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MODELS FOR THE CIRCUMSTELLAR MEDIUM OF LONG GAMMA-RAY BURST PROGENITOR CANDIDATES

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RESUMEN

Presentamos modelos hidrodinámicos del medio circunestelar (CSM) alrededor de candidatos progenitores de estallidos de rayos gamma (GRB) largos. Estos son estrellas masivas que han perdido gran parte de sus masas en forma de vientos estelares durante sus evoluciones.

Hay dos formas posibles de examinar el CSM de progenitores de GRB largos. Primeramente, el residuo del GRB se observa en radiación sincrotrón, emitida cuando el chorro supersónico del GRB barre el medio circundante. De esta forma, la curva de luz está directamente relacionada con el perfil de densidad del CSM. La densidad puede tanto decrecer como el cuadrado del radio (como es el caso de un viento estelar que se expande libremente) o ser constante (como se esperaría para un viento chocado o para el medio interestelar). Segundamente, el material entre el GRB y el observador absorberá parte de la radiación del residuo del GRB, causando líneas de absorción en el espectro del residuo. En algunos casos, tales líneas de absorción estarán corridas al azul con respecto a la fuente, indicando que el material se aleja de la estrella progenitora. Esto puede ser explicado en términos de interacciónes de vientos en el CSM. Se pueden usar los CSM de estas estrellas para investigar sus estados de evolución previa.

ABSTRACT

We present hydrodynamical models of circumstellar medium (CSM) of long gamma-ray burst (GRB) progenitor candidates. These are massive stars that have lost a large amount of mass in the form of stellar wind during their evolution.

There are two possible ways to probe the CSM of long GRB progenitors. Firstly, the GRB afterglow consists of synchrotron radiation, emitted when the GRB jet sweeps up the surrounding medium. Therefore, the lightcurve is directly related to the density profile of the CSM. The density can either decrease with the radius squared (as is the case for a freely expanding stellar wind) or be constant (as we would expect for shocked wind or the interstellar medium). Secondly, material between the GRB and the observer will absorb part of the afterglow radiation, causing absorption lines in the afterglow spectrum. In some cases, such absorption lines are blue-shifted relative to the source indicating that the material is moving away from the progenitor star. This can be explained in terms of wind interactions in the CSM. We can use the CSM of these stars to investigate their prior evolutionary stage.

Key Words: **GAMMA RAYS: BURSTS — HYDRODYNAMICS — LINE: IDENTIFICATION — METHODS: NUMERICAL — STARS: CIRCUMSTELLAR MATTER — STARS: WINDS, OUTFLOWS — STARS: WOLF-RAYET**

1. INTRODUCTION

The generally accepted model for long gamma-ray bursts (GRBs) is the collapsar model (Woosley 1993). According to this model a gamma-ray burst occurs if a rapidly rotating Wolf-Rayet star (the final evolutionary stage of a massive star) collapses toward a black hole. During the collapse, an accretion disk is formed around the black hole. The GRB is produced by a relativistic jet that shoots out of the pole, driven by energy generated by the accretion onto the black hole. As the jet moves outward it first encounters the outer envelope of the progenitor star. Beyond this it moves into the circumstellar medium that has been formed by the stellar wind of the progenitor (see Figure 1). The jet hits a region of free streaming stellar wind, then moves through the wind termination shock into the shocked wind region and eventually – provided it has sufficient energy to penetrate that far – into the interstellar medium (ISM)

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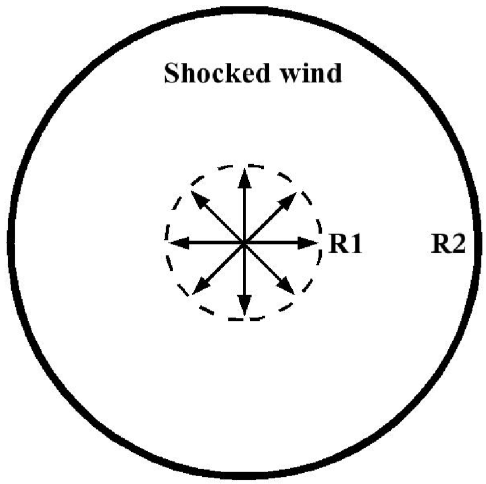

Fig. 1. Schematic view of a circumstellar bubble (not to scale). The free-streaming stellar wind passes through the wind termination shock (R1) to enter the hot bubble of shocked wind material. The high thermal pressure in the hot bubble sweeps up a shell (R2), which expands into the ISM.

(Chevalier et al. 2004; Eldridge et al. 2005; Ramirez-Ruiz et al. 2005; van Marle et al. 2006, 2007).

