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Spectroscopy of the optical afterglow of GRB 021004: Origin of the blue-shifted hydrogen lines(*)

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Summary. — We present spectra of the afterglow of GRB 021004 taken with WHT ISIS and VLT FORS1 at three epochs spanning 0.49–6.62 days after the burst. Alongside absorption lines from the host galaxy, we identify absorption in HI, SiIV and CIV with blueshifts of up to 2800 km s^{-1} from the explosion centre which we assume originates close to the progenitor. We investigate the origin of the outflowing material and evaluate various possible progenitor models, in particular a binary progenitor consisting of a Wolf-Rayet star and hydrogen-rich companion.

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1. – Introduction

GRB 021004 was detected by HETE-2 on 4th October 2002 [16]. The optical afterglow was caught very early, was unusually bright and rich in line features. Hence it is one of the most well-studied bursts. The spectrum is dominated by absorption lines from material at a wide range of distances from the explosion centre, including an apparent outflow, the origin of which remains unclear. We present spectra taken at both early and late times over the duration of the optical afterglow and discuss the origin of the spectral features, paying particular attention to the hydrogen contribution.

2. – Observations and results

The WHT spectra were taken on 2002 October 4, 23:52:60 UT, 11.78 hours after the burst — the earliest optical spectra of GRB 021004 taken by a 4-m class telescope,

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and October 6, 01:23:55 UT, 1.55 days after burst, with the ISIS spectrograph's blue (B300B) and red (R316R + GG495 filter) gratings. Exposures totalling 4000 s at epoch 1 and 4800 s at epoch 2 were taken with each grating. A third epoch observation was made with the VLT-Antu on 2002 October 11, 02:57:09 UT, 6.62 days after burst. The observations were made with the FORS1 instrument in the Longslit Spectroscopy mode. Six 1200 s exposures were taken with the 600B grism.

All species, except the intervening lines, have a component at $z = 2.327$, the highest redshift absorption system we observe, which we identify as the host galaxy redshift (system I). We identify H Lyα, SiIV and CIV absorption features at a further 2 redshifts (systems II and IV), and H Lyα and CIV at a fourth redshift (system III). If systems II–IV are an outflow, their observed velocities would be approximately 570, 2400 and 2800 km s^{-1} (as reported in [14], fig. 1). We measure column densities of $\log N \geq 14$, 14.0 ± 0.9 and $14.6 \pm 0.9\,\mathrm{cm}^{-2}$ for HI, SiIV and CIV, respectively. We find no significant variability in line equivalent widths (EW, within the 2σ errors, see [18]) between the 3 epochs. The EWs we measure are consistent with those reported for other spectra of this afterglow [12, 10, 11, 2]. For further details see Starling *et al.* [18].

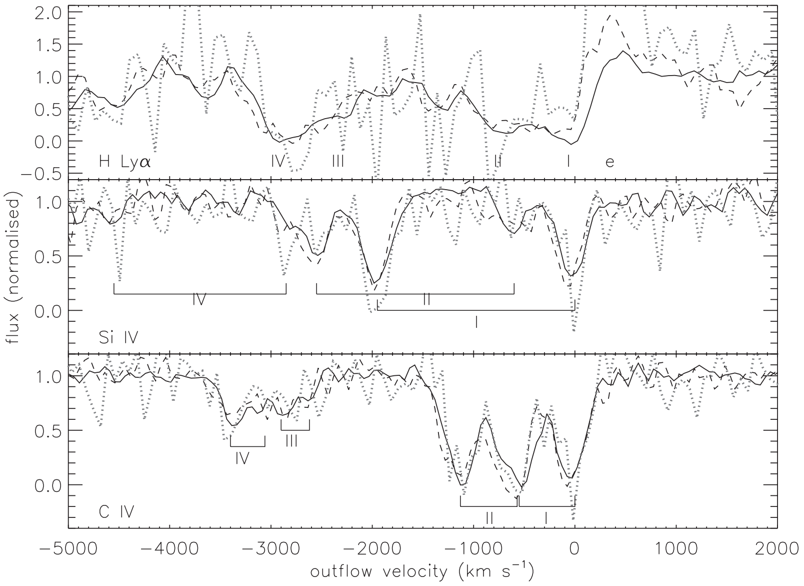

Fig. 1. – Outflow velocities of the SiIV, CIV (velocities plotted are for the longer wavelength components only) and H Lyα complexes with respect to the host redshift of $z = 2.327$. Epochs 1–3 are overlaid in black, dashed and grey-dotted lines respectively. The Lyα emission line (too large at epoch 3 to be shown fully on this plot) is labelled "e".

3. – Discussion

We interpret the lines at $z = 2.327$ as coming from within the host, but many parsecs from the explosion so that the absorber was not affected by the explosion or by the GRB progenitor. The blue-shifted lines we interpret as coming from the region affected by the explosion or the progenitor. The Lyα absorption could in principle come from either region, but since its velocity structure is identical to that of the high-ionisation lines of SiIV and CIV, and Lyβ absorption has also been observed with components spanning approximately the same velocity range [11], we interpret it as coming from the outflow close to the GRB. The origin of the observed outflow has been discussed by numerous authors, with several different suggestions including intervening systems, overdense regions (shells) and partial covering models. However, we limit our discussion to the stellar wind models, since the focus here is on the origin of the hydrogen outflow.

