



Toward an Understanding of GRB Prompt Emission Mechanism. II. Patterns of Peak Energy Evolution and Their Connection to Spectral Lags

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Abstract

The prompt emission phase of gamma-ray bursts (GRBs) exhibits two distinct patterns of the peak energy (E_p) evolution, i.e., time-resolved spectral analyses of νF_ν spectra of broad pulses reveal (1) “hard-to-soft” and (2) “flux-tracking” patterns of E_p evolution in time, the physical origin of which still remains not well understood. We show here that these two patterns can be successfully reproduced within a simple physical model invoking synchrotron radiation in a bulk-accelerating emission region. We show further that the evolution patterns of the peak energy have, in fact, direct connections to the existence of two different (positive or negative) types of spectral lags, seen in the broad pulses. In particular, we predict that (1) only the positive type of spectral lags is possible for the hard-to-soft evolution of the peak energy, (2) both the positive and negative type of spectral lags can occur in the case of the flux-tracking pattern of the peak energy, (3) for the flux-tracking pattern the peak location of the flux light curve slightly lags behind the peak of the E_p evolution with time if the spectral lags are positive, and (4) in the case of the flux-tracking pattern double-peaked broad pulses can appear in the light curves, the shape of which is energy dependent.

Key words: gamma-ray burst: general – radiation mechanisms: non-thermal – relativistic processes

1. Introduction

Although it is agreed that the gamma-ray bursts (GRBs), the most energetic electromagnetic explosions in the universe, invoke highly relativistic jets with bulk Lorentz factors of a few hundreds, the exact physical mechanism producing such powerful gamma rays still remains debated (e.g., Kumar & Zhang 2015, for a recent review). Three outstanding questions in the field concern (1) the composition of GRB jets, (2) the involved radiative process responsible for the observed gamma rays, and (3) the distance of the emitting region from the central engine where the prompt gamma rays are released.

One class of proposed models invokes a matter-dominated outflow. Paczyński (1986) and Goodman (1986) considered an optically thick “fireball” made of electron–positron plasma and photons, which gives rise to thermal blackbody radiation from the fireball photosphere at a photospheric radius of $\sim 10^{11}$ – 10^{12} cm. Shemi & Piran (1990) examined the influence of baryonic matter on the fireball expansion. An optically thin region above the photosphere was then considered where the internal shocks resulting from the relativistic unsteady outflow emit nonthermal (synchrotron and/or inverse Compton) radiation at a typical internal-collision radius of $\sim 10^{13}$ – 10^{14} cm (Rees & Mészáros 1994; Daigne & Mochkovitch 1998). Motivated by steep low-energy spectral slopes observed in some GRBs, Mészáros & Rees (2000) examined the role of a photospheric component and Comptonization in the internal-shock model. Rees & Mészáros (2005) introduced a dissipative photospheric model where an additional energy dissipation occurs below the baryonic photosphere, suggesting that the GRB spectral peak is essentially due to the Comptonized thermal component of the photosphere.

An alternative class of proposed models invokes a Poynting-flux-dominated outflow. Thompson (1994) considered a

relativistic, strongly magnetized outflow, which generates the gamma-ray emission via inverse Compton of seed photons at a small distance. He also considered a magnetically dissipative photosphere picture where a thin layer of Wolf–Rayet material entrained by the jet head becomes transparent (Thompson 2006). Drenkhahn & Spruit (2002) showed that local magnetic energy dissipation in a Poynting-flux-powered outflow efficiently accelerates the flow to a high bulk Lorentz factor through magnetic pressure gradients both below and above the photosphere, and for typical GRB parameters the dissipation takes place mainly above the photosphere, producing non-thermal radiation up to a saturation radius of $\sim 10^{13}$ – 10^{14} cm. McKinney & Uzdensky (2012) used the magnetohydrodynamical models of ultrarelativistic jets and invoked a switch from the slow collisional to fast collisionless reconnection regime, to produce GRBs at a radius of $\sim 10^{14}$ cm.

Motivated by solving several issues of GRB prompt emission, such as the missing photosphere problem, low efficiency problem, low electron number problem, and inconsistency between prompt emission correlations with the internal-shock model, Zhang & Yan (2011) proposed the internal-collision-induced magnetic reconnection and turbulence (ICMART) model. This model envisages that the GRB central engine launches an intermittent, magnetically dominated outflow, where fast reconnection and relativistic turbulence induced by internally colliding mini-shells, similar to the internal-shock model, result in a runaway release of the stored magnetic energy at a relatively large distance of $\sim 10^{15}$ – 10^{16} cm, producing synchrotron radiation to power the observed gamma rays. This model was further developed with a different trigger mechanism due to the kink instability (Lazarian et al. 2018).

During the prompt emission phase of GRBs, the observed gamma-ray spectra typically show a smoothly connected broken power-law shape and are usually well described by a phenomenological “Band function” (Band et al. 1993). In

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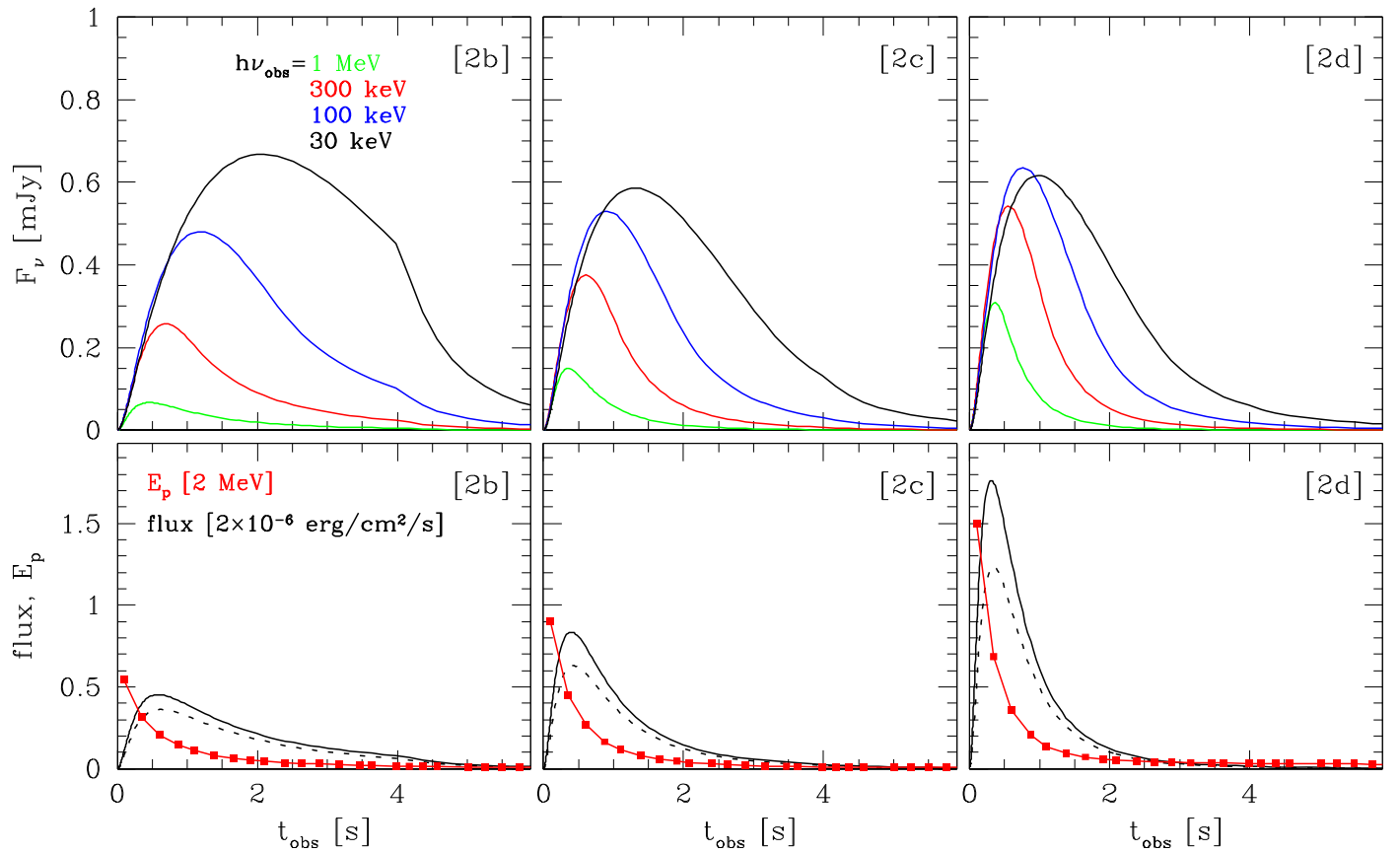


Figure 1. Observed spectral flux, total flux, and peak energy, emitted from a relativistically expanding spherical shell, for the numerical models [2b], [2c], and [2d]. Top panels show the four different light curves at 30 keV (black), 100 keV (blue), 300 keV (red), and 1 MeV (green). Bottom panels show the temporal curves for the total flux (solid black), a detector-energy-range flux from 10 keV to 10 MeV (dashed black), and the peak energy E_p of νF_ν spectra (red). Left, middle, and right columns correspond to models [2b], [2c], and [2d], respectively. We consider a globally decreasing strength of magnetic fields, $B(r) \propto r^{-b}$, in the comoving frame of the shell, and the index b is set to be 1.0, 1.25, and 1.5 for models [2b], [2c], and [2d], respectively. For a detailed physical picture and the model parameters, see the text. In particular, the characteristic Lorentz factor γ_{ch} of the electrons in the shell takes a constant value here in all three models.

recent years, extensive efforts have been made in modeling this shape of prompt emission spectra (e.g., Mészáros & Rees 2000; Pe’er et al. 2006; Beloborodov 2010; Lazzati & Begelman 2010; Daigne et al. 2011; Uhm et al. 2011; Lundman et al. 2013; Uhm & Zhang 2014), and some detailed direct comparisons to the observational data have also been made in different contexts (e.g., Burgess et al. 2014; Ahlgren et al. 2015; Zhang et al. 2016).

Needless to say, it is clear that any viable physical model for GRB prompt emission needs to interpret both the spectral and temporal behavior of the observed emission. The prompt gamma-ray light curves display diverse and complex features such that the light curves of thousands of observed GRBs are all essentially different from one another. Nevertheless, a large fraction of those complicated light curves contain an interesting, common characteristic, i.e., the existence of a single or multiple “broad pulses” (Norris et al. 1996; Hakkila & Preece 2011) that either are separated from or overlapped with one another and that are slowly varying as opposed to the rapid variabilities.

Noteworthy, two important properties of broad pulses are observationally revealed. The first of those regards two distinct patterns of the peak energy (E_p) evolution across the broad pulses (e.g., Hakkila & Preece 2011; Lu et al. 2012). The time-resolved spectral analyses of νF_ν spectra of broad pulses reveal either “hard-to-soft” (Norris et al. 1986) or “flux-tracking” (Golenetskii et al. 1983; Bhat et al. 1994; Kargatis et al. 1994)

patterns of E_p evolution in time. The second important property is the so-called “spectral lags” between the pulse light curves at different energies (e.g., Cheng et al. 1995; Norris et al. 1996; Band 1997; Norris et al. 2000; Wu & Fenimore 2000; Liang et al. 2006). Namely, a broad pulse’s light curves at different frequencies exhibit a sequential pattern in their peak time with systematic time lags or spectral lags between those light curves. These two features are usually connected (Ryde & Svensson 2000; Boronovo & Ryde 2001; Kocevski et al. 2003). In most cases, the observed spectral lags are “positive,” i.e., the higher the energy of a light curve, the earlier the peak time of the light curve. A small fraction of the observed pulses shows an opposite pattern, i.e., “negative” spectral lags (where the higher the energy of a light curve, the later the peak time of the light curve) or no spectral lags.

