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Discovery and identification of the very high redshift afterglow of GRB 050904

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In 2000, Lamb and Reichart[1] predicted that γ-ray bursts (GRBs) and their afterglows occur in sufficient numbers and at sufficient brightnesses at very high redshifts ($z > 5$) to eventually replace quasars as the preferred probe of element formation and reionization in the early universe and to be used to characterize the star-formation history of the early universe, perhaps back to when the first stars formed (see also Refs. [2,3]). Here we report the discovery of the afterglow of GRB 050904 and the identification of GRB 050904 as the first very high redshift GRB.[4−7] We measure its redshift to be $6.39^{+0.11}_{-0.12}$, which is consistent with the reported spectroscopic redshift (6.29 ± 0.01).[8] Furthermore, just redward of Lyα the flux is suppressed by a factor of three on the first night, but returns to expected levels by the fourth night. We propose that this is due to absorption by molecular hydrogen that was excited to rovibrational states by the GRB's prompt emission, but was then overtaken by the jet. Now that very high redshift GRBs have been shown to exist, and at least in this case the afterglow was very bright, observing programs that are designed

to capitalize on this science will likely drive a new era of study of the early universe, using GRBs as probes.

At 01:51:44 UT on September 4, 2005, Swift's Burst Alert Telescope (BAT) detected GRB 050904 and 81 seconds later a $4'$-radius localization was distributed to observers on the ground. Swift's X-Ray Telescope (XRT) automatically slewed to the BAT localization and 76 minutes after the burst a $6''$-radius XRT localization was distributed.[9] We began remote observations with the 4.1-m Southern Observatory for Astrophysical Research (SOAR) telescope atop Cerro Pachon in Chile beginning 3.0 hours after the burst. Using the Ohio State InfraRed Imager/Spectrometer (OSIRIS) in imaging mode, we discovered a relatively bright ($\mathrm{J} \approx 17.4$ mag) and fading near-infrared (NIR) source within the XRT localization (Fig. 1).[4]

Simultaneously, we also observed the XRT localization at visible wavelengths with three telescopes: one of the six 0.41-m Panchromatic Robotic Optical Monitoring and Polarimetry Telescopes (PROMPT) that we are building atop Cerro Tololo, which is only 10 km away from Cerro Pachon; the 60-inch telescope at Palomar Observatory in California; and the 3.5-m telescope at Calar Alto Observatory in Spain. None of these telescopes detected the afterglow to relatively deep limiting magnitudes[4,10] (Fig. 1), nor did the 0.30-m Burst Observer and Optical Transient Exploring System (BOOTES) 1B telescope in El Arenosillo, Spain, which began imaging the field only 2.1 minutes after the burst.[11] This implied that the GRB either occurred at a very high redshift or that it was very heavily extinguished by dust.[4]

We then ruled out the extinction hypothesis by obtaining longer-wavelength NIR observations with SOAR that same night: In the NIR, the spectral index of the afterglow is $-1.25^{+0.15}_{-0.14}$; however, the spectral index between NIR and visible wavelengths is steeper than -5.9 (Fig. 2). This is too sharp of a transition to be explained by dust extinction.[12] Consequently, we identified GRB 050904 as a very high redshift GRB and constrained its redshift to be $6 \lesssim z \lesssim 8$.[5,6] We then obtained shorter-wavelength NIR detections with SOAR the following night, from which we narrowed this range to its lower end: $z \approx 6$.[7]

Our photometric redshift was later confirmed by two other groups: a photometric redshift that was obtained with one of the 8.2-m Very Large Telescopes[13] and a spectroscopic redshift of 6.29 ± 0.01 that was obtained with the 8.2-m Subaru telescope.[8]

Our global monitoring campaign spanned four nights and also included the 8.1-m Gemini South (Fig. 1), 3.8-m UKIRT, and 3.0-m IRTF telescopes (Tab. 1). Between $\approx$3 hours and $\approx$0.5 days after the burst, the fading of the afterglow appears to be well described by a power law of index $-1.36^{+0.07}_{-0.06}$[5,6] However, after this time the fading appears to have slowed to a temporal index of $-0.82^{+0.21}_{-0.08}$.[7,14,15] A single power law description is ruled out at the 3.7σ credible level. One possible explanation is that our initial SOAR observations caught the tail end of a reverse shock that had been stretched out in time by a factor of 7.29 due to cosmological time dilation. Another possibility is that we are undersampling a light curve that is undergoing temporal variations, such as in the afterglows of GRBs 021004 and 030329.

