PROBING THE STRUCTURE OF THE OUTFLOW IN THE TIDAL DISRUPTION FLARE Sw J1644+57 WITH LONG-TERM RADIO EMISSION

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ABSTRACT

The recently discovered high-energy transient Sw J1644+57 is thought to arise from the tidal disruption of a passing star by a dormant massive black hole. The long-term, bright radio emission of Sw J1644+57 is believed to result from the synchrotron emission of the blast wave produced by an outflow expanding into the surrounding medium. Using the detailed multi-epoch radio spectral data, we are able to determine the total number of radiating electrons in the outflow at different times, and further the evolution of the cross section of the outflow with time. We find that the outflow gradually transits from a conical jet to a cylindrical one at later times. The transition may be due to collimation of the outflow by the pressure of the shocked jet cocoon that forms while the outflow is propagating in the ambient medium. Since cylindrical jets usually exist in active galactic nuclei (AGNs) and extragalactic jets, this may provide independent evidence that Sw J1644+57 signals the onset of an AGN.

Key words: galaxies: nuclei – gamma-ray burst: general

1. INTRODUCTION

The high-energy transient Swift J164449.3+573451 (hereafter Sw J1644+57) was detected by the Swift Burst Alert Telescope on 2011 March 28 (Burrows et al. 2011). It was first considered to be a gamma-ray burst (GRB). However, Sw J1644+57 was later shown to have characteristics different to those of GRBs and also to those of active galactic nuclei (AGNs). It has a lifetime much longer than GRBs and is much more luminous than AGNs. Further observations showed that the position of this event is coincident with the nucleus of a galaxy at redshift \( z = 0.3534 \) (Levan et al. 2011; Bloom et al. 2011). Its long-term X-ray luminosity varies as \( L_X \propto t^{-5/3} \), consistent with the expected fallback rate of tidally disrupted material (Rees 1998). Thus, this event was later considered to be a star being tidally disrupted by a \( \sim 10^6 M_\odot \) supermassive black hole (SMBH) in the center of the galaxy. Since the \( \gamma \)-ray and X-ray luminosity of this event are \( 2-3 \) orders of magnitude larger than the Eddington luminosity of a \( \sim 10^6 M_\odot \) SMBH, the emission is likely to be produced by a collimated outflow. It is worth noting that Sw J1644+57 has bright long-term radio synchrotron emission (Zauderer et al. 2011), which provides a unique chance for us to study how the physical parameters of the outflow evolve as it interacts with the ambient medium.

Metzger et al. (2012) modeled the radio–microwave emission for 5–23 days after the trigger with the blast wave emission, in analogy to GRB afterglows (see, e.g., Giannios & Metzger 2011). They found that a narrow jet with opening angle \( \theta_j \lesssim 1/\gamma_j \) expanding into a medium with a density profile \( n \propto R^{-2} \) could fit the radio data. Berger et al. (2012) reconsidered this model based on much longer radio data over 5–216 days. They noticed that the energy injection model used in Metzger et al. (2012) was no longer suitable after 23 days. Instead they made an assumption that the energy distribution in the jet is described by \( E(\gamma) \propto \Gamma^{-2.5} \) (where \( \Gamma \) is the bulk Lorentz factor of the jet), so that substantial energy is added to the blast wave at later times. The radial density profile after 23 days was inferred to be \( n \propto R^{-1.5} \) with a plateau at \( r \approx 0.4-0.6 \) pc. Both works made a pre-assumption that the jet has a conical structure with a constant opening angle \( \theta_j \lesssim 1/\gamma_j \). However, the jet structure of this transient has not yet been resolved. The cross sections of extragalactic AGN radio jets do not increase at large radii and a cylindrical jet structure (or blob) has been usually assumed (Bridle & Perley 1984). Since Sw J1644+57 involves a jet from an SMBH similar to an AGN, it is necessary to consider the possibility of a cylindrical jet.\textsuperscript{3} In this paper, we first present an approach to calculate directly the parameters of the jet blast wave at any instantaneous time by using the radiation spectrum at that time (Section 2). This approach applies to both conical and cylindrical jets. Then, using these parameters, we calculate the jet cross section of Sw J1644+57 at different times and study how it evolves as the jet propagates outward (Section 3). We find that the outflow gradually transits from a conical jet to a cylindrical one at later times. The possible mechanism for the collimation is further discussed (Section 3.2). Finally, we give our conclusions (Section 4).