The physical origin of these rich observational features still remains not properly understood. As it is clear that these distinct patterns displayed by the broad pulses carry important observational clues to unveil the physical mechanism of GRB prompt emission, we started to systematically model these features in a series of papers. In the first paper (Uhm & Zhang 2016b), we studied the origin of spectral lags and showed that the traditional view invoking the high-latitude emission “curvature effect” (e.g., Dermer 2004; Shen et al. 2005) cannot account for the spectral lags. Instead, we showed that the observed spectral lags are successfully reproduced within a simple physical model that invokes

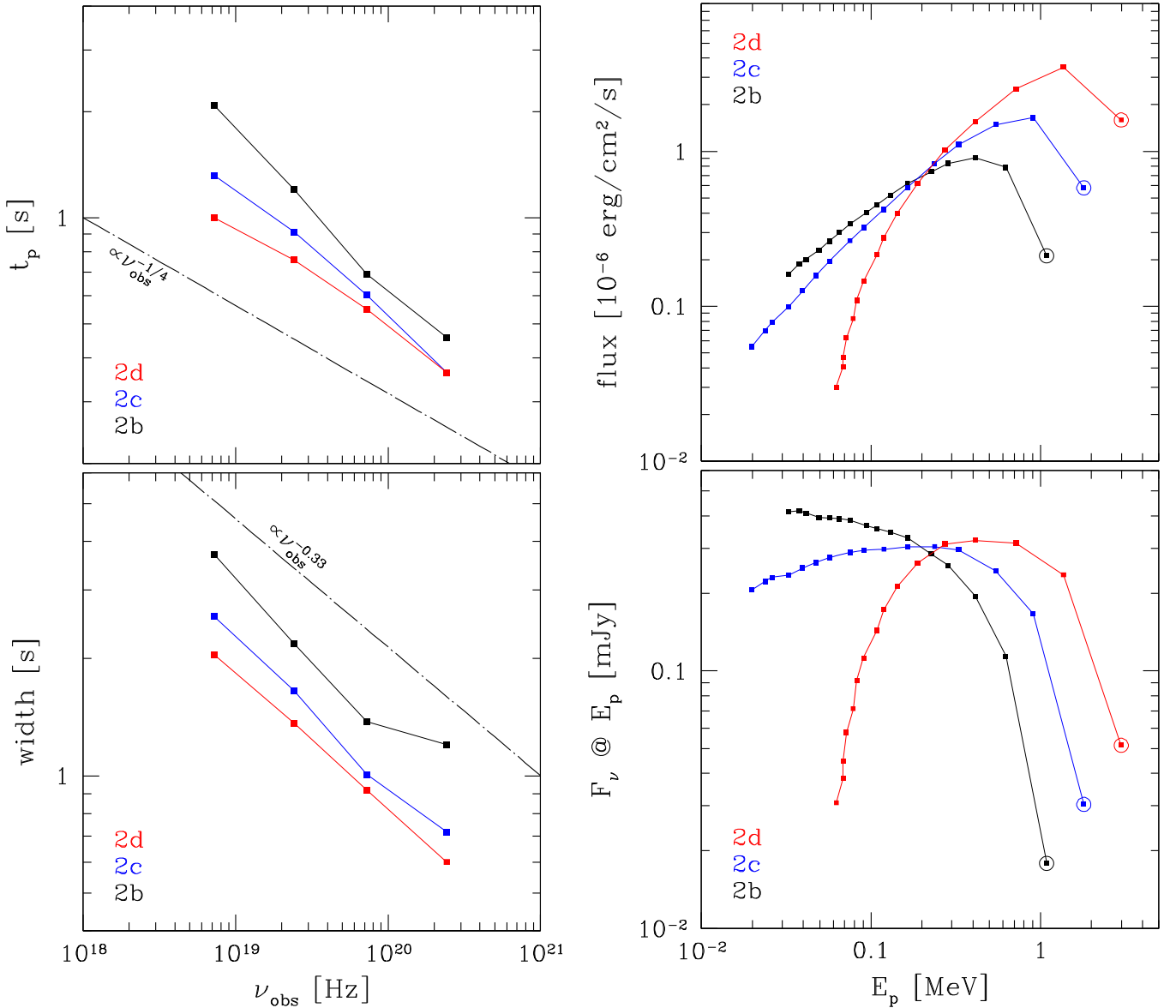


Figure 2. Properties of broad pulses and the pattern curves of the peak evolution, for the numerical models [2b], [2c], and [2d]. The left column shows the peak time t_p (top panel) and the width (bottom panel) of four broad-pulse light curves in each model, which are also compared to the observations indicated by the dot-dashed lines (Norris et al. 1996; Liang et al. 2006). Note that these two dot-dashed lines here are meant to show the slope only and thus are plotted with an arbitrary normalization. The right column shows a time-evolving pattern curve of the (E_p, flux) points (top panel) and the $(E_p, F_\nu @ E_p)$ points (bottom panel) in each model. The point enclosed by an open circle in each model marks the first in observer time among the plotted points.

synchrotron radiation emitted from a bulk-accelerating outflow at a large distance ($\sim 10^{15}$ – 10^{16} cm) from the central engine.

In this second paper, in addition to modeling the spectral lags, we also produce the two distinctive patterns of the spectral energy (E_p) evolution across the broad pulses and show that the E_p evolution pattern has, in fact, close and direct connections to the occurrence of positive or negative spectral lags, with some predicted properties that can be tested against observations in the future. We briefly summarize our physical picture in Section 2 and present the results of our numerical models in Section 3. In Section 4, we conclude the paper and provide a discussion.

2. A Simple Physical Model

In this paper, we adopt the same physical picture as in the first paper (Uhm & Zhang 2016b), in which a thin relativistic

spherical shell expands in space radially and emits photons uniformly from all locations in the shell. In the comoving frame of the shell, the emission produced at every location has an isotropic angular distribution for the emitted power, and the shape of the emission spectrum is described by a functional form (Uhm & Zhang 2015)

$$H(x) \quad \text{with} \quad x = \nu'/\nu'_{\text{ch}}. \quad (1)$$

This concept of giving a shape of the photon spectrum without specifying a specific radiative process allows the physical picture to remain general and is particularly useful in dealing with the relativistic effects between the comoving frame and the observer frame (Uhm & Zhang 2015). The function $H(x)$ here has an arbitrary shape and is a function of the frequency ν' . A characteristic frequency ν'_{ch} indicates a characteristic location of the spectrum in the frequency space. Both

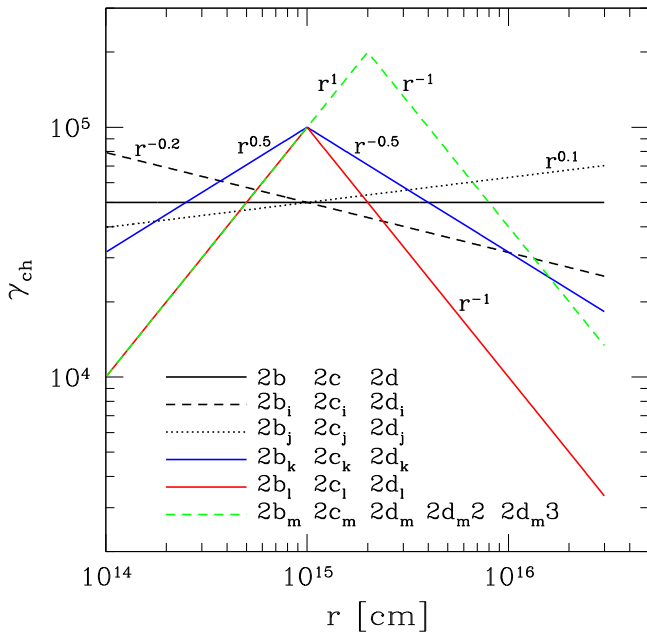


Figure 3. Profiles of characteristic Lorentz factor γ_{ch} of electrons in the shell, for the 20 numerical models presented in the paper. The first three models [2b], [2c], and [2d] have a constant value of $\gamma_{\text{ch}} = 5 \times 10^4$. Then, we explore five different variations on the γ_{ch} profile, which are indicated by five subscripts i, j, k, l , and m contained in the model names. As in models [2b], [2c], and [2d], the letters “b,” “c,” and “d” included in a model name always indicate a b index of 1.0, 1.25, and 1.5, respectively, for a globally decreasing strength of magnetic fields, $B(r) \propto r^{-b}$. The number “2” in the beginning of all model names is to indicate that the emitting region of these models undergoes bulk acceleration, $\Gamma(r) \propto r^s$, and one single index $s = 0.35$ is used in all 20 models shown here. Lastly, unless an additional number is added at the end of a model name, the low-energy photon index α_B of the Band function shape is taken to be -0.8 . The two models [2d_{m2}] and [2d_{m3}] have an α_B index of -0.7 and -0.9 , respectively.

frequencies ν' and ν'_{ch} are measured in the comoving frame. A uniform radiation power from all locations in the shell is given by a uniform distribution of radiating electrons that are placed in the shell. We assume that the total number of radiating electrons N in the shell increases at an injection rate $R_{\text{inj}} \equiv dN/dt'$ from an initial value of $N = 0$. The time t' here is measured in the comoving frame. Lastly, the electrons in the shell are assumed to have the same value of spectral power P'_0 (measured in the comoving frame), thus ensuring the uniformity of the shell’s radiation. We remark that the two quantities ν'_{ch} and P'_0 of characterizing the emission do not necessarily remain at a constant value as the shell propagates in space.

The GRB explosions occur at cosmological distances from Earth. In the local lab frame of a GRB, the prompt emission is produced at a certain distance from the explosion center, and thus we consider that the emission is turned on at a radius r_{on} and at a lab-frame time t_{on} . Upon the receipt of first photons from this turn-on point along the line of sight, an observer on Earth sets an observer time t_{obs} to be equal to zero. Subsequent photons emitted at a radius r ($> r_{\text{on}}$) and at a lab-frame time t ($> t_{\text{on}}$) are then detected by the observer at observer time (Uhm & Zhang 2016b)

$$t_{\text{obs}} = \left[\left(t - \frac{r}{c} \cos \theta \right) - \left(t_{\text{on}} - \frac{r_{\text{on}}}{c} \right) \right] (1 + z). \quad (2)$$

Here c is the speed of light, and z is the cosmological redshift of the GRB site. The photons are emitted from a spherical shell, and thus the angle θ here denotes the latitude of their emission location measured from the observer’s line of sight. As the shell travels radially with a profile of the Lorentz factor $\Gamma(r)$, the lab-frame time t can be calculated as $t = t_{\text{on}} + \int_{r_{\text{on}}}^r dr / (c\beta)$ starting from the turn-on point, where $c\beta$ is the speed of the shell as given by $\beta = (1 - 1/\Gamma^2)^{1/2}$.

We follow the formulation given in Uhm & Zhang (2015) and take fully into account the high-latitude emission effect of the spherical shell, by including the relativistic Doppler boosting from the shell comoving frame to the lab frame for each latitude and by considering the delayed arrival time of emitted photons for each emission latitude as given by Equation (2). For each observer time t_{obs} , we integrate over its equal-arrival-time surface and find the observed spectral flux, $F_{\nu_{\text{obs}}}^{\text{obs}}$, as a function of two variables t_{obs} and ν_{obs} . Here, ν_{obs} is the observed frequency of photons (when detected by the observer) and is given by

$$\nu_{\text{obs}} = \nu' [\Gamma(1 - \beta \cos \theta)]^{-1} (1 + z)^{-1}. \quad (3)$$

The angle θ here denotes the latitude of the emission location again.

