Gamma-Ray Bursts: Cosmic Beacons

Daniel Perley, Caltech

Gamma-ray bursts (GRBs) are the most luminous explosions in the universe. Keck has played a leading role of the study of these events, starting with its groundbreaking discovery in 1997 that gamma-ray bursts come from exploding stars far beyond our Milky Way Galaxy, a result which ended decades of confusion and debate and launched the modern scientific study of the phenomenon. Keck continues to be at the forefront of this field, providing seminal results on the origin of a second class of short-duration gamma-ray bursts (thought to be merging neutron stars or black holes) and in using these energetic explosions to understand the properties of distant galaxies and of the universe as a whole.

***Figure 1: Artist's conception of a long-duration gamma-ray burst** escaping from a dying star. Long GRBs originate from collapsin stars that are able to power energetic jets via the neutron star or black hole in their cores the star. Earth-based observers see a GRB if the radiation beam intersects Earth, even if the event is billions of light-years distant.*

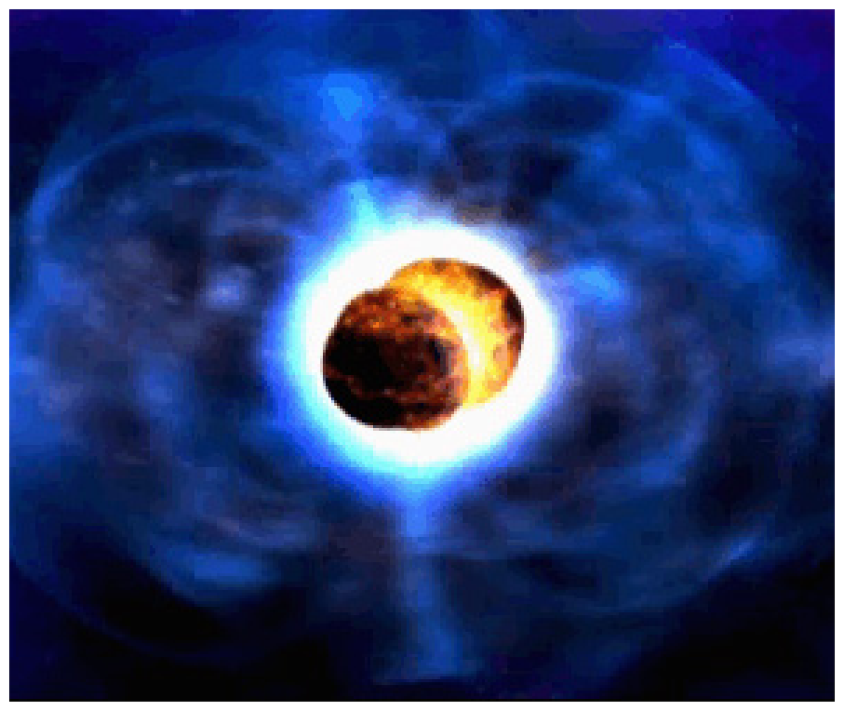


***Figure 2: Artist's conception of a short-duration gamma-ray burst** produced by the collision and merger of two neutron stars orbiting in a binary, an event that is thought to produce much shorter-duration (2 seconds or less) radiation blasts. Keck observations of the host galaxies have helped establish a connection between the shortest GRBs and neutron star mergers.*

A 30-year mystery, solved in a flash by Keck

Gamma-ray bursts were discovered in the late 1960s when early gamma-ray satellites – launched into space by the US government to search for illicit Soviet nuclear tests – instead detected unexplained flashes of radiation from deep space.

The origin of these events was debated for decades, and hundreds of ideas were presented in scientific journals during the 1970s and 1980s to interpret this discovery. Most models relied on explosions on the surfaces of compact stars such as white dwarfs within (or in the halo of) our Milky Way Galaxy.

