RBS 1032: A TIDAL DISRUPTION EVENT IN ANOTHER DWARF GALAXY?

W. Peter Maksym1, Dacheng Lin1,2, and Jimmy A. Irwin1
1 University of Alabama, Department of Physics and Astronomy, Tuscaloosa, AL 35487, USA; wpmaksym@ua.edu
2 Space Science Center, University of New Hampshire, Durham, NH 03824, USA

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ABSTRACT

RBS 1032 is a supersoft (Γ ∼ 5), luminous (∼10^{43} erg s^{-1}) ROSAT PSPC source which has been associated with an inactive dwarf galaxy at z = 0.026, SDSS J114726.69+494257.8. We have analyzed an XMM-Newton observation that confirms that RBS 1032 is indeed associated with the dwarf galaxy. Moreover, RBS 1032 has undergone a factor of ∼100–300 decay since 1990 November. This variability suggests that RBS 1032 may not be a steadily accreting intermediate-mass black hole, but rather an accretion flare from the tidal disruption of a star by the central black hole (which may or may not be intermediate-mass). We suggest that additional tidal disruption events may remain unidentified in archival ROSAT data, such that disruption rate estimates based upon ROSAT All-Sky Survey data may need reconsideration.

Key words: galaxies: dwarf – galaxies: nuclei – X-rays: bursts – X-rays: individual (RBS 1032)

1. INTRODUCTION

Most (if not all) galaxies are thought to host massive (M_\bullet \gtrsim 10^5 M_\odot) black holes (MBHs) at their nuclei. An important consequence is that occasionally a star may pass within the tidal disruption radius (R_T) of the MBH and be disrupted. The tidal forces overwhelm the star’s self-gravity, and the star is ripped apart in a tidal disruption event (TDE; Hills 1975; Rees 1988). The bound debris falls back onto the MBH, generating an accretion-powered flare whose evolution is (to first order) governed by the approximately Keplerian orbits and the energy spread of the debris. The flare itself is thought to typically be most luminous in X-rays and ultraviolet (e.g., Ulmer 1999) but may also produce a relativistic jet that emits hard X-rays and gamma-rays (Fischer et al. 1998). The optical counterpart was initially suggested to be a star by Zickgraf et al. (2003). Later work by Ghosh et al. (2006) using the Sloan Digital Sky Survey (Ahn et al. 2014), the Russian–Turkish 1.5 m telescope in Anatalya, Turkey, and the 6 m telescope of the Special Astrophysical Observatory in Russia, however, showed the most likely optical counterpart to be a dwarf galaxy at z ∼ 0.026 without emission lines, SDSS J114726.69+494257.8. They considered, and rejected as unlikely, numerous possible explanations for the X-ray emission. They also suggested that the system may be a binary with an intermediate-mass black hole (IMBH) as the primary component and a star, possibly a white dwarf, as the secondary.

We have investigated the most recent X-ray observation of RBS 1032 taken using XMM-Newton, and suggest an alternative explanation that RBS 1032 is certainly a transient source, and is a strong candidate for a TDE. If so, this adds to the list of TDEs reported in dwarf galaxies which may indicate the presence of IMBHs in dwarf galaxies, including WINGS J1348 in A1795 (Maksym et al. 2013, 2014; Donato et al. 2014) and GRB 060218 (Shcherbakov et al. 2013). Such IMBHs are important clues to the formation of the first black holes (Maksym et al. 2013, and references therein). Furthermore, we note that the discovery of new TDEs in archival ROSAT data has implications for γ_D as determined by Donley et al. (2002). We have conducted our analysis and arrived at this conclusion independently from the recent paper by Khabibullin & Sazonov (2014), who count RBS 1032 among their TDE candidates. We find that, with minor differences, our analysis is largely in agreement with theirs.

Through this Letter, we adopt concordant cosmological parameters\(^3\) of H_0 = 70 km^{-1} sec^{-1} Mpc^{-1}, \Omega_m = 0.3, and \Omega_{\Lambda,0} = 0.7. All coordinates are J2000.