3˙1. *A single star as progenitor.* – Perhaps the most natural origin for the blue-shifted absorption features is in a stellar wind, given that a GRB-SN connection has been firmly established (*e.g.*, GRB 980425, SN1998bw [5] and GRB 030329, SN2003dh [7, 17]). A $1/r^2$ density profile is inferred from the early-time light curve [9] suggesting a stellar wind circumburst medium. The highest outflow velocity observed is $2800\,\mathrm{km\ s^{-1}}$ which, if interpreted as the terminal velocity of a stellar wind, implies the star is a Wolf-Rayet (WR) star [11,15]. Such stars evolve to type-Ib supernovae and are characterised by large mass loss rates in high velocity, optically thick stellar winds. The 3 outflow velocities observed in this afterglow could correspond to the fast WR wind, a slower wind from an earlier evolutionary phase and the slow bubble moving into the ISM or mixing of winds from different phases as demonstrated in simulations of massive star evolution [19].

3˙2. *The hydrogen problem.* – A major challenge for the interpretation of these spectra is the presence of hydrogen in the spectra with approximately the same velocity structure as SiIV and CIV, strongly suggesting that significant amounts of neutral hydrogen are present in the stellar wind with a column of $\geq 10^{14}\,\mathrm{cm^{-2}}$. This is not usual for a WR wind. A WR star will once have been hydrogen-rich, so the outer wind can have hydrogen, but its velocity structure will not be the same as the later, hydrogen-deficient wind. 21-cm measurements have revealed HI shells around WR stars, *e.g.*, WR 102 [6], but with low expansion velocities of $\sim 50\,\mathrm{km\ s^{-1}}$.

In most Galactic WR stars H is not detected at all. However in the Small Magellanic Cloud (SMC) a large fraction, if not all single WN-types (nitrogen-rich WR stars) show hydrogen in their spectra [3]. This was an unexpected find, leading to the conclusion that the WN population in the SMC is fundamentally different from that of the Milky Way. So in the SMC, where the metallicity is low causing less severe mass loss, massive stars can remain H-rich in the WR phase. But the strength of CIV and SiIV and non-detection of nitrogen (NIV and NV in particular) in GRB 021004 suggests we are seeing the wind of a WC-type (carbon-rich) WR star rather than a WN-type, *e.g.*, [11,15], thought to be the last evolutionary stage of the WR phase. On the other hand we do not detect CIII $\lambda1247$ which is a strong UV feature of WC-types, *e.g.*, FUSE [20] and IUE [13].

3˙3. *A binary system progenitor.* – So, whilst a WR star is the obvious choice to explain the blue shifted absorption complexes, this is difficult to reconcile with the large amount of HI observed, particularly at very high velocities. This conundrum leaves us with few options. Either carbon-rich WR stars at high redshift are very different to those in our local group and are able to retain a large fraction of their hydrogen, or the hydrogen comes from an external source — perhaps in a companion star wind.

Let us consider a WR star in a close binary with a hydrogen-rich main-sequence star. Even for an O star companion, the momentum loss rate $\dot{M}v_\infty$ of the WR star exceeds that of the companion, and so the wind velocity structure at distances much greater than the binary separation will be dominated by the WR star. However, a few to 10% of the mass will come from the H-rich companion, and when mixed in can cause the observed phenomenon of H Lyα emission accompanying otherwise typical WR lines. So what is the probability that a WR star is in a binary with an O star? Theoretical binary frequency limits for WR+O systems are $\geq 0.41\pm0.13$ for the LMC and $\geq 0.98\pm0.32$ for the SMC [3], assuming a mass loss — metallicity relation of $\dot{M} \propto Z^{0.5}$ and excluding rotation effects. The same authors find significantly lower *observed* fractions of $\sim 40\%$ [3, 4]. Various observed values suggest that the binary frequency of WR stars is identical to that of their progenitors and independent of metallicity.

There is also the possibility that the WR star is in a binary with a less massive star that provides the observed hydrogen. The probability of a WR star having a lower-mass companion (perhaps 1–3 $M_{\odot}$) is even less well known, because such low-luminosity companions are difficult to detect. The only evidence for the existence of such binaries is the population of soft X-ray transients in our Galaxy, which consist of a black hole orbited closely by a low-mass star. Their ancestors must have been WR stars with a low-mass main-sequence binary companion. It has been suggested that these systems produce a GRB at the time of black hole formation [8]. One consequence of this wind-mixing model is that hydrogen may only be mixed in to the WR wind within some angle from the orbital plane of the binary. This will constrain our viewing angle to the system to being not too far out of the orbital plane. For an O star, still having a relatively strong wind, this is not a severe constraint, but for a low-mass star with a very weak wind, the system would have to be viewed at or close to edge-on. However, an edge-on viewing angle appears inconsistent with the collapsar model for GRBs, which predicts that the jets emerge from the poles of the progenitor star.

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