In our first paper (Uhm & Zhang 2016b), we showed that the spectral lags and their observed properties can be successfully modeled within this simple physical picture while invoking synchrotron radiation, provided that (1) the emission spectrum $H(x)$ is curved, (2) the strength of magnetic field $B(r)$ in the emitting region globally decreases with radius as the emitting shell travels, and (3) the emitting region itself undergoes rapid bulk acceleration (i.e., an increasing profile of $\Gamma(r)$), during which the prompt gamma rays are released. The observed gamma-ray spectra are indeed curved and are usually well described by the Band function (Band et al. 1993). The second requirement is naturally expected for a jet expanding in a 3D space and was the essential physical ingredient to explain the low-energy photon index of the Band function for a majority of prompt emission spectra (Uhm & Zhang 2014). The third requirement of bulk acceleration is recently evidenced by an independent analysis as well, made on the steep decay phase of GRB X-ray flares (Jia et al. 2016; Uhm & Zhang 2016a).⁴

Hence, we follow these findings here. For the functional form $H(x)$ of giving the emission spectrum in the comoving frame, we take a Band function shape as

$$H(x) = \begin{cases} x^{\alpha_B+1} \exp(-x) & \text{if } x \leq x_c, \\ (x_c)^{x_c} \exp(-x_c) x^{\beta_B+1} & \text{if } x \geq x_c, \end{cases} \quad (4)$$

where $x_c \equiv \alpha_B - \beta_B$. Note that the indices α_B and β_B are the low- and high-energy photon index of this smoothly connected two power-law shape, respectively. Synchrotron radiation is then invoked to give the characteristic frequency ν'_{ch} and the spectral

⁴ It is suggested that the steep decay phase of GRB X-ray flares may be partially interpreted with anisotropic synchrotron radiation invoked in the comoving frame of the jet (Beloborodov et al. 2011; Geng et al. 2017), but in order to fully reproduce the data, the bulk acceleration of the jet is still required.

Table 1
Model Parameters of Our Numerical Models

Model Name ^a	Index s ^b	Index b ^c	γ_{ch} Profile ^d	Index g ^e	γ_{ch}^0 ^f	r_0 for γ_{ch} (cm) ^g	α_B ^h
2b	0.35	1.0	const	...	5×10^4	...	-0.8
2c	0.35	1.25	const	...	5×10^4	...	-0.8
2d	0.35	1.5	const	...	5×10^4	...	-0.8
2b _i	0.35	1.0	Equation (8)	-0.2	5×10^4	10^{15}	-0.8
2c _i	0.35	1.25	Equation (8)	-0.2	5×10^4	10^{15}	-0.8
2d _i	0.35	1.5	Equation (8)	-0.2	5×10^4	10^{15}	-0.8
2b _j	0.35	1.0	Equation (8)	0.1	5×10^4	10^{15}	-0.8
2c _j	0.35	1.25	Equation (8)	0.1	5×10^4	10^{15}	-0.8
2d _j	0.35	1.5	Equation (8)	0.1	5×10^4	10^{15}	-0.8
2b _k	0.35	1.0	Equation (9)	0.5	10^5	10^{15}	-0.8
2c _k	0.35	1.25	Equation (9)	0.5	10^5	10^{15}	-0.8
2d _k	0.35	1.5	Equation (9)	0.5	10^5	10^{15}	-0.8
2b _l	0.35	1.0	Equation (9)	1.0	10^5	10^{15}	-0.8
2c _l	0.35	1.25	Equation (9)	1.0	10^5	10^{15}	-0.8
2d _l	0.35	1.5	Equation (9)	1.0	10^5	10^{15}	-0.8
2b _m	0.35	1.0	Equation (9)	1.0	2×10^5	2×10^{15}	-0.8
2c _m	0.35	1.25	Equation (9)	1.0	2×10^5	2×10^{15}	-0.8
2d _m	0.35	1.5	Equation (9)	1.0	2×10^5	2×10^{15}	-0.8
2d _m 2	0.35	1.5	Equation (9)	1.0	2×10^5	2×10^{15}	-0.7
2d _m 3	0.35	1.5	Equation (9)	1.0	2×10^5	2×10^{15}	-0.9

Notes.

^a Names of the 20 numerical models presented in the paper.

^b Power-law index in the profile of the bulk Lorentz factor $\Gamma(r)$ in Equation (6).

^c Power-law index in the profile of the magnetic field strength $B(r)$ in Equation (7).

^d Profile $\gamma_{\text{ch}}(r)$ for the characteristic Lorentz factor of electrons.

^e Single or broken power-law index in the γ_{ch} profile in Equations (8) or (9).

^f Normalization value for the γ_{ch} profile in Equations (8) or (9).

^g Normalization radius for the γ_{ch} profile in Equations (8) or (9).

^h Low-energy photon index of the Band function shape $H(x)$ in Equation (4).

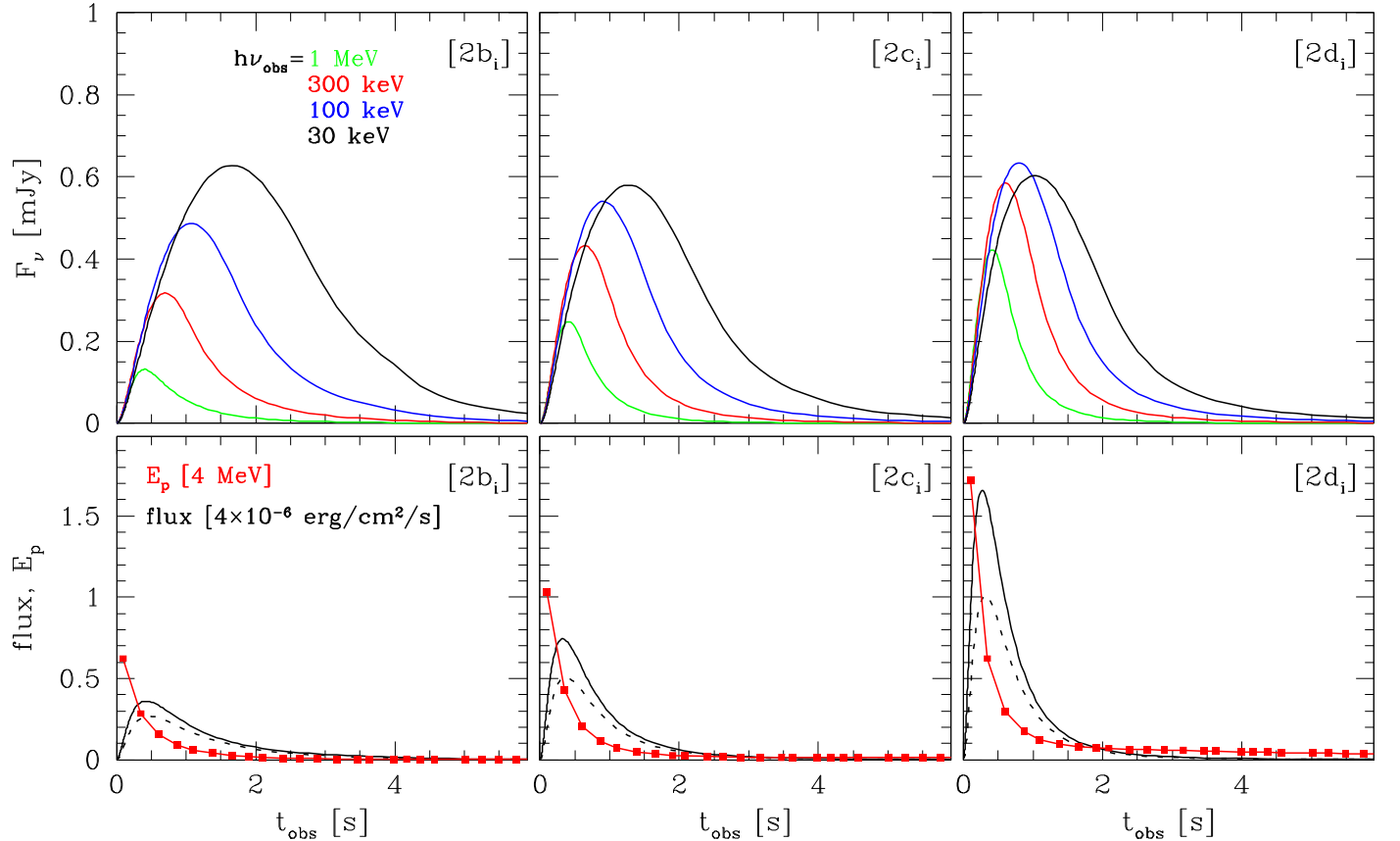


Figure 4. Same as in Figure 1, but for the i models [2b_i], [2c_i], and [2d_i].

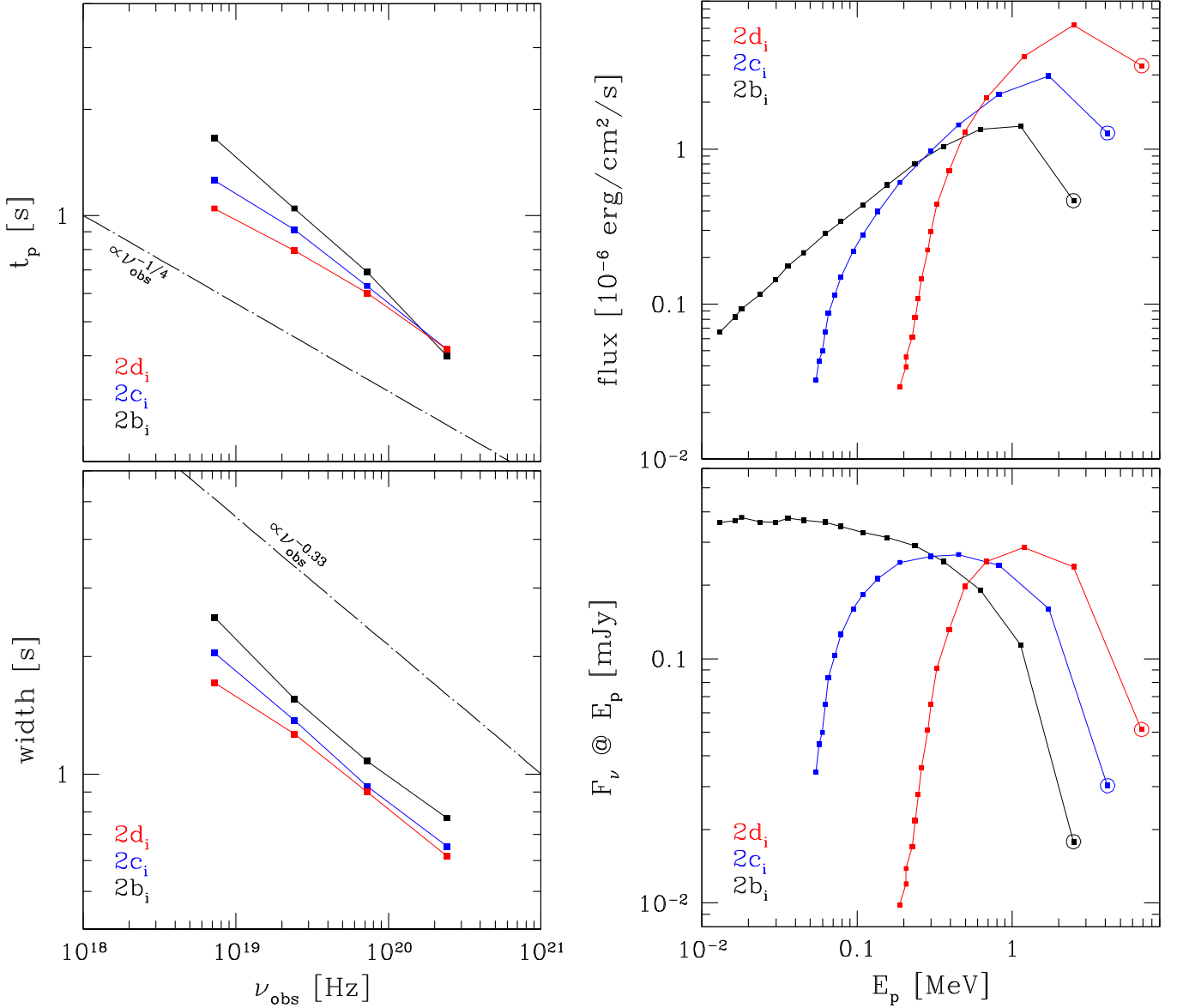


Figure 5. Same as in Figure 2, but for the *i* models [2b_{*i*}], [2c_{*i*}], and [2d_{*i*}].

power P'_0 of the electrons as follows (Rybicki & Lightman 1979):

$$\nu'_{\text{ch}} = \frac{3}{16} \frac{q_e B}{m_e c} \gamma_{\text{ch}}^2, \quad P'_0 = \frac{3\sqrt{3}}{32} \frac{m_e c^2 \sigma_T B}{q_e}, \quad (5)$$

where q_e and m_e are the electron charge and mass, respectively, and σ_T is the Thomson cross section. The strength of magnetic fields B and the characteristic Lorentz factor γ_{ch} of the electrons in the shell are measured in the comoving frame.

