

# Gamma-ray burst has highest redshift yet seen

Bursts signaling the collapse of stars more than 13 billion years ago should elucidate early star formation and the cosmic reionization it engendered.

On 23 April, NASA's *Swift* orbiter detected the most distant and therefore earliest stellar object ever seen.<sup>1</sup> With a record redshift  $z$  of 8.26, the gamma-ray burst recorded by *Swift* is presumed to manifest the collapse of a rapidly spinning massive star—a collapsar—to a black hole about 625 million years after the Big Bang. In fact, GRB090423 is earlier than anything yet observed, at any electromagnetic wavelength, except the cosmic microwave background.

No redshift as high as 7 has ever been confirmed for a galaxy or quasar, or for any previous GRB. (Supernovae, not in the same league, are rarely seen with  $z$  beyond 2.) But typical GRBs are luminous enough to be detectable at least out to  $z = 20$ , corresponding to 180 Myr after the Big Bang—if there were any back then. Harvard University theorist Avi Loeb has been arguing for a decade that GRBs beyond  $z = 7$  would be excellent probes of the earliest generations of stars and of the cosmic reionization of intergalactic hydrogen that their UV emission began.

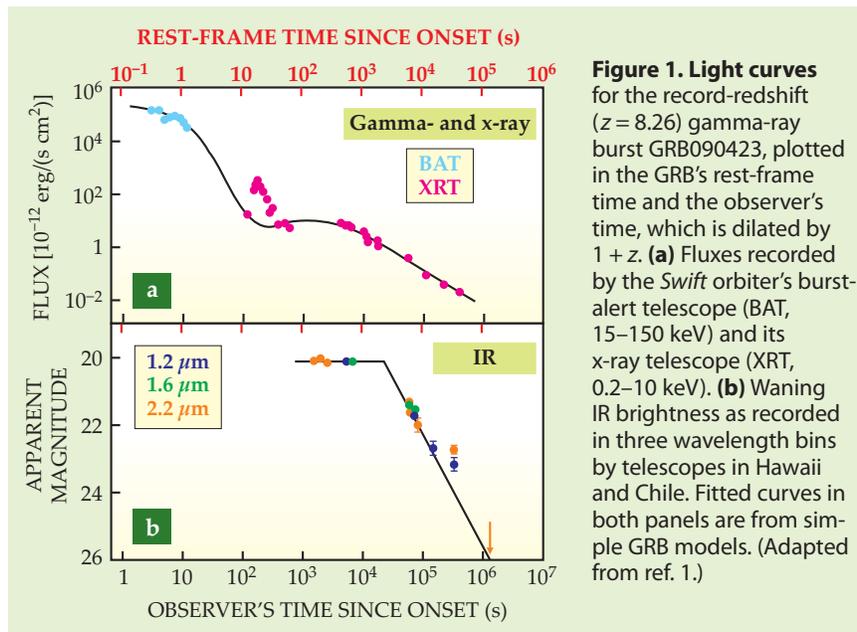
Aside from record distance and the dimming, redshifting, and  $1 + z$  time dilation that go with it, GRB090423 looks like an unremarkable representative of the majority class of latter-day GRBs, which are attributed to collapsars (see PHYSICS TODAY, August 2005, page 21). Thus we learn that such stars already

existed at 0.6 Gyr, and we begin to learn something of their formation rate in that early epoch. (The minority class of GRBs, characterized by unusually short burst durations and presumably having nothing to do with collapsars, are not luminous enough to be seen much beyond  $z = 1$ .)

In 2006 Loeb and Volker Bromm predicted that the rate of GRB occurrence at  $z = 8$  would already have been 40% of the rate at  $z = 6$ , some 300 million years later.<sup>2</sup> That's consistent with the fact that *Swift* has thus far seen only this one GRB above  $z = 7$  in the five years since its launch, *provided* one takes account of how easily an observer might miss evidence of high redshift.

## Recognizing high redshift

A GRB's initial burst of gammas and its x-ray afterglow (see figure 1a) provide no direct measure of  $z$ . Determining redshift requires spectrographic, or at least photometric, recording of the burst's optical afterglow—usually with telescopes on the ground. Of course, high  $z$  moves optical afterglow well into the IR. So when several small robotically alerted ground telescopes failed to find any optical afterglow from the April GRB within minutes of its onset, two large telescopes in Hawaii swung into action and found it at IR wavelengths beyond  $1.1 \mu\text{m}$  (see figure 1b).

