GRBS: STANDARD MODEL & BEYOND

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There have been great and rapid progresses in the field of $\gamma$-ray bursts since BeppoSAX and other telescopes discovered their afterglows in 1997. In this talk, the main observational facts of $\gamma$-ray bursts and their afterglows, and the standard fireball shock model are reviewed briefly. And then, various post-standard effects, deviations from the standard model, are presented.

1 Observational Features

A $\gamma$-ray burst (or shortly, GRB) was discovered by R.W. Klebesadel et al. in 1967 and published in 1973. Although more than 2000 GRBs have been discovered, they are still among the most mysterious astronomical objects even at present time.

The GRB duration ($T$) is very short, usually only a few seconds or tens of seconds, or occasionally as long as a few tens of minutes or as short as a few milli-seconds. Their time profiles are diverse, may be rather complicated. The time scales of variability ($\delta T$) may be only milli-seconds or even sub-milli-seconds. The photon energy radiated in GRB is typically in the range of tens keV to a few MeV. However, high energy tail up to GeV or even higher than 10 GeV does exist. The spectra are definitely non-thermal and can usually be fitted by power law or broken power law with $\alpha$ ~ 1.8 to 2.0. The cosmological distances of GRBs were first inferred statistically by the BATSE observation of their highly isotropic spatial distribution.

The definite results of their cosmological origin come from the observations of the red-shifts of their host galaxies after the discovery of afterglows by BeppoSAX and various Satellites and Observatories since 1997. Thus, GRBs are known to be the most energetic events ever known since the Big Bang.

Afterglows are the counterparts of GRBs at wave bands other than $\gamma$-rays. They are variable, typically decaying according to power laws: $F_\nu \propto t^{-\alpha}$ ($\nu$ = X, optical, .......) with $\alpha$ = 1.1 - 1.6 for X-ray, $\alpha$ = 1.1 - 2.1 for optical band. Their spectra appear to be also of power law or broken power law. X-ray afterglows can last days or even weeks; optical afterglows and radio afterglows months or even one year. The light curves of afterglows are much more smooth and simple than that of GRBs themselves.

2 The Standard Fireball Shock Model

First of all, the millisecond variabilities indicate that the GRBs should be compact stellar events only. In other words, the size of their initial burst region should be less than 300 km and the mass of a GRB source should be less than 100 M$_\odot$. As GRBs are at cosmological distances, their radiation (if isotropic) should be about $10^{51}$ to $10^{54}$ ergs. So large an energy contained in so small a volume, it must be a fireball. The free path of a photon in the fireball can be shown to be less than its radius by a factor of about $10^{14}$, it is highly optically thick. Such a fireball must be a black body. However, the observed radiations from GRBs are non-thermal, they must not come directly from the fireball. So large an optical depth also means that its pressure must be very high, and the fireball will expand relativistically to be a shell. If its expansion reaches ultra-relativistic speed with Lorentz factor of more than 100, the shell can then begin to be optically thin, and the non-thermal radiation of GRB can be observed.

Now, people have obtained a simple standard picture of GRBs. The inner engine at the center of the GRB source can send out several shells impulsively. As shell expansion reaches ultra-relativistic speed, the late fast shell can catch up and collide with the early slow shell and produce shocks (known as internal shocks), and all shells will finally sweep the interstellar medium and produce shocks (known as external shocks). The electrons accelerated by shocks will emit synchrotron radiations. The internal shocks appear at about $10^{13}$ cm from the center and give out GRBs, and the external shocks at about $10^{16}$ cm and give out afterglows.

3 The Post-standard Effects

The standard model described above is based on the following simple assumptions: (1) the fireball expanding relativistically and isotropically; (2) impulsive injection of energy from inner engine to the fireball(s); (3) synchrotron radiation as the main radiation mechanism; (4) uniform environment with typical particle number density of $n = 1 \text{ cm}^{-3}$. This model is rather successful in that its physical picture is clear, results obtained are simple, and observations on GRB afterglows support it at least qualitatively but generally. However, various quantitative deviations have been found. Thus, the simplifi-
cations made in the standard model should be improved. These deviations may reveal important new information. In the following, we will present some work of our group on the effects due to these deviations (the post-standard effects).

The fireball expansion is initially ultra-relativistic and highly radiative, this phase has been well described by some simple scaling laws. The key equation here is

$$\frac{d\gamma}{dm} = -\frac{\gamma^2 - 1}{M}, \tag{1}$$

$m$ denotes the rest mass of the swept-up medium, $\gamma$ the bulk Lorentz factor, and $M$ the total mass in the comoving frame including internal energy $U$. This equation was originally derived under ultra-relativistic condition. The widely accepted results derived under this equation are correct for ultra-relativistic expansion. Accidentally, these results are also suitable for the non-relativistic and radiative case. However, for the important non-relativistic and adiabatic case, they will lead to wrong result $\propto R^{-3n}$ ($v$ and $R$ is the velocity and radius of the fireball), perfectly different from the famous Sedov result of $\propto R^{-3/2n}$, as first pointed out by Huang, Dai and Lu\cite{12}. It is important to note that a fireball will usually become non-relativistic and adiabatic only several days after the burst, while the afterglows can remain observable for several months or even about one year, so any useful model should be able to account for both relativistic and non-relativistic, and both radiative and adiabatic phases. In order for solving this problem, Huang, Dai & Lu\cite{13} further pointed out that the above equation (1) should be replaced by

$$\frac{d\gamma}{dm} = -\frac{\gamma^2 - 1}{M_{ej} + \epsilon m + 2(1-\epsilon)\gamma m}, \tag{2}$$

here $M_{ej}$ is the mass ejected from GRB central engine, $\epsilon$ (assumed to be approximately a constant) is the radiated fraction of the shock generated thermal energy in the comoving frame. This equation leads to correct results for all cases including the Sedov limit for the non-relativistic and adiabatic phase.