The redshift affects the observed spectral flux in a global manner (Uhm & Zhang 2015), and thus we take a typical value of $z = 1$ in all numerical models presented in this paper. The luminosity distance to the GRB explosion is calculated for a flat Λ CDM universe with the cosmological parameters $\Omega_m = 0.31$, $\Omega_\Lambda = 0.69$, and $H_0 = 68 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Planck Collaboration et al. 2016).

3. Results of Example Models

We begin with the three numerical models presented in Uhm & Zhang (2016b), which are named as [2b], [2c], and [2d]. These three models have the following parameters. The low- and high-energy photon index of the Band function shape $H(x)$ is $\alpha_B = -0.8$ and $\beta_B = -2.3$, respectively. The number of radiating electrons in the shell increases at a constant injection rate $R_{\text{inj}} = 10^{47} \text{ s}^{-1}$. The Lorentz factor profile $\Gamma(r)$ of showing an accelerating bulk motion of the shell takes a power-law form in radius as follows:

$$\Gamma(r) = \Gamma_0 (r/r_0)^s, \quad (6)$$

where a normalization value Γ_0 is set to be $\Gamma_0 = 250$ at radius $r_0 = 10^{15} \text{ cm}$ with an index $s = 0.35$. The index s here describes a degree of bulk acceleration. The emission of the spherical shell is turned on at a turn-on radius $r_{\text{on}} = 10^{14} \text{ cm}$, and we turn off its emission at a turn-off radius $r_{\text{off}} = 3 \times 10^{16} \text{ cm}$. For the bulk

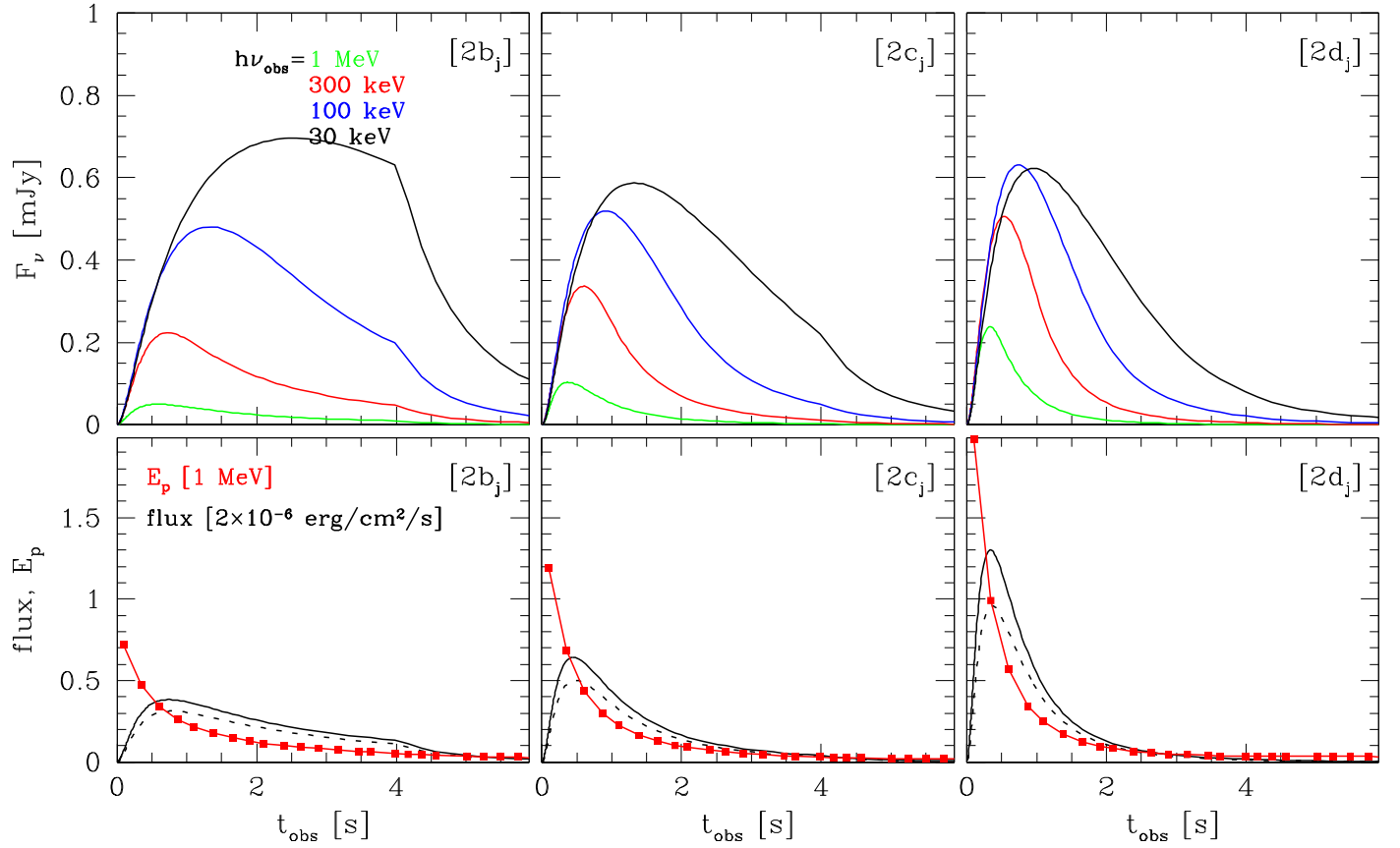


Figure 6. Same as in Figure 1, but for the j models [2b_j], [2c_j], and [2d_j].

motion given in Equation (6), this turn-off radius corresponds to a turn-off time at about $t_{\text{obs}} = 4.0$ s. The strength of magnetic fields $B(r)$ in the comoving frame has also a power-law profile in radius

$$B(r) = B_0(r/r_0)^{-b}, \quad (7)$$

with a normalization value $B_0 = 30$ G at radius $r_0 = 10^{15}$ cm. The index b is set to be 1.0, 1.25, and 1.5 for models [2b], [2c], and [2d], respectively.⁵ Lastly, the characteristic Lorentz factor γ_{ch} of the electrons in the shell takes $\gamma_{\text{ch}} = 5 \times 10^4$ for all three models [2b], [2c], and [2d]. Hence, the model parameters of these three models differ only by the b index. Note that these parameters were adjusted to assure that the observed duration of broad pulses in the prompt gamma-ray light curves is about a few seconds and the observed peak energy E_p of νF_ν spectra is of the order of 1 MeV.

Beginning with these three models, we present a total of 20 numerical models. As in models [2b], [2c], and [2d], the letters “b,” “c,” and “d” contained in a model name will always indicate a decreasing strength of magnetic fields, given in Equation (7), with b index 1.0, 1.25, and 1.5, respectively. Also, the number “2” in the beginning of any model names is to indicate that the emitting region of those models undergoes

bulk acceleration as shown in Equation (6). One single index $s = 0.35$ will be used in all 20 models.

The calculation results for the three models [2b], [2c], and [2d] are shown in Figure 1. The top panels show the four different light curves at 30 keV (black), 100 keV (blue), 300 keV (red), and 1 MeV (green). The bottom panels show the temporal curves for the peak energy E_p (red) and the observed flux (solid black). The dashed black curves in the bottom panels show the flux received in a detector energy range from 10 keV to 10 MeV. The left, middle, and right columns correspond to models [2b], [2c], and [2d], respectively, as indicated by the model name shown in the upper right corner of each panel. An abrupt decrease at about $t_{\text{obs}} = 4$ s in the low-energy light curves of model [2b] is caused by our sudden turning off of the shell’s emission at the turn-off radius r_{off} , and thus is not likely to be physical. As one can see, in all three models, the light curves exhibit a clear pattern of positive spectral lags, while the E_p temporal curve exhibits a hard-to-soft evolution. We point out here that a decreasing profile of $B(r)$ with $b \geq 1$ provides a natural ground for the hard-to-soft evolution of E_p since the frequency ν_{obs} along the observer’s line of sight roughly follows $\nu_{\text{obs}} \propto \Gamma B \propto r^{s-b}$ with $s - b < 0$.

Figure 2 shows some detailed properties of models [2b], [2c], and [2d]. In the top left panel, we show for each of the models the four different points (ν_{obs}, t_p) and connect them by a solid line where ν_{obs} and t_p are, respectively, the frequency and the peak time of each of the four different light curves in the model. Hence, a negative slope in this panel indicates the positive type of spectral lags. In the bottom left panel, we repeat the same, but instead of showing the peak time t_p , we show the width of the light curves

⁵ One can consider a simple flux conservation of magnetic fields that are frozen in a spherical jet expanding in a 3D space and get $b = 1$ for the toroidal component. Also, the strength of magnetic fields can decrease faster than the case of $b = 1$ owing to possible dissipation of magnetic energy via the reconnection of field lines.

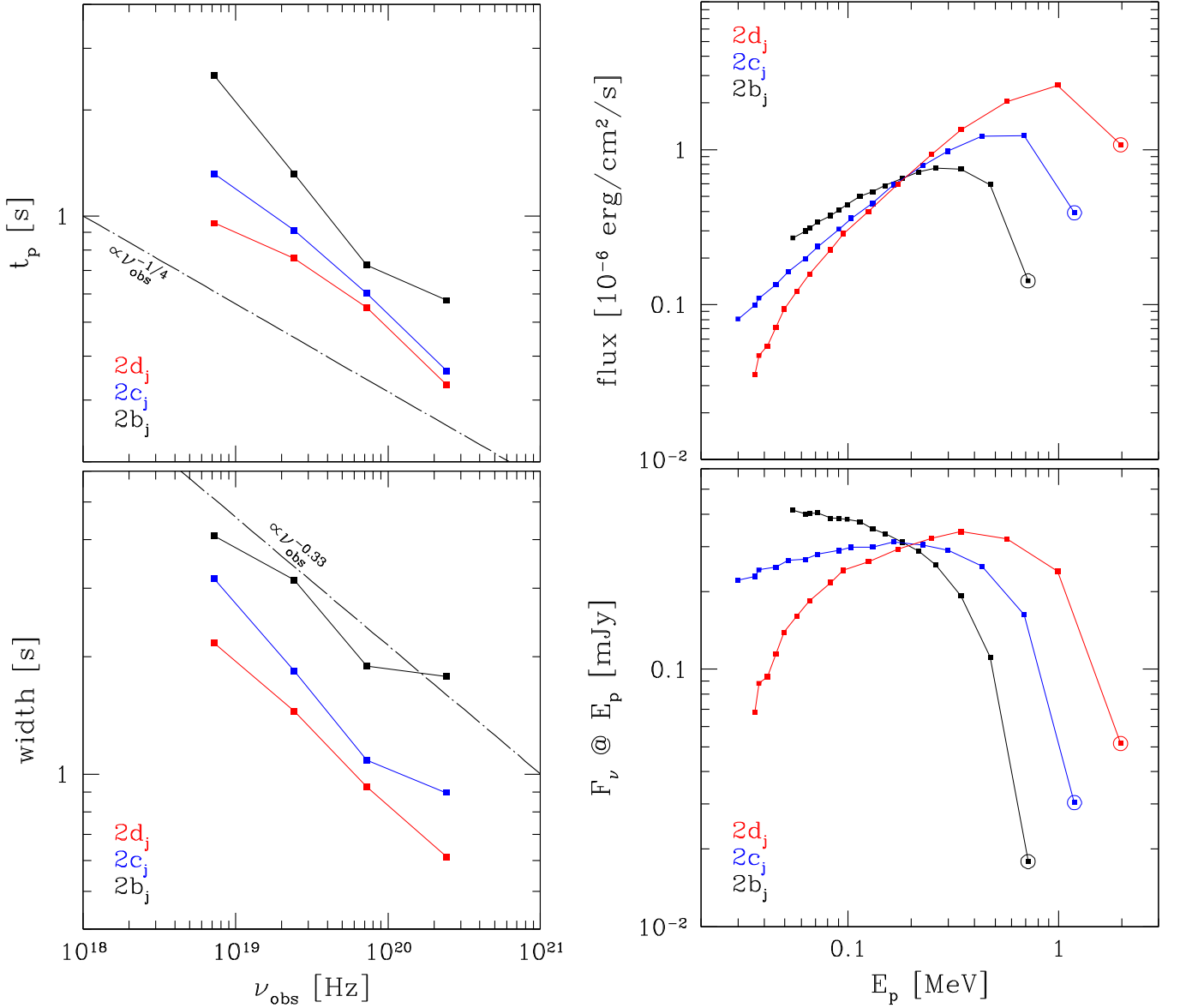


Figure 7. Same as in Figure 2, but for the j models [2b_j], [2c_j], and [2d_j].