A major breakthrough came in February 1997, when for the first time *optical* and *X-ray* emission was detected from an gamma-ray burst. When the explosion faded away, the emission was seen to originate from an extremely faint small, barely-resolved object resembling an extremely distant galaxy. However, few telescopes at the time were sensitive enough to actually definitively establish this was a galaxy, and not some sort of exotic nebula around a nearby neutron star.

Less than three months later, the mystery was solved once and for all when Caltech observers repointed Keck II at the optical counterpart of another GRB and acquired a spectrum. The light from the explosion showed the unmistakable signatures of absorption from interstellar magnesium and iron at a redshift of **z=0.835**, corresponding to a distance of **7 billion light years**. This meant that this GRB (and, presumably, most or all others) unambiguously originated with extremely distant galaxies – and, given this distance,that they must be incredibly energetic, with an amount of energy comparable to the rest-mass of a small star converted into radiation within a few seconds. Producing so much energy so quickly essentially required the complete destruction of an entire star, and only two models were left standing: the collapse of an extremely massive star to a neutron star or black hole, or the merger of a neutron star with another neutron star or a black hole.

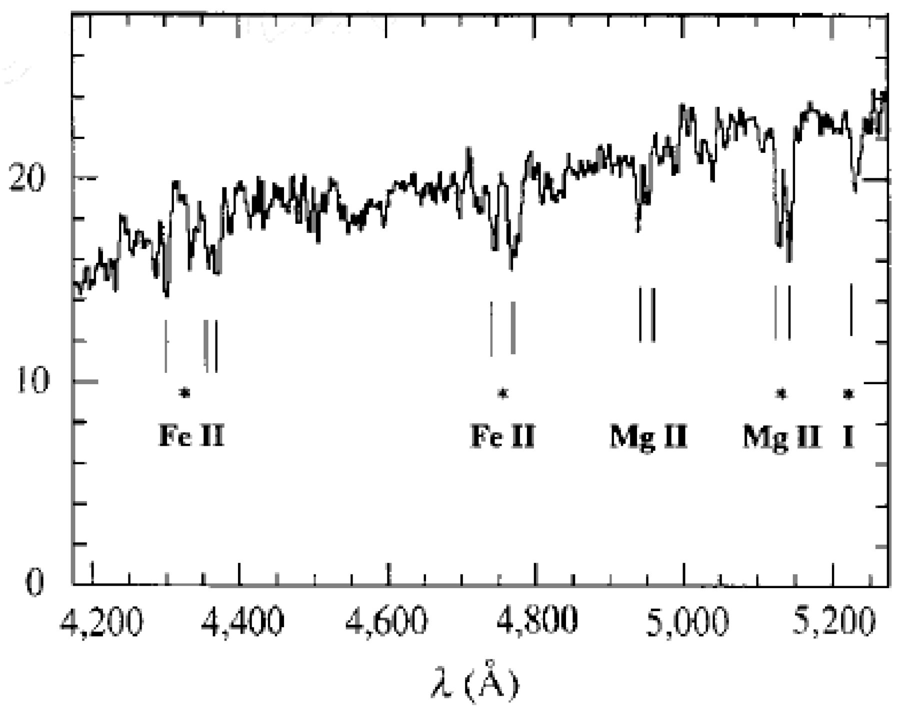


***Figure 3: The first-ever optical spectrum of a gamma-ray burst afterglow**, taken with LRIS on Keck II (Metzger et al. 1997). The detection of iron and magnesium lines at a redshift of z=0.835 unambiguously indicated that this event was at cosmological distance, ruling out all Galactic models and implying the event was enormously energetic. This single observation ended a three-decade debate about the distance and energy scales of GRBs.*

Later, Keck's sensitive spectrometer was also trained on the faint sources underlying these gamma-ray bursts, showing conclusively that the February event and many others all originated in extremely distant sources – and furthermore, that these galaxies were ubiquitously rapidly star-forming (Bloom et al. 1998, 2001). This association with recent stars pinned the origin of GRBs on massive stars, leading to the paradigm that remains today: GRBs represent exotic explosions of rare, extremely massive stars at the moment of core collapse.

