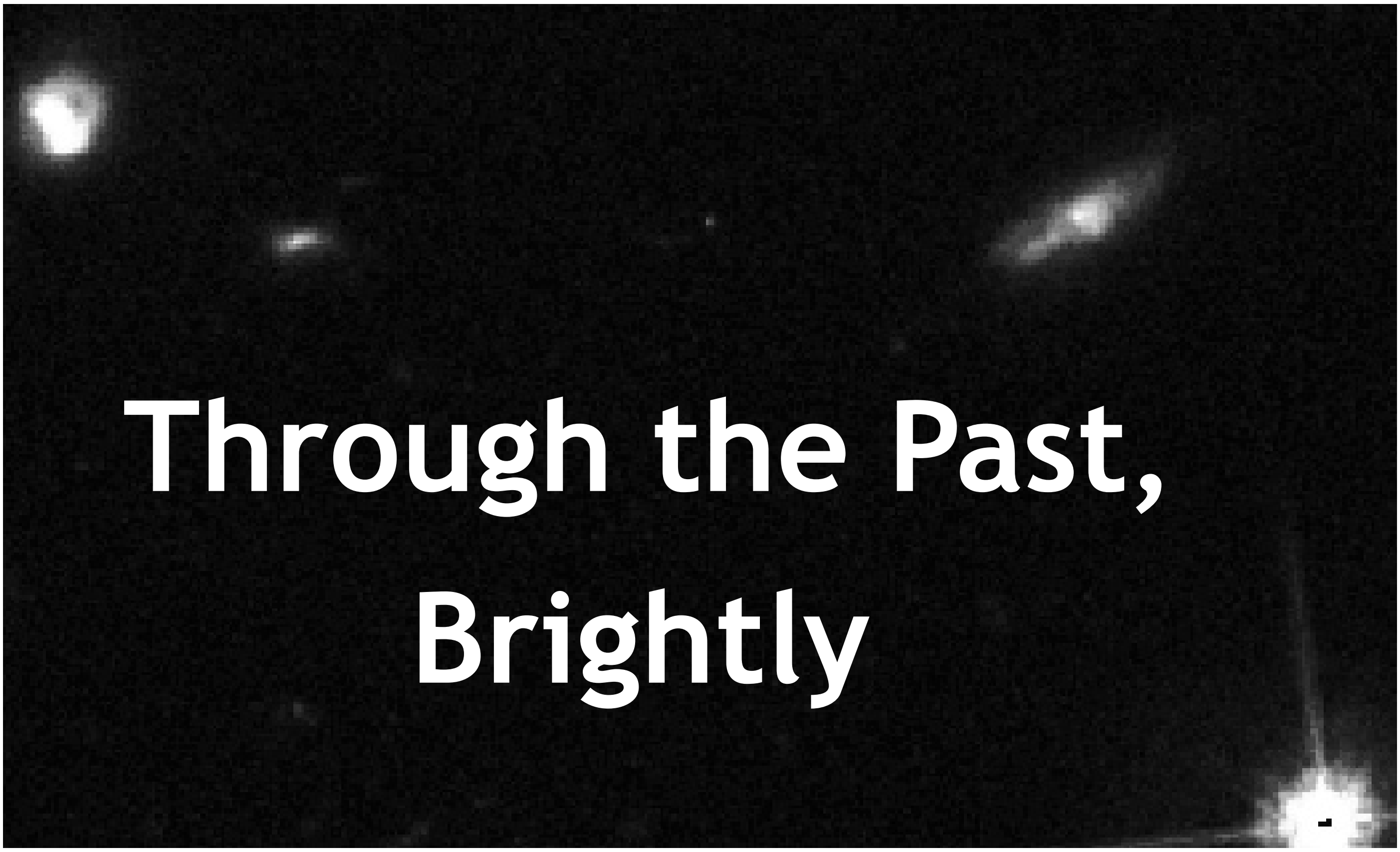


Credit: Edo Berger, Harvard University.

Through the Past, Brightly

Gamma-Ray Bursts and the Early Universe

By Sarah Harland-Logan

> *"The astronomy equivalent of working at the ER"*

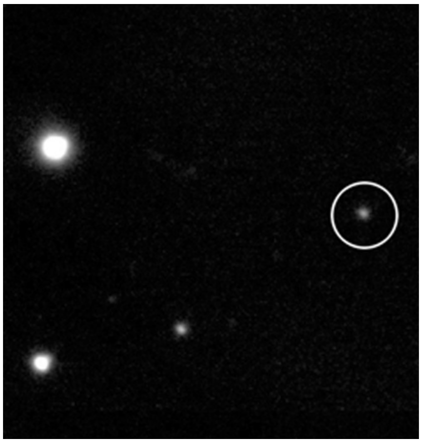
Midnight Messages

Just like many undergraduates, Professor Edo Berger (of the Harvard astronomy department) is used to receiving the occasional late-night text message. Berger's midnight texts, however, are sent to his iPhone directly from NASA's Swift telescope, our most powerful tool for detecting the phenomena known as Gamma-Ray Bursts (GRBs) (1). Berger holds the record for discovering the most distant, and therefore the oldest, object in the known universe; this object is somewhat disappointingly named GRB 090423 (to indicate that it was discovered on April 23, 2009) (2, 3).

