted off the surface by radiation pressure, its gravitational redshift carries no information about the NS mass and radius.

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**Facility:** NuSTAR

### REFERENCES


Table 3

<table>
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<th>Ion</th>
<th>$E_{Kα}$ (keV)</th>
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<tbody>
<tr>
<td>Zn</td>
<td>9.31</td>
<td>1.71</td>
</tr>
<tr>
<td>Ni</td>
<td>8.10</td>
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<tr>
<td>Fe</td>
<td>6.97</td>
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<tr>
<td>V</td>
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