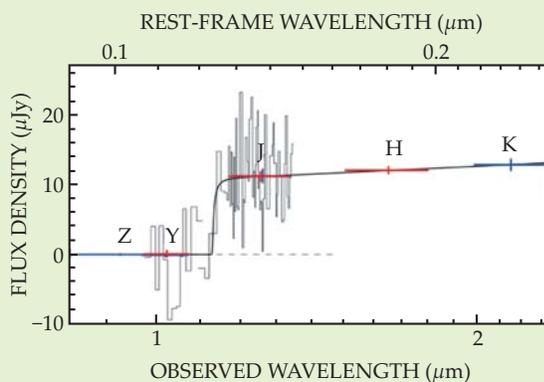


**Figure 1. Light curves** for the record-redshift ( $z = 8.26$ ) gamma-ray burst GRB090423, plotted in the GRB's rest-frame time and the observer's time, which is dilated by  $1 + z$ . (a) Fluxes recorded by the *Swift* orbiter's burst-alert telescope (BAT, 15–150 keV) and its x-ray telescope (XRT, 0.2–10 keV). (b) Waning IR brightness as recorded in three wavelength bins by telescopes in Hawaii and Chile. Fitted curves in both panels are from simple GRB models. (Adapted from ref. 1.)

Within a few hours, a team led by Derek Fox (Pennsylvania State University) had established with photometric data from the 8-m Gemini North telescope that the new GRB's redshift was about 8, clearly a record!

By then dawn was breaking over Hawaii, so IR spectroscopy had to wait for nightfall at large telescopes in Chile and the Canaries.<sup>3</sup> Together with the earlier photometry, the IR spectra yielded  $z = 8.26 \pm 0.08$  (see figure 2). But because a GRB's afterglow fades rapidly after a few hours, the spectra were too noisy to reveal absorption features that could address two cosmologically important issues: the abundance of "metals" (astronomers' jargon for anything heavier than helium) in this very early star and its galaxy, and the abundance of neutral atomic hydrogen in the intergalactic medium (IGM) nearby.

*Swift's* burst-alert telescope monitors more than 10% of the entire sky at once. So it discovers GRBs almost daily. For about a third of them, however, no optical afterglow is found and therefore no redshift is measured. It's likely that among those discards, most of them local, are a few high- $z$  GRBs for which no one troubled to look for the IR afterglow. "So there was some serendipity in the recognition of GRB090423's record redshift," says Edo Berger (Harvard) of the Gemini North team. "And a handful of comparably distant GRBs recorded by



**Figure 2. IR spectrum** (the noisy gray curve) recorded 17 hours after the onset of GRB090423 with the 16-m Very Large Telescope in Chile. The GRB's redshift is determined primarily from the fitted wavelength of the Lyman- $\alpha$  absorption break near  $1.1 \mu\text{m}$ . (In the laboratory, the Lyman- $\alpha$  line is at  $122 \text{ nm}$  in the UV.) The fitted break position is strengthened by photo-

metric observations (the colored data points labeled by IR wavelength band) recorded much earlier by various ground telescopes. The absence of any photometric signal blueward of  $1.1 \mu\text{m}$  was the first evidence that the GRB had a record redshift. (Adapted from ref. 1.)

*Swift* have almost certainly evaded such recognition."

### Population III stars and reionization

Because Big Bang nucleosynthesis produced almost nothing but hydrogen and helium, it's assumed that the first generation of stars—perversely called "population III"—began life with no metals. Astronomers have yet to find a population III star. The population III epoch had probably begun by  $z = 20$ . "But we don't know how long it lasted or how much of a role it played in cosmic reionization," says Loeb. "Nor do we know if population III stars could

have produced GRBs." They were probably massive enough. But to generate an observable GRB, a collapsar must previously have shed its hydrogen envelope, and the stellar wind that strips off the envelope may require some threshold metallicity to get the job done.

There's no spectral information about GRB090423's metallicity. But its progenitor was probably not a population III star. Population III GRBs, if they exist at all, are expected to have atypically long durations.

