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The origin of blue-shifted absorption lines in a gamma-ray burst afterglow(*)

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Summary. — The afterglow spectrum of GRB 021004 shows a system of blue-shifted absorption lines, indicating the presence of matter moving towards us at discrete velocities in the range from 0 to more than 2000 km/s. We propose that these lines are the result of absorption by circumstellar matter, which was ejected by gamma-ray burst progenitor (a massive star) during its evolution. We have simulated the evolution of the circumstellar medium around such a star and find that the evolutionary sequence: main-sequence, Red Supergiant, Wolf-Rayet star can qualitatively reproduce the various absorption lines systems.

PACS 97.10.Fy – Circumstellar shells, clouds, and expanding envelopes; circumstellar masers.
PACS 97.10.Me – Mass loss and stellar winds.
PACS 97.30.Eh – Emission-line stars (Of, Be, Luminous Blue Variables, Wolf-Rayet, etc.).
PACS 98.70.Rz – γ-ray sources; γ-ray bursts.
PACS 01.30.Cc – Conference proceedings.

1. – Introduction

Observations of the optical part of the afterglow of Gamma-Ray Burst GRB 021004 clearly show a pattern of blue-shifted absorption lines, indicating the presence of material moving away from the star at certain discrete velocities. We present a model of the circumstellar medium that explains the presence of these lines.

As Gamma-Ray Bursts are thought to be the result of the explosion of massive stars, we take the model of such a star and use its mass-loss history to simulate the evolution of

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the circumstellar medium. For the final stages of the evolution we calculate the column density along the line of sight as a function of the radial velocity. This can be linked directly to the absorption as a function of the blue-shift. The result shows a series of time-dependent absorption features, directly comparable to the observations. This helps us to determine the original mass of the star and the type of Wolf-Rayet star that produced this gamma-ray burst.

2. – The GRB afterglow absorption spectrum

Observations of the afterglow of Gamma-Ray Burst 021004 (Schaller *et al.* [8], Mirabal *et al.* [6], Fiore *et al.* [1] and Starling *et al.* [9]) show an absorption spectrum in which the same lines can be found at different blue-shifts, indicating several discrete velocity components. In both CIV and SiIV a similar pattern is detected. Roughly speaking, the line patterns can be divided into three groups: There is absorption by matter that is not moving relative to the star, absorption by matter moving at velocities of a few hundred km/s and absorption by matter moving at more than two thousand km/s. The first component is not difficult to explain, since it is always possible to find matter at rest relative to the star. The third component can be identified with the Wolf-Rayet wind, which moves at velocities of several thousand km/s. It is the intermediate velocity component that presents a problem, as the observed velocities are too high for a Red Supergiant wind, but too low for a Wolf-Rayet wind.

3. – The evolution of the circumstellar medium

We simulate the hydrodynamical interactions between the stellar wind and its surroundings by using the same method as described by García-Segura *et al.* [2]. This means that the evolution of the circumstellar medium during the main sequence and early Red Supergiant phase was calculated on a one dimensional grid. The transition from Red Supergiant to Wolf-Rayet stage and the further evolution during the Wolf-Rayet stage was treated in two dimensions. We added the effects of photo-ionization in a fashion, similar to that in García-Segura *et al.* [3]. As input model for the simulations, we took the $40\,M_\odot$ model, as described by Schaller *et al.* [7]. For each stage of the evolution: main sequence, Red Supergiant and Wolf-Rayet we have calculated the average mass-loss rate, wind velocity and high energy photon count. The result of our simulations is as follows:

During the main sequence the combined effects of stellar wind and photo-ionization create an isothermal bubble, which pushes a shell into the interstellar medium (ISM). This bubble has a sharp density discontinuity at the point were shocked wind material meets photo-ionized ISM. As the star becomes a Red Supergiant its surface temperature decreases and the photo-ionization stops. As a result the temperature in the outer part of the bubble drops. The shell, which is no longer supported by the HII region, stops moving and starts to dissipate. A new shell is formed on the density discontinuity pushed by the hot, wind-blown bubble into the former HII region. A third shell is formed on the wind termination shock by the dense, but slow Red Supergiant wind (fig. 1) This sequence of events was described by van Marle *et al.* [5]. As the star becomes a Wolf-Rayet star, the wind velocity increases, pushing a new shell outward, which collides with the shell on the wind termination shock. The remnants of both shells dissipate into the surrounding bubble (fig. 1). Photo-ionization becomes important again and a new HII region appears outside the wind bubble. However, the high ram-pressure of the Wolf-Rayet wind causes the bubble to expand so rapidly that this HII region eventually disappears.

