RADIO MONITORING OF THE TIDAL DISRUPTION EVENT SWIFT J164449.3+573451. II. THE RELATIVISTIC JET SHUTS OFF AND A TRANSITION TO FORWARD SHOCK X-RAY/RADIO EMISSION

B. A. Zauderer1, E. Berger1, R. Margutti1, G. G. Pooley2, R. Sari3, A. M. Soderberg1, A. Brunthaler1, and M. F. Bietenholz5,6

1 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
2 Mullard Radio Observatory, Cavendish Laboratory, Cambridge, CB3 0HE, UK
3 Racah Institute of Physics, The Hebrew University, 91904 Jerusalem, Israel
4 Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
5 Department of Physics and Astronomy, York University, Toronto, Ontario, Canada
6 Hartebeesthoek Radio Astronomy Observatory, P.O. Box 443, Krugersdorp 1740, South Africa

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ABSTRACT

We present continued multi-frequency radio observations of the relativistic tidal disruption event Swift J164449.3+573451 (Sw 1644+57) extending to $t \approx 600$ days. The data were obtained with the JVLA and AMI Large Array as part of our ongoing study of the jet energetics and the density structure of the parsec-scale environment around the disrupting supermassive black hole. We combine these data with public Swift/XRT and Chandra X-ray observations over the same time frame to show that the jet has undergone a dramatic transition starting at $\approx 500$ days, with a sharp decline in the X-ray flux by about a factor of 170 on a timescale of $\delta t/t \approx 0.2$ (and by a factor of 15 in $\delta t/t \approx 0.05$). The rapid decline rules out a forward shock origin (direct or reprocessing) for the X-ray emission at $\lesssim 500$ days, and instead points to internal dissipation in the inner jet. On the other hand, our radio data uniquely demonstrate that the low X-ray flux measured by Chandra at $\approx 610$ days is consistent with emission from the forward shock. Furthermore, the Chandra data are inconsistent with thermal emission from the accretion disk itself since the expected temperature of $\sim 30$–60 eV and inner radius of $\sim 2$–10 $R_g$ cannot accommodate the observed flux level or the detected emission at $\gtrsim 1$ keV. We associate the rapid decline with a turn off of the relativistic jet when the mass accretion rate dropped below $\dot{M}_{\text{Edd}} \approx 0.006 M_\odot$ yr$^{-1}$ (for a $3 \times 10^9 M_\odot$ black hole and order unity efficiency) indicating that the peak accretion rate was about 330 $M_{\text{Edd}}$, and the total accreted mass by $t \approx 500$ days is about 0.15 $M_\odot$. From the radio data we further find significant flattening in the integrated energy of the forward shock at $t \gtrsim 250$ days with $E_{\text{iso}} \approx 2 \times 10^{54}$ erg ($E_{\text{j}} \approx 10^{52}$ erg for a jet opening angle, $\theta_j = 0.1$) following a rise by about a factor of 15 at $\approx 30$–250 days. Projecting forward, we predict that the emission in the radio and X-ray bands will evolve in tandem with similar decline rates.

Key words: accretion, accretion disks – radiation mechanisms: non-thermal – techniques: interferometric