where the width of a broad pulse is calculated as the FWHM of the pulse. The obtained curves are also compared to the dot-dashed lines showing the relations $t_p \propto \nu_{\text{obs}}^{-1/4}$ and $\text{width} \propto \nu_{\text{obs}}^{-0.33}$, which are revealed by observations (Norris et al. 1996; Liang et al. 2006). Note that the two dot-dashed lines here are meant to show the slope only and thus are plotted with an arbitrary normalization. The top right panel shows the flux against the peak energy E_p for each model, while the bottom right panel shows the peak spectral flux F_{ν, E_p} against E_p for the three models. Here, F_{ν, E_p} is the observed spectral flux measured at the location of E_p , namely, $F_\nu @ E_p$. The points shown in these two panels are with $t_{\text{obs}} < 4$ s only, so as to avoid any effects caused by the sudden turning-off of the shell’s emission. The point enclosed by an open circle in each model marks the point with the earliest observer time t_{obs} among the plotted points in the model. Therefore, a “counterclockwise” evolving pattern is evident in all three models [2b], [2c], and [2d], which show a hard-to-soft pattern of E_p

evolution with the positive type of spectral lags in Figure 1. As we will demonstrate with more examples below, this counterclockwise pattern will be a “defining signature” of the positive type of spectral lags. We also point out that the two panels in the right column are closely related to each other since the flux is very roughly given by $(E_p/h)F_{\nu, E_p}$. Here, h is the Planck constant. Therefore, the panel with (E_p, flux) points contains an underlying linear relationship by default. After this linear relationship is removed, the panel with (E_p, F_{ν, E_p}) points displays a more informative pattern of the peak evolution, which will become clear with more examples below. As we are aware that a figure like the top right panel is more often presented in the literature, in this paper we will stress the usefulness of the bottom right panel.

Now in attempts of reproducing various patterns of the peak evolution, including the E_p tracking behavior with the flux, we explore one very intuitively clear method, in which the characteristic Lorentz factor γ_{ch} of electrons in the shell is

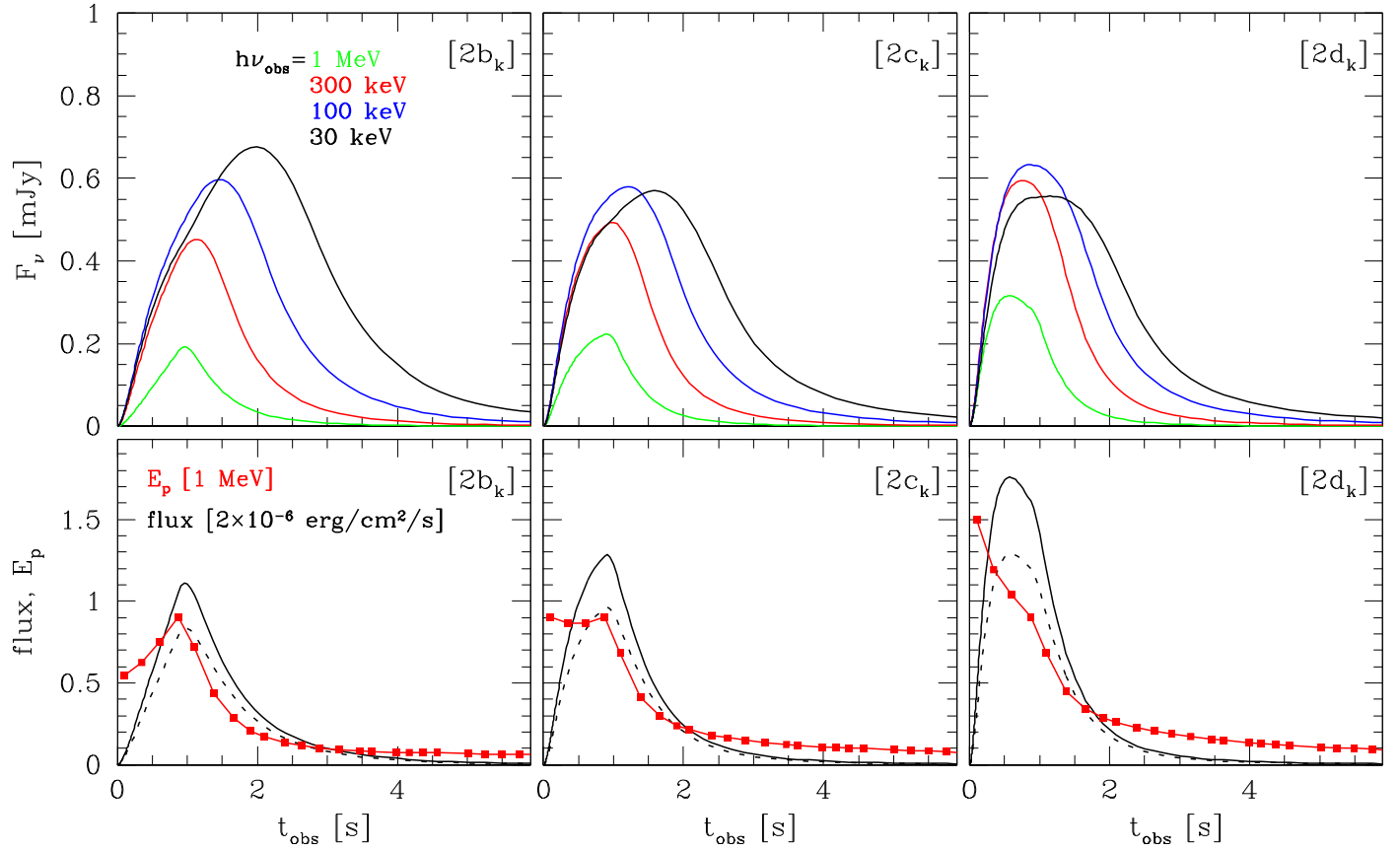


Figure 8. Same as in Figure 1, but for the k models [2b_k], [2c_k], and [2d_k].

allowed to evolve as the shell propagates in space. Initially, we consider a single power-law profile in radius

$$\gamma_{\text{ch}}(r) = \gamma_{\text{ch}}^0 (r/r_0)^g, \quad (8)$$

where a normalization value γ_{ch}^0 is set to be $\gamma_{\text{ch}}^0 = 5 \times 10^4$ at radius $r_0 = 10^{15}$ cm with an index $g = -0.2$. Besides this profile of $\gamma_{\text{ch}}(r)$, we keep all other model parameters the same as in models [2b], [2c], and [2d] and name three new models as [2b_i], [2c_i], and [2d_i], respectively. The subscript i here indicates this γ_{ch} profile, which is shown in Figure 3. Note that Figure 3 also shows the γ_{ch} profiles of other example models to be presented below; in the paper, we explore five different variations on the γ_{ch} profile, which are indicated by five subscripts i, j, k, l , and m contained in the model names. Also, see Table 1, which summarizes the model parameters of our numerical models.

Figure 4 shows the calculation results for the i models [2b_i], [2c_i], and [2d_i], in which the four different light curves (top panels) and the temporal curves for the peak energy E_p and the flux (bottom panels) are shown in the same way as in Figure 1. In this case, the frequency ν_{obs} along the observer's line of sight roughly follows $\nu_{\text{obs}} \propto \Gamma B \gamma_{\text{ch}}^2 \propto r^{s-b+2g}$, and thus the peak energy E_p decreases faster than in Figure 1. As a result, the light curves form a broad pulse earlier than in Figure 1, and the turning-off signature at about $t_{\text{obs}} = 4$ s becomes nearly invisible. It is clear again that the E_p temporal curve exhibits a hard-to-soft pattern while the light curves show the positive type of spectral lags. Figure 5 shows the properties of the i models [2b_i], [2c_i], and [2d_i] in the same way as in Figure 2. The peak time t_p and the width of broad-pulse light curves,

plotted in the left column, generally agree with the observations again. Also, a counterclockwise pattern of the peak evolution is evident in each model, as shown in the right column. We remark here that a similar set of the results is to be obtained for other values of g index as long as $g < 0$.

Figures 6 and 7 show the results for a new set of three models [2b_j], [2c_j], and [2d_j], whose model parameters are the same as in models [2b_i], [2c_i], and [2d_i], respectively, except that a small, positive value of g index with $g = 0.1$ is taken. Overall, the obtained results are reasonably good and compatible with the observations, while exhibiting a clear hard-to-soft pattern of the E_p evolution together with the positive type of spectral lags. However, since the peak energy E_p here decreases slower than in Figure 1, it becomes more difficult for the light curves to form a well-behaved broad pulse than in Figure 1.

Now, in order to see the possibility of reproducing the flux-tracking pattern of E_p evolution, we consider a broken power-law profile of $\gamma_{\text{ch}}(r)$ as follows:

$$\gamma_{\text{ch}}(r) = \gamma_{\text{ch}}^0 \times \begin{cases} (r/r_0)^g & \text{if } r \leq r_0, \\ (r/r_0)^{-g} & \text{if } r \geq r_0, \end{cases} \quad (9)$$

where a normalization value γ_{ch}^0 is set to be $\gamma_{\text{ch}}^0 = 10^5$ at radius $r_0 = 10^{15}$ cm with an index $g = 0.5$. A broken power-law function of γ_{ch} may be possible when magnetic dissipation behavior changes at a critical radius r_0 . For example, in the numerical simulations of Deng et al. (2015), it is found that one ICMART event includes four different stages. Each stage involves different magnetic configurations and may introduce slightly different behaviors of particle acceleration. Besides this