2. MODELING THE RADIO EMISSION

In our model, the radio afterglow of Sw J1644+57 is produced by electrons accelerated by the forward shock that forms as the jet interacts with the ambient medium. The radiation can be simply described by a cloud of relativistic electrons radiating synchrotron emission in the magnetic fields, so it is completely determined by the following parameters: the total number of radiating electrons \( N_e \), the bulk motion Lorentz factor \( \Gamma \), the magnetic field \( B \), the thermal Lorentz factor of electrons \( \gamma_e \), and the power-law distribution index \( p \). We made the same assumption that \( \theta_j \lesssim 1/\gamma_j \) in the conical jet case, so the parameter \( \theta_j \) is not involved. The bulk Lorentz factor is related to the jet energy \( E_j \) through

\[
\Gamma = \left( \frac{E_j}{m_p n_e c^2} \right)^{1/2}.
\] \( \text{(1)} \)

Assuming that the magnetic field energy density is a factor \( \varepsilon_B \) of the shock internal energy, the magnetic field is related to the

\textsuperscript{3} The possibility of cylindrical jets has also been discussed for GRBs (Cheng et al. 2001; Wang et al. 2005).
number density of the ambient medium $n$ through

$$B = \Gamma c (32\pi nm_p e_B)^{1/2}. \quad (2)$$

The minimum energy of the accelerated power-law electrons is given by

$$\gamma_m = \varepsilon_e \frac{m_p}{m_e} (p - 2) \Gamma, \quad (3)$$

where $\varepsilon_e$ is the equipartition factor of the electron energy density.

The radio synchrotron emission produced by the power-law electrons can be described by three characteristic quantities, namely the typical frequency $\nu_m$, the self-absorption frequency $\nu_a$, and the peak flux $F_{\nu_m}$ (Sari et al. 1998). The two break frequencies are respectively given by

$$\nu_a = \frac{\Gamma \nu_m^2 e B}{2 \pi m_e c} \quad (4)$$

and

$$\nu_a = \nu_m \left( C_0 (p - 1) \frac{e n R}{B \nu_m^3} \right)^{3/5}, \quad (5)$$

where $C_0 \approx 10.4((p + 2)/(p + 2/3))$ (Wu et al. 2005). The emission radius $R$ is given by

$$R = \frac{2 \Gamma^2 c t}{1 + z}, \quad (6)$$

where $t$ is the observer time.

In a relativistic cylindrical jet, the radiation emitted by electrons is distributed over a solid angle of $2\pi / \Gamma^2$. The peak flux can be obtained by calculating the total emission of the radiating electrons $N_e P_{\nu,\text{max}}$, where $P_{\nu,\text{max}}$ is the peak spectral power (Sari et al. 1998), so that the observed peak flux density is

$$F_{\nu_m} = \frac{N_e P_{\nu,\text{max}} (1 + z)}{2 \pi D_L^2 / \Gamma^2}. \quad (7)$$

On the other hand, for a conical jet with $\theta_j \lesssim 1 / \Gamma$, the observed peak flux density can be written as

$$F_{\nu_m} = \frac{N_{e,\text{iso}} P_{\nu,\text{max}} (1 + z) \Gamma^2 \theta_j^2}{4 \pi D_L^2} \frac{2}{2}, \quad (8)$$

where $N_{e,\text{iso}}$ is the equivalent isotropic electron number which is related to the total number of electrons $N_e$ by

$$N_e \approx N_{e,\text{iso}} \frac{\theta_j^2}{4}. \quad (9)$$

Substituting $N_{e,\text{iso}}$ from Equation (9) into Equation (8), we find that the expressions for the peak flux are the same for both cylindrical and conical jet models. Thus, Equations (4)–(7) apply to both cylindrical and conical jets.