GRBs are the brightest objects in the known universe, and the most powerful explosions since the Big Bang (4, 5). For the brief period that a GRB is occurring, it shines thousands of times more brightly than the entire galaxy in which it resides (1). In fact, GRBs are so bright that the energy released by one GRB is equivalent to the energy output of 1,000 stars the size of the Sun, throughout their entire lives (3).

These incredibly intense bursts of gamma radiation (the highest-energy portion of the light spectrum) are now believed to occur somewhere in the universe at least once to a few times per day, and perhaps far more frequently (3, 6). Berger typically receives about two texts per week informing him of the appearance of a new one. At this point, he will "jump out of bed and start calling observatories around the world to observe the burst," and then begin analyzing its properties as soon as possible (1).

Some of us might resent this frequent incursion upon our sleep patterns, but Berger explains that the unpredictable and "fast-paced nature" of his work is "part of the fun." He describes his job as "the astronomy equivalent of working at the ER," and is happy both to be free from the type of work "where



Credit: Edo Berger (Harvard).

Figure 1. The record-breaking GRB (090423).

people . . . plan things months in advance," and that he and his colleagues actually get "to look at pretty pictures of the universe in real time" (also unlike many astrophysicists) (1).

Star Wars?

Humans first encountered Gamma-Ray Bursts by accident, during a military operation. The first GRB detection occurred on July 2, 1967, thanks to a U.S. Department of Defense program that launched the Vela satellite system, in order to monitor Soviet compliance with the Nuclear Test Ban Treaty. The Vela satellites were fitted with equipment that could detect gamma-rays, so as to identify the radiation signature of any Soviet warheads illegally detonated in space (6, 7, 8).

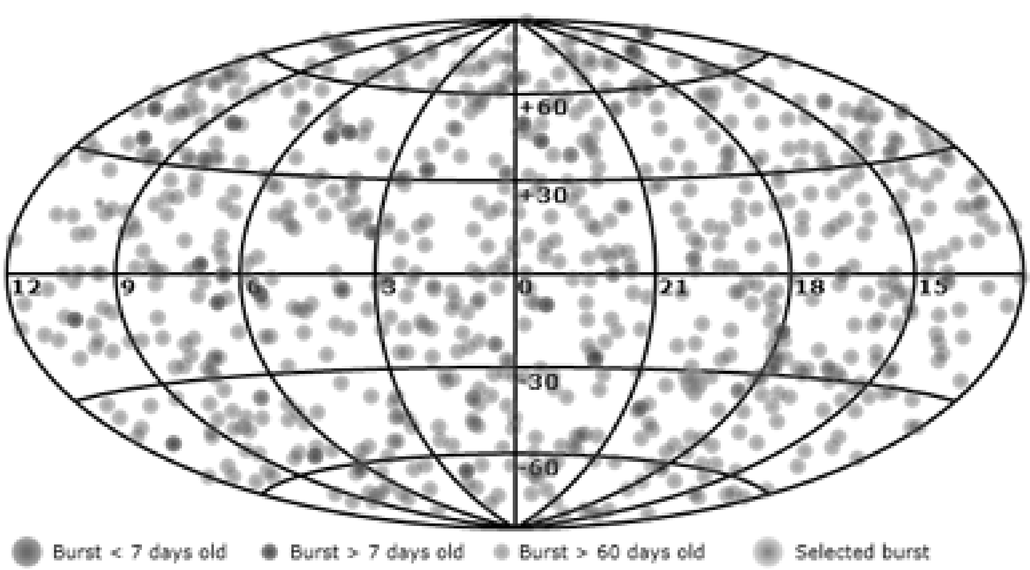


Figure 2. Accumulated GRB map, highlighting the most recent burst at any given moment (April 15, 2010). Credit: Lynn Cominski, Sonoma.