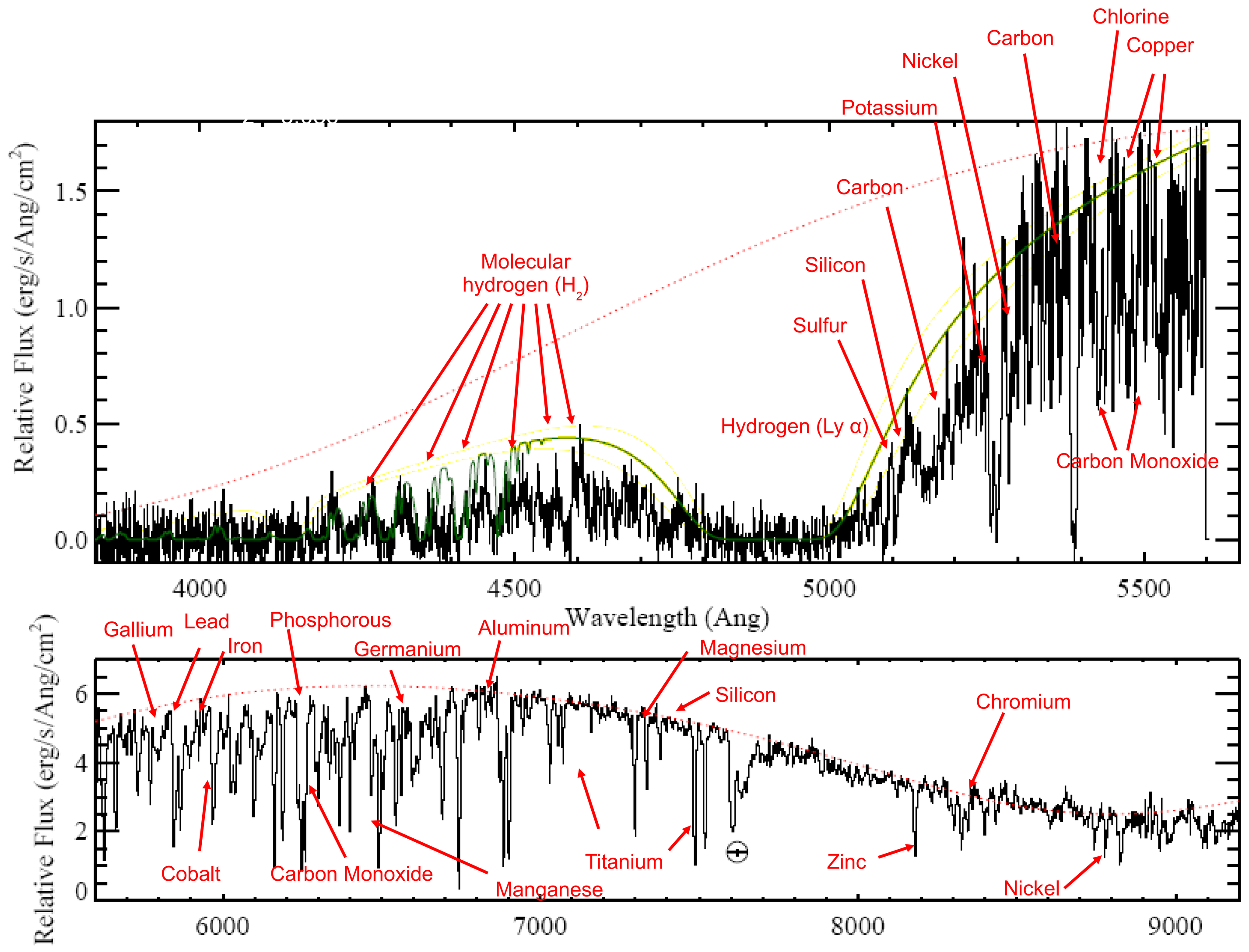
References:

