The Apparent Size of GRB Afterglows as a Test of the Fireball Model

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ABSTRACT

Taylor et al. (2004) reported recently on the first direct measurement of the apparent size of a GRB afterglow. Here we confront these observations with the predictions of the fireball model. We use a simple model to study numerically the evolution of the fireball and determine its apparent size, starting at the early spherical expansion phase through the jet break and into the Newtonian regime. We perform these calculations on the background of a uniform interstellar medium and a massive stellar wind environment. We find that the calculated apparent size at the time of the measurements taken by Taylor et al. (2004) depends only weakly on the chosen parameters (the jet opening angle, the energy, and the external density profile). Thus it is reassuring that the only possible outcome of the model, within the plausible range of parameters, agrees very well with the data. These measurements therefore present us with a strong test of possible GRB models, which the fireball model passes successfully.

1. Introduction

Quite early in the study of the “standard” afterglow fireball model, it was realized that an observation of the size and structure of the image of an afterglow would provide an almost direct test of this model (Waxman 1997, Sari 1998, Granot Piran & Sari, 1999). Waxman (1997) calculated the ring shape of the afterglow image while Sari (1998) calculated also the size of this ring, noticing that the relativistic velocity of the afterglow would result in a superluminal expansion. Until recently there were no direct observations of the afterglow angular size. Observations of decaying amplitude fluctuations in the radio afterglow of GRB 970508 (Frail et. al., 1997) confirmed the prediction of Goodman (1997) and enabled an estimate of the size of this afterglow as $10^{17}$ cm four weeks after the burst. This observation agreed with an independent estimate based on the fact that the system is optically thick to radio emission (Katz & Piran, 1997, Frail et. al., 1997). However, both methods are somewhat model dependent and require assumptions on the source or on the nature of the
GRB 030329 is one of the most remarkable GRBs observed so far. It was detected by HETE-II on March 29, 2003. Observations at many different wavelengths followed, and a very bright afterglow emission was detected over the whole spectrum. Its redshift, $z = 0.1685$ (Greiner et al. 2003), places it as one of the nearest GRBs whose redshift was firmly established. It is therefore natural that it turned out to provide us with the first direct measurement of the afterglow size and its expansion.

This difficult task was achieved by Taylor et al. (2004) who used a large group of radio telescopes to resolve the radio afterglow of GRB 030329 and demonstrated its relativistic expansion. They find that the size of the afterglow is $0.07 \text{mas} (0.2 \text{pc})$ 25 days after the burst, and $0.17 \text{mas} (0.5 \text{pc})$ 83 days after the burst. The corresponding superluminal expansion is at a rate of 3-5$c$. At a 15GHz observations taken 52 days after the burst Taylor et al., (2004) detect an additional compact component at a distance from the main component of $0.28 \pm 0.05 \text{mas} (0.8 \text{pc})$. As this component was detected only once and then only in one band (it was not detected at 22GHz at the same time or at any other epoch at any other band) we focus here on the observations of the main component and we discuss only briefly the implications of this additional component.

Before turning to the superluminal motion it is worthwhile to mention several features of GRB 030329 that are relevant to this discussion. During the first day the optical light curve of GRB 030329 looks rather typical, featuring an achromatic steepening from $\alpha_1 = 0.87 \pm 0.03$ to $\alpha_2 = 1.97 \pm 0.12$ at $T_j \approx 0.5$ days. Interpreting this steepening as a jet-break, results in a half-opening angle of $\theta_{j,0} \approx 0.07 \text{rad}$, and a total $\gamma$-ray energy output of $E_\gamma \sim 3 \times 10^{50} \text{erg}$ (Price et al. 2003). After one day however, the optical light curve shows an unusual variability, as several re-brightening episodes increase the observed flux by a large factor. Granot et al., (2003) interpret these re-brightening events as refreshed shocks and estimate that the total energy in these late shocks is about a factor of 10 larger than the initial energy seen in $\gamma$-rays, implying a total energy of a few $10^{50} \text{ergs}$. Berger et al. (2003) suggest as an alternative explanation a two-component jet, where the wide component has a half-opening angle of $\theta_{j,0} \approx 0.3 \text{rad}$ (corresponding to $T_j \approx 10$ days) and an energy of $\sim 3 \cdot 10^{50} \text{ergs}$. Thus both models brings the total energy of GRB 030329 to a few $10^{50}$ (the same level as most GRBs) where the main difference in the context of this paper is the break time.

