GRB 021004: A Possible Shell Nebula around a Wolf-Rayet Star Gamma-Ray Burst Progenitor

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Abstract. The rapid localization of GRB 021004 by the HETE-2 satellite allowed nearly continuous monitoring of its early optical afterglow decay, as well as high-quality optical spectra that determined a redshift of \( z = 2.328 \) for its host, an active starburst galaxy with strong Lyman-\( \alpha \) emission and several absorption lines. Spectral observations show multiple absorbers blueshifted by up to 3,155 km s\(^{-1}\) relative to the host galaxy Lyman-\( \alpha \) emission. We argue that these correspond to a fragmented shell nebula, gradually enriched by a Wolf-Rayet wind over the lifetime of a massive progenitor bubble. In this scenario, the absorbers can be explained by circumstellar material that have been radiatively accelerated by the GRB emission. Dynamical and photoionization models are used to provide constraints on the radiative acceleration from the early afterglow.

INTRODUCTION

Gamma-ray bursts (GRBs) have been a challenge for astronomers ever since their serendipitous discovery by the Vela satellites in the late 1960s [3]. However, evidence collected over the past six years now links “long-duration” (> 2 s) GRBs to the deaths of massive stars. Some of the clearest information about the nature of GRBs comes from the coincidence of the unusual GRB 980425 with SN 1998bw [6], and the discovery of the Type-Ic supernova, SN 2003dh, nearly simultaneous with GRB 030329 [13]. The temporal coincidence of these events proves that long-duration GRBs are associated with peculiar Type-Ic supernovae (SNe), and thus are a consequence of the evolution of massive stars [7]. The evidence also strongly supports the collapsar model for GRBs where a rotating massive star (typically a Wolf-Rayet star) undergoes core collapse to a black hole surrounded by an accretion disk wind [14].

While it is now generally accepted that some long-duration GRBs are associated with the deaths of massive stars, considerable uncertainty remains as to what the precise nature of the progenitor star is. Theories of stellar evolution suggest that massive stars lose a large fraction of their mass through strong stellar winds [2]. As a result, one expects to find a substantial amount of circumstellar material in the vicinity of long-duration GRBs. Indeed, observations of some GRB environments show compatibility with a wind-like medium [3]. There have also been reports of strong UV absorption lines in GRB afterglows with outflow velocities of up to 4,260 km s\(^{-1}\) [1, 11, 5]. We discuss how these observations can provide information on the GRB progenitor.
FIGURE 1. Outflowing Ly $\alpha$, Ly $\beta$, C IV, and Si IV absorbers in the GRB 021004 afterglow spectrum plotted in velocity space. As zero velocity we use the systemic redshift of the host galaxy $z = 2.328$. The dashed lines indicate blueshifted absorbers at 450, 990, and 3,155 km s$^{-1}$.

SPECTRAL OBSERVATIONS OF THE GRB 021004 AFTERGLOW

Possibly the best example of velocity shifts in GRB afterglows is the optical spectrum of GRB 021004, an active starburst galaxy with strong Ly-$\alpha$ emission and several absorption lines. Spectral observations of its afterglow revealed multiple blueshifted kinematic components at $z_{3A} = 2.323$, $z_{3B} = 2.317$, and $z_{3C} = 2.293$ with radial velocities of $\sim 450$, $\sim 990$, and $\sim 3,155$ km s$^{-1}$ relative to the systemic velocity of the host galaxy (Figure 1). The absorption components also show velocity widths broader than the expected thermal widths at the instrumental resolution, indicating internal motions within each component. Such velocity structure is highly unusual for large-scale absorbing material near or around the GRB host galaxy.

One is thus led to consider scenarios where the absorbers are closer to the GRB progenitor system (i.e., associated). Hot, massive stars generally have expanding material characterized by velocities of up to 3,000 km s$^{-1}$, which originates through the scattering of stellar radiation in the stellar wind. Radial outflows seen via blueshifted resonance lines are also a common trait of a large fraction of Seyfert galaxies [4]. These are thought to represent massive outflows of highly ionized gas from their active galactic nuclei. Although there are marked differences between Seyferts and GRBs, the similarities in their spectra may shed light on the physical conditions of the blueshifted components. Building off this premise, we explore a scenario where the absorbers in the GRB 021004 spectrum are the result of outflowing stellar material associated with the GRB progenitor.
SHELLS, FILAMENTS AND CLUMPS

One of the most interesting consequences of stellar evolution is that stellar-wind bubbles are intimately connected to the mass-loss history of their central star. On its way to the Wolf-Rayet phase, a main-sequence star is thought to evolve through a luminous blue variable (LBV) or red supergiant (RSG) stage. The slow winds (10–50 km s$^{-1}$) generated during the LBV or RSG phase expand into the interior of the main-sequence bubble until the mass driven by the wind is comparable to the mass of circumstellar material. This condition sets the characteristic radius of expansion $R$ roughly given by

$$ R = \sqrt{\frac{\dot{M} \tau}{n_0}} \text{ pc}. $$

where $\tau$ is wind lifetime in units of $10^6$ years, $\dot{M}$ is the mass-loss rate in units of $10^{-6} M_\odot$ yr$^{-1}$, and $n_0$ corresponds to the density of the surroundings in units of cm$^{-3}$.