2. OBSERVATIONS AND DATA

2.1. Previous ROSAT Work

RBS 1032 was detected by ROSAT as part of RASS on 1990 November 5, and was re-observed with pointed PSPC observations on 1992 December 7 and 1994 June 05. For these epochs, Ghosh et al. (2006) determined an unabsorbed F_X(0.1–2.4 keV) = [6.0, 2.3, 1.1] \times 10^{-12} erg cm^{-2} s^{-1},

\(\text{Distances are calculated according to http://www.astro.ucla.edu/~wright/CosmoCalc.html.}\)
Table 1

| Model       | Parameter | Value       | $F_X$ (0.1–2.4 keV) | cstat/dof$^a$ |
|-------------|-----------|-------------|---------------------|---------------|
| zpowerlw    | $\Gamma$  | 3.42±0.33   | 7.4±3.1             | 20.69/20      |
| zbbbody     | $kT_{bb}$ (keV) | 0.11±0.01  | 2.0±0.5             | 19.62/20      |
| diskbb      | $kT_{bb}$ (keV) | 0.15±0.02  | 2.7±0.7             | 19.25/20      |

Note. Fits use the Cash (1979) statistic (cstat) for given degrees of freedom (dof). $N_H$ is fixed and assumed at Galactic ($1.98 \times 10^{20}$ cm$^{-2}$) as per colden (http://cxc.harvard.edu/toolkit/colden.jsp) and Dickey & Lockman (1990). $F_X$ is in units of $10^{-14}$ erg cm$^{-2}$ s$^{-1}$. $F_X$ is unabsorbed, with 1σ uncertainties.

respective$^4$, assuming a blackbody with $kT_{bb} = 0.055$ keV and Galactic $N_H = 1.98 \times 10^{20}$ cm$^{-2}$, although they also fitted the data to a variety of models, including power law and multicolor blackbody disk models. In all epochs, they found the spectrum to be supersoft ($\Gamma_{pl} \sim 5$ or $kT_{bb} \sim 0.06$ keV).

2.2. XMM Observation

RBS 1032 was observed by XMM-Newton on 2009 November 21 for $\sim 17$ ks (obs. id 0604020101, PI: K. Ghosh). The observation was badly contaminated by background flaring, leaving only [1.5, 4.7, 9.8] ks of usable [PN, M1, M2] data. Inspection of the pipeline-produced broadband image reveals a faint point source within the $\sim 30''$ ROSAT PSPC PSF when compared to the location of RBS 1032 ($r \sim 6''$ separation). This source is also recovered by the XMM-Newton pipeline, with a corresponding UVW1 ($\sim 2910$ Å) source detected by the optical monitor pipeline at $n_{UVW1} = 20.3$ ($M_{UVW1} = -15$, $\nu L_v(\text{UVW1}) = 1.2 \times 10^{41}$ erg s$^{-1}$). This corresponds to the source 3XMM J114726.7+494257 ([α, δ] = [11°47'26.73'', 49°42'57.3''], XMM-Newton Survey Science Centre 2013, coordinates are J2000 with 1σ error of 1''45). This is the only such source within 30''. The next-closest pipeline source is at $\gtrsim 3''$ separation.

This XMM source is $r \sim 0.8$ from SDSS J114726.69+494257.8, and within the 1σ error (1''45 in [α, δ]), from the 3XMM catalog position. The next-closest SDSS source is at $r \sim 6.0$ (comparable to the XMM-Newton FWHM) and 5.6 mag fainter. The UVW1 source is also coincident with SDSS J114726.69+494257.8.

2.3. Data Reduction

To perform our own spectral analysis, we reduced the data for 3XMM J114726.7+494257 using XMMAS. As per standard procedure, we used evselect to filter the MOS and PN event files for periods of high background, and then to extract the spectrum for a region with $r = 15''$ and $\gtrsim 3$ counts per bin. We then similarly extracted a background spectrum from a nearby 33'' region. We then used arfgen and rmfgen to produce response matrix files.

We used XSPEC to fit the spectra to zbbbody, zpowerlw, and diskbb models, in order to compare to the analysis of ROSAT data by Ghosh et al. (2006). With only $\sim 17$ net PN counts (32 total), meaningful constraint of $N_H$ is not possible. We can, however, address the general shape of the spectrum and constrain the normalization of an assumed spectral type. We present the results of these fits in Table 1 and Figure 1.