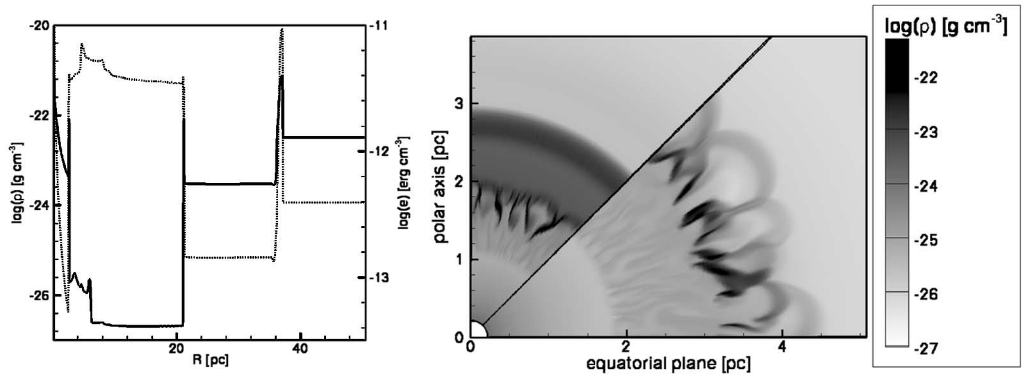

Fig. 1. – The evolution of the circumstellar medium. On the left: The end of the Red Supergiant phase. This figure gives the density (continuous line) and thermal pressure (dotted line) as a function of the radius. From left to right we have: The Red Supergiant wind, the Red Supergiant shell, the hot bubble, the energy driven shell, the former HII region, the "old" shell and the interstellar medium. On the right: Density [g cm^{-3}] of the circumstellar medium close to the star before (above) and after (below) the Wolf-Rayet shell collides with the Red Supergiant shell. The shell fragments continue to move outward and will eventually dissipate into the surrounding medium.

4. – Calculating the absorption components

From our simulations of the circumstellar medium we calculate the column density as a function of the radial velocity. This is equivalent to the absorption as a function of blue shift, that photons coming from the central star would encounter. We correct the result for thermal broadening by calculating the Maxwell-Boltzmann distribution for the temperature in each gridpoint. The result can be seen in fig. 2. the quantity presented here is

$$d_c(v, \Delta v) = \int_{r=0}^{r=R} \rho(r) P(v_r) \Delta v_r \mathrm{d}r \tag{1}$$

with: v_r the radial velocity, ρ the mass density and P the probability function for a particle to have a velocity in a given velocity interval along a single axis. For the interval Δv we use 1 km/s. At the left side of the figure, the star is still in the Red Supergiant phase. This means that all matter in the circumstellar medium is either moving very slowly, or standing still. Therefore, only one absorption line is visible for each ion. As the Wolf-Rayet stage begins, the fast wind creates a high velocity ($v \sim 2200$ km/s) absorption feature. A transient feature appears at about 200 km/s. This feature is the result of the moving shell, pushed by the Wolf-Rayet wind. It is clearly visible during the early stages of the Wolf-Rayet period, but disappears as the fragments of this shell dissipate into the circumstellar medium.

5. – Conclusions

Our simulations produce an absorption spectrum that consists of several discrete features, some of which are time-dependent. Comparison with the observations of GRB 021004 indicate that this star was still in its early Wolf-Rayet phase when the Gamma-

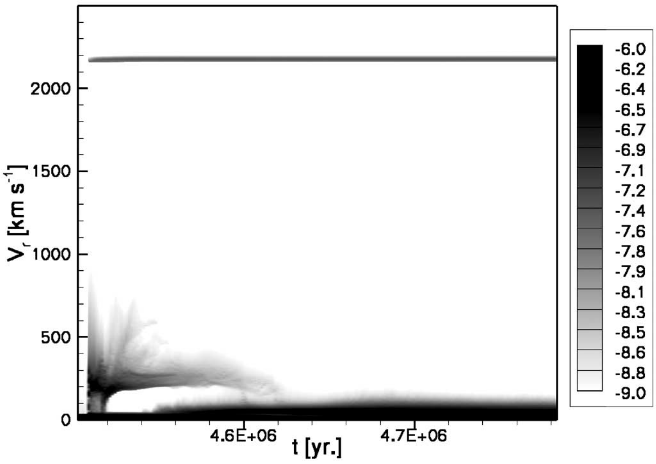

Fig. 2. – The column density as defined in eq. (1) in [g cm^{-2}] as a function of radial velocity. The zero velocity component is always present. The Wolf-Rayet wind component at 2200 km/s is visible during the entire Wolf-Rayet period. However, the 200 km/s component, caused by the Wolf-Rayet wind driven shell is short-lived.

Ray Burst went off, since a feature at intermediate velocity is clearly visible in the spectrum and can only be accounted for during the early Wolf-Rayet period. Generaly speaking, the more massive a star, the more time it spends as a Wolf-Rayet star (see Maeder and Meynet [4]). Therefore, a short lifetime as a Wolf-Rayet star would indicate that the progenitor of this particular Gamma-Ray burst was a star of no more than about 25–30 $M_\odot$ on the main sequence, which are the lowest mass stars that can still produce a Wolf-Rayet star. More massive stars would remain Wolf-Rayet stars too long ($\geq 10^5$ years) for the intermediate velocity line to be visible in the afterglow absorption spectrum.

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