Bloom et al. 1998, ApJL 507, 25
Bloom et al. 2001, ApJ 554:678
Bloom et al. 2006, ApJ 638, 354
Bloom et al. 2007, ApJ 654, 878
Metzger et al. 1997, Nature 387, 878
Perley et al. 2011a, AJ 141, 36
Perley et al. 2011b, PhD Thesis
Perley et al. 2013, arXiv:/1301.5903
Prochaska et al. 2009, ApJ 691, 27
Sheffer et al. 2009, ApJ 701, 63

Backlights of Distant Galaxies

Absorption spectra of GRBs do much more than tell us the distance of the burst – they also reveal the chemical composition and physical conditions of the galaxy in which the burst happened. The light from the GRB passes through gas and dust in its host galaxy, which leave absorption-line imprints that can be detected and studied with a sensitive spectrograph (especially high-resolution instruments such as HIRES). These observations have shown us that even relatively small galaxies in the universe can be fairly chemically enriched, providing evidence that (at least in some systems) star formation and the synthesis of heavy elements must have proceeded relatively rapidly after the Big Bang.

***Figure 4 (right): Absorption features in the distant universe revealed by a GRB**, observed with LRIS on Keck I in 2008 (Prochaska et al. 2009). This GRB penetrated a dark molecular cloud in its host galaxy at z=3.04, providing a detailed look at the chemistry of a galaxy 11.5 billion years ago. At least 22 different chemical elements (including rare species such as germanium) and two molecular species are identified in the spectrum, as is a broad dust absorption feature (Perley et al. 2011). This is the highest-redshift absorption detection of many of these tracers. In spite of the early epoch in the Universe's history this galaxy was observed at (only 2.5 Gyr after the Big Bang), the characteristics of the cloud are remarkably similar to those seen in our own Milky Way (Sheffer et al. 2009).*



Probes of Galaxy Evolution

Since GRBs are produced from explosions of massive, young stars, they sample places where star-formation is active – effectively providing a randomly-chosen "census" of the Universe's star-forming galaxies. By studying samples of GRB hosts – the distant galaxies unveiled after the light from the GRB fades away – in aggregate, we hope characterize the types of environments in which typical stars formed (for example, how many occurred in very massive galaxies, and how many in smaller galaxies?) as well as quantify *when* in the Universe's history star-formation was most active – the cosmic star-formation history.

On the other hand, GRBs may not select all star-formation sites equally: recent work using Keck supports the notion that the GRB host population is biased towards metal-poor galaxies, even at moderate redshifts. This is true even when optically-obscured "dark" GRBs (which do not have bright optical emission and were largely absent from early studies) are considered (Perley et al. 2013).

New Classes of Burst

While the majority of detected GRBs originate from massive stars, a smaller subset sees to have a completely different physical cause (Figure 2). The host galaxies of short-duration GRBs (those whose gamma-ray emission lasts for 2 seconds or less) observed with Keck have been localized to a completely different host-galaxy population, one with characteristically low star-formation rates and in a few cases evidence of no active star-formation at all. They have also been found far off in the halos of galaxies, as if they had been "kicked" out by a previous explosion long ago (Bloom et al. 2006, 2007). These properties are quite inconsistent with the idea that short-duration bursts have the same origin as the more commonly-seen long-duration events but are consistent with the expectations of the neutron star merger model, in which two neutron stars (or a neutron star and a black hole) spiral together under the influence of gravitational radiation and merge. These types events are expected to be gravitational sources, and should be detected by LIGO within a few years.