Interestingly, stellar winds carry not only mass but kinetic energy into the ambient medium. Such injection of energy leads naturally to the formation of overdense shell nebulae (with expansion velocities $v \approx 40$ km s$^{-1}$) along the wind profile. Figure 2 shows the predicted physical structure of a shell nebula formed at the termination of a massive stellar wind. Soon after entering its Wolf-Rayet phase, a fast wind (1000–3000 km s$^{-1}$) starts sweeping the LBV or RSG material, eventually overtaking the main-sequence gas residing around the progenitor star. The combination of streaming winds and internal instabilities within the wind results in a complex morphology characterized by fragmented shells, filaments and clumps. Additional structure is likely to be introduced by wind-wind collisions in close-binary systems. But the basic picture is confirmed through the variety of morphologies observed in the surroundings of isolated Wolf-Rayet stars [9].
Apart from providing a complex circumstellar environment, a wind bubble configuration either isolated or in a close-binary system will contain a significant amount of mass from all past stellar phases. If GRBs are indeed formed by the death of massive stars, overdense stellar regions within the bubble may produce detectable spectral features in the optical afterglow. From the absence of N V and the presence of Ly α, Si IV and C IV, we inferred that the absorbing material in the GRB 021004 spectrum was dominated by He-burning and core nucleosynthesis products. Such composition is in good agreement with a massive late-type carbon-rich Wolf-Rayet star embedded inside an interstellar bubble, in which the Wolf-Rayet wind has gradually enriched the bubble interior. So far the argument is consistent with the abundances, but let us explore the kinematics.

PHOTOIONIZATION AND DYNAMICAL MODELS

As part of the analysis, we modeled the radiation environment in a wind bubble system following a GRB explosion using detailed photoionization models. The models are especially constructed to provide constraints on the physical conditions of blueshifted absorbers. For these particular simulations, we used the photoionization code IONIZEIT described in [10], which includes time-dependent photoionization processes taking place under a predetermined GRB afterglow ionizing flux. Perhaps the most dramatic outcome of the simulations is that material intrinsic to the GRB progenitor should be subjected to increasing velocity and gradual ionization.

In order to explain the absence of significant variability following the first afterglow spectrum, we concluded that radiation acceleration by bound-free transitions had to be most efficient in the early stages of the GRB [11, 12]. Figure 3 shows the predicted velocity profile for one set of initial conditions. Faster outflowing absorbers can be explained by nearby circumstellar material, while more distant absorbers will evolve slower. After final velocity is achieved the absorbers simply coast along. In particular, the simulations are able to reproduce the kinematics of GRB 021004 if high-density clouds are placed at a distance 0.3 < d < 30 pc from the GRB. The constraints from these models are consistent with the typical sizes of stellar winds around Wolf-Rayet stars in our Galaxy, and provide quite possibly the first direct spectral signature of circumstellar material around a GRB progenitor. They also lend support to the collapsar model for GRBs where a rotating massive star undergoes core collapse to a black hole [14].

CONCLUSIONS AND FUTURE WORK

Observations of the early afterglow of GRB021004 show multiple absorption features blueshifted by up to 3,155 km s\(^{-1}\) relative to the host galaxy of the GRB. The features may indeed have been caused by circumstellar material from a Wolf-Rayet progenitor wind located at a distance 0.3 < d < 30 pc from the GRB site that has been radiatively accelerated by the GRB afterglow emission. While at this stage we cannot distinguish between an isolated Wolf-Rayet star and a close-binary system, the observational data on GRB 021004 could be the first direct spectral signature of material in the surroundings
of a GRB. Our findings motivate the need to undertake intensive surveys for variable and accelerating resonance lines (C IV, Si IV, N V, and O VI), along with Ly $\alpha$ and lower ionization species. In addition to the observations, intensive numerical modeling is required to deal with the overionization that takes place when the progenitor gas is exposed to strong GRB emission. Lastly, we note that the advent of the Swift GRB mission (see [http://swift.gsfc.nasa.gov](http://swift.gsfc.nasa.gov)) should bring unique access to early multiwavelength observations of GRBs, which will provide a critical diagnostic tool for GRB progenitors.

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