Our goal here is to confront the fireball model with the new observations of the size of the afterglow. This task is rather simple for the spherical case, both at the early ultra-relativistic phase (i.e. before the jet break; Sari, 1998), and during the late transition to the non-relativistic phase. It is more complicated when we consider jets. Specifically, the
rate of the superluminal expansion depends on a combination of the radius of emission, the Lorentz factor of the emitting region and the direction of emission in the source frame. As we show later the relation between the radius, the Lorentz factor and the angle depends on the sideways expansion of the jet (past the jet break). Thus, quite naturally, the superluminal behavior depends critically on the full hydrodynamic behavior of the jet. In the simplest model (Sari et al. 1999), the jet expands sideways relativistically. On the other hand, numerical solutions (Granot et al., 2001, Cannizzo et al., 2004) suggest that the expansion may be much slower. A complete solution of the problem requires a detailed hydrodynamic solution of the evolution of the jet combined with a calculation of the time of arrival of the photons from different emitting regions within the jet. Lacking such a solution we present here simple analytic and numerical toy models that enables us to explore the possible range of superluminal expansion.

We show first that the angular size predicted by the fireball model after a few weeks is rather robust (i.e does not depend strongly on the details such as the external density profile and the exact expansion velocity). Even so, detailed observations can be used to distinguish between extreme expansion models (i.e. relativistic vs. no expansion). We use these results to investigate GRB 030329.

In section 2 we present the theoretical framework for our analysis, including the numerical model and the analytic estimates. In section 3 we discuss the results and compare them with the observation of GRB 030329. Finally we discuss the implications of these predictions in view of future observations in section 4.

2. Theory

A point source moving toward a distant observer at an angle \( \theta \) to the line of sight would appear to move superluminally across the plane of the sky (Couderc 1939). This has been noted as an important feature of relativistically expanding radio sources by Rees (1966). The apparent velocity \( v_{ap} \) is given in Eq. 1 where \( \beta \) and \( \gamma \) are the source velocity and Lorentz factor,

\[
\frac{v_{ap}}{c} = \frac{\sin(\theta)}{\beta^{-1} - \cos(\theta)} \approx \frac{2\gamma}{\theta \gamma + 1/\theta \gamma},
\]

which reduces in the relativistic limit and for \( \theta \) close to \( 1/\gamma \) to the simple self similar form given in the right term. The maximal value of \( v_{ap} \approx \gamma c \) is obtained for \( \theta \approx 1/\gamma \).

For a spherically expanding fireball the dominant portion of flux arrives from an angle of \( 1/\gamma \) relative to the line of sight, making \( 1/\gamma \) a good approximation for the angular size of the observed image. This also happens to be the direction at which we see the fastest
superluminal motion (see Fig. 1), \( v_{ap} = \gamma c \). During this phase we can, in principle, track directly the Lorentz factor of the shock through its image size. Unfortunately, the size of the afterglow is rather small at this stage and this measurement is extremely difficult.

For a collimated and non-sideways expanding jet, we will observe the \( \theta = 1/\gamma \) ring until \( 1/\gamma = \theta_{jet} \), where \( \theta_{jet} \) is the jet half opening angle, and then continue to observe emission from the edge of the jet, \( \theta = \theta_{jet} \). This will still appear superluminal but with \( v_{ap} \) decreasing faster, reaching asymptotically \( 2\theta_{jet}\gamma^2c \). Thus, we expect to see a break in the expansion velocity that is roughly simultaneous with the break in the light curve. The break will be complete when the \( 1/(\theta\gamma) \) term in the denominator will dominate over the \( \theta\gamma \) term, roughly over an order of magnitude in \( \gamma \). The same qualitative behavior is seen for a sideways-expanding jet but here a more cumbersome analysis is required. As expected we find in this case an intermediate decrease in \( v_{ap} \), between the two cases (spherical expansion and a non sideways-expanding jet).

The superluminal velocity, \( v_{ap} \), cannot be measured directly. Instead one measures the apparent size of the fireball:

\[
R_\perp = R \sin(\theta_{obs}) ,
\]

and its dependence on the observer time:

\[
T_{obs} = t - R \cos(\theta_{obs}) ,
\]

where \( t \) is the time in the source frame. The angle \( \theta_{obs}(R, \Gamma, \theta_{jet}) \) is the typical observing
angle (i.e. the polar angle in the source frame from which the dominant amount of flux reaches the observer). It satisfies $\theta_{\text{obs}} = \min(\theta_{\text{jet}}, \theta_{\text{beaming}})$, where $\theta_{\text{jet}}$ is the jet opening angle and $\theta_{\text{beaming}}$ is the relativistic beaming angle, $\theta_{\text{beaming}} = \tan^{-1}[(\gamma^2 - 1)^{-1/2}]$.