Why is the ionization of intergalactic hydrogen by UV radiation from early stars called *reionization*? The cosmic

## physics update

These items, with supplementary material, first appeared at <http://www.physicstoday.org>.

**Glacier-related seismicity.** Iceland, located on top of the Mid-Atlantic Ridge, is one of the most geologically active places on Earth. Its Katla volcano—buried deep under a huge glacier—is particularly large and active: It tends to explosively erupt every 50 or 60 years, although its most recent eruption was back in 1918. One type of nearby seismic activity is so-called long-period (lp) earthquakes, which have shallow origins and magnitudes of less than 3.3. Swarms of those quakes are sometimes thought to indicate an imminent eruption; after more than 900 lp events took place in October 2002, local authorities developed evacuation plans.



But Kristín Jónsdóttir (shown here making field measurements) and her colleagues at Uppsala University in Sweden conclude that the glacier, not the volcano, is the culprit. As the glacier

gradually flows down a long valley, part of it reaches a cliff where gargantuan 80-meter-thick ice sheets break off and drop 100 meters, carrying more than enough energy to account for the seismicity. The researchers analyzed data from more than 14 000 lp events in 1991–2007. The events' locations, waveforms, seasonal variations, and other variables all pointed to the calving outlet glacier as the seismic source. The authors note that continued global warming could increase such seismicity. For more on glaciers and earthquakes, see *PHYSICS TODAY*, September 2008, page 17. (K. Jónsdóttir et al., *Geophys. Res. Lett.* **36**, L11402, 2009.) —SGB

**Measuring a quark–antiquark mass difference.** In any Lorentz-invariant local field theory, particle and antiparticle masses must be identical. That equality has been verified to high precision for leptons and hadrons, but not for quarks. With one exception, it's impossible to measure quark masses directly because a newly created quark "dresses itself" in other quarks and gluons to form a hadron within  $10^{-22}$  seconds. And hadron masses yield, at best, only rough estimates of the quark masses. The exception is the top quark. Almost 200 times heavier than the proton, the top is by far the most massive quark. Its lifetime of  $10^{-24}$  seconds is much too brief to form a hadron. Thus by measuring its decay products, experiments at Fermilab's Tevatron collider have determined the top mass (173 GeV) with a precision of better than 1%. Those experiments were based on the production of top–antitop pairs, and the analyses assumed that the masses were equal. Now the DZero collaboration at the Tevatron has reanalyzed its data to

microwave background is a snapshot of the cosmos at about  $z = 1100$ , its first moment of transparency, 0.4 Myr after the Big Bang. That's when the opaque primordial plasma first became cool enough for neutral hydrogen to survive. Nowadays the hydrogen in the IGM is almost entirely reionized. It's known from neutral-hydrogen absorption features in the spectra of high-redshift quasars that the reionization was largely complete by  $z = 6$  (see *PHYSICS TODAY*, October 2001, page 17). But cosmologists want an observational record of its progress to completion as early galaxies evolved, at least back to  $z = 12$ .

Quasars are hyperactive galactic nuclei energized by accretion onto exceptionally massive central black holes. None have been found beyond  $z = 6.5$ , probably because the earliest galaxies were small, with correspondingly modest central black holes. In any case, the telltale absorption feature (the so-called Gunn–Peterson trough) in the quasar spectrum saturates at about  $z = 6$ , when there was as little as 1% neutral hydrogen left in the IGM. So to study earlier stages of reionization, one has to look elsewhere.

Because GRBs manifest individual stars rather than galaxies, they occur in galaxies large and small. So they let astronomers look back to when there were only small galaxies, and they illuminate more typical intergalactic envi-

ronments than those around quasars. In the vicinity of a high- $z$  quasar, the IGM is likely to have suffered atypically severe reionization.

### Prompt spectroscopy

For the study of cosmic reionization, GRBs, like quasars, serve to backlight the IGM. One seeks to measure how much light has been lost by Lyman- $\alpha$  absorption in neutral atomic hydrogen along the continuum of redshifts on the way here. For probing cosmic reionization, it turns out to be an advantage for GRBs that they, unlike quasars, have no Lyman- $\alpha$  line emission of their own. Their optical afterglow is entirely synchrotron emission from electrons spiraling in shock-driven magnetic fields.