5. We consider a plausible upper bound for $M_*$, given the $L_{\text{bulge}}-M_*$ relationship (e.g., Marconi & Hunt 2003; Kormendy & Ho 2013). The applicability of $L_{\text{bulge}}-M_*$ in this regime is uncertain, and would be affected by the galaxy morphology (see, e.g., Kormendy & Ho 2013, and references therein), including the nature of any nuclear

Figure 1. Best-fit power law model for XMM-Newton spectrum, as per Table 1. Data from [PN, MOS1, MOS2] are represented as [black square, red triangle, green circle] and fit simultaneously, with model values of a given bin represented as [solid, dot-dashed, dashed] lines. Data are fit in the 0.2–10 keV range.

3. LIGHT CURVE ANALYSIS

Depending upon the spectral model, $F_X$ (0.1–2.4 keV) decreases by a factor of $\sim 100$–300 from 1990 to 2009. Given the strong variability, the extreme luminosity ($L_X > L_{\text{Edd}}$ for $M_* \sim 10^5 M_\odot$), and the supersoft spectrum, we must therefore consider the possibility that RBS 1032 is a TDE. At a very basic level, we can examine the X-ray light curve to compare against the assumption that the X-ray luminosity tracks the accretion rate $\dot{M}$, for which $L_X \propto (t - t_0)^{-5/3}$ (to first order), where $t_0$ is the time of stellar pericenter. We plot a variety of simple model fits to the light curve in Figure 2, assuming the best-fit value for zpowerlw in 2009. The data generally fit a simple $\dot{\nu}^{-5/3}$ approximation, although the XMM-Newton data point is below the prediction of a $\dot{\nu}^{-5/3}$ curve which fits only the ROSAT points. Unlike zpowerlw, the inferred luminosities from the zbbbody and diskbb models are below all light curve fits in Figure 2. Lodato & Rossi (2011) suggest that the monochromatic flux from a TDE may pass through three major evolutionary phases ($\dot{\nu}^{-5/12}, \dot{\nu}^{-5/3}, \dot{\nu}^{-1}$, and exponential decay) as it cools, depending upon the relation of the bandpass to the peak emission wavelength. For X-rays, the $\dot{\nu}^{-5/12}$ phase is not seen, whereas the $\dot{\nu}^{-5/3}$ phase may last years. Maksym et al. (2013) suggest that there is some evidence for this late-time exponential decay. Simulations by Guillochon & Ramirez-Ruiz (2013) and Guillochon et al. (2014) paint a more complicated picture, as $M$ may be affected by the retention of an intact stellar core and may asymptote to $\dot{\nu}^{-22}$.

In order to evaluate the applicability of such decay models, we consider the plausible $M_*$ range. Ghosh et al. (2006) suggest $M_* \sim 5 \times 10^4 M_\odot$ based on blackbody disk models, which requires sustained super-Eddington accretion in the 1990 epoch, given that $L_X \sim L_{\text{Edd}}$ implies $M_* \gtrsim 10^5 M_\odot$ for a bolometric correction of $\gtrsim 1.5$. We consider a plausible upper bound for $M_*$, given the $L_{\text{bulge}}-M_*$ relationship (e.g., Marconi & Hunt 2003; Kormendy & Ho 2013). The applicability of $L_{\text{bulge}}-M_*$ in this regime is uncertain, and would be affected by the galaxy morphology (see, e.g., Kormendy & Ho 2013, and references therein), including the nature of any nuclear
component in SDSS J114726.69+494257.8. Although Ghosh et al. (2006) label this galaxy as a nucleated dwarf spheroidal, the Galaxy Zoo morphology is uncertain (Lintott et al. 2008). Since \( L_{\text{nujge}} \lesssim L_{\text{total}} \), we find \( \log(M_*/M_\odot) \lesssim 6.4 \) for \( I = 15.98 \) (Ghosh et al. 2006), according to Jiang et al. (2011).