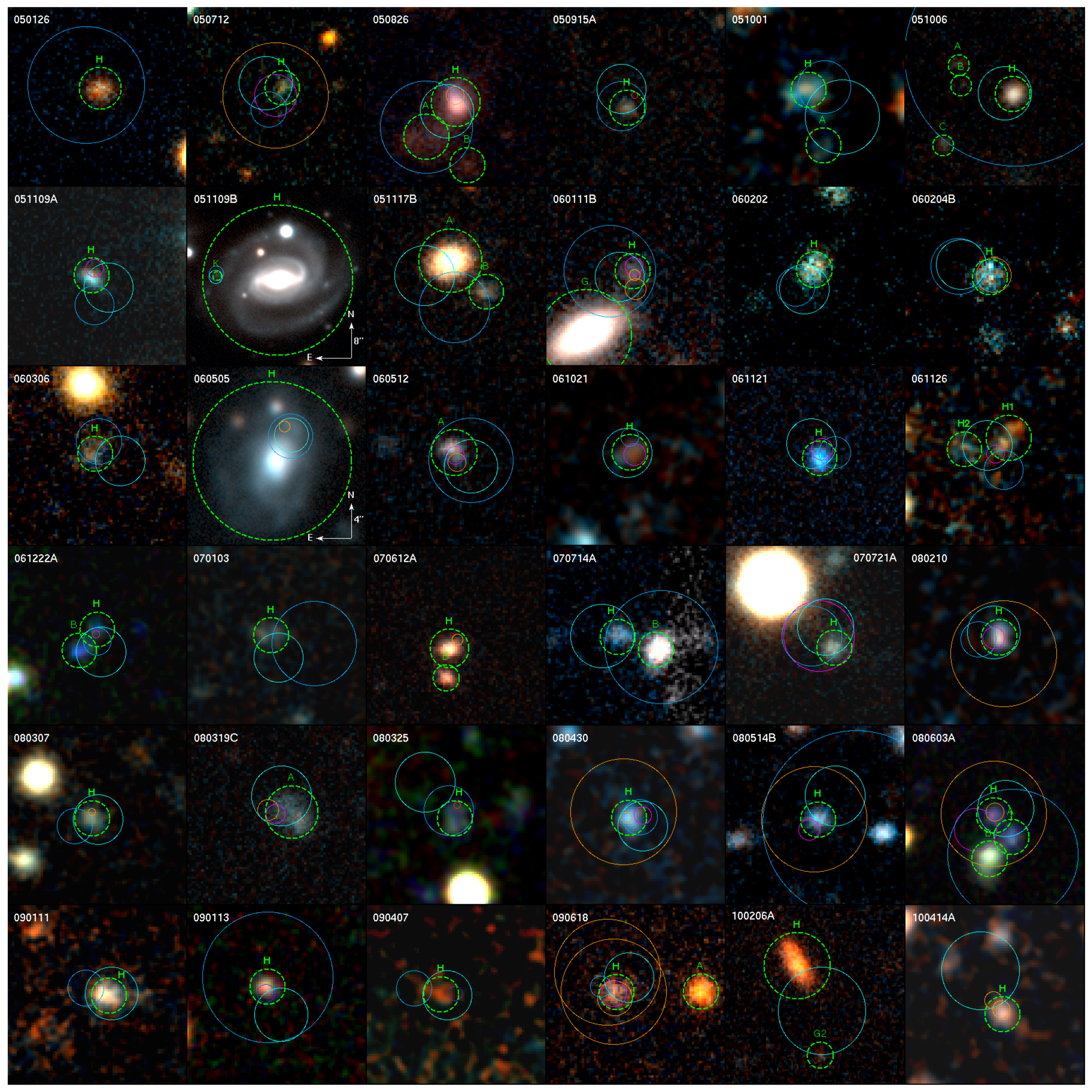


***Figure 5: Keck imaging of 36 GRB host galaxies**. With only a few rare exceptions, the hosts in which GRBs occur (generally designated by "H") are faint, unresolved high-redshift galaxies that require deep integrations to unveil. Large samples of events observed with Keck are being used to study the connection between GRB hosts and "typical" star-forming galaxies at these redshifts to evaluate the utility of GRBs as tracers of the star-formation rate in the distant universe. From Perley et al. 2011b.*