In principle one needs two dimensional hydrodynamic calculations in order to follow the evolution of the jet and to obtain $R(t)$, $\gamma(t)$ and $\theta_{\text{jet}}(t)$ as functions of $t$. Lacking such computations we construct a simple hydrodynamic model for the expanding jet. Within this simple model, which follows the common assumptions made in analyzing jets we approximate the full two dimensional evolution by a one dimensional solution in the radial direction. Instead of calculating the exact lateral expansion we assume a sideways propagation speed $\beta_{\text{jet}}$. We examine the upper and lower limits $0 \leq \beta_{\text{jet}} \leq 1$ as well as two physical models for $\beta_{\text{jet}}$. We also assume that the jet is uniform in its lateral direction and that its shape remains spherical.

Ignoring the kinetic energy involved in the lateral expansion we use the adiabatic equation for the energy transferred to the ISM by the blast wave:

$$E = C(\gamma)(\gamma^2 - 1)Mc^2,$$

where $\gamma$ is the (radial) Lorentz factor of the freshly shocked material ($\sqrt{2\gamma} = \Gamma$, the Lorentz factor of the shock front) and $M$ is the accumulated mass swept by the blast wave. $C(\gamma)$ is a numerical factor of order unity. It is a constant in the relativistic regime. Its $\gamma$ dependence enables us to extend the evolution of the fireball into the Newtonian regime. We find its value using the shock crossing conditions. Adding to Eq. 4 a model for the external density, $\rho(R) \propto R^{-k}$, ($k = 0$ for ISM and $k = 2$ for wind), and a model for the sideways expansion of the jet which we will discuss later, we can calculate the hydrodynamic evolution of the jet.

Within our simplified model the jet evolution is described by a set of four ordinary differential equations:

\[
\begin{align*}
\frac{dR}{dt} & = c\sqrt{1-\Gamma^2} \\
\frac{d\theta_{\text{jet}}}{dt} & = \frac{\beta_{\text{jet}}}{R} \\
\frac{dM}{dR} & = 4\pi \bar{\rho}R^{2-k}[1 - \cos(\theta_{\text{jet}})] \\
\frac{d\gamma}{dM} & = -\left[\frac{2\gamma}{\gamma^2 - 1} M + \frac{M}{C} \frac{dC}{d\gamma}\right]^{-1},
\end{align*}
\]

where $c = 1$ and

$$\bar{\rho} = \begin{cases} n_0 m_p, & \text{for ISM;} \\ 5 \cdot 10^{11} \text{gr/cm}A_s, & \text{for a wind with } k=2. \end{cases}$$
We close this system with expressions for $\Gamma(\gamma)$ and $C(\gamma)$ derived from the (radial) shock crossing conditions, and a model for $\beta_{\text{jet}}$, the sideways expansion velocity of the jet in the shock frame. We consider four cases: (i) $\beta_{\text{jet}} = 0$, representing models in which the jet does not expand or expands very slowly. There are some indications from numerical works (Granot et al., Cannizzo et al., 2004, Kumar & Granot 2003) for such a behavior. (ii) $\beta_{\text{jet}} = 1$, which represents the limit of ultra-relativistic expansion. This approximation was used, for example, by Sari, Piran, & Halpern (1999) for their calculations of the post jet break light curves. These two cases serve as lower and upper limits on the expansion rate. The two other, more physical models, feature a variable expansion speed that follows the physical conditions in the shocked matter: (iii) $\beta_{\text{jet}} = \beta_s$, the sound speed (see for example Panaitescu and Meszaros, 1999). $\beta_s$ approaches $1/\sqrt{3}$ in the limit of relativistic shocks. It vanishes in the limit of a cold, Newtonian shock. (iv) $\beta_{\text{jet}} = \beta_T$, the thermal velocity of the shocked material. If we consider the lateral dimension alone, the low density and pressure outside the jet will give rise to a rarefication wave at the edges that will propagate with approximately $\beta_T$. At the relativistic limit $\beta_T$ approaches 1, and it vanishes in the Newtonian limit.