Online-only material: color figures

1. INTRODUCTION

The unusual $\gamma$-ray/X-ray transient Sw 1644+57 has been broadly interpreted as the first example of a tidal disruption event (TDE) powering a relativistic jet (e.g., Bloom et al. 2011; Burrows et al. 2011; Levan et al. 2011; Zauderer et al. 2011). As such, Sw 1644+57 provides unique insight into the formation (and potentially termination) of relativistic jets in supermassive black holes (SMBHs), a process that is not observed in active galactic nuclei (AGNs) due to long lifetimes of $\gtrsim 10^7$ yr. One of the primary observations supporting the TDE relativistic jet scenario in Sw 1644+57 is the long-term evolution of the X-ray light curve, roughly following a $\Gamma^{-5/3}$ power law decline (Burrows et al. 2011) as expected for the fallback rate of tidally disrupted material (e.g., Rees 1988). In addition, the mean X-ray luminosity at early time, $L_{\text{X,iso}} \approx 10^{47}$ erg s$^{-1}$ (flaring to $\approx 3 \times 10^{48}$ erg s$^{-1}$ on a $\sim 10^{5}$ s timescale; Burrows et al. 2011), exceeded the Eddington limit of a $10^{5}–10^{6} M_\odot$ black hole by about 2–3 orders of magnitude, supporting the presence of a collimated relativistic outflow. Independently, our discovery of bright radio synchrotron emission from Sw 1644+57 established the presence of a relativistic outflow with a Lorentz factor of $\Gamma \sim$ few, launched at the same time as the onset of $\gamma$-ray emission (Zauderer et al. 2011; Berger et al. 2012). The basic picture, therefore, is of X-ray emission likely from internal dissipation in the inner part of the jet (at $r \sim 10^{15}$–$10^{16}$ cm) and radio emission from the expanding forward shock (at $r \sim 10^{15}$–$10^{19}$ cm).

While the formation of relativistic jets was not predicted in TDE models, a super-Eddington accretion phase was expected (e.g., Evans & Kochanek 1989; Ulmer 1999; Strubbe & Quataert 2009) and the potential for jets was discussed (Giannios & Metzger 2011). The latter paper considered two distinct possibilities for jet formation, during the super-Eddington phase, or at a later time when the accretion rate drops below a few percent of the Eddington rate (motivated by observations of steady jets in X-ray binaries). The rapid formation of the relativistic jet in Sw 1644+57 points to the former scenario. The peak mass accretion rate and duration of the super-Eddington phase are expected to depend on the mass of the black hole, with $\dot{M}_p \approx 1.4 M_\odot$ yr$^{-1}$ and $t_{\text{Edd}} \approx 1.5$ yr for a $3 \times 10^9 M_\odot$ black hole (e.g., Evans & Kochanek 1989; De Colle et al. 2012), the mid-range inferred mass of the disrupting SMBH in Sw 1644+57 (Bloom et al. 2011; Burrows et al. 2011; Levan et al. 2011; Zauderer et al. 2011). Although it is unclear what, if anything, happens to a TDE jet when the accretion declines below the Eddington limit, an analogy with X-ray binaries indicates that relativistic jet ejections will likely be restricted to the super-Eddington phase (e.g., Fender et al. 1999; De Colle et al. 2012).
To take advantage of this unique opportunity to study the birth and evolution of a relativistic jet from an SMBH, and to track the jet properties of a TDE, we have been carrying out a long-term monitoring campaign of the radio emission from Sw 1644+57, in conjunction with X-ray data (Zauderer et al. 2011; Berger et al. 2012). Here we present new radio observations that extend to \( t \approx 600 \) days, and use these data to determine the continued evolution of the integrated forward shock energy. We combine these measurements with public \textit{Swift}/XRT and \textit{Chandra} observations over the same timescale to show that the relativistic jet has shut off at \( t \approx 500 \) days, marked by a steep decline in the X-ray luminosity (Shafarudatti et al. 2012; Levan & Tanvir 2012). The radio data allow us to uniquely determine that the X-ray flux measured in the \textit{Chandra} data is consistent with emission from the forward shock; a model of thermal emission from the accretion disk can be ruled out by the flux and spectrum of the X-ray emission. Associating the rapid decline with the timescale at which \( M \approx M_{\text{Edd}} \), we infer the peak mass accretion rate and the total accreted mass at \( t \lesssim 500 \) days.

2. RADIO OBSERVATIONS

Previous radio observations of Sw 1644+57 extending to \( t \approx 26 \) days were presented in Zauderer et al. (2011), while data extending to \( t \approx 216 \) days were presented in Berger et al. (2012, hereafter Paper I). Here we report new observations extending to \( t \approx 600 \) days. All times are measured relative to a \( \gamma \)-ray onset date of 2011 March 25.5 UT. Throughout the paper we use the standard cosmological constants with \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_m = 0.27 \) and \( \Omega_{\Lambda} = 0.73 \).