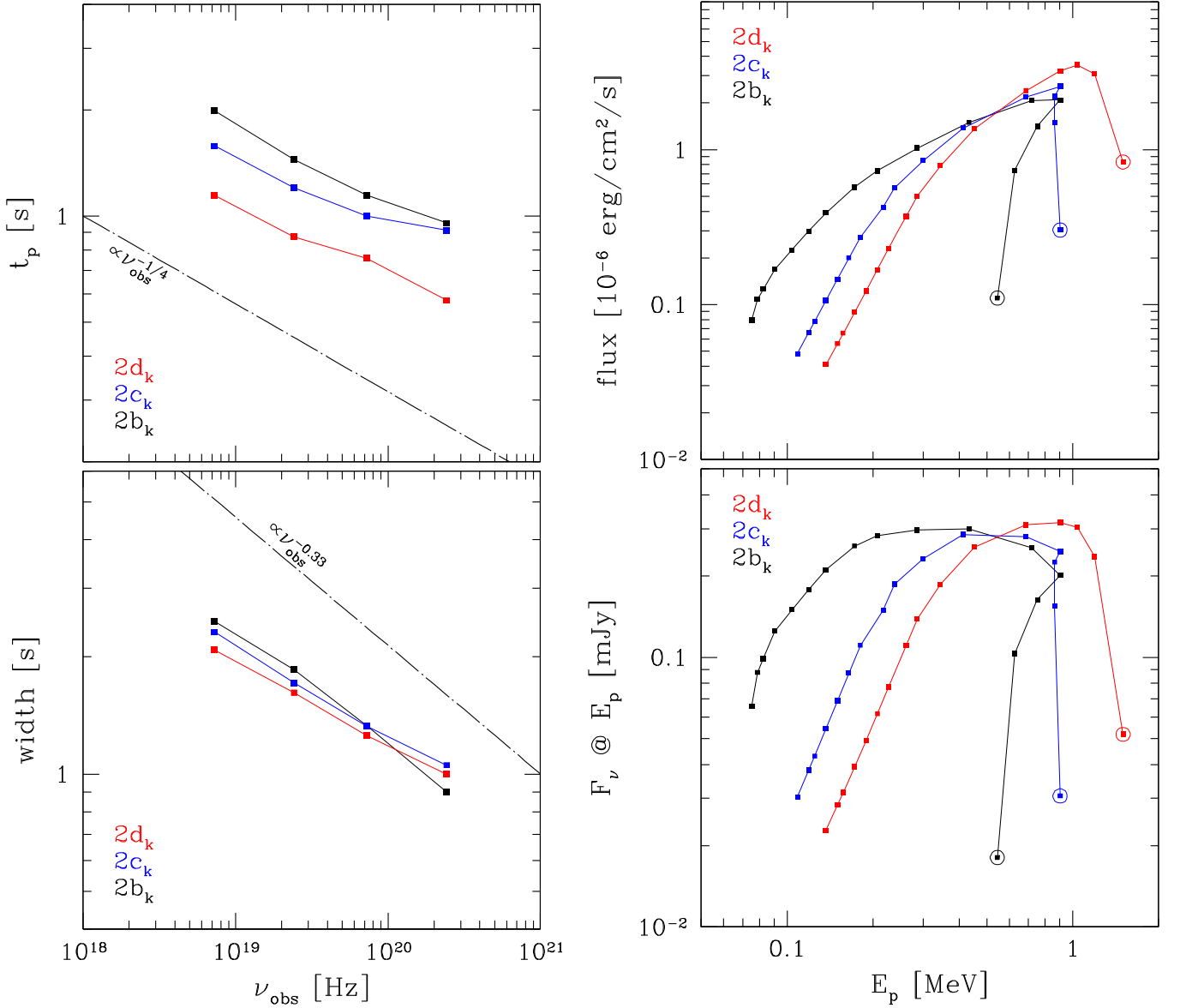


Figure 9. Same as in Figure 2, but for the k models [2b_k], [2c_k], and [2d_k].

γ_{ch} profile, we keep all others the same as in models [2b], [2c], and [2d] and have three new models [2b_k], [2c_k], and [2d_k], respectively.

Figures 8 and 9 show the results of the k models [2b_k], [2c_k], and [2d_k]. First, we note that we indeed have a flux-tracking pattern of E_p evolution here in model [2b_k]. Also, interestingly, we have three different types of the peak evolution in this case, namely, we have a hardening, flattening, and softening pattern, seen in models [2b_k], [2c_k], and [2d_k], respectively, during the rising phase of the flux curve. This can be understood by recalling that the frequency ν_{obs} along the observer's line of sight roughly follows $\nu_{\text{obs}} \propto r^{s-b+2g}$ when $r \leq r_0$, and $s - b + 2g = (0.35, 0.1, -0.15)$ for ([2b_k], [2c_k], [2d_k]), respectively. In all three models, the light curves exhibit the positive type of spectral lags, with the broad-pulse properties well compatible with the observations. The bottom right panel of Figure 9 clearly displays a counterclockwise pattern of the peak evolution in each model.

It is then clear that we can reproduce more examples showing the flux-tracking pattern by increasing the value of g

index in Equation (9). We replace the g index in Equation (9) by $g = 1.0$ and form three new models named [2b_l], [2c_l], and [2d_l], respectively. The results of the l models are shown in Figures 10 and 11. As one can see, a flux-tracking pattern of E_p evolution is firmly reproduced in all three models. The light curves in models [2b_l] and [2c_l] still show the positive type of spectral lags. However, the light curves in model [2d_l] exhibit a hint on the opposite pattern, i.e., the negative type of spectral lags. This can also be noticed, in the top left panel of Figure 11, by a positive slope for model [2d_l]. The width properties of the broad pulses are in a good agreement with the observations in all three models. We now point out that there exists an important difference between the positive and negative types of spectral lags. Since the (E_p, flux) points in the top right panel of Figure 11 are populated too densely, we ask the readers to look at the (E_p, F_ν, E_p) points in the bottom right panel of Figure 11. For models [2b_l] and [2c_l] with the positive type of spectral lags, we still have a counterclockwise pattern of the peak evolution (with a self-crossing in its pattern curve this time). However, for model [2d_l] with the negative type of spectral

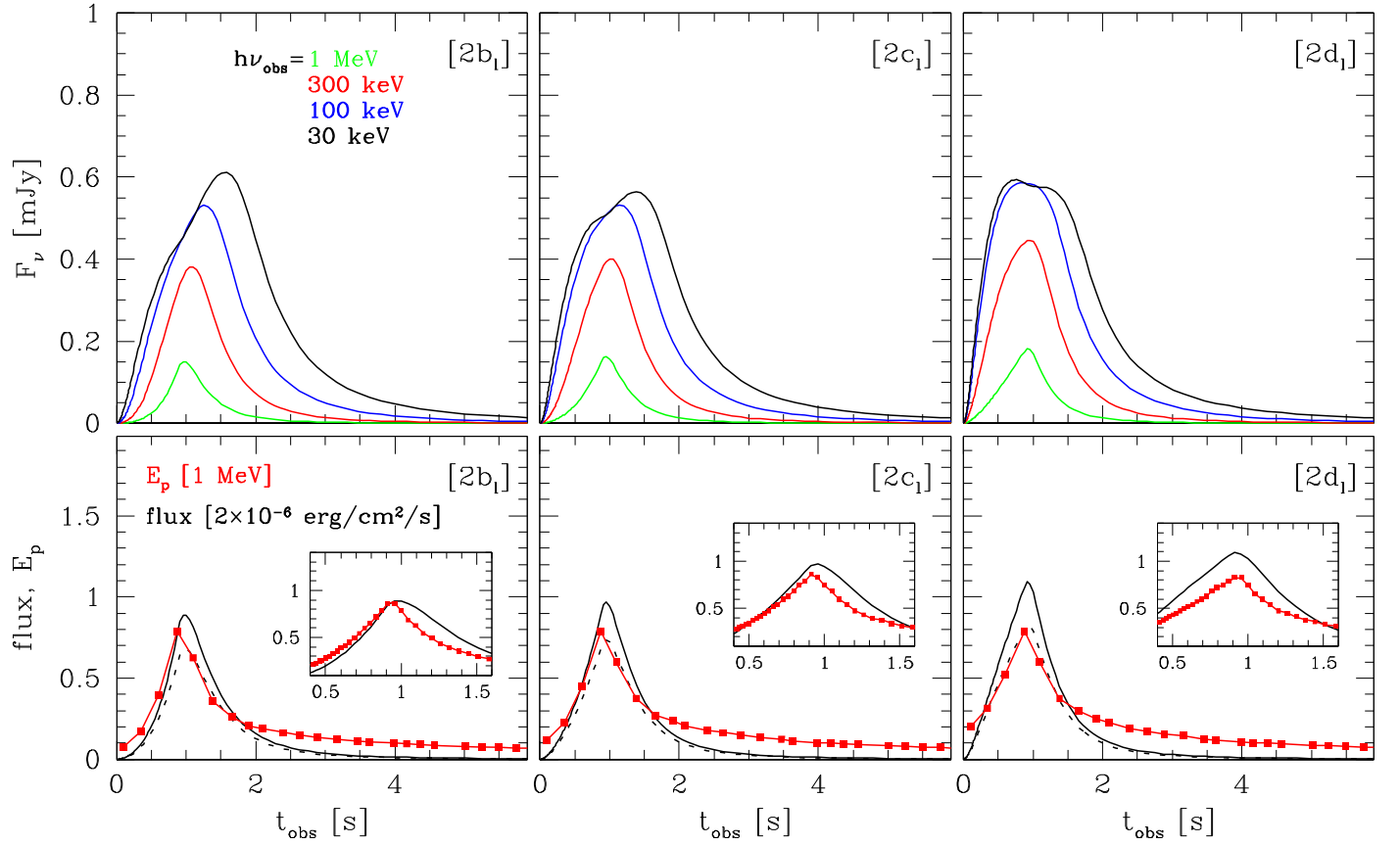


Figure 10. Same as in Figure 1, but for the l models [2b_l], [2c_l], and [2d_l]. The insets in the bottom panels show a zoom-in view around the peak area of E_p and flux curves.

lags, we have an evolving curve that starts to show a clockwise pattern rather than a counterclockwise pattern; we will present better examples below regarding this point. Furthermore, we find another difference between the positive and negative types of spectral lags by closely looking at the peak area of E_p and flux curves. The insets inserted in the bottom panels of Figure 10 show a zoom-in plot around the peak area. As one can see, for the models with the positive type of spectral lags, the peak location of the flux curve slightly lags behind the peak of the E_p curve. On the other hand, for the model with the negative type of spectral lags, there is no longer a visible lag between the two curves.

Figures 12 and 13 show the results of three new models, called [2b_m], [2c_m], and [2d_m], whose model parameters are the same as in models [2b_l], [2c_l], and [2d_l], respectively, except that Equation (9) has $\gamma_{\text{ch}}^0 = 2 \times 10^5$ and $r_0 = 2 \times 10^{15}$ cm. The γ_{ch} profile for the m models is identical to that of the l models when $r \leq 10^{15}$ cm, and then it extends further up to a higher value than in the l models (see Figure 3). In all three m models, we have a strong flux-tracking pattern of E_p evolution. While the light curves in models [2b_m] and [2c_m] show the positive type of spectral lags, the light curves in model [2d_m] exhibit, very clearly this time, the negative type of spectral lags. This can also be seen in the top left panel of Figure 13. Once again, in the right column of Figure 13, it is more useful for the readers to look at the (E_p, F_{ν, E_p}) points than the (E_p, flux) points, in order to understand and differentiate the characteristics of the models. It is clear that model [2d_m] with the negative type of spectral lags shows a clockwise pattern in its peak-evolving curve, whereas models [2b_m] and [2c_m] with the positive type

of spectral lags show a counterclockwise pattern of the peak evolution with a self-crossing in their pattern curve. Also, as shown in the insets inserted in the bottom panels of Figure 12, the models with the positive type of spectral lags have a flux curve that slightly lags behind the E_p curve in their peaking time. On the other hand, the model with the negative type of spectral lags does not show a visible lag between the two curves.

Another interesting thing that we note from the light curves of the m models in Figure 12 is that the “double-peaked” broad pulses are chromatically present in the low-energy curves. We now demonstrate that this double-peaked feature depends sensitively on the Band function α_B index that we use to describe the functional form $H(x)$ in the comoving frame. We take model [2d_m] as an example, whose α_B index is -0.8 , and form two new models [2d_m2] and [2d_m3] by replacing the α_B index by -0.7 and -0.9 , respectively. The result is shown in Figure 14. As one can see, the harder the α_B index is, the stronger the double-peaked feature is. A flux-tracking pattern of E_p evolution and the negative type of spectral lags still remain in the new models [2d_m2] and [2d_m3]. It is clear in Figure 15 that these models have the negative type of spectral lags with a clockwise pattern curve of the peak evolution.