The 2009 observation of RBS 1032 is sufficiently late that it is likely to be in the Lodato & Rossi (2011) exponential decay regime for \( M_* \gtrsim 10^8 M_\odot \), which is compatible with the observations. The ROSAT epochs may instead be described by a more gradual decay than \( t^{-5/3} \) (see Lodato & Rossi 2011), if early accretion is significantly affected by stellar structure (Lodato et al. 2009) and \( M \) in the super-Eddington regime is strongly modulated by outflows (Dotan & Shaviv 2010). For example, Lodato & Rossi (2011) show that during the first \( \sim 4 \) yr of a disruption where \( M_* = 10^8 M_\odot, L_X \) may vary by an amount comparable to the RBS 1032 ROSAT data. The super-Eddington phase may last \( \sim 0.76 (M_*/10^8 M_\odot)^{-2/5} \) yr (Ulmer 1999), or \( \sim 4.8 \) yr at \( M_* \sim 10^8 M_\odot \). Alternately, a disrupted red giant may exhibit similar slow evolving \( M \) (MacLeod et al. 2012). When \( n \) for \( L_X \propto t^{-n} \) is left free, we find \( n = 2.5 \pm 1.3 \), which is closer to the Guillochon & Ramirez-Ruiz (2013) suggestion of \( r^{-2.2} \) for a surviving stellar core than to the Keplerian \( n = 5/3 \) value, but compatible with both.

4. DISCUSSION

The small separation between 3XMM J114726.7+494257 and RBS 1032, and the lack of other likely XMM-Newton counterparts to RBS 1032 both strongly suggest that they are the same X-ray source (see, e.g., the Donato et al. 2014 analysis of EUVE data for WINGS J1348). If so, the Ghosh et al. (2006) attribution of RBS 1032 to SDSS J114726.69+494257.8 is likely correct.

As with other X-ray selected TDE candidates (e.g., Maksym et al. 2010, 2013), the extreme luminosity (\( L_X \gtrsim 10^{43} \text{erg s}^{-1} \)) supersoft spectrum (\( \Gamma \sim 5 \)) at early times, and extreme variability (a factor of \( \gtrsim 200 \) decay) make this a strong candidate for a TDE. This is not a surprising conclusion, given Wang & Merritt (2004) suggest significantly elevated \( \gamma_p \) for nucleated dwarf spheroidal galaxies. Other possible explanations can be rejected via arguments similar to those advanced by Maksym et al. (2010, 2013) and others. The X-ray spectrum is too soft for a gamma-ray burst (GRB). Supernovae may exhibit soft thermal spectra, but \( L_X \) would make RBS 1032 among the most X-ray luminous supernovae (Levan et al. 2013). RBS 1032 is, however, significantly softer at early times than the super-luminous supernova SCP 06F6 (\( \Gamma \sim 5 \) versus \( \Gamma \sim 2.5 \)). The early X-ray emission in RBS 1032 is orders of magnitude too luminous for a stellar mass X-ray binary in SDSS J114726.69+494257.8. Ghosh et al. (2006) suggest a classical (and presumably Galactic) nova as possible but unlikely. In addition to their arguments, we suggest the high galactic latitude (\( b \sim 64^\circ \)) makes a Galactic foreground object unlikely (Maksym et al. 2010, 2013). Classical novae in particular are rare at \( b \gtrsim 30^\circ \) (Imamura & Tanabe 2012).

Ghosh et al. (2006) suggest that RBS 1032 may be an IMBH binary, possibly with a white dwarf secondary component. At least one other IMBH binary has been suggested, ESO 243-09 HLX-1 (Lasota et al. 2011 suggest a donor giant star). As with ESO 243-09 HLX-1, an eccentric orbit could mimic the extreme variability seen in RBS 1032. Additional X-ray monitoring observations could verify or disprove such an explanation.

Given that both Narrow-Line Seyfert 1 (e.g., Grupe et al. 1995) and Seyfert 2 (Saxton et al. 2011) galaxies may exhibit extreme supersoft X-ray variability on timescales similarly short to TDEs, an AGN origin is typically the most difficult explanation to dismiss for an X-ray source with these characteristics. Variability in such a case may be attributed to change in \( M \) or \( N_H \). Ghosh et al. (2006) demonstrate, however, that RBS 1032 has no significant emission lines. Steady accretion by an AGN is therefore disfavored. TDEs may temporarily excite emission lines (e.g., Bogdanović et al. 2004; Clausen & Eracleous 2011; Gezari et al. 2012), but such lines might not be visible at \( t_0 \gtrsim 15 \) yr.