The evolution from the observer point of view proceeds in three asymptotic stages: (i) The pre-break (spherical) stage, $\gamma \gg \theta_{\text{jet}}^{-1}$, where the dynamics are similar to spherical expansion and the visible part of the jet is $\theta_{\text{obs}} = 1/\gamma$. (ii) The relativistic post-break stage, $\theta_{\text{jet}}^{-1} \gg \gamma \gg 1$, when the visible region is determined by the edge of the jet $\theta_{\text{obs}} = \theta_{\text{jet}}$ (this is the only stage that is sensitive to $\beta_{\text{jet}}$) (iii) The Newtonian stage when $\gamma \sim 1$, where the expansion is Newtonian and the entire fireball is visible.

It is possible to derive analytical expressions for the behavior of the observed size $R_\perp$ in these three asymptotic stages of the afterglow. We do this by employing the adiabatic equation and different approximations for the value of $\theta_{\text{obs}}(T)$. Our results agree with those of Sari (1998) for spherical propagation into an ISM and with those of Galama et al. (2003) for a jet expanding relativistically into an ISM ($\beta_{\text{jet}} = 1$). We are also in agreement with the results of Galama et al. (2003) for the spherical propagation into a wind at asymptotically late times (before the newtonian phase). In the first stage we take the spherical adiabatic equation and $\theta_{\text{obs}} = 1/\gamma$. In the second stage, if $\beta_{\text{jet}}$ vanishes than the spherical adiabatic equation still holds but $\theta_{\text{obs}}(T) = \theta_0$. If $\beta_{\text{jet}} \sim 1$ the adiabatic equation implies $R \sim \text{const}$ and $\theta_{\text{obs}} \sim 1/\gamma$. In the last, Newtonian, stage the emission is not beamed anymore and the evolution becomes simply the Sedov-Taylor solution (Sedov 1946, Taylor 1950, Von Neumann 1947). At this stage the the apparent expansion speed naturally becomes sub-luminal. We summarize the different approximations in table 1 (Note that here and elsewhere in the paper $E$ stands for the total energy of the flow and $E_{\text{iso}}$ for the isotropic equivalent energy.):

The transition between the asymptotic stages must be calculated numerically using Eq.
Table 1: Analytic approximations in the 3 asymptotic stages for the observed size $R_\perp$. The absence of an entry for the post break stage in wind is due to the fact that the break in this case is so gradual that the analytic solution is not a good approximation at any point between the jet break and the Newtonian regime.

5. The transition from the first to the second stage (i.e. the jet break of $R_\perp$) has similar properties to the jet-break in the light curve. It is a result of two effects, the sideways expansion (that is relevant only when $\beta_{jet}$ is relativistic) and the decrease in the relativistic beaming that brings (when $1/\gamma > \theta_{jet}$) the edge of the jet into view. The sideways expansion becomes important when $1/\gamma \theta_0 = \theta_{jet}(T = 0)$. This takes place at the canonical estimate of the break time (Sari et. al. 1999, Chevalier & Li 2000)

$$T_{jet} \approx \begin{cases} 
1(E_{51}/n)^{1/3}(\theta_0/0.1)^2(1 + z) \text{ days} & \text{ISM} \\
1(E_{51}/A_*)(^{1/3}(\theta_0/0.1)^2(1 + z) \text{ days} & \text{WIND}
\end{cases}$$

(7)

The edges of the jet are actually observed only when $1/\gamma(T) = \theta_{jet}(T)$. When the jet expansion is negligible $\theta_{jet}(T) \approx \theta_0$ at any $T$ and both effects occur the same time. When $\beta_{jet}$ is relativistic then the edges of the jet are observed later than $T_j$, in an ISM by a factor of few and in a wind by more then an order of magnitude. Kumar and Panaiteescu (2000) explore the effect of these two phenomena on the break in the light curve assuming a relativistic $\beta_{jet}$. They find that the beaming effect is more dominant, and that the break takes about one decade in time in an ISM and more than two decades in time in a wind. Similar behavior is observed in the break of $R_\perp(T)$. As a result of the very long break in a wind environment (when $\beta_{jet} \sim 1$), the second stage never reaches its asymptotic behavior and it is impossible to find an accurate analytic approximation to this stage. Finally, We find that when $\beta_{jet} \ll 1$ the break take place at $T_j$ and it takes about one decade in time both for ISM and wind. The transition to Newtonian stage takes about one time decade in an ISM and two decades in a wind.
The break is also affected by the viewing angle of the jet. The observation of a prompt emission of $\gamma$ rays implies that our viewing angle is smaller than $\theta_0$, but we are still uncertain of the angle between the axis of the jet and the line of sight. If we are not viewing the jet exactly on axis, the $1/\gamma$ ring will cross the edge of the jet at different times for different azimuthal angles, an effect which will alter the shape of the break. We ignore this effect here for the sake of simplicity, as it should not affect our results in a significant manner.

