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The very high-z GRB 210905A

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We present the follow-up of the very high-redshift GRB 210905A and its luminous X-ray and optical afterglow. Our analysis covers the prompt and afterglow emission from a few minutes up to 20 Ms after burst. Its afterglow is among the most luminous ever observed, and, in particular, it is the most luminous known in the optical at $t \gtrsim 0.5$ d in the rest frame. Its spectral energy distribution is in agreement with slow cooling in a constant-density environment within the standard fireball theory. Our analysis reveals the presence of a jet break at $\sim 46.2 \pm 16.3$ d (6.3 ± 2.2 d rest-frame). This break is very clear in the X-ray light curve but it is hidden in the H band due to a constant contribution from the host galaxy, which is only the fourth but the brightest GRB host at $z > 6$ known to date. The half-opening angle of $8.4^\circ \pm 1.0^\circ$ is the highest ever measured for a $z \gtrsim 6$ burst, but within the range covered by closer events. The resulting collimation-corrected gamma-ray energy release of $\simeq 1 \times 10^{52}$ erg is also among the highest ever measured and the highest in the Konus-*Wind* catalogue. The total jet energy is too large to be sustained by a standard magnetar, and it suggests that the central engine of this burst was a newly formed black hole. Finally, we show that the energetics and luminosity of both GRB 210905A and its afterglow are consistent with those of less distant bursts, suggesting that they share the same powering mechanisms and progenitors.

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1. Introduction

Long GRBs, with gamma-ray emission generally longer than 2 s **in the observer frame**[1], originate from the explosions of very massive stars [2–4]. So far, out of the ≈ 555 GRBs with a well-constrained spectroscopic redshift (as of 20 July 2022), only five have been detected[1] at $z \gtrsim 6$. **An additional four have very low signal-to-noise spectra or photometric redshifts.** Like the best studied GRBs at redshift $z \lesssim 1$, for which it is also possible to observe the associated supernova and thus infer the massive star origin, very-high redshift GRBs follow the $E_{\mathrm{peak},z} - E_{\mathrm{iso}}$ and $E_{\mathrm{peak},z} - L_{\mathrm{iso}}$ correlations ['Amati' and 'Yonetoku' correlations; 5, 6].

In the following we highlight the results presented in [7], where the follow-up of the bright GRB 210905A is presented in full fashion. This is the tenth burst with redshift $z \gtrsim 6$ detected in the last 16 years (**considering the photometric redshift cases too**). It was detected by the *Neil Gehrels Swift Observatory* [8, *Swift* hereafter] and Konus-*Wind* [9]. X-ray as well as optical and near-infrared (NIR) follow-up observations of its bright afterglow led us to determine a spectroscopic redshift of $z = 6.312$ [refined with respect to 10]. Throughout this work, the flux density of the afterglow is described as $F_\nu(t) \propto t^{-\alpha}\nu^{-\beta}$. A ΛCDM cosmological model with $\Omega_M = 0.308$, $\Omega_\Lambda = 0.692$, and $H_0 = 67.8$ km s^{-1} Mpc^{-1} [11] has been assumed for calculations. All data are in the observer frame and 1σ errors are used throughout the paper, unless otherwise specified.