GRBs went unnoticed until mid-1969, when physicist Ray Klebasabel was working with the data produced by Vela, and noticed an earlier burst of gamma radiation that had to be extraterrestrial in origin (6, 7, 8). His discovery catalyzed a fierce debate on the origin and nature of GRBs that would continue for decades (1). Like any good scientific mystery, GRBs soon attracted a spectacular array of theories, which ran the gamut from the reasonable-sounding (e.g., GRBs were caused by collisions between comets and neutron stars) to the hilariously outlandish (e.g., they were produced not by Soviet nuclear testing but rather by alien nuclear warfare) (6, 8). A 1975 review paper presented at the Texas Symposium on Relativistic Astrophysics included literally 100 different GRB theories (6).

Today, the remarkable GRB-finding satellite Swift (named for the bird) enables scientists to make rapid progress toward GRBs' true origin. Swift has identified approximately 100 GRBs per year since its launch on November 20th, 2004 (4). It alerts astrophysicists like Dr. Berger to the location of each new GRB within about 1 minute of detecting it, and autonomously reorients itself in the direction of the burst, where it observes the burst's afterglow. Perhaps unsurprisingly, both types of GRBs are now believed to result from the formation of black holes, everyone's favorite space monsters (4, 9).

Black Holes and Revelations

GRBs are subdivided into two categories, "long" and "short." Long GRBs, which can last for hundreds of seconds, begin life with the supernova of a star at least 20 to 30 times (and perhaps even 100 times) more massive than the Sun (1). When giant stars like these explode, a black hole is created at the center of the supernova, and matter from the exploded star then forms an accretion disc around the black hole. As this taurus of material is sucked into the black hole, some of the matter is ejected (along with electromagnetic radiation), at velocities as high as 99.9995% of the speed of light (10); the precise details of this process are still unknown to cosmologists (11). The matter is thrown outward in several different "shells," each traveling at a different speed (3). GRBs occur when more rapidly moving "shells" catch up to slower shells and collide with them, releasing very high-energy photons; hundreds of these collisions are possible in a single GRB (3, 11, 12).

But although astrophysicists are confident that long GRBs are indeed

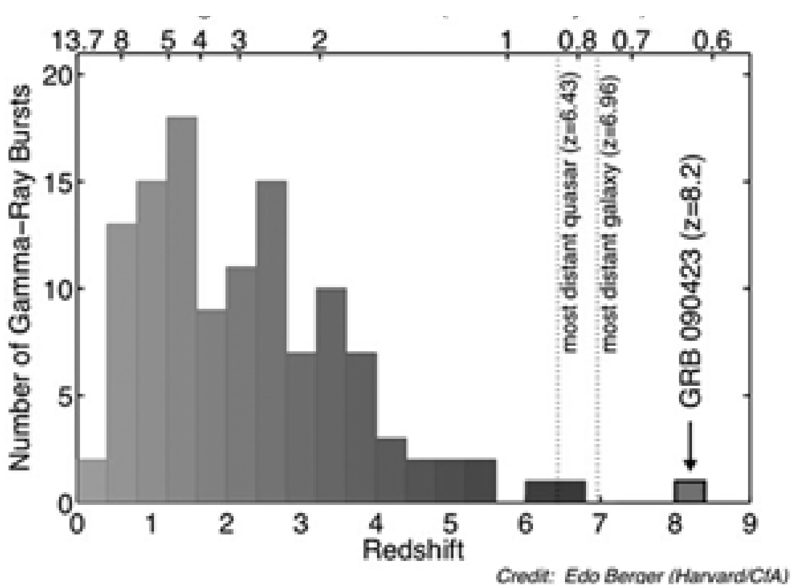


Figure 3. GRB 090423 shatters distance records.

produced from these supernovae, Berger emphasized that their origin story is not yet complete, because "we only have one GRB for every 1,000 supernova explosions. We must need something very special to happen [to produce a GRB]; we just don't know what it is. Yet." (1)

The story of short GRBs, which can be as brief as a few milliseconds, remains enmeshed in even greater mystery. The current theory (which Berger emphasizes is "something that we're [still] trying to prove or disprove at this point") is that they are produced when a pair of neutron stars nearly collide, after the stars lose the angular momentum that keeps their orbit stable (1, 6). As Berger colorfully puts it, "eventually they get so close to each other that they're almost touching; then they start shredding each other. . . . At the end, they don't actually collide; but they just tear each other apart, in those last few seconds." (1) A black hole forms at the site of the shredded remnant; it is surrounded by an accretion disc of matter from the neutron stars, which is sucked into the black hole; and again, this process drives the incredibly rapid throwing-off of shells of matter that collide with each other, producing the bursts (14).