We observed Sw 1644+57 with the Karl G. Jansky Very Large Array (JVLA)\(^5\) using the Wideband Interferometric Digital Architecture (Perley et al. 2011) correlator to obtain up to 2 GHz of bandwidth at several frequencies. At all frequencies we used 3C286 for bandpass and flux calibration, while phase calibration was performed using J1634+6245 at 1.8 GHz and J1638+5720 at all other frequencies. We reduced and imaged the data with the Astronomical Image Processing System (Greisen 2003) software package. The observations are summarized in Table 1.

We also observed Sw 1644+57 with the AMI Large Array (AMI-LA) at 15.4 GHz with a bandwidth of 3.75 GHz using J1638+5720 for phase calibration and 3C48 and 3C286 for flux calibration. The AMI-LA observations are summarized in Table 1.

3. X-RAY OBSERVATIONS

\textit{Chandra}/ACIS-S observations of Sw 1644+57 (PI: Tanvir; Levan & Tanvir 2012) started on 2012 November 26.42 UT (\( t \approx 610 \) days), with a total exposure time of 24.7 ks. We analyzed the public data with the CIAO software package (v4.4), using the calibration database CALDB (v4.5.3) and standard ACIS data filtering. Using \texttt{wavdetect} we detect Sw 1644+57 at a significance level of 2.8\( \sigma \) with a count rate of \( (2.0 \pm 0.9) \times 10^{-4} \text{ count s}^{-1} \) (0.5–8 keV; 1\( \arcmin \) radius aperture). We note that emission is detected with a roughly flat distribution in counts s\(^{-1}\) keV\(^{-1}\) at \( \approx 1–3.5 \) keV (Figure 1); formally, the spectral index is only weakly constrained, with \( \Gamma = 1.0 \pm 1.3 \).

\(^5\) The JVLA is operated by the National Radio Astronomy Observatory, a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. The observations presented here were obtained as part of programs 11A-266 and 12A-280.
To convert the observed count rate to a flux we note that starting at $t \approx 23$ days the X-ray emission from Sw 1644+57 undergoes spectral hardening, with the photon index evolving to $\Gamma \approx 1.3$ at $t \gtrsim 230$ days. We therefore use an absorbed power law spectrum with an index of $\Gamma = 1.3$, intrinsic absorption of $N_{H, \text{int}} = 1.4 \times 10^{22}$ cm$^{-2}$, and Galactic absorption of $N_{H, \text{MW}} \approx 1.7 \times 10^{20}$ cm$^{-2}$ (Kalberla et al. 2005). With this model, the unabsorbed flux is $(5.8 \pm 2.0) \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ (0.3–10 keV). For a power law model$^9$ with $\Gamma = 2.2$ the resulting flux is only $\approx 5\%$ lower. Finally, a multi-temperature accretion disk blackbody model (diskbb in xspec) can also fit the data, with a resulting temperature at the inner disk radius of $kT \approx 1$ keV; thermal disk models with a temperature appropriate to a $\sim 10^5–10^7 M_\odot$ SMBH ($kT \lesssim 60$ eV) cannot reproduce the 
Chandra data (Figure 1) and furthermore require an inconsistent radius (see Section 5).