3. Application to GRB 030329

The key measurements made by Taylor et al. (2004) on GRB 030329 indicate that the angular size of the emitting region in the radio band is $0.04 - 0.11$ mas 25 days after the burst, and between $0.13 - 0.21$ mas 83 days after the burst, with nominal values 0.077 and 0.172 mas at these times. Another measurement at 51 days after the burst gives a $2\sigma$ upper limit of 0.1 mas (see, e.g., Fig. 2). The angular distance to the burst corrected for cosmological effects is estimated as $589 Mpc$, which leads to a radial size of $6.7 \cdot 10^{17} cm$, $8.7 \cdot 10^{17} cm$ and $15 \cdot 10^{17} cm$ respectively for the three measurements. Given a power law expansion of the observed size with time, $R_\perp \propto T^\alpha$, these measurements constrain the exponent to be $0.5 \lesssim \alpha \lesssim 1.1$ in the neighborhood of the observations. Taylor et al. (2004) fit the observations using the analytical asymptotic equations of $R_\perp(T)$ given by Galama et al. (2003) for the spherical stage and the post-break stage (with $\beta_{jet} \approx 1$). They find that all the models can fit the observations. They find the best fit values of $E_{51}/n$ in ISM (or $E_{51}/A_*$ in a wind) to be $\sim 10$ for a spherical wind and a jet with $T_j = 10$ days, and $\sim 2$ for a jet with $T_j = 0.5$ days.

We used our numerical model to try and confront these measurements with the predictions of the fireball model. The first and the most remarkable result is that the angular size ($\sim 10^{18}$ cm) and its increment index $0.5 \lesssim \alpha \lesssim 1.1$ are similar to the predictions for the most typical GRB parameters ($E_{51}/n = 0.1 - 10$) with little dependence on the beaming factor, expansion velocity and external density profile, with the exception of a non expanding jet in ISM. The rather constant values of $\alpha$ for the different models ($\alpha = 0.5 - 0.75$ when a non expanding jet in ISM is excluded), and the weak dependence of $R_\perp$ on $E/n$ leave a very narrow range of possible results, making the measurement of $R_\perp(T_{obs})$ a very strong test of the fireball model.

However, the same feature that make this measurement such a strong consistency check on the fireball model also makes it a rather poor instrument for distinguishing between the different models. It is evident that the current measurements do not allow us to rule out any of the suggested models (Fig. 2, Fig. 3), except for the non expanding jet in ISM where $\alpha \approx 0.25$. This value of $\alpha$ makes any such configuration with $T_{jet} < 25$ days inconsistent with
Fig. 2.— upper panel: \( R_\perp \) as a function of \( T_d \) for different sideways expansion models in ISM. The energy to external density ratio \( E/n = 0.6 \cdot 10^{51}\text{erg cm}^3 \) and \( \theta_0 = 0.06\text{rad} \).

Lower panel: \( R_\perp \) as a function of \( T_d \) for different opening angles in ISM, with constant \( E/n = 0.6 \cdot 10^{51}\text{erg cm}^3 \). \( T_j \) is in days, \( \beta_s = \beta_{\text{thermal}} \)

the data. This result is the first observational hint of the value of \( \beta_{\text{jet}} \). On the other hand even a model with \( \beta_{\text{jet}} = \beta_s \) gives almost the same results as \( \beta_{\text{jet}} = 1 \).