Equations (4), (5), and (7) can be rewritten as explicit expressions of five independent parameters $\varepsilon_B$, $\varepsilon_e$, $N_e$, $n$, and $E_j$;

$$F_{\nu_m} = C_F \varepsilon_B \frac{1}{n^2} E_j^4 N_e^{-1}, \quad (10)$$

$$\nu_a = C_a \varepsilon_e^{-1} \frac{1}{n^2} \theta_j^2 E_j^4 N_e^{-1}, \quad (11)$$

$$\nu_m = C_m \varepsilon_e \frac{1}{n^2} \theta_j^2 E_j^4 N_e^{-2}, \quad (12)$$

| $r$ (days) | $\nu_a$ (GHz) | $\nu_m$ (GHz) | $F_{\nu m}$ (mJy) | $F_{\nu m}$ (mJy) |
|------------|---------------|---------------|------------------|------------------|
| 5          | 40            | 386           | 28.6             | ...              |
| 23         | 11.6          | 50.9          | 15.3             | ...              |
| 36         | 8.12          | ...           | 10.56            | ...              |
| 51         | 9.34          | ...           | 12.93            | ...              |
| 68         | 8.87          | ...           | 17.08            | ...              |
| 95         | 8.15          | 23.8          | 31.3             | ...              |
| 126.5      | 7.42          | 23.6          | 30.3             | ...              |
| 161        | 6.04          | 18.2          | 28.2             | ...              |
| 197        | 5.38          | 15.3          | 26.5             | ...              |
| 216        | 5.89          | 17.9          | 26.2             | ...              |

Notes. Data over 5–23 days are taken from Metzger et al. (2012). The rest are obtained from the data of Berger et al. (2012) using the broken power-law spectral fit.

where $C_F$, $C_a$, and $C_m$ are three constant coefficients. After setting typical values for $\varepsilon_B$ and $\varepsilon_e$ (for instance, $\varepsilon_B = 0.1$ and $\varepsilon_e = 0.1$; Panaitescu & Kumar 2000), we can solve for the other three quantities $N_e$, $n$, and $E_j$ using the radio spectral data at different times.

Once we know the evolution of $N_e$, $n$, and $E_j$ with the observer time $t$, we can obtain $\Gamma(t)$, $R(t)$, and $(n/R)$ with the assistance of Equations (1) and (6).

3. Parameter Evolution of Sw J1644+57

The jet energy of Sw J164+57 evolves as $E_j \propto t^{0.6}$ over 5–23 days (Figure 2(a)), $E_j \propto t^1$ at later times, and after 126 days $E_j \propto t^{0.6}$ again. This indicates that Sw J164+57 has a continuous energy injection lasting much longer than previously thought. The Swift X-ray Telescope data for Sw J164+57 obey the power-law decay $L_X \propto t^{-5/3}$. Such a slow energy injection is insufficient to account for the required energy increase, so an extra or new energy supply mechanism.
is required. In Figure 2(b), we can see that the ambient density profile varies as $n \propto R^{-(1.3-1.5)}$, which is consistent with the prediction of Bondi accretion as suggested by Berger et al. (2012). The radius of the jet displayed in Figure 2(c) evolves as $R \propto t^{1.1}$ over 23–168 days and $R \propto t^{0.7}$ over 5–23 days. Since $R \propto \Gamma^2 t$, this relation indicates that the Lorentz factor of the ejecta varies as $\Gamma \propto t^{-0.15}$ over 5–23 days and remains almost constant ($\Gamma \propto t^{0.05}$) over 23–168 days. This behavior is clearly seen in Figure 2(d). This is the reason why we assume $\Gamma \simeq 3$ over 36–68 days in the calculation.

3.2. Jet Cross Section Evolution

The above equations apply to both conical and cylindrical jets. However, the structure would be known if we know how the cross section of the jet evolves as the radius $R$ increases. The size of the cross section can be derived from the evolution of $N_e$, $n$, and $R$. Since the total number of electrons swept up by the jet is related to the cross section radius through

$$N_e(R) = \int \pi r_j^2(R) n(R) dR,$$  

we can derive the cross section radius as

$$r_j(R) = \sqrt{\frac{1}{\pi n(R)} \frac{dN_e}{dR}}.$$  

To obtain $dN_e/dR$, we first find an empirical function to fit the relation between $N_e$ and $R$, and then calculate the differential