Using all of our photometry except for a Z-band ($0.84 - 0.93$ μm) measurement from the first night (see below), we refine our earlier measurement of the redshift, again by assuming negligible emission blueward of Lyα (Fig. 2): We measure $z = 6.39^{+0.11}_{-0.12}$, which is consistent with the reported spectroscopic redshift. For $H_0 = 71$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.27$, and $\Omega_\Lambda = 0.73$,[16] this corresponds to about 900 million years after the Big Bang, when the universe was about 6% of its current age. The next most distant GRB that has been identified occurred at $z = 4.50$,[17] which was about 500 million years later when the universe was about 10% of its current age.

The Z-band measurement, which was obtained with UKIRT 11 hours after the burst, is a factor of three below the fitted model (Fig. 3). We have carefully modeled the spectral responses of the filter and of the detector and have checked the magnitudes of other sources in the field against similar z$'$-band measurements that we obtained with Gemini South 3.2 days after the burst (Tab. 1). This appears to be real and corresponds to a factor-of-three suppression of the flux between source-frame 1270 Å and Lyα $\approx$0.5 days after the burst. However, there was negligible suppression of the flux redward of source-frame 1600 Å, which is again too sharp of a transition to be explained by dust extinction.[12] Furthermore, by $\approx$3 days after the burst this signature had disappeared completely. We propose that this is due to absorption by molecular hydrogen that was excited to rovibrational states by the GRB's prompt emission,[18] but then overtaken by the jet. This implies a column density of molecular hydrogen along the line of sight of $>10^{18} - 10^{19}$ cm^{-2} [18] and a density of $\sim$200 cm^{-3} (Fig. 3), which is consistent with a molecular cloud environment.[19]

One of the most exciting aspects of this discovery is the brightness of the afterglow: Extrapolating back to a few minutes after the burst, the afterglow must have been exceptionally bright redward of Lyα for the robotic 0.25-m TAROT telescope to detect it in unfiltered visible-light observations.[20] Extrapolating our J-band light curve back to these times yields J $\sim 11 - 12$ mag. This suggests that by pairing visible-light robotic telescopes with NIR robotic telescopes, and these with larger telescopes that are capable of quick-response NIR spectroscopy, all preferably at the same site, at least some very high redshift afterglows will be discovered, identified, and their NIR spectrum taken while still sufficiently bright to serve as an effective probe of the conditions of the early universe.[21]

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Date (UT)	Mean Δt	Filter	Magnitude[a]	Telescope
Sep 4.0795	2.80 min	R	>18.2	0.30-m BOOTES-1B
Sep 4.0821	6.46 min	R	>18.3	0.30-m BOOTES-1B
Sep 4.0868	13.22 min	R	>19.2	0.30-m BOOTES-1B
Sep 4.0956	25.95 min	R	>19.5	0.30-m BOOTES-1B
Sep 4.1151	53.96 min	R	>19.9	0.30-m BOOTES-1B
Sep 4.1535	109.30 min	R	>21.0	3.5-m Calar Alto
Sep 4.206	3.07 hr	J	17.36 ± 0.04	4.1-m SOAR
Sep 4.213	3.25 hr	J	17.35 ± 0.04	4.1-m SOAR
Sep 4.220	3.42 hr	J	17.61 ± 0.04	4.1-m SOAR
Sep 4.248	4.08 hr	z	>18.8	60-inch Palomar
Sep 4.355	6.66 hr	R	>22.3	60-inch Palomar
Sep 4.366	6.91 hr	[b]	>20.1	0.41-m PROMPT-5
Sep 4.390	7.49 hr	J	18.66 ± 0.15	4.1-m SOAR
Sep 4.402	7.78 hr	K_s	16.77 ± 0.07	4.1-m SOAR
Sep 4.416	8.12 hr	i	>21.1	60-inch Palomar
Sep 4.486	9.79 hr	H	18.17 ± 0.06	3.8-m UKIRT
Sep 4.488	9.86 hr	J	19.02 ± 0.06	3.8-m UKIRT
Sep 4.502	10.18 hr	K	17.38 ± 0.06	3.8-m UKIRT
Sep 4.518	10.57 hr	K′	17.55 ± 0.03	3.0-m IRTF
Sep 4.551	11.35 hr	Z	22.08 ± 0.16	3.8-m UKIRT
Sep 4.565	11.69 hr	J	19.25 ± 0.07	3.8-m UKIRT
Sep 5.198	26.90 hr	Y	20.42 ± 0.26	4.1-m SOAR
Sep 5.246	28.03 hr	J	20.16 ± 0.17	4.1-m SOAR
Sep 5.322	29.87 hr	I_c	>20.2	0.41-m PROMPT-3 + 0.41-m PROMPT-5
Sep 6.30	2.22 day	J	20.60 ± 0.23	4.1-m SOAR
Sep 6.35	2.27 day	Y	20.98 ± 0.34	4.1-m SOAR
Sep 7.21	3.13 day	i′	>25.4	8.1-m Gemini South
Sep 7.23	3.15 day	r′	>26.5	8.1-m Gemini South
Sep 7.24	3.16 day	z′	23.36 ± 0.14	8.1-m Gemini South

[a] Upper limits are 3σ.