2. The optical and NIR afterglow

The last XRT detection, together with the late observation by the *Chandra* X-ray Observatory [12], shows that the light curve breaks at ∼ 30 d (Fig. 1). However, the NIR light curve, taken up to 232 d in the observer frame, shows no simultaneous steep break**, but is dominated by a source which is elongated in the NNE-SSW direction and has a FWHM of $0.''3\times0.''4$, larger than the FWHM of field stars** ($0.''25 \pm 0.''02$)**, indicating that this is a galaxy** (Figure 1). In [13] we show that the break in X-rays is indicative of a jet break with the last NIR detection likely dominated by the host galaxy. We modelled jointly the H-band and X-ray light curves after 0.7 d with a smoothly broken power-law [14]: $F = (F_1^\kappa + F_2^\kappa)^{-1/\kappa}$, with $F_{\mathrm{x}} = f_{\mathrm{break}}(t/t_{\mathrm{break}})^{-\alpha_x}$, f_{break} being the flux density at break time t_{break}, κ the break smoothness parameter, and the subscripts $1, 2$ indicate pre- and post-break, respectively. In [13], we adopted the jet model (with sideways expansion) and slow cooling [15, 16] and find that the data is best modelled by the pre-jet-break index values $\alpha_{1,\mathrm{opt}} = 0.9$ and $\alpha_{1,\mathrm{X}} = 1.15$. In the H-band we have considered an additional constant contribution from the host. **We have also tested whether a single power-law without an additional constant component can best fit the observations. We stress that in doing so we do not consider the evidence that a galaxy lies at the position of the afterglow in the HST observation. The single power-law can fit the optical data, but it does not fit well the last 2 X-ray points. Indeed, a Bayesian Criterion information statistical criteria indicates that the best model is the one with the jet-break and constant contribution from the host galaxy. The modelling is shown in the right panel of Figure 1.** The best-fit break time in the observer frame is $t_{\mathrm{jet}} = 46.2 \pm 16.3$ d with the host galaxy having $H_{AB} = 25.8 \pm 0.2$ mag.

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[1] See `http://www.mpe.mpg.de/~jcg/grbgen.html`

The likely discovery of the host of GRB 210905A is a rare discovery, given that up to July 2022 only three hosts (those of GRBs 050904, 130606A, and 140515A) had been confirmed at $z > 6$ [17]. The rest-frame luminosity $m_{1900\text{Å}} \sim -21$ mag is consistent with the characteristic magnitude at 1600 Å of $z = 6-7$ galaxies [e.g. 18] and it is also larger than that of other GRB hosts. Such a rest-frame UV luminosity corresponds to a SFR $\sim 16\,M_{\odot}\,\text{yr}^{-1}$ [19], similar to the other three known hosts at $z \gtrsim 6$ [17], although it is more luminous in the UV than galaxies that contribute the most to the star-formation at these redshifts. It would also be bright enough to be characterised via spectroscopy with the *JWST* [e.g. 17], providing one of the first and better estimates on the SFR, metallicity and dust content of a GRB host at very high redshift.