The GRB jet sweeps up the surrounding medium as it expands, accelerating particles to relativistic speeds. As a result, synchrotron radiation is emitted, which we observe as the GRB afterglow. There are two methods to use the afterglow radiation to investigate the surrounding medium.

1.1. *Circumstellar density profiles*

The afterglow lightcurve is directly related to the density profile of the surrounding medium. Numerical models show that the density can either decrease with the radius squared or be constant (Chevalier & Li 2000; Panaitescu & Kumar 2001, 2002; Chevalier et al. 2004). The latter is surprising for we would expect to find a free streaming wind region close to the star, which would show as $\rho \propto 1/R^2$. The most likely explanation for te occurance of a constant density medium is that the jet has already passed beyond the free-streaming wind region and has entered the shocked wind region where the density is indeed nearly constant (Wijers 2001; Chevalier et al. 2004; van Marle et al. 2006, 2007). However, this requires the wind termination shock to be extremely close to the star, which is difficult to understand in the case of a Wolf-Rayet stars because they tend to have powerful winds. This is discussed in more detail in § 2.

1.2. *GRB afterglow absorption spectra*

Circumstellar matter between the GRB and the observer will cause absorption lines in the GRB afterglow spectrum. These lines provide information about the composition of the circumstellar medium (CSM). Some GRBs show the same line several times. These lines are blue-shifted relative to the progenitor indicating a system of discrete velocities in the CSM. This can be explained by hydrodynamical interactions between the stellar wind and the ISM or between different phases of the stellar wind (van Marle et al. 2005a,b, 2007). We will discuss this in more detail in § 3.

2. FORMING A CONSTANT DENSITY MEDIUM CLOSE TO A GRB

Most Wolf-Rayet stars have powerful stellar winds, which means that the wind termination shock lies far ($\sim$ 10 pc) from the progenitor star. If this is the case, the GRB afterglow can never be generated in the shocked wind material, since the GRB jet will have ceased to be relativistic long before it has reached this distance. If the afterglow is to be (partially) generated in the shocked wind, the termination shock has to be at $\lesssim$ 0.1 pc (Chevalier et al. 2004).

2.1. *Outside influence*

There are several possible causes for the wind termination shock to be close to the progenitor star, as was discussed in detail in our earlier papers (van Marle et al. 2006, 2007). Most of these scenarios involve an increase of the 'confining pressure', the pressure that restricts the expansion of the circumstellar bubble. For example, by increasing either the density or the thermal pressure of the ISM, the expansion rate of the circumstellar bubble decreases. Similarly, if the star has a supersonic velocity relative to the surrounding medium, the ram pressure of the stellar motion performs a similar function. Unfortunately, the effect of the confining pressure is limited. One needs an increase of three orders of magnitude to bring the wind termination shock one order of magnitude closer to the star (van Marle et al. 2006). This means either a very high density ($\sim 10^4$ cm^{-3}) or a very high temperature ($\sim 10^8$ K) in the ISM. Stellar motion is more effective, especially since it can be combined with high ISM density. Even so, the star has to move quite rapidly to create a bow shock (keeping in mind that it may be moving through an H II region or a circumstellar bubble where the local sound speed is high because of the temperature).

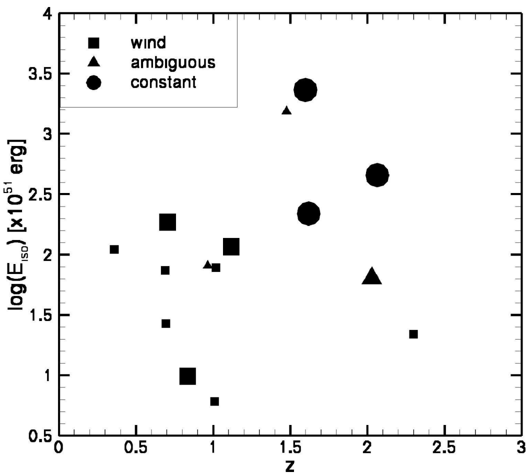

Fig. 2. Distribution of GRBs over the redshift-isotropic energy space published previously by (van Marle et al. 2006). GRBs whose afterglows show a constant density profile (circle) tend to have high energy and occur at larger redshifts than the afterglows which are formed in a free-streaming wind (square). The ones marked as triangles are ambiguous, which means that either different groups disagree on the nature of its afterglow, or no group has decided on its nature.If the symbol is large, several groups have reached the same conclusion. References for these afterglow models are: Chevalier & Li (2000), Panaitescu & Kumar (2001), Panaitescu & Kumar (2002) and Chevalier et al. (2004).