[b] Unfiltered, calibrated to R_c.

Table 1. Observations of the afterglow of GRB 050904. We calibrated the i′r′z′ measurements using stellar SDSS sources and derived R_cI_c field calibrations from the SDSS field calibrations. We obtained $YJHK_sK$ field calibrations using SOAR and ZJHK field calibrations using UKIRT. The JHK field calibrations are in agreement with each other and with 2MASS. The UKIRT WFCAM Z bandpass was designed to match the effective wavelength of the SDSS z′ bandpass (0.876 vs. 0.887 μm), but with a rectangular profile. The standard deviation of the magnitude differences for all stellar SDSS sources in the UKIRT Z and Gemini South z′ fields is only 0.064 mag. When converting from magnitudes to spectral fluxes, we used the correct zero points for Z and z′, respectively. When fitting to these spectral fluxes, we used the actual UKIRT WFCAM Z and Gemini South GMOS-S z′ bandpasses. Consequently, we conclude that the factor of three deficit that we measure in the Z band relative to the fitted model 11 hours after the burst is real.

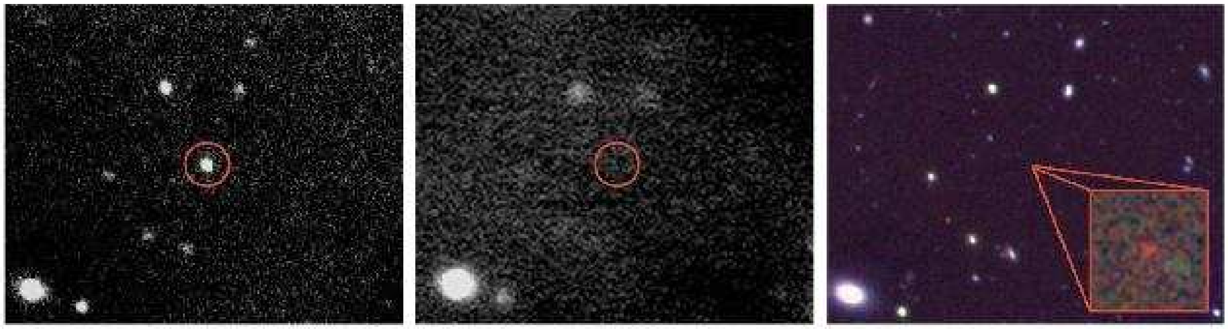

Figure 1. *Left panel:* NIR discovery image of the bright (J = 17.36 ± 0.04 mag) afterglow of GRB 050904 from 4.1-m SOAR atop Cerro Pachon, Chile. *Middle panel:* Near-simultaneous non-detection of the afterglow at visible wavelengths (unfiltered, calibrated to $R_c > 20.1$ mag) from one of the six 0.41-m PROMPT telescopes that we are building atop Cerro Tololo, which is only 10 km away from Cerro Pachon. *Right panel:* Color composite (riz) image of the afterglow 3.2 days after the burst from 8.1-m Gemini South, which is also atop Cerro Pachon.