4. MODELING OF THE RADIO EMISSION

We model the radio emission from Sw 1644+57 following the approach detailed in Paper I, which is based on the afterglow formulation of Metzger et al. (2012) and Granot & Sari (2002). For details of the model we refer the reader to these papers. For the purpose of estimating the X-ray emission from the forward shock we also include in the analysis here the effects of the synchrotron cooling frequency, given by (Granot & Sari 2002):

$$v_c = 2.5 \times 10^{14} \epsilon_B^{-3/2} \epsilon_{B,48}^{-1/2} N_{15}^{-2} \left( \frac{t}{t_j} \right)^{0.5} \text{Hz},$$  (1)

where $\epsilon_B$ is the fraction of post-shock energy in the magnetic fields, $L_{j,\text{iso}}$ is the kinetic luminosity of the outflow, $t_j$ is the timescale over which $L_{j,\text{iso}}$ is assumed to be constant (followed by $L_{j,\text{iso}} \propto t^{-5/3}$ at $t \gtrsim t_j$), $n_{15}$ is the circumnuclear density ($\rho_{\text{CNM}}$) at a fiducial radius of $r = 10^{19}$ cm, and we use the notation $X \equiv 10^3 X_y$, as described in Paper I. We further assume$^{10}$ that $\epsilon_B = 0.01$ and find from the radio data that $p = 2.45 \pm 0.05$.

As in Paper I, we independently model each broadband radio spectral energy distribution (SED) to extract the temporal evolution of the synchrotron parameters, and in turn the evolution of $L_{j,\text{iso}}$, the emission radius, the jet Lorentz factor ($\Gamma_j$), and the radial density profile. The individual SED fits are shown in Figure 2 and the relevant extracted parameters are listed in Table 2. In Figure 3 we plot the light curves at frequencies of 1.8–43 GHz, extending to $\approx 600$ days. Finally, in Figure 4 we plot the X-ray data from Swift/XRT$^{11}$ and Chandra along with the predicted forward shock emission in the X-ray band based on the radio SED modeling.

5. THE RELATIVISTIC JET SHUTS OFF

The X-ray light curve at $t \approx 15–500$ days follows a power law decline, with the expected $F_X \propto t^{-5/3}$ (Figure 4; Burrows

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**Table 1 (Continued)**

| $t^a$ (days) | Facility | Frequency (GHz) | Flux Density (mJy) |
|-------------|----------|-----------------|--------------------|
| 513.76      | AMI-LA   | 15.4            | 6.00 ± 0.77        |
| 532.39      | AMI-LA   | 15.4            | 5.38 ± 0.64        |
| 525.29      | AMI-LA   | 15.4            | 5.47 ± 0.42        |
| 528.25      | AMI-LA   | 15.4            | 5.55 ± 0.20        |
| 534.40      | AMI-LA   | 15.4            | 6.00 ± 0.10        |
| 538.26      | AMI-LA   | 15.4            | 5.36 ± 0.43        |
| 550.31      | AMI-LA   | 15.4            | 5.16 ± 0.35        |
| 561.13      | AMI-LA   | 15.4            | 4.72 ± 0.25        |
| 567.36      | AMI-LA   | 15.4            | 4.46 ± 0.24        |
| 592.10      | AMI-LA   | 15.4            | 4.51 ± 0.27        |
| 243.09      | JVLA     | 22.4            | 21.89 ± 0.10       |
| 298.96      | JVLA     | 22.4            | 15.75 ± 0.06       |
| 394.72      | JVLA     | 22.4            | 8.46 ± 0.03        |
| 460.67      | JVLA     | 22.4            | 6.03 ± 0.03        |
| 582.21      | JVLA     | 22.4            | 3.94 ± 0.03        |
| 243.09      | JVLA     | 22.4            | 20.65 ± 0.11       |
| 298.96      | JVLA     | 22.4            | 13.64 ± 0.06       |
| 394.72      | JVLA     | 22.4            | 6.77 ± 0.04        |
| 460.67      | JVLA     | 22.4            | 4.83 ± 0.03        |
| 582.21      | JVLA     | 22.4            | 3.26 ± 0.03        |
| 394.72      | JVLA     | 22.4            | 5.26 ± 0.04        |
| 460.67      | JVLA     | 22.4            | 3.58 ± 0.04        |
| 582.21      | JVLA     | 22.4            | 2.41 ± 0.05        |