4. Conclusions and Discussion

In this paper, we consider a simple physical picture, in which a thin relativistic spherical shell expands in space radially while emitting radiation uniformly from all locations in the shell. An isotropic angular distribution of the emitted power is also

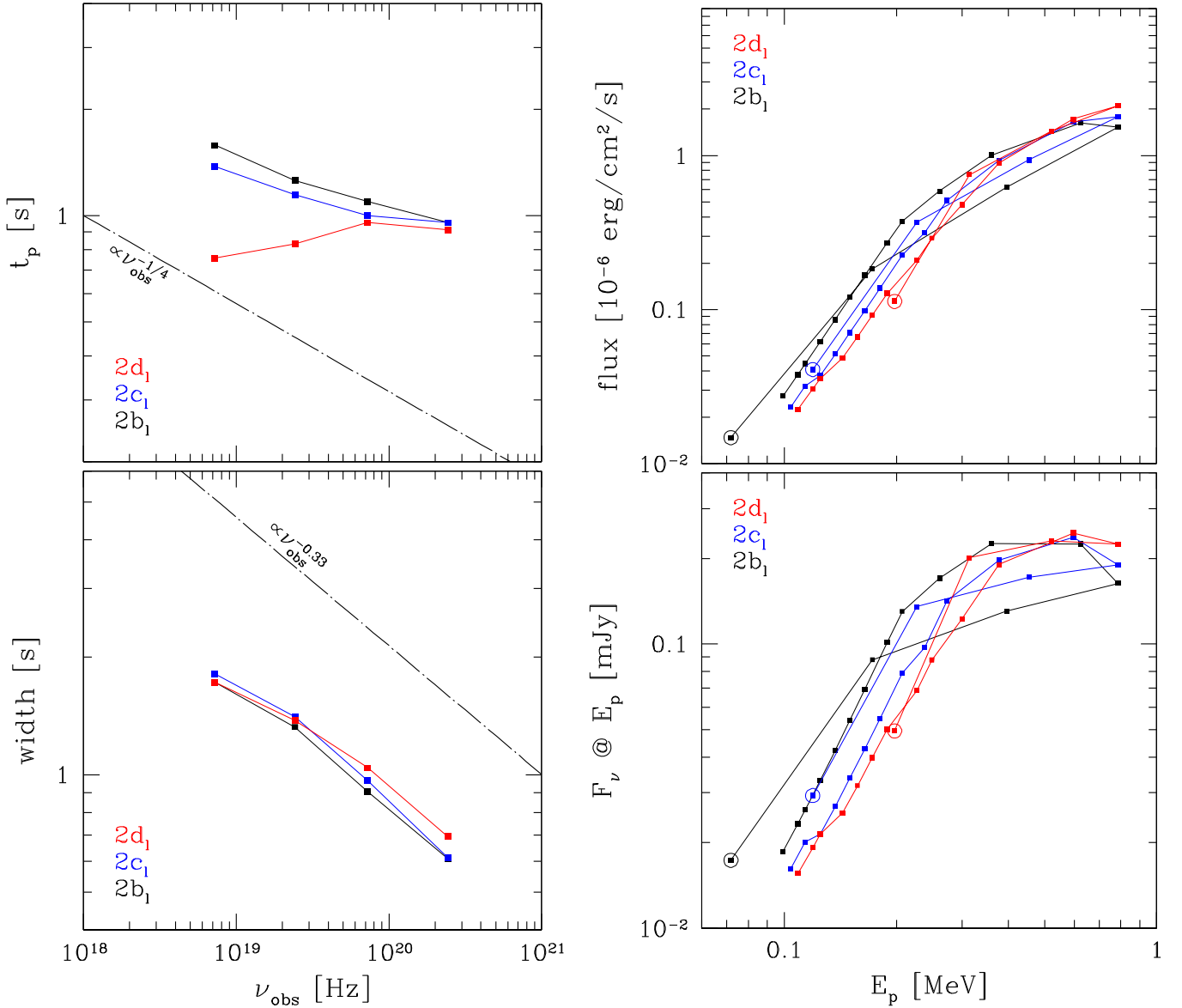


Figure 11. Same as in Figure 2, but for the l models [2b_{*l*}], [2c_{*l*}], and [2d_{*l*}].

assumed in the comoving frame of the shell. We take fully into account the high-latitude emission effect of the spherical shell, by making use of the formulation given in Uhm & Zhang (2015), and calculate the observed spectral flux as a function of the observer time t_{obs} and the observed frequency ν_{obs} . Following the findings shown in the first paper (Uhm & Zhang 2016b), we first take a Band function shape to describe the emission spectrum $H(x)$ in the comoving frame and invoke synchrotron radiation to give the characteristic frequency and the spectral power of the electrons. Then we consider a globally decreasing strength of magnetic fields, $B(r) \propto r^{-b}$, in the comoving frame of the shell, with three different b indices 1.0, 1.25, and 1.5 for the b, c, and d models, respectively. Also, we let the emitting region itself undergo bulk acceleration by using an increasing profile of the Lorentz factor, $\Gamma(r) \propto r^s$, with the index $s = 0.35$.

Since there is no concrete prediction of the electron characteristic Lorentz factor $\gamma_{\text{ch}}(r)$ in the shell from the first principles, we explore a variety of analytical $\gamma_{\text{ch}}(r)$ profiles, as

shown in Figure 3, and show that the two distinct patterns of the peak energy (E_p) evolution, i.e., the hard-to-soft and the flux-tracking behavior, are successfully and clearly reproduced in the results of our numerical models, just as revealed by the observations of broad pulses in the prompt phase of GRBs. Also, we show that the two different (i.e., the positive and the negative) types of spectral lags are successfully reproduced in the broad-pulse light curves of our numerical models. We stress that this is the first time that all these intriguing observational features, seen in the prompt gamma rays of GRBs, are successfully reproduced within a physically motivated model.⁶ We further show that the patterns of the E_p evolution have, in fact, close connections to the occurrence of the positive and the negative type of spectral lags. In particular, we find the following:

⁶ There have been previous efforts of fitting the data using the physically motivated models (e.g., using the curvature effect; Ryde & Petrosian 2002; Kocevski et al. 2003), but these models did not consider the details of particle acceleration and synchrotron radiation.

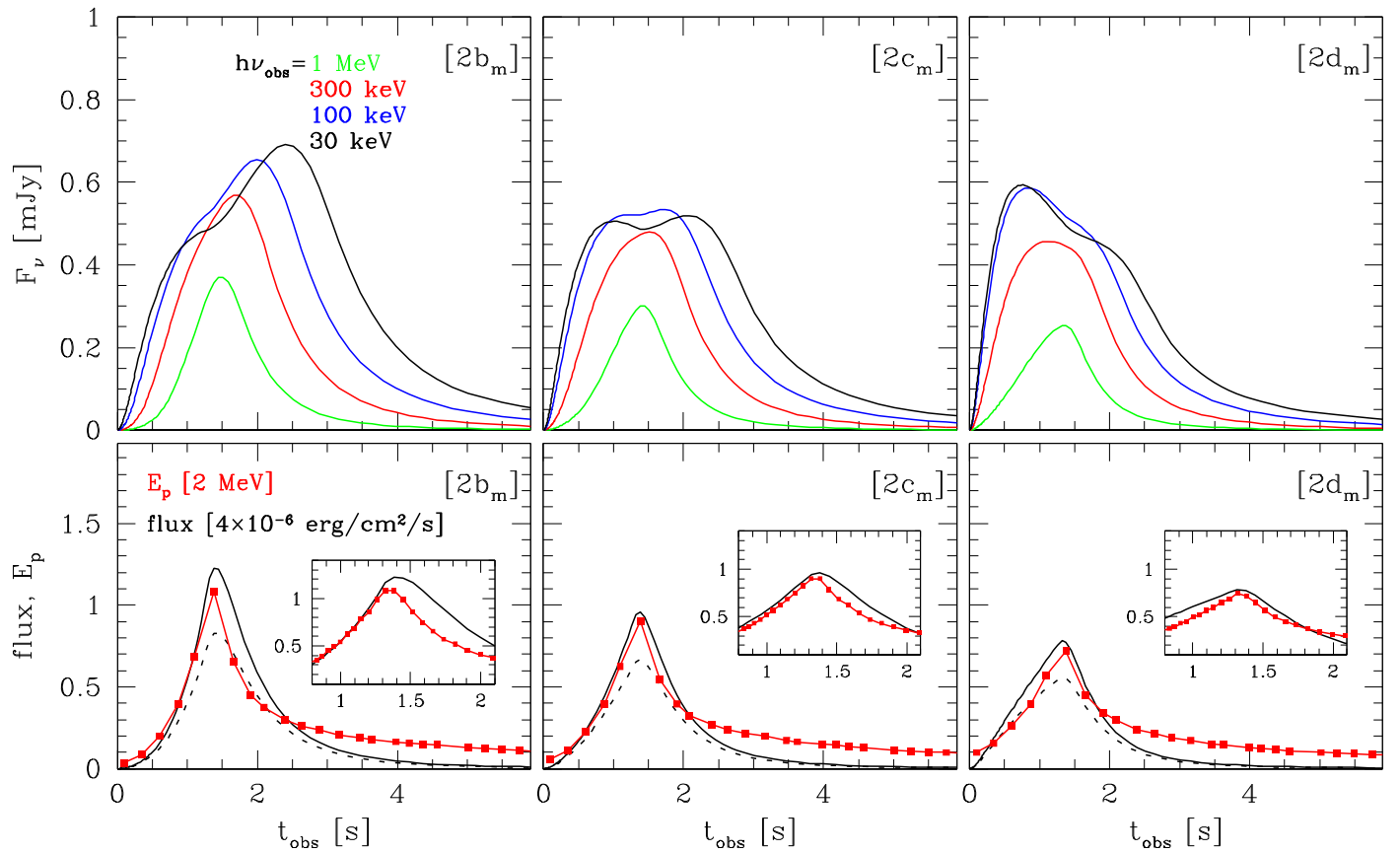


Figure 12. Same as in Figure 1, but for the m models [2b_m], [2c_m], and [2d_m]. The insets in the bottom panels show a zoom-in view around the peak area of E_p and flux curves.

1. Only the positive type of spectral lags can occur in the case of a hard-to-soft evolution of the peak energy.
2. Both the positive and the negative types of spectral lags can occur in the case of a flux-tracking pattern of the peak energy.
3. A time-evolving curve showing the (E_p, F_{ν, E_p}) points, which describes the peak evolution, exhibits a counterclockwise pattern for the positive type of spectral lags, but a clockwise pattern for the negative type of spectral lags.
4. For the flux-tracking pattern, the peak location of the flux curve slightly lags behind the peak of the E_p curve if the spectral lags are positive, whereas there is no longer a visible lag between the two curves if the spectral lags are negative;
5. For the flux-tracking pattern, double-peaked broad pulses can chromatically appear in the low-energy light curves. The harder the low-energy photon index α_B of the Band function shape, the stronger the double-peaked feature.

These points may be understood intuitively. Here we have a curved shape for the emission spectrum $H(x)$. In the case of a counterclockwise pattern, the observed spectrum sweeps through the observer energy space in a counterclockwise manner, as represented by the spectral flux F_{ν, E_p} at the peak energy E_p , and therefore the observed spectral flux gets larger at higher energy first and then progressively at lower energy

later, hence resulting in the positive type of spectral lags. On the other hand, in the case of a clockwise pattern, it happens in the opposite way, thus leading to the negative type of spectral lags.

For the hard-to-soft behavior of the peak energy, it is only possible to have a counterclockwise pattern since the peak energy should always decrease while the flux rises and then falls. Therefore, only the positive type of spectral lags is expected to be possible. For the flux-tracking behavior of the peak energy, both a counterclockwise and a clockwise pattern of the peak evolution is plausible depending on the physical parameters, and thus we have both the positive and negative types of spectral lags.

The numerical models presented in this paper have three different values for the index b and invoke many different γ_{ch} profiles, in order to explore diverse patterns of the peak evolution and to reproduce all those intriguing observational features, mentioned above. Nevertheless, it appears that the properties of broad-pulse light curves, in particular, the width relations of broad pulses, remain compatible with the observations for all the numerical models presented here. This strongly suggests that the s index (showing the bulk acceleration) is probably the “main shaper” of the pulse properties. Also, as we stressed in the first paper (Uhm & Zhang 2016b), this requirement of bulk acceleration provides “smoking-gun” evidence for a significant Poynting flux carried by relativistic jets in GRBs.