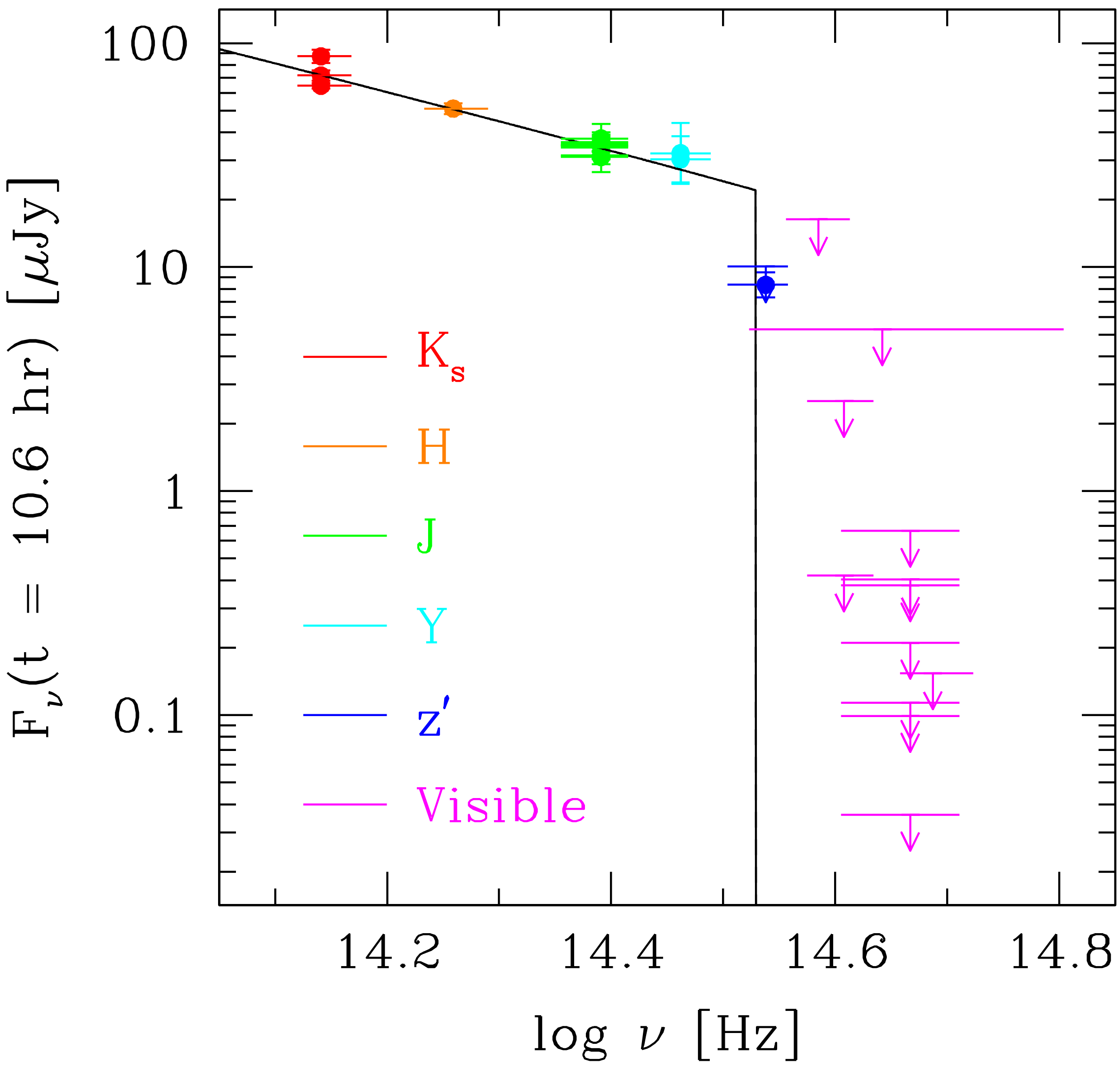

Figure 2. Spectral flux distribution of the afterglow of GRB 050904 scaled to 10.6 hours after the burst and our best-fit model: a power-law spectrum with negligible emission blueward of Lyα. Shallower power-law spectra can be obtained with the addition of source-frame dust, but this alone cannot explain the sharp drop in and blueward of the z′ band.[12] We take Galactic $E(B-V) = 0.060$ mag.[22]