Quasars, for all their limitations, do wait patiently for observers. They shine for millions of years. But a GRB's afterglow grows fainter with every passing hour. "So we're obliged to move fast," says Fox. How is one to promptly identify high- $z$  GRBs and catch their IR afterglow fast enough to yield spectra adequate for studying cosmic reionization—and for measuring the collapsing star's metallicity?

Happily, the promptness problem is less exacerbated by increasing distance than one might think. That's because the inverse-square falloff of the afterglow's brightness with distance is largely compensated by the  $1 + z$  time

dilation of its duration.

The main problem has been the shift from optical to IR. *Swift*, whose name celebrates the speed with which it can turn to and pinpoint a GRB, carries no IR instrument. In the short run, new broad-spectrum IR spectrometers soon to be fitted onto large telescopes in Chile and Hawaii should greatly speed up the identification and spectrography of high- $z$  GRBs.

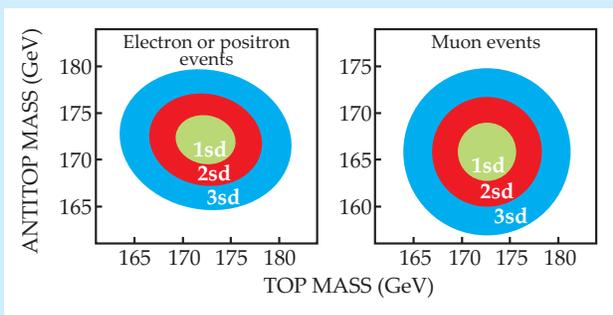
By the middle of the next decade, the 6.5-m *James Webb Space Telescope* should be able to acquire afterglow spectra of GRBs even at  $z = 30$ , sometimes together with long-exposure images of the host galaxies. There might be some advantage in also having a smaller, dedicated GRB/IR space telescope that could report faster than the mammoth, multipurpose *JWST* in response to a burst alert.

"After 10 years of anticipation, we've finally seen a GRB more distant than any galaxy whose redshift we can measure," says Loeb. "With *JWST* and such a dedicated satellite in place, we could expect to harvest about one GRB spectrum a month with redshift beyond 8."

Bertram Schwarzschild

### References

1. N. R. Tanvir et al., <http://arxiv.org/abs/0906.1577>.
2. V. Bromm, A. Loeb, *Astrophys. J.* **642**, 382 (2006).
3. R. Salvaterra et al., <http://arxiv.org/abs/0906.1578>.



look for a possible mass difference between the two. One can distinguish the top from the antitop by the charge of an energetic lone decay lepton (a muon, electron, or positron) in the event. The reanalysis yields a mass difference of  $3.8 \pm 3.7$  GeV, consistent with zero. But that wasn't a foregone conclusion. The ultimate unified theory of particle interactions might well be something other than a local field theory—perhaps a string theory. (V. M. Abazov et al., <http://arxiv.org/abs/0906.1172>.)—BMS

**Metal-insulator transition in vanadium dioxide.** Below 68 °C vanadium dioxide is an insulator. Above that temperature it's a metal. The nature of the transition has long remained elusive, though, because bulk  $\text{VO}_2$  has a domain structure that complicates its behavior. David Cobden and colleagues from the University of Washington have found an elegant way to avoid that difficulty and map the effective phase diagram. The team grew

rectangular nanobeams that were thinner than the characteristic domain size of a few microns. They then suspended each beam between two electrical contacts. The metallic and insulating phases differ in lattice constant, but the constrained geometry creates a uniform stress field in a  $\text{VO}_2$  beam such that the two phases coexist in a range of temperatures between 68 °C and 105 °C. Thanks to the dramatic change in optical properties that accompanies the transition, Cobden's team could visually track the nucleation and growth of the metallic phase as a function of temperature. The figure here shows five snapshots of a 20- $\mu\text{m}$ -long beam (red indicates the insulating phase). By measuring the electrical resistance in the coexistence regime, the researchers found that the resistivity of the insulating phase is independent of temperature. That remarkable result, they argue, implies that the phase transition occurs at a fixed carrier density in the material and is consistent with a picture in which electron–electron interactions drive the transition. (J. Wei, Z. Wang, W. Chen, D. H. Cobden, *Nat. Nanotech.* **4**, 420, 2009.) —RMW

