2006aj). But astronomers quickly noted that the burst was extremely soft, and most are now calling it an X-ray flash rather than a GRB. Despite the event's longevity, its total emitted energy was very weak for a long burst. As Swift lead scientist Neil Gehrels (NASA/Goddard Space Flight Center) says, "It is a very different burst than any we have seen."

Some astronomers suspect that the star's core collapsed into a fast-spinning neutron star rather than a black hole, and instead of producing a narrow beam of highly relativistic ejecta, it produced a broad outflow of mildly relativistic ejecta. This event may signify a GRB that nearly failed — where the ejecta barely managed to punch out of the star.

Nearby GRBs like 980425 and 060218 pack only 1% to 10% the total energy of high-redshift GRBs, indicating some important difference in the progenitor stars. In fact, Swift and other satellites lack the sensitivity to detect these low-luminosity bursts beyond a billion light-years. But since subenergetic bursts dominate the local population, they may constitute the majority of GRBs in the universe.

Location, Location, Location

While Swift continues to localize new GRBs, astronomers are attacking the remaining mysteries on multiple fronts. When a GRB jet rams into interstellar gas, it injects huge amounts of energy into the material, generating a bright radio source regardless of the jet's direction. SN 1998bw in particular was a powerful radio emitter. Alicia Soderberg (Caltech) and her colleagues are targeting Type Ic supernovae and their close cousins, Type Ib supernovae, which have helium in their spectra. The team is using the Very Large Array in New Mexico to see how many of these supernovae might be associated with off-axis GRBs (those whose jets don't point at Earth). But despite examining about 150 supernovae, they have yet to find a single radio source indicating an off-axis GRB. This implies that less than 1% of all Type Ib/c supernovae produce relativistic ejecta. "GRBs are intrinsically rare events, so we know it takes a very special supernova to produce one," says Soderberg.

Astronomers are also gaining insight into the nature of GRB progenitors by studying their host galaxies, which almost always turn out to be irregular dwarf galaxies that are vigorously forming massive stars. Since dwarf galaxies usually have very low concentrations of elements heavier than hydrogen and helium ("metals" in astronomy parlance), these results strongly suggest that GRB progenitor stars have low metallicity — another prediction of the collapsar model.

Using GRBs for Cosmology

By Andrew Samuel Friedman

Taking on Einstein has become a cottage industry for scientists. At the January 2006 American Astronomical Society meeting, Bradley Schaefer (Louisiana State University) reported that he had used long-duration gamma-ray bursts (GRBs) as standard candles (distance indicators of known luminosity) to measure the universe's expansion history. Schaefer boldly concluded that the dark energy responsible for accelerating the expansion had changed in strength over time. This result called into question the constancy of one of Einstein's most storied concepts, the cosmological constant (June issue, page 22). Schaefer's effort exemplifies the excitement and controversy surrounding the emerging field of GRB cosmology.

For the past decade, two competing teams have used supernovae of the Type Ia class as standard candles. With their extraordinary luminosities, these white-dwarf explosions can be seen across billions of light-years, which allowed the teams to make their remarkable 1998 discovery that the universe's expansion is accelerating. This surprising result resurrected Einstein's cosmological constant.

Could GRB standard candles be the new game in town? GRBs are much more luminous than Type Ia supernovae, so they can be seen further back in time. But they suffer from a host of problems. In contrast to Type Ia supernovae, which have relatively uniform properties, GRB luminosities vary by a factor up to a million when not adjusted for beaming. To correct for this wide variation, astronomers must correlate several observed properties, such as the burst's peak gamma-ray energy and the time when the afterglow exhibits a sharp decrease in brightness. Astronomers have developed several other GRB standardization methods, but each has its own pitfalls that could undermine accurate distance estimates. This is of particular concern when different methods are combined, as in Schaefer's analysis.

While hundreds of Type Ia supernovae have measured distances, only about 20 GRBs can be placed on a reliable Hubble diagram — a graph that plots distance versus redshift (Schaefer used about 50). Swift, combined with other satellites, is contributing some of the higher-redshift bursts that most constrain the current Hubble diagram. But there haven't been enough GRBs nearby to calibrate their luminosities. This problem has long been resolved for Type Ia supernovae because they have been well studied in nearby galaxies, some with independent distance measurements from Cepheid variable stars. Unfortunately, the paltry few nearby GRBs have exhibited low energies and strange properties, suggesting that their progenitors differ from their more-distant cousins. Without local calibration, GRBs have limited utility for tracking dark energy's behavior through time.

Still, since gamma rays penetrate dust and GRB spectra are simpler than supernova spectra, GRB standard candles could avoid some of the problems that have plagued Type Ia supernova distance estimates. Moreover, since GRBs can be detected at much greater distances, astronomers could, in principle, map the expansion history out to a time when the universe was less than a billion years old. But the early universe's expansion was dominated by matter's gravitational attraction, not dark energy's repulsion — which took over only within the past few billion years. This also limits GRBs' usefulness for studying dark energy.

Rather than pointing to the evolution of dark energy's strength, Schaefer's results are more convincingly interpreted as indirect evidence for the evolution of GRB luminosity, with more-distant GRBs yielding higher-energy explosions (though this was already suspected). Our knowledge of GRBs is not yet mature enough to draw conclusions on dark energy's time variation. Although GRBs may not have Einstein turning over in his grave, it is safe to say that if he were alive today, the brightest explosions in the universe would certainly have piqued his interest.

Harvard PhD student ANDREW SAMUEL FRIEDMAN*'s research involves developing novel standard candles such as GRBs and supernovae at near-infrared wavelengths as tools to map cosmic expansion history.*