**Figure 1.** Spectrum of the X-ray emission from the 
Chandra observation at $t \approx 610$ days (black points). Also shown are the best fit power law model (red line), and a multi-temperature disk blackbody model with $kT \approx 60$ eV, appropriate for an accretion disk with an inner radius of 2 $R_g$ around a $3 \times 10^9 M_\odot$ black hole (blue line). The disk model provides a poor fit to the data at $E > 1$ keV. In addition, to fit the flux at $\sim 1$ keV this model requires a radius of $3.4 \times 10^{13}$ cm $\approx 40 R_g$, which is inconsistent with the temperature. We therefore conclude that the X-ray emission at late time is not due to the accretion disk.

(A color version of this figure is available in the online journal.)

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Note. $^a$All values of $t$ are relative to the initial $\gamma$-ray detection: 2011 March 25.5 UT.

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8 [http://www.swift.ac.uk/burst_analyser/00450158](http://www.swift.ac.uk/burst_analyser/00450158)

9 This model is appropriate for the expected forward shock emission with the X-ray band located above the synchrotron cooling frequency ($v_c < v_X$), and with an electron power law index of $p = 2.45$ ($N_{\gamma_e} \propto \gamma_{\gamma_e}^{-p}$ for $\gamma_{\gamma_e} > \gamma_{\min}$, where $\gamma_{\gamma_e}$ is the electron Lorentz factor and $\gamma_{\min}$ is the minimum value for the distribution); see Section 5.

10 Note that in Paper I we assumed $\epsilon_B = 0.1$ and $p = 2.5$, which lead to an overall difference in scaling compared to the results here that can be determined from the equations in Paper I. However, the temporal and radial evolution of the kinetic energy and radial density profile presented in Paper I remain unchanged.

11 [http://www.swift.ac.uk/xrt_curves/00450158](http://www.swift.ac.uk/xrt_curves/00450158)
Figure 2. Multi-frequency radio spectral energy distributions of Sw 1644+57 at $t \approx 244$–$582$ days. The solid lines are fits based on the model described in Paper I, Metzger et al. (2012), and Section 4. In each epoch we fit for $L_j$,iso and $n_{18}$ with fixed values of $\epsilon_e = 0.1$, $\epsilon_B = 0.01$, and $p = 2.45$.

(A color version of this figure is available in the online journal.)

Table 2

| $t$ (days) | $\log(v_a)$ (Hz) | $\log(v_m)$ (Hz) | $\log(v_c)$ (Hz) | $\log(F_{\nu_a})$ (mJy) | $\log(r_{18})$ (cm) | $\log(\Gamma_{sh})$ | $\log(\Gamma_j)$ | $\log(L_{j,iso,48})$ (erg s$^{-1}$) | $\log(n_{18})$ (cm$^{-3}$) | $\log(n_{CNM})$ (cm$^{-3}$) |
|------------|------------------|------------------|------------------|--------------------------|----------------------|-------------------|-----------------|----------------------------------|-------------------------|--------------------------|
| 244        | 10.04            | 9.67             | 13.00            | 1.99                     | 0.59                 | 0.31              | 0.35            | 2.22                             | 1.08                    | -0.10                    |
| 301        | 9.96             | 9.54             | 13.09            | 1.92                     | 0.66                 | 0.30              | 0.33            | 2.24                             | 1.07                    | -0.24                    |
| 390        | 9.71             | 9.38             | 13.45            | 1.72                     | 0.79                 | 0.31              | 0.33            | 2.25                             | 0.92                    | -0.66                    |
| 457        | 9.62             | 9.28             | 13.56            | 1.64                     | 0.85                 | 0.30              | 0.33            | 2.26                             | 0.88                    | -0.81                    |
| 582        | 9.58             | 9.13             | 13.58            | 1.60                     | 0.90                 | 0.28              | 0.30            | 2.28                             | 0.90                    | -0.90                    |