2.2. *Internal influence*

Apart from these outside influences, it is also possible to move the wind termination shock closer to the star by decreasing the ram pressure of the stellar wind. Since weak stellar winds usually occur at low metallicities (Nugis & Lamers 2000; Eldridge & Vink 2006), this would mean that GRBs showing a constant density in their afterglow lightcurve should occur more often at higher redshift. Finally, the penetration of the GRB jet into the surrounding medium depends directly on the energy of he GRB. Therefore, a powerful GRB can penetrate much deeper into the CSM and bring the wind termination shock within reach even at larger distances.

2.3. *Observational test*

Density slopes around several GRBs have been determined from the afterglow light curves of a number of bursts (Chevalier & Li 2000; Panaitescu & Kumar 2001, 2002; Chevalier et al. 2004). Their distribution over the redshift-isotropic energy space (see Figure 2) seems to support our idea (van Marle et al. 2006). The GRBs with a constant density profile occur mostly at high redshift and have a high isotropic energy. (We use the isotropic energy of the burst, since it is irrelevant whether the burst has a high absolute energy, or a narrow beam. Both cause it to penetrate deeply into the surrounding medium).

If the afterglow is generated partially in the free streaming wind and partially in the shocked wind, as is quite feasible, one would expect to be able to observe the transition form one medium to another because of the jump in the local density. However, recent work (Nakar & Granot 2006) shows that the transition may not be visible.

2.4. *Alternative explanation*

Another way to constrain the wind bubble is to suppose a period of extremely high mass loss before the onset of the Wolf-Rayet phase. Such an outburst can be observed in the case of η Carinae, which lost a considerable amount of mass ($\dot{M} \gtrsim 10^{-2}\ M_{\odot}$ yr) during the nineteenth century (Davidson 1987). Whether such a shell would actually constrain the Wolf-Rayet wind bubble is not certain. Hydrodynamical calculations (García-Segura et al. 1996; van Marle et al. 2005b) show that a shell, driven by a Wolf-Rayet wind, can break quite easily through the shell of shocked Red Supergiant wind material sitting at the wind termination shock. The latter shell contains 10-20 $M_{\odot}$ but apparently does not impede the Wolf-Rayet wind driven expansion.

3. BLUE-SHIFTED ABSORPTION LINES IN GRB AFTERGLOW SPECTRA

Some GRBs show a series of absorption lines that are blue-shifted relative to the progenitor; notably GRB 021004, which shows at least **six** absorption lines both in C IV and Si IV (Fiore et al. 2005; Starling et al. 2005). These absorption lines show that there is a complicated system of discreet velocity features between the GRB and the observer. In van Marle et al. (2005a,b), we showed that these absorption features can be explained by stellar wind interactions that take place in the CSM of the progenitor star, using a 40 $M_{\odot}$ star as described by Schaller et al. (1992). The fastest absorption features ($\sim$ 3000 km/s) correspond to the wind from the Wolf-Rayet star, whereas the slower features ($\sim$ 150 − 650 km/s) are caused by fragments of the shell that the Wolf-Rayet wind swept up into the surrounding medium. The presence of these intermediate velocity components places a time constraint on the evolution of the progenitor star. They are comparatively short lived ($\lesssim 5 \times 10^4$ yrs), since they will eventually dissipate into the surrounding gas (see Figure 3). This means that the progenitor

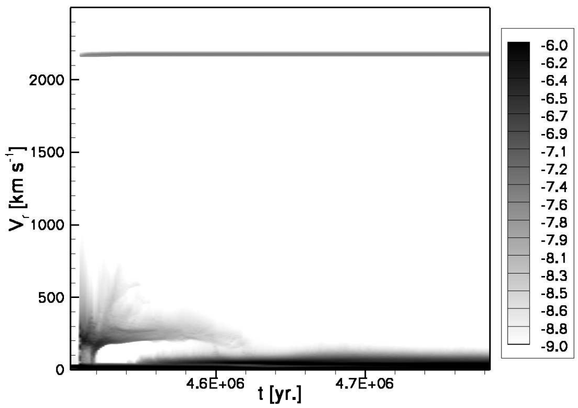

Fig. 3. The column density in [g/cm^2] as a function of radial velocity for a 40 $M_\odot$ star during the Wolf-Rayet stage (van Marle et al. 2005a,b). The zero velocity component is always present, as the interstellar medium itself provides gas that is standing still relative to the star. The Wolf-Rayet wind component at 2200 km/s is visible during the entire Wolf-Rayet period. However, the 150...650 km/s component, caused by the Wolf-Rayet wind driven shell is short-lived. The column density in this figure is the average result for 200 radial gridlines.

of GRB 021004 must have had a short Wolf-Rayet phase prior to its explosion.