Figure 1. Best fit to the radio data of Sw J1644+57 using the synchrotron broken power-law spectra. Observation data are taken from Berger et al. (2012).
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Figure 2. Time evolution of the parameters \( E_j \), \( n \), \( R \), and \( \Gamma \), corresponding to panels (a)–(d). The equipartition factors of electron energy density and magnetic density are \( \varepsilon_e = 0.1 \) and \( \varepsilon_B = 0.1 \), respectively. The power-law index is \( p = 2.4 \). Due to the incompleteness of radio data over 36–68 days, we plot the parameters obtained during this period with different symbols. Stars represent data calculated using \( \nu_a \) and \( F_{\nu_a} \) only. Diamonds represent values of the number density \( n \) derived using the assumption \( \Gamma = 3.16 \).

Figure 3. Evolution of jet cross section radius \( r_j \). The dotted line exhibits the expected evolution of \( r_j \) for the conical jet model. The solid line shows the evolution of \( r_j \) derived from the radio data.

The transition may be due to the collimation of the jet by the surrounding cocoon which forms while the jet is propagating in the ambient medium (Bromberg et al. 2011). Such a mechanism has been discussed for long-lived AGN jets (Begelman & Cioffi 1989) as well as for microquasar jets and GRB jets (Bromberg et al. 2011). In this mechanism, matter in the jet head is heated and flows sideways due to its pressure being higher than that of the ambient medium, which leads to the formation of a pressured cocoon around the jet. If the cocoon pressure is sufficiently high, it collimates the jet and reduces its opening angle. Thus, a jet can be conical initially and transit to a cylindrical jet at later times. Bromberg et al. (2011) find the condition under which the jet will be collimated:

\[
\tilde{L} \simeq \frac{L_j}{\Sigma j \rho_a c^3} \lesssim \theta_0^{-4/3},
\]

where \( \tilde{L} \) is a dimensionless parameter that defines the ratio between the energy density of the jet and the rest-mass energy density of the surrounding medium at the location of the head, \( L_j \) is the jet luminosity, \( \Sigma_j \) is the jet cross section, \( \rho_a \) is the density of the ambient medium, and \( \theta_0 \) is the initial opening angle of the jet. This condition gives the critical transition radius as

\[
R_c \gtrsim \sqrt{\frac{L_j}{\pi \rho_a \theta_0^{2/3} c^3}},
\]

above which the jet becomes collimated and transits to a cylindrical jet.

For the case of Sw J1644+57, we can obtain the critical transition radius by taking \( L_j = dE_j/dt \), \( \rho_a = n m_p \), and
Dotted line denotes the critical radius of jet collimation for the parameters of Sw J1644+57, obtained with the condition found by Bromberg et al (2011). The solid line shows the evolution of the jet radius $R$ inferred from the observed radio data.

assuming a typical initial opening angle of $\theta_0 = 10^\circ$. Figure 4 shows the critical radius $R_c$ as a function of time (the dotted line). It clearly shows that the critical radius approaches the jet radius at late times, which means that the jet tends to be collimated at later times. The transition radius is $\sim (5–8) \times 10^{18}$ cm, which agrees roughly (within a factor of a few) with the result above obtained by modeling the radio spectral data (Figure 3). The fact that the jet in a tidal disruption event transits from a conical to a cylindrical structure in a way similar to long-lived AGN jets provides independent support that Sw J1644+57 may result from the onset of an AGN.

4. CONCLUSIONS

The structure of the jets in tidally disrupted flares such as Sw J1644+57, whether it is conical as usually assumed in GRB jets or cylindrical as seen in some extragalactic radio jets, is largely unknown. We propose that the long-term radio data can be used to probe the jet structure. By fitting the observed radio data of Sw J1644+57, we find that the jet structure of Sw J1644+57 undergoes a transition from a conical jet to a cylindrical one at tens of days after the initial flare. It is natural to expect that the jets are initially conical and later become cylindrical due to collimation by the surrounding cocoon. Observations of extragalactic radio AGN jets show that the jets are indeed cylindrical on large scales. The similar processes occurring in AGNs and Sw J1644+57 may possibly indicate that Sw J1644+57 also arises from an accretion process in an SMBH, likely fed by the tidally captured stellar material.

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