Notes. Measured and inferred parameters of the relativistic outflow and environment of Sw 1644+57 from model fits of the individual multi-frequency SEDs shown in Figure 2. The model is described in Paper I, Metzger et al. (2012), and Section 4.

et al. 2011; Paper I). However, beyond this point the X-ray flux rapidly declines by a factor of about 15 in the span of only 25 days, followed by an additional (slower) decline of about a factor of 11 in the subsequent 95 days (see also Sbarufatti et al. 2012; Levan & Tanvir 2012). While the X-ray light curve exhibits order of magnitude variability in the first few days, followed by milder variability at later time, a decline by a factor of $\approx 170$ in a narrow span of $\delta t/t \lesssim 0.2$ (and by a factor of 15 in $\delta t/t \approx 0.05$) is unprecedented and points to a fundamental change in the nature of the emission. In particular, we conclude that the mechanism powering the X-ray emission at $t \lesssim 500$ days has ceased to operate. The absence of a similar rapid decline in the radio band supports earlier conclusions that the radio and X-ray emission arise from distinct physical components (Bloom et al. 2011; Zauderer et al. 2011; Metzger et al. 2012; Liu et al. 2012).

In addition, the rapid decline rules out models in which the X-ray emission at $t \lesssim 500$ days is due to the forward shock or to reprocessing of radiation by the forward shock, since processes at the forward shock are expected to occur on a timescale comparable to the duration of the event, $\delta t/t \approx 1$. Thus, given the rapid decline we conclude that the early X-ray emission originated at a smaller radius than the forward shock, presumably from internal dissipation in the inner part of the relativistic outflow (at $r \approx \text{few} \times 10^{15}$ cm; e.g., De Colle et al. 2012). On the other hand, the low X-ray flux following
the steep decline, as measured in the Chandra observation, is fully consistent with emission from the forward shock at $r \approx 8 \times 10^{18} \text{ cm}$ (Figure 4 and Table 2), the same component powering the long-term radio emission. While residual emission from the inner jet cannot be definitively ruled out, the observed flattening in the decline rate between the final XRT measurement and the Chandra measurement points to a transition to forward shock dominated emission.

An alternative explanation for the low X-ray flux at $t \approx 610$ days is thermal emission from the accretion disk itself. In this scenario, for a $3 \times 10^6 M_\odot$ black hole the effective temperature is $kT \approx 25 \text{ eV}$ for an inner radius at the tidal disruption radius, $R_i \approx 12 R_s \approx 1.1 \times 10^{13} \text{ cm}$ (e.g., Ulmer 1999); here $R_s$ is the Schwarzschild radius. The resulting SED severely under-predicts the observed X-ray flux density, and cannot accommodate the X-ray spectrum at $\gtrsim 1 \text{ keV}$ due to the expected steep Wien spectrum. Even a model with a temperature of $kT \approx 60 \text{ eV}$ (corresponding to an inner disk radius of only 2 $R_s$) cannot accommodate the detected X-ray emission at $\gtrsim 1 \text{ keV}$ (Figure 1). In particular, for this model to even fit the flux normalization of the Chandra data at $\lesssim 1 \text{ keV}$ requires an inconsistent inner disk radius of about 40 $R_s$ (using the standard disk blackbody model with $L_{\text{disk}} = 4\pi R_a \sigma T_e^4$). A thermal model only fits the data for a high temperature of $kT \approx 1 \text{ keV}$, but this is not expected for an SMBH.