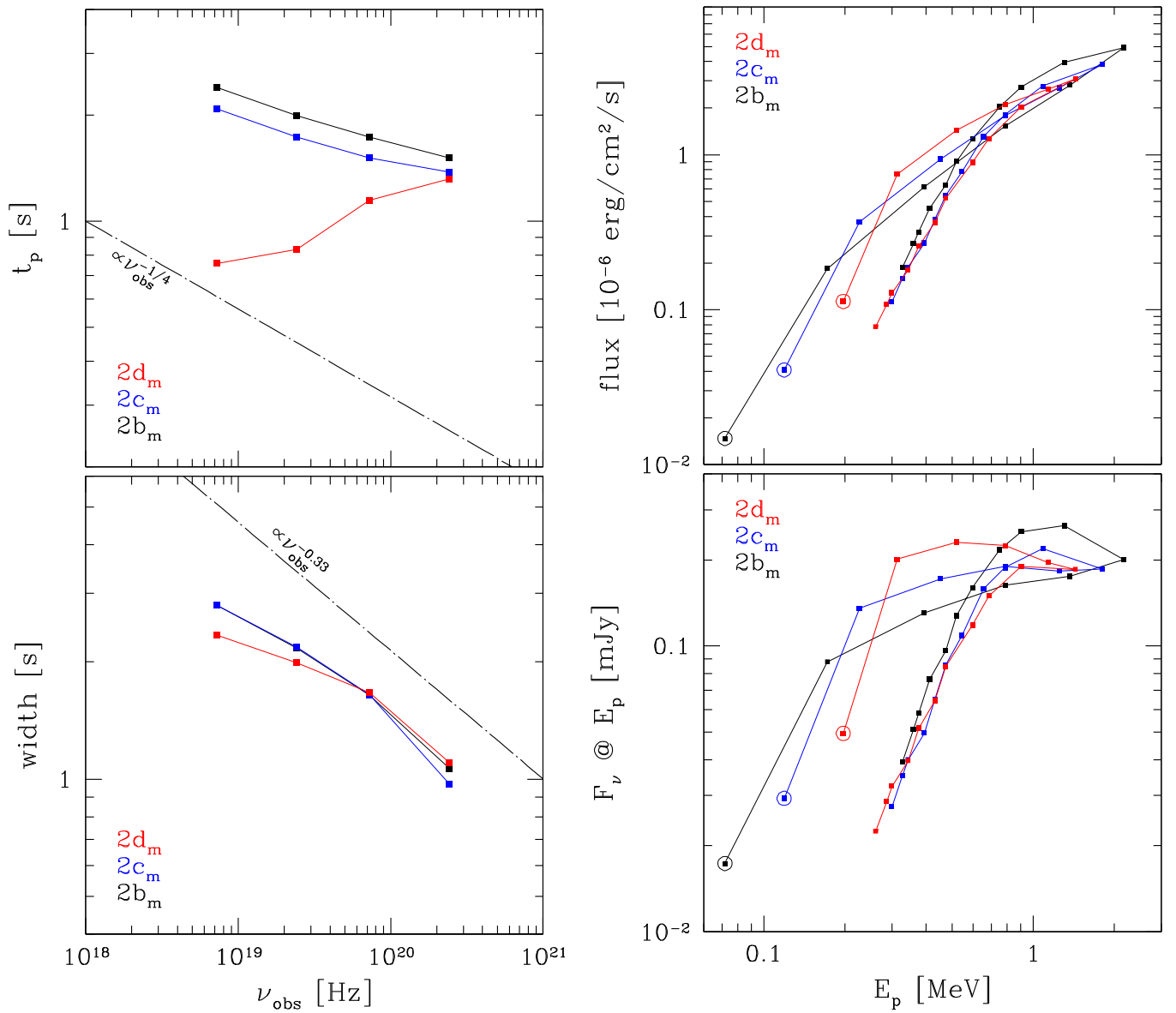


Figure 13. Same as in Figure 2, but for the m models [$2b_m$], [$2c_m$], and [$2d_m$].

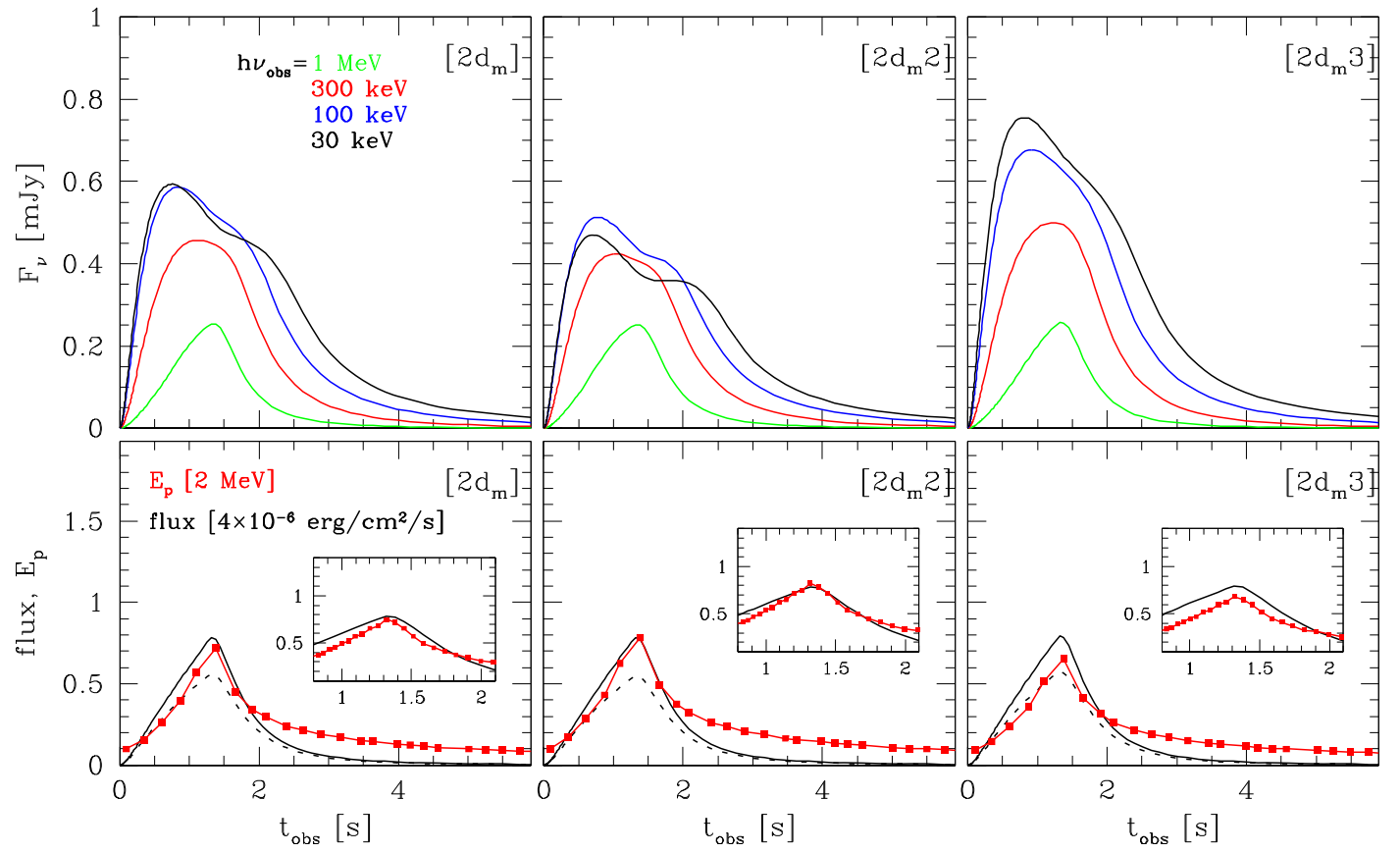


Figure 14. Same as in Figure 1, but for the m models $[2d_m]$, $[2d_m2]$, and $[2d_m3]$. These three models are identical to one another except for the Band function α_B index; see the text. The insets in the bottom panels show a zoom-in view around the peak area of E_p and flux curves.

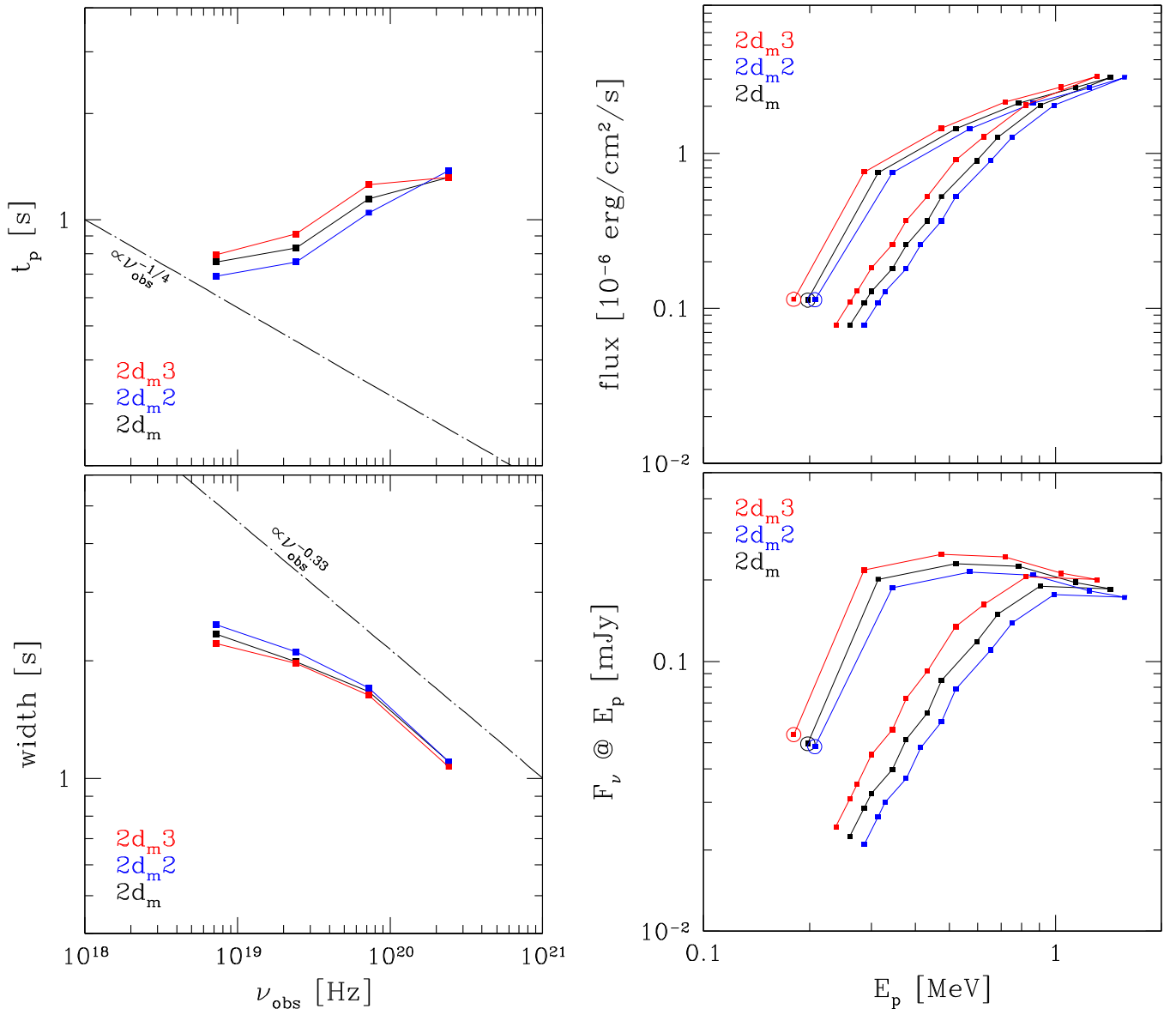


Figure 15. Same as in Figure 2, but for the m models $[2d_m]$, $[2d_{m2}]$, and $[2d_{m3}]$. These three models are identical to one another except for the Band function α_B index.

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