Brilliant Afterglows

We owe the preponderance of our current GRB knowledge to the 1997 detection (by the BeppoSAX satellite) of the "afterglows" that they leave behind; we are currently able to detect about two-thirds of them (15, 16, 17). Once the collisions of the ejected shells of matter have ceased (and therefore the GRB is over), the large shell that has resulted from these collisions continues to travel outward at nearly the speed of light, colliding with the interstellar medium; Dr. Berger compares its advance to "a snowplow pushing snow." (18)

Dr. Berger's record-holding GRB has a redshift of 8.2, which means that this GRB occurred about 630 million years after the Big Bang; the light from this burst has been traveling for over 13 of the universe's 13.7 billion years of existence.

This collision generates emissions in the lower portions of the spectrum (X-rays, optical, and microwaves), which linger for a period ranging from days to years (1, 12). Because these afterglows last so much longer than the bursts that produced them, they have enabled astrophysicists to measure GRBs' redshifts, localize them with sufficient precision to identify their host galaxies, quantify how much energy they release, and definitively associate long GRBs with supernovae (15, 16, 17). Without the afterglows, we would still be groping around in the dark.

Illuminating the Cosmic Dark Age

Not only are GRBs interesting phenomena in themselves, but Dr. Berger and his colleagues hope to use them as "the best flashlight" to illuminate the early history of the universe (1). Dr. Berger reminded me that "When we look at the universe, we're looking at light travelling from distant objects. Given that the speed of light is finite," the more distant the object we are looking at, "the further back in time we're looking." In other words, "the key" to answering questions like "How did the first stars form?" is to "look at extremely distant objects, [from] when the universe was young" (1).

Between the beginning of time and the present day, the universe passed through a period of literal darkness that is referred to as the Cosmic Dark Age. In the aftermath of the Big Bang, the universe was incredibly hot, and its matter was entirely ionized (1, 9); the formation of atoms did not occur for about 400,000 years (1). This process created the Cosmic Microwave Background (CMB), the low-level microwave radiation that glows evenly at all points throughout the cosmos (5).

During this period, the universe was plunged into darkness, since visible light was absorbed by clouds of hydrogen gas. Since ionized matter allows photons to flow freely, whereas atomic gas absorbs them (18), the universe remained dark until the first stars had been formed. Photons emitted by the early stars and galaxies then "reionized" the matter of the intergalactic medium, by dislodging electrons from neutral atoms (1, 20). This process had been completed by the billionth year after the Big Bang (19). Scientists currently know relatively little for certain about the processes that led to the formation of the first stars and the re-ionization of the universe, since it has been impossible to directly observe any objects dating from this time (21, 22).

The oldest GRBs that we have observed, however, occurred well back into the Cosmic Dark Age. Dr. Berger's record-holding GRB has a redshift of 8.2, which means that this GRB occurred about 630 million years after the Big Bang; the light from this burst has been traveling for over 13 of the universe's 13.7 billion years of existence (5, 23).

Berger used the classic "raisin bread example" to explain how the concept of redshift works: "because the universe is expanding, objects that are further away from us are moving away from us at faster speeds. Imagine that you have raisin bread," and think about the speed with which, as you pull the dough apart, raisins at different positions would move away (1). This expansion causes light from distant objects to be shifted toward the longer, red end of the visual spectrum (1). Cosmologists use the redshift, z, to indicate the general time period in which a cosmic event took place. 1 + z gives both the factor by which the wavelength has been stretched into the infrared portion of the spectrum, and the factor by which the universe has expanded from that time period to the present (20). An object's redshift is therefore calculated by taking the observed wavelength over the expected wavelength (if the object were not moving away from us), + 1 (1).

> *"We're going to find them when they die."*

Finding a GRB with a redshift of 8.2 is an extraordinary achievement; by comparison, the redshifts of the furthest galaxy and quasar to be discovered are 6.96 and 6.48, respectively, placing them at the tail end of the reionization period (5, 20). This redshift means that the GRB in question occurred during the Cosmic Dark Age, providing a rare glimpse into the universe's hidden early years (1).

A long time ago and far, far away . . .

Thanks to Swift, and to a number of telescopes on the ground, Dr. Berger anticipates breaking his own distance record, perhaps in a matter of months.

Credit: Edo Berger, Harvard University.

Figure 4. Professor Edo Berger.

He expects that we will soon have identified enough of these very early GRBs to begin to elucidate the Cosmic Dark Age in earnest. Since Swift is expected to be operational for the next ten years, he and his team will have ample opportunity to amass this kind of data. Berger also reported that GRB-detecting satellites even more sensitive than Swift, named EXIST and JANUS, are now in the planning stage (1).

Since GRBs are, after all, "the result of the explosion of extremely massive stars," Berger looks forward to using GRB data to learn far more about the formation of the first generations of stars in the universe (1). Although these early stars themselves remain elusive, they become traceable through their explosive endings. Berger grinned and told me, "We're going to find them when they die." (1)

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