Finally, the late-time X-ray emission may also be due to Comptonization of the disk UV photons (for example, by a hot corona). This effect is seen in AGNs, with a typical resulting soft X-ray luminosity of $L_X/\nu_{\text{UV}} \approx (\nu_{\text{X}}/\nu_{\text{UV}})^{-0.5}$ (e.g., Steffen et al. 2006). Using the disk model above ($kT \approx 25 \text{ eV}$ and $R_a \approx R_i \approx 1.1 \times 10^{13} \text{ cm}$), we find an expected peak UV luminosity of $\nu_{\text{UV}}L_{\nu,\text{UV}} \approx 4 \times 10^{44} \text{ erg s}^{-1}$, and hence an expected X-ray luminosity of $L_X \approx 5 \times 10^{33} \text{ erg s}^{-1}$. This is an order of magnitude larger than the observed value, suggesting that Comptonization typical of quasars is not relevant here, although this does not rule out the Comptonization scenario. Still, since the forward shock emission is inevitable and provides an excellent match to the observed luminosity, we conclude that forward shock emission is the most natural explanation for the late-time X-ray flux.

While the nature of relativistic jet generation in TDEs is not fully understood, an analogy with X-ray binaries suggests that a powerful jet can be supported as long as the disk is geometrically thick, with an accretion rate of $M \gtrsim M_{\text{Edd}}$. De Colle et al. (2012) recently presented simulations of the tidal disruption of a $1 M_\odot$ star and showed that for a $3 \times 10^6 M_\odot$ black hole, the peak mass accretion rate is about $240 M_{\text{Edd}}$ (for order unity efficiency), while $M \approx M_{\text{Edd}}$ at $t \approx 1.5 \text{ yr}$. This timescale is remarkably similar to the time of rapid X-ray decline for Sw 1644+57, about 370 days in the rest-frame. Associating this timescale with an accretion rate of about $M_{\text{Edd}}$, we find that the beaming-corrected X-ray luminosity prior to the rapid decline, $L_X \approx 2 \times 10^{42} \text{ erg s}^{-1}$ (for $\theta_e = 0.1$), is about 0.01 $L_{\text{Edd}}$ for a $3 \times 10^6 M_\odot$ black hole. However, the resulting low efficiency is not surprising given the hard power index of $\Gamma \approx 1.3$ at $\lesssim 500$ days, which suggests that the bulk of the energy is radiated above the XRT band.

Figure 3. Radio light curves of Sw 1644+57 extending to $t \approx 600$ days. The data at $t \approx 5–216$ days were previously presented in Zauderer et al. (2011) and Paper I. The solid lines are models based on independent fits of broadband SEDs (Figure 2) using the model described in Paper I, Metzger et al. (2012), and Section 4.

(A color version of this figure is available in the online journal.)

Figure 4. X-ray light curve from Swift/XRT (circles) and a late-time Chandra observation (square). The gray line is a simple model with a constant flux at $t < t_j$ and $F_X \propto t^{-5/3}$ at $t_j \geq t_j$, with $t_j \approx 15$ days. A rapid decline in the X-ray flux is evident at $t \gtrsim 500$ days. The blue line shows the X-ray emission expected from the forward shock using the synchrotron model described in Section 4; the light blue band marks the region for an uncertainty of $\pm 0.05$ in the value of $p$. The model indicates that the flux measured in the Chandra observation is consistent with arising from the forward shock.

(A color version of this figure is available in the online journal.)
The rapid rise at $E_t$ value of The Astrophysical Journal energy (Burrows et al. 2011; De Colle et al. 2012; Metzger et al. 2012) for $M_t \approx 15$. Integrating the mass accretion rate to our measurements at $\theta_j$ an assumed jet opening angle of $≈ 250–600$ days point to a beaming-corrected kinetic energy of $E_{j,\text{iso}} ≈ 2 \times 10^{54}$ erg. The rapid decline at $t ≈ 30–250$ days is followed by a mild rise or plateau to a value of $E_{j,\text{iso}} ≈ 2 \times 10^{54}$ erg.

