Shiho Kobayashi: Brief discussion on Optical Flash and Radio Flare

1. Reverse Shock Synchrotron Emission

Radio flares (revese shock emission at $\sim$ 1 day) can be well modeled especially when optical flash (prompt optical emission from reverse shock) is detected at earlier time (Sari & Piran 1999; Kobayashi & Sari 2000). Optical flash is expected to peak at the deceleration time of a fireball. Since early peaks are observationally harder to catch, we assume a Newtonian reverse shock case (i.e. $t_d > T_{90}$; Kobayashi 2000) in the following discussion. Relativistic reverse shocks ($t_d \sim T_{90}$) can be discussed in a very similar way. Even if optical flash is not clearly detected, we can still use optical observations for a better radio flare modeling (Melandri et al. 2010).

Let us assume that optical flash peaks at t_d and the temporal peak flux is F_p. If the peak flux is large, it would be reasonable to assume that the typical frequency of the reverse shock at t_d is close to the optical band: $\nu_{m,r}(t_d) \sim \nu_{opt}$ and the spectral peak $F_{\nu,max,r} \sim F_p$[1]. After the deceleration time t_d, the typical frequency and the spectral peak power decay as $\nu_{m,r} \sim t^{-3/2}$ and $F_{\nu,max,r} \sim t^{-1}$. The radio flux initially decays as $F_{radio} = (\nu_{radio}/\nu_{m,r})^{1/3} F_{\nu,max,r} \sim t^{-1/2}$ and then $(\nu_{radio}/\nu_{m,r})^{-(p-1)/2} F_{\nu,max,r} \sim t^{-(3p+1)/4}$ after $\nu_{m,r}$ crosses the radio band. This crossing happens at $t \sim t_p(\nu_{opt}/\nu_{radio})^{2/3}$. Since no electrons are accelerated to high energies after the reverse shock crosses the fireball ejecta, basically there is no emission above the cooling frequency. Once the break frequency $\sim t^{-3/2}$ crosses the radio band, reverse shock emission disappears (Kobayashi 2000).

2. Synchrotron Self-Absorption

At low frequencies and early times, self absorption takes an important role and significantly reduces the flux. A simple estimate of the maximal flux is the emission from the black body with the reverse shock temperature.

$$F_{\nu,BB} = \pi \left(\frac{R_\perp}{D}\right)^2 \left(\frac{2\nu^2}{c^2}\right) k_B T \Gamma \tag{1}$$

where $R_\perp \sim 2\Gamma ct$ is the observed size of the fireball. The temperature is given by the random energy of the typical electron $m_e c^2 \gamma_m$ for a frequency below the typical frequency $\nu_{m,r}$. If the

[1]For a better modeling, it is possible to introduce a parameter to define the ratio $\nu_{m,r}/\nu_{opt}$ at t_d. The raising/decay indexes of an optical light curve would give constraints on the parameter.

observed radio frequency is above it, the electron radiating into the observed frequency has energy higher by a factor $(\nu/\nu_m)^{1/2}$ since the synchrotron emission frequency is proportional to the square of the Lorentz factor.

$$k_B T = m_e c^2 \gamma_m \max\left[1, \left(\frac{\nu}{\nu_{m,r}}\right)^{1/2}\right] \tag{2}$$

$$\gamma_m = \epsilon_e \left(\frac{p-2}{p-1}\right)\left(\frac{m_p}{m_e}\right)\left(\frac{e}{\rho}\right) \tag{3}$$

Since the Newtonian reverse shock can not heat the fireball ejecta to a relativistic temperature that the Blandford-McKee solution assumes, the BM solution is not a good approximation to described the evolution of the reverse shocked ejecta. However, we can derive scaling laws for cold ejecta, assuming that the Lorentz factor is described by a power law $\Gamma \sim R^{-g}$ and the ejecta shell expands adiabatically with a sound speed in the comoving frame. We numerically showed that the scalings with $g \sim 2$ fit the evolution: $\Gamma \sim t^{-2/5}$ and $e/\rho \sim t^{-2/7}$ (Kobayashi & Sari 2000; Kobayashi 2000). Therefore, the black body limit initially increases as $\sim t^{1/2}$ and then as $t^{5/4}$ after $\nu_{m,r}$ crosses the radio band at $t \sim t_p(\nu_{opt}/\nu_{radio})^{2/3}$.

The reverse shock emission is determined by the minimum between the synchrotron emission and the black body limit.

3. Forward Shock Emission

At late times, the typical frequency of the forward shock $\nu_{m,f} \sim t^{-3/2}$ comes down to the radio frequency, and it dominates the radio band. At the deceleration time t_d, the typical frequencies and the peak spectral power of the two shock emissions are related as (Kobayashi & Zhang 2003):

$$\nu_{m,r} \sim \Gamma_0^{-2}\, \nu_{m,f} \tag{4}$$

$$F_{\nu,max,r} \sim \Gamma_0\, F_{\nu,max,f} \tag{5}$$

where Γ_0 is the initial Lorentz factor and it can be estimated by using the observed peak time $t_p \sim R_{dec}/2\Gamma_0^2 c$ (the onset of afterglow)

$$\Gamma_0 \sim \left(\frac{3E}{32\pi n m_p c^5 t_p^3}\right)^{1/8}. \tag{6}$$

The forward shock emission initially increases as $t^{1/2}$ and then it decays as $t^{-3(p-1)/4}$ after the typical frequency crosses the radio band (Sari, Piran & Narayan 1998). This crossing happens at $t \sim t_p(\nu_{opt}/\nu_{radio})^{2/3}\Gamma_0^{4/3}$. and the peak should be about the optical peak flux F_p for the ISM case.

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