The best fit for the observations in an ISM where \( \beta_{\text{jet}} \) is relativistic is obtained with the following values of \( E_{51}/n: \sim 0.5(T_j \sim 0.5\text{days}), \sim 1(T_j \sim 10\text{days}) \) and \( \sim 10 \) if the ejecta is spherical. In a wind environment all the different models require \( E_{51}/n \sim (1 - a \text{ few}) \) to fit the observations. If we interpret, however, the sharp break in the optical afterglow at 0.5days to be a jet break, than we can argue against the wind scenario with \( \beta_{\text{jet}} \sim 1 \), as it would imply a much more gradual break spanning roughly two orders of magnitude in time (Kumar & Panaitescu 2000). Another interesting feature of the results is that the estimates of the burst energy out of the optical (Granot et al. 2003) and the radio (Berger et al. 2003) observations, a few \( \times 10^{50}\text{ergs} \) with the observed break time (0.5day or 10days) is also the energy value that provides the best fit to \( R_\perp(T_{\text{obs}}) \) (assuming the canonical value of \( n = 1\text{cm}^{-3} \)). Even though the weak dependance of \( R_\perp \) on \( E \) (a power of 1/6) makes it a blunt tool to probe the energy, this result is reassuring.

Note that the best fit values of Taylor et. al. (2004) of \( E/n \) for the beamed models (\( T_j = 0.5 \) or 10days) are an order of magnitude larger than our best fit values. The reason is the sharp break taken in the modelling of Galama et. al. (2003) compared to the gradual break in the numerical results. This deficiency however is within the uncertainty of the model due to the weak dependance of \( R_\perp \) on \( E \) (i.e. a difference of a factor ten in the energy reflects
only a difference of a factor 1.4 in $E/n$).

Finally we note that Taylor et al. (2004) report a single detection of a secondary component at 15GHz after 51 days at a distance of $\sim 0.8$pc, implying an average apparent velocity of $19c$ (apart for the detection of the main afterglow component). It is important to note this component was not detected at any other epoch, and more importantly it was not detected in a less sensitive observation at 22GHz taken at the same time (while the detection at 15GHz was at a level of $> 20\sigma$). Thus, we think that it is premature to contrive a theory based on this observation.

Still, we address this observation at face value, assuming that the source of the emission was ejected at the time of the burst from the same location of the main component. The apparent velocity of a source moving at the speed of light at an angle $\theta$ to the observer is $v_{ap} = 2/\theta$. Therefore, the source of the secondary component must be at an angle $\leq 0.1rad$ implying $R = R_\perp / \sin(\theta) \geq 2 \cdot 10^{19}cm$ and $\Gamma \geq 10$ at this radius (see Eq. 1) . This combination is incompatible with the fireball model with any reasonable parameters. Thus, if the exitance of such a component would be confirmed in the future it will probably require a theoretical revolution. However, as we stressed earlier, it is premature to reach such a drastic conclusion, particularly in view of the remarkable success of this theory in explaining the main component.
4. Conclusions

Until recently no direct measurement of the size of the emitting region in a GRB afterglow was available, due to the large distances and relatively small sizes involved. In a situation where most of the information we have on the sources of GRB’s is indirect and often ambiguous, such a measurement is extremely important as it allows us to test directly some of the predictions of existing models. This goal has been achieved with the afterglow of GRB 030329 (Taylor et al. 2004), and in this work we tried to test the compatibility of the fireball model with this new data and to derive some general predictions for future observations.

Relativistically expanding fireballs cast an image on the plane of the sky that grows superluminally with the observer time. A detailed modelling of this scenario would require a full 3D, or at least 2D relativistic hydrodynamic code. Lacking such a code we made a simpler analysis that captures the essential features of interest. We consider a jet described by a radial shock, bounded to a cone of opening angle $\theta_{\text{jet}}$, which grows at a rate determined by the properties of the ejecta in its rest frame. This simple scheme enables us to model the superluminal expansion of GRB afterglows in general and the afterglow of GRB 030329 in particular and try to constrain some of its parameters.

Our main result is that both the value and the time evolution of $R_\perp$ depends rather weakly on the exact variant of the fireball model and its parameters. We find that the main afterglow component of GRB 030329 fits remarkably well the predictions of the fireball model. Specifically we find that the exact values of the current estimates in the literature on the energy and opening angle of GRB 030329 give excellent fits to the data. There is only one variant of the fireball model which appears to be rejected by the observations, the non expanding jet in ISM. We consider the fact that a direct measurement confirms a robust prediction of the fireball model as one of the model’s most important achievements.

We conclude with the reflection that while the direct observations of angular size are maybe a strong test of the fireball model, they cannot be used (at least in their current quality) as a tool to distinguish between different scenarios. However, if in the future we will have more accurate and more frequent observations then it might be possible to use them in order to achieve this task as well.

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