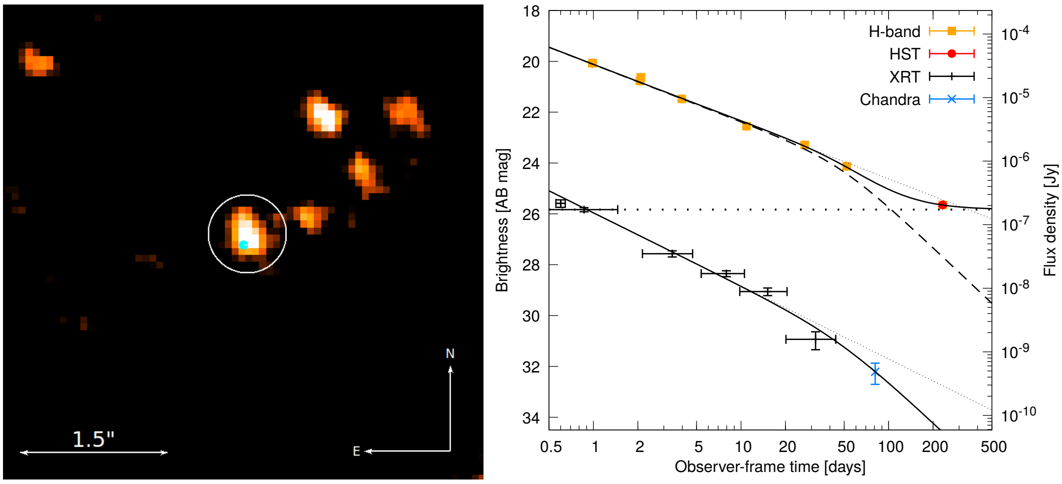

Figure 1: ***Left:*** Zoom-in to the $5'' \times 5''$ region centred on the afterglow using the he *HST*/*F*140*W* image obtained 232 days after the GRB trigger. The cyan point indicates the ALMA localisation of the afterglow. The host galaxy, highlighted with a white circle, lies at the afterglow position. The radius of the circle is that of the aperture used for photometry. Several other sources lie nearby, which are possibly responsible for the foreground intervening system found in X-shooter spectra at $z = 2.8$ with high-EW Mg II absorption [see 20]. ***Right:*** Observer-frame *H*-band (orange) and X-ray (black) light curves. XRT data has been re-binned to have at least 50 counts per bin. The late Chandra detection indicates a steeper decay. Solid lines show the joint fit with a smoothly-broken power-law, assuming common achromatic breaks. The dashed line shows the *H*-band light curve without constant component. The horizontal dotted line shows the modeled *H*-band contribution of the host, dominating the HST observation (red) shown in the left panel. **The dotted lines show the joint fit with a single power-law.**

2.1 Collimation–corrected energy and central engine

Knowing the value of the jet opening angle is crucially important because it enables us to estimate the 'true', collimation-corrected, energetics of the outflow [21, 22]. In [7], following [23], we find an angle $\theta_{\text{jet}} = 0.147 \pm 0.017$ rad, or 8.41 ± 0.97 degrees, using the isotropic energy $E_{\gamma,\text{iso}} = 12.7 \times 10^{53}$ found in our analysis of the Konus-*Wind* and *Swift*/BAT data [7]. This value lies in the top ~7% for the KW sample of 338 GRBs with known redshifts [24, 25]. The 'true' gamma-ray energy of the jet is $E_{\gamma} = E_{\gamma,\text{iso}}\,(1-\cos(\theta_{\text{jet}})) \simeq 1 \times 10^{52}$ erg. Assuming an efficiency $\eta = E_{\gamma,\text{iso}}/E_{\text{total,iso}} = 0.2$, we can estimate the 'total collimated energy' of the jet to be $E_{\text{total}} \simeq E_{\gamma}/\eta \simeq 3-8 \times 10^{52}$ erg.