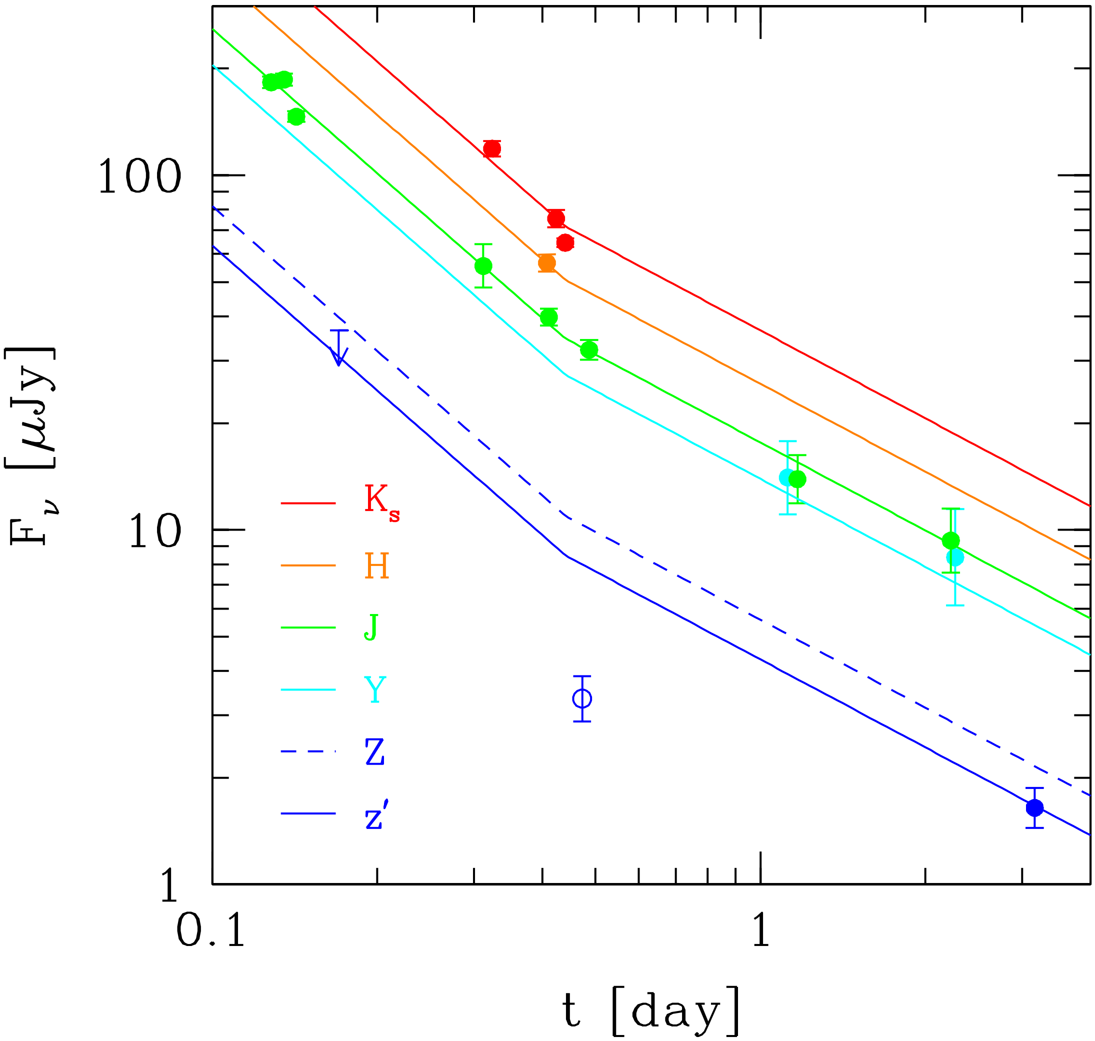

Figure 3. NIR and z′-band light curves of the afterglow of GRB 050904 and our best-fit model. A single power law description is ruled out at the 3.7σ credible level. Following the formalism of Frail et al.,[23] given GRB 050904's redshift and fluence[24] the non-detection of a jet break in the light curve prior to 3.2 days after the burst implies that the opening/viewing angle of the jet is $\gtrsim$2.6° and that the total energy that was released in γ rays is $\gtrsim 4.0 \times 10^{50}$ erg. Finally, the Z-band measurement (unfilled circle) is a factor of three below the fitted model, but this appears to be real. If due to absorption by excited molecular hydrogen as we propose, in this wavelength range a factor-of-three supression of the flux implies that the column density of excited molecular hydrogen in front of the jet at $\approx$11 hours after the burst in the observer frame is $N(H_2) \sim 3 \times 10^{18}$ cm^{-2}.[18] Consequently, this absorption signature should disappear by the time that the jet travels an additional distance $N(H_2)/n(H_2)$. The distance that the jet travels as a function of observer-frame time t_{obs} is given by $2\gamma^2(t_{obs})ct_{obs}/(1+z)$, where for GRB 050904 $\gamma(t_{obs}) \approx 30n^{-1/8}(t_{obs}/11\,\mathrm{hr})^{-3/8}$ [25,24] and n is the overall density of the medium. Consequently, the jet should overtake the region of excited molecular hydrogen at $t_{obs} \sim 11[1 + 10n^{1/4}/n(H_2)]^4$ hours. For $n^{4/3}(H_2)/n^{1/3} \sim 200$, $t_{obs} \sim 1$ day after the burst. Absorption by excited molecular hydrogen might also have been seen in the afterglow of GRB 980329.[26,27,18]