3.1. *Photo-ionization*

The comparatively low ionization states of the ions that produce the absorption lines is not so easy to explain. If the ions are in the direct line of the GRB, one would expect the atoms to be at high ionization states out to very large radii (Prochaska et al. 2006; Lazzati et al. 2006). However, evidence so far suggests that GRB 021004 had a very strong wind, with a high density (Lazzati et al. 2006). This would put the wind termination shock far away from the star. Alternatively, the wind might be highly clumped with optically thick clumps shielding part of the material from the ionizing photons (Chen et al. 2006). A second explanation lies in the possibility that the GRB jet is not homogeneous. This may mean that the γ-radiation of the burst passed through a smaller area than the afterglow. Therefore, the material that is absorbing the afterglow was not photo-ionized by the burst (Starling et al. 2005; van der Horst et al. 2006). Even so, the wind termination shock could not have been very close to the progenitor star, since the afterglow itself produces enough high energy photons to ionize the gas to high ionization states at shorter range (Prochaska et al. 2006).

3.2. *Alternative explanations*

It was suggested by Mirabal et al. (2003) that radiative acceleration could account for the presence of blue-shifted absorption lines in a GRB afterglow spectrum. However, for the radiative force on the particles to be that powerful one would expect higher ionization states than those observed for GRB 021004 (Starling et al. 2005). Nor can this explanation account for the large number of discreet velocity features. Alternatively, the absorption features could be interstellar rather than circumstellar in origin. E.g., the intermediate velocity lines could be caused by an expanding superbubble. The velocities are rather high, for superbubbles in local galaxies typically have expansion velocities of less than 150 km/s (Heiles 1979; Tenorio-Tagle & Bodenheimer 1988; Martin 1998), but certainly not impossible if the progenitor is sitting inside a starburst region. However, the chances of a single GRB progenitor sitting at the center of three expanding superbubbles, each with a different velocity are not very large. While a superbubble shell may account for one of the absorption features it is unlikely to account for all of them. Similarly, the high velocity components of the absorption spectrum can be a galactic wind rather than the stellar wind (Prochaska et al. 2006). While this would eliminate the problem of the low ionization states mentioned before, a galactic wind should produce an asymmetric absorption feature since the acceleration phase of the wind would absorb part of the radiation. Moreover, it is difficult to explain two discreet absorption components at high velocities in this fashion.

3.3. *A possible supernova connection*

Recently, three GRBs were detected that showed absorption lines at very high blue-shift relative to the progenitor: GRBs 050730, 050922 and 060418 (D'Elia 2006; Piranomonte et al. 2007a,b). If the lines observed in these afterglows are indeed produced in the GRB progenitor host galaxy, the relative velocity of the gas would be of the order of 10^4...10^5 km/s. Such velocities would be very difficult to explain in terms of Wolf-Rayet wind velocities, which are usually at least an order of magnitude lower. This may indicate, that these lines are just foreground noise, occurring in a different galaxy with a lower redshift than the GRB host galaxy. However, there is another possible explanation. Velocities such as these do occasionally occur in supernova explosions, as observed in blue-shifted absorption lines in the spectra of Type II supernova SN2005cs (Pastorello et al. 2006) and Type Ib supernova SN1987M

(Elhamdi et al. 2004). See also Mazner & McKee (1999) and Chevalier & Fransson (2006). For the supernova ejecta to appear in absorption in the GRB afterglow, the supernova has to happen well in advance of the GRB. This is not part of the normal collapsar model, but the possibility was suggested by Vietri & Stella (1998), who proposed a 'supranova' model, where a supermassive neutron star falls back into a black hole after the original supernova. The time interval between the two events could be as large as several years. If some of the high velocity absorption lines observed in GRBs 050730, 050922 and 060418 are indeed caused by the 'supranova ejecta' this would be a considerable step forward in our understanding of GRB formation.

4. DISCUSSION

The circumstellar medium of a massive star carries the fingerprints of the previous stages of the stellar evolution. It provides an excellent opportunity to investigate the evolutionary past of the central star. We have presented two methods for analyzing the CSM of GRB progenitors. Through blueshifted absorption lines in the GRB afterglow spectra we cannot only study the composition of the CSM, but also the hydrodynamical interactions that took place, which in turn give us clues about the wind parameters of the previous evolutionary phases of the progenitor star. The density profiles of the CSM provide us with information on the balance between the ram pressure of the stellar wind and the confining pressure of the ISM. There is no reason, why these tools can not be used in other situations as well, e.g., on supernovae and Wolf-Rayet stars. If the CSM of these objects can be matched to the CSM around GRBs, it will be a major step forward in our understanding of the evolution of GRB progenitor stars. In the future we hope to provide similar models of the circumstellar medium around rapidly rotating stars (Yoon & Langer 2005; Yoon, Langer, & Norman 2006; Woosley & Heger 2006), which are thought to be GRB progenitors.

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