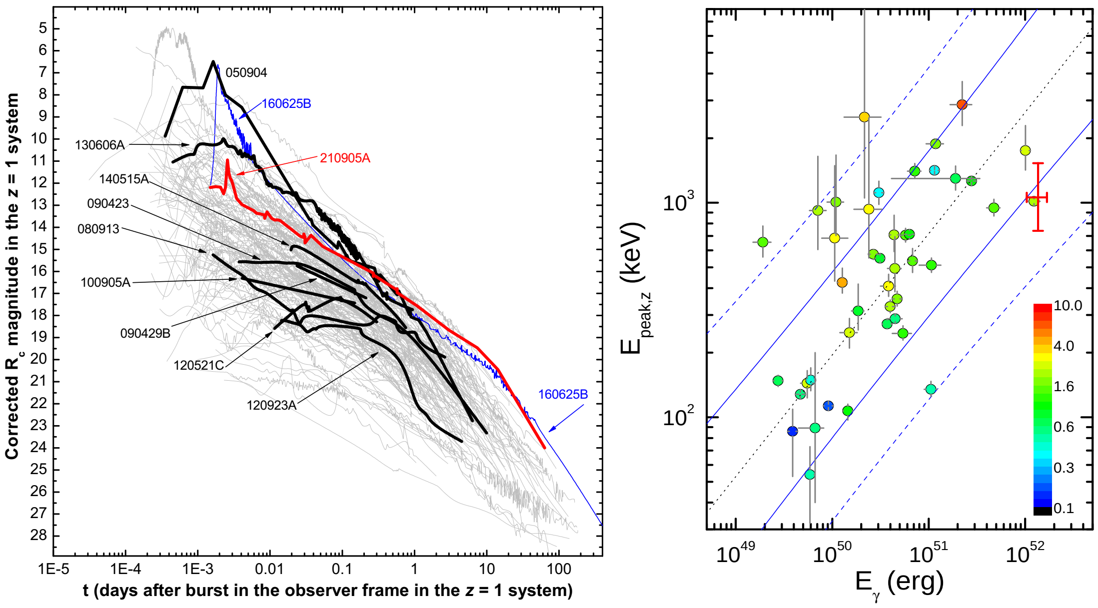

Figure 2: ***Left:*** The optical afterglow compared to a sample of optical afterglows which have all been shifted to $z = 1$, from Kann et al., in preparation [see also 34–36]. Light grey are LGRBs, thicker black lines GRBs with redshifts $z \gtrsim 6$. The afterglow of GRB 210905A is the most luminous afterglow ever detected at moderately late times, before finally decaying faster than that of GRB 160625B (blue line). For this light curve, the host component has been subtracted. The late-time break in the light curve is clearly visible. ***Right:*** $E_\gamma - E_{\rm peak,z}$ diagram. The colour of each data point represents the burst's redshift. GRB 210905A follows the "Ghirlanda" relation (plotted together with its 68% and 90% prediction intervals). GRB 210905A has the highest E_γ in the Konus-Wind catalogue.

The most widely discussed models of central engines of GRBs are accreting magnetars or accreting black holes. A standard neutron star has a maximum rotation energy below 10^{53} erg [26, 27], therefore our analysis allows us to disfavour a standard magnetar as central engine of this GRB, unless one assumes absurd efficiencies. On the other hand, black holes of mass $M \sim 3\,M_\odot$ possess rotational energies up to $E_{\rm rot} \sim 10^{54}$ erg [e.g. 28]. An energy budget of $\sim 10^{53}$ erg (like the one we have estimated for GRB 210905A) can be extracted via the Blandford-Żnajek mechanism [29], thereby suggesting that the central engine of this GRB was a rotating black hole.

At high redshift the Universe is expected to be populated by pop-III stars, the first stars that formed out of gas clouds of pristine composition. All models [e.g. 30–32] predict pop-III GRBs to be very energetic events, and with very long intrinsic durations of 10^4 s, making their detection possible even at the highest redshifts. In Figure 2 we compare the collimated energy E_γ of GRB 210905A with the KW sample of 43 long GRBs with reliable jet-break time estimates [24, 25]. GRB 210905A has the highest E_γ in the Konus-*Wind* catalogue. Considering the uncertainty on the collimation-corrected energy, GRB 210905A lies just outside the 1σ confidence level of the $E_{\rm peak,z} - E_\gamma$ ['Ghirlanda' relation, see 22, 33] and thus well compatible with this relation [as well as Amati and Yonetoku relations, see 7]. Therefore, GRB 210905A, although extremely bright, is not separated markedly from other classical GRBs at low redshift and no features of this event point to a different origin, like from a pop-III star.

3. Conclusions

GRB 210905A was a long burst at redshift $z = 6.312$. Among the sample of ten $z \gtrsim 6$ GRBs known to date, GRB 210905A stands out, having the highest isotropic energy release and among the highest afterglow luminosity at late times. The large collimated total energy budget of $E_{\mathrm{total}} > 10^{52}$ erg likely excludes a magnetar as a central engine. The Kerr black hole is the preferred scenario. In late *HST* imaging, we find evidence for an underlying host, which is the fourth and brightest GRB host at $z > 6$ detected to date. GRB 210905A follows the Ghirlanda relation, thus the origin of GRB 210905A is likely similar to low-redshift GRBs. GRBs at z > 6 are just the tip of the iceberg of a larger population that future proposed missions promise to uncover.

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