In the early days after the discovery of afterglows, Dai and Lu\cite{14} studied the possible non-uniformity of the surrounding medium. They used the general form of $n \propto R^{-k}$ to describe the non-uniform environment number density. By fitting the X-ray afterglow of GRB970616, they found $k = 2$ which is just the form of a wind environment. This indicates that the surrounding medium of GRB970616 was just a stellar wind. After the detailed studies by Chevalier and Li\cite{21} the stellar wind model for the environment of GRBs has now become widely interested. As the properties of GRBs’ environment contain important information related with their pregeni-
tors, this stellar wind model provides strong support to the view of massive star origin of GRBs.

Another environment effect is due to the deviation from the standard number density of $n = 1 \text{ cm}^{-3}$. Some afterglows of GRBs show that their lightcurves obey a broken power law. For example, according to Fruchter et al.\cite{22}, the optical lightcurve of GRB990123 shows a break after about two days, its slope being steepened from -1.09 to -1.8. Dai and Lu\cite{13} pointed out that a shock undergoing the transition from a relativistic phase to a non-relativistic phase may show such a break in the light curve. If there are dense media and/or clouds in the way, this break may happen earlier to fit the observed steepening. Recently, Wang, Dai & Lu\cite{15} proved that the dense environment model can also explain well the radio afterglow of GRB 980519\cite{30}.

Lightcurves of some optical afterglows even show the down-up-down variation such as GRB970228 and 970508. These features can be explained by additional long-time scale energy injection from their central engines.\cite{22,23,24,25}

In some model, a millisecond pulsar with strong magnetic field can be produced at birth of a GRB. As the fireball expands, the central pulse can continuously supply energy through magnetic dipole radiation. Initially, the energy supply is rather small, the afterglow shows declining. As it becomes important, the afterglow shows rising. However, the magnetic dipole radiation should itself attenuate later. Thus, the down-up-down shape would appear naturally. Dai & Lu\cite{13} further analysed GRB980519, 990510 and 980326, with dense environment also being taken into account, and found results agreeing well with observations.

Recently, the GRB000301c afterglow shows three break appearance in the R-band light curve, and extremely steep decay slope -3.0 at late time. This unusual afterglow can be explained by assuming more complicated additional energy injections and dense medium.\cite{31}

Though synchrotron radiation is usually thought to be the main radiation mechanism, however, under some circumstances, the inverse Compton scattering may play an important role in the emission spectrum, and this may influence the temporal properties of GRB afterglows.\cite{32,33} Wang, Dai & Lu\cite{15} even consider the inverse Compton scattering of the synchrotron photons from relativistic electrons in the reverse shock. Under appropriate physical parameters of the GRBs and the interstellar medium, this mechanism can excellently account for the prompt high energy gamma-rays detected by EGRET, such as from GRB930131.

As some GRBs showed their isotropic radiation energy to be as high as $\sim M_{ej}c^2$, this has been regarded as an energy crisis. A natural way to relax this crisis is to assume that the radiation of GRB is jet-like, rather than isotropic. However, we should find out its obser-
vational evidences. Rhoads\textsuperscript{34} analysed this question, and predicted that the sideways expansion in jet-like case will produce a sharp break in the GRB afterglow light curves (see also Pugliese et al.\textsuperscript{35} Sari et al.\textsuperscript{36} and Wei & Lu\textsuperscript{37}). Kulkarni et al.\textsuperscript{38} found that a sharp break can only exist in the case of extremely small beaming angle. Recently, Huang et al.\textsuperscript{39} and Wei and Lu\textsuperscript{40} reanalysed the dynamical evolution of the jet blast wave and found that a sharp break can only exist in the case of extremely small beaming angle. Recently, Huang et al.\textsuperscript{41} made a detailed calculation and proved that the breaks in the lightcurves are mainly due to the relativistic to non-relativistic transition, not due to edge effect and lateral expansion effect of the jet, and may appear only for small electron energy fraction and small magnetic energy fraction. However, they stressed that the afterglows of jetted ejecta can be clearly characterized by rapid fading in the non-relativistic phase with index $\alpha \geq 2.1$.\textsuperscript{42}

Gou et al.\textsuperscript{43} used a set of refined dynamical equations and a realistic lateral speed of the jet, calculated the evolution of a highly collimated jet that expands in a stellar wind environment and the expected afterglow from such a jet. They found that in the wind environment, no obvious break will appear even at the time when the blast wave transits from the relativistic phase to the non-relativistic phase, and there will be no flattening tendency even up to $10^9$ s.

Acknowledgments

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