The XMM-Newton spectrum is harder than previous epochs (\( \Gamma \sim 3 \) versus \( \sim 5 \)). Such evolution has been seen in X-ray observations at \( t_0 \gtrsim 10 \) yr (Halpern et al. 2004). This could be a state change due to a lower \( M \), or a weak “hard” physical component only visible when the soft component subsides. The
lack of emission lines indicates little star formation or nuclear activity. Contamination due to hot gas or X-ray binaries is thus likely to be small ($\lesssim$few $\times$ $10^{39}$ erg s$^{-1}$).

Given the importance of RASS for determining $\gamma_D$, Donley et al. (2002) remains an important reference for discussion of the observed $\gamma_D$. At $\gamma_D \sim 10^{-5}$ galaxy$^{-1}$ yr$^{-1}$, this also remains one of the most conservative $\gamma_D$ values in the literature. The discovery of a single RASS flare would not have a major impact on Donley et al. (2002) even given they only assume three outbursts from inactive galaxies. However, the presence of other unidentified flares (undetected due to long periods of shallow evolution, for example) might require a re-evaluation of Donley et al. (2002) and its applicability to TDEs. Donley et al. (2002) assume that any flare which varies by $\gtrsim 20$ during RASS and the preceding $\sim$six months would be detected by their study. This assumption was reasonable according to TDE theory at the time, and was confirmed by all known TDEs identified by ROSAT.

RBS 1032, though observed by ROSAT three times over $\sim$4 yr, only varied by $\sim$5 and thus was not selected. Under certain models, however, TDEs may have relatively shallow X-ray light curves for years at a time. In particular, certain models (e.g., Lodato & Rossi 2011) may have relatively shallow X-ray light curves for years. But even with modest deviations from best-fit $t^{-5/3}$ decay, RBS 1032 could fall within the Donley et al. (2002) window. As a result, we expect that not all RASS TDEs had been detected. The TDE in A3571 identified by Cappelluti et al. (2009) also complicates the Donley et al. (2002) rate estimation, as the RASS $F_X$ upper limit falls earlier than their best-fit $t_0$, but is also above their earliest detected X-ray flux. Given the flare’s proximity to the diffuse intracluster X-ray emission from A3571, and the likely importance of galaxy clusters in TDE production (Wang & Merritt 2004; Cappelluti et al. 2009; Maksym et al. 2010, 2013), such cluster background may be important to any RASS-derived $\gamma_D$.

Given this state of affairs, we therefore argue that the results of Donley et al. (2002) should be considered a lower limit to $\gamma_D$, and that long baseline X-ray studies (such as may use RASS and Chandra, XMM-Newton, Swift, or eROSITA) are necessary to investigate the occurrence of TDEs which may display such gradual evolution. This assertion is supported by the recent work by Khabibullin & Sazonov (2014), who found several gradual evolution. This assertion was reasonable according to TDE theory at the time, and was confirmed by all known TDEs identified by ROSAT.

5. CONCLUSIONS

By comparing archival XMM-Newton observations with previous work by Ghosh et al. (2006), we confirm that RBS 1032 is associated with the dwarf galaxy SDSS J114726.69+494257.8. We suggest that RBS 1032 is also likely to be a TDE. Its peak luminosity ($L_X \gtrsim 10^{42}$ erg s$^{-1}$), softness ($\Gamma \sim 5$), and extreme variability (factor of $\sim$200) in a quiescent galaxy are typical of X-ray selected TDEs. Via the absence of AGN emission lines, Ghosh et al. (2006) have already demonstrated that an AGN is an unlikely explanation. Other explanations, such as GRBs, supernovae, and X-ray binaries are disfavored. Although the nuclear black hole could be an IMBH, a more massive black hole ($\gtrsim$10$^6$ $M_\odot$) would be consistent with the host galaxy lu-