With the inference that $M(500 \text{ days}) \approx M_{\text{Edd}} \approx 0.006 M_\odot \text{ yr}^{-1}$ we can also determine the total accreted mass. Using a simple model with $\dot{M}(t) = \dot{M}_p$ at $t < 15$ days and $\dot{M}(t) = \dot{M}_p (t/t_j)^{-3/3}$ at $t > 15$ days, motivated by the X-ray light curve (Burrows et al. 2011; De Colle et al. 2012; Metzger et al. 2012), we find $\dot{M}_p \approx 350 M_{\text{Edd}}$, in good agreement with the predictions of De Colle et al. (2012) for a $3 \times 10^6 M_\odot$ black hole. Integrating the mass accretion rate to $t \approx 370$ days in the rest-frame, we find a total accreted mass of $≈ 0.15 M_\odot$. This result is consistent with the disruption of a $< 1 M_\odot$ star.

In addition to the rapid decline in X-ray emission, which marks the jet turning off, we also find a change in behavior in the integrated energy of the forward shock. Following an increase in $E_{j,\text{iso}}$ by about a factor of 15 at $t ≈ 30–250$ days, our measurements at $t ≈ 250–600$ days point to a mild rise or a plateau at a level of $E_{j,\text{iso}} ≈ 2 \times 10^{54}$ erg (Figure 5). For an assumed jet opening angle of $\theta_j \sim 0.1$, this corresponds to a beaming-corrected kinetic energy of $E_K \approx 10^{52}$ erg. The flattening in the temporal evolution of $E_{j,\text{iso}}$ is unlikely to be related to the cessation of jet activity since it begins at an earlier phase. Instead, it is more likely related to the velocity profile of the ejecta, as discussed in Paper I, or to a delayed response of the forward shock to the drop in mass accretion rate below the peak rate (De Colle et al. 2012). As a result, we expect that the turn off of the relativistic jet will have only a mild impact on the forward shock energy, on a timescale of $t \approx 10^3$ days.

6. CONCLUSIONS

We present a joint analysis of radio and X-ray observations of Sw 1644+57 extending to $t \approx 600$ days. From the multi-frequency radio data we determine the integrated energy of the forward shock as a function of time and find that following an increase in $E_{j,\text{iso}}$ by about a factor of 15 at $t \approx 30–250$ days, measurements to $t \approx 600$ days reveal a mild rise or plateau with $E_{j,\text{iso}} \approx 2 \times 10^{54}$ erg. X-ray observations with Swift/XRT and Chandra reveal a dramatic change in the light curve evolution, with a sharp decline by about a factor of 170 at $t ≳ 500–610$ days following a steady $t^{-3/3}$ decline at $t \approx 500–500$ days. Using the radio data, we conclude that the low X-ray flux measured by Chandra is consistent with emission from the forward shock. The alternative explanation of thermal disk emission is ruled out by the X-ray flux and spectrum, which instead require a temperature of $kT \approx 1 \text{ keV}$, compared to an expected value of $\lesssim 60 \text{ eV}$ for an SMBH accretion disk.

The rapid decline suggests that the relativistic jet has turned off, most likely as a result of a decline in the mass accretion rate below $\sim M_{\text{Edd}}$. With this interpretation, the overall accreted mass by $t \approx 500$ days is $\approx 0.15 M_\odot$, consistent with the disruption of a solar mass star. Moreover, the rapid decline, with $\delta t/t \lesssim 0.2$, indicates that the X-ray emission at $t \lesssim 500$ days did not originate from the forward shock or from radiation reprocessed by the forward shock. Instead it was likely due to internal dissipation in the inner part of the jet.

Projecting forward, we expect that the X-ray flux evolution will track the decline rate in the optically thin high-frequency radio bands with a potential dispersion of about $±0.25$ due to the response of the synchrotron cooling frequency to variations in the radial density profile. Additional Chandra or XMM-Newton observations in the coming year will test this prediction.

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Figure 5. Temporal evolution of the isotropic-equivalent integrated kinetic energy ($E_{j,\text{iso}} \equiv L_{j,\text{iso}}/\dot{f}_j$) based on modeling of the radio emission (Figure 2). The rapid rise at $t ≈ 30–250$ days is followed by a mild rise or plateau to a value of $E_{j,\text{iso}} ≈ 2 \times 10^{54}$ erg.