First Identification of Host Galaxies for Short Gamma-Ray Bursts

The long search for observational evidence of the sources of a particularly puzzling class of gamma-ray bursts has at last borne fruit. The new evidence suggests that short-duration GRBs are caused by mergers of neutron stars and black holes.

It's hard to learn much about a celestial explosion if you know neither its host environment nor how far away it was. For a given apparent brightness, distance determines energy output and the environment suggests some mechanisms and precludes others. For the majority class of gamma-ray bursts (the so-called long GRBs, which last longer than a few seconds), the breakthrough came in 1997, when the first detection of optical and x-ray afterglows made it possible to pinpoint them to young star-forming galaxies at cosmological distances measurable by redshift. Nowadays it is widely accepted that long GRBs are caused by unusually energetic supernova explosions of massive young stars (see PHYSICS TODAY, August 2005, page 21).

There is, however, a distinct minority class of GRBs—those with burst durations shorter than two seconds—for which the determinations of distances and hosts are only now becoming available. The 6 October issue of *Nature* reports the first two localizations of short GRBs—one that erupted on 9 May of this year[1] and the second[2–4] on 9 July. A subsequent issue will report on the 24 July short GRB, the third to be successfully localized.[5,6]

What do these first few localizations tell us about the intrinsic differences between the short and long GRBs? The short GRBs appear to be less luminous—in prompt gammas and in x-ray, optical, and radio afterglows—than their longer-duration cousins by two or three orders of magnitude. Also, whereas the long GRBs are always found in populations of young stars, typically in spiral galaxies glowing with active star formation, the three short GRBs were found in quite different surroundings: Two appear to come from elliptical galaxies dominated by old stars,[1,5,6] and the other was pinpointed to a non-star-forming neighborhood within an elderly spiral galaxy.[4] Another important distinction is that the three short GRBs, despite being an order of magnitude closer than most long GRBs, show no sign of the supernovae that are almost always found in conjunction with the closest of the long GRBs.

Such different observational character strongly suggests a totally different astrophysical origin for the short GRBs. All the evidence, thus far, favors the presumption that a short GRB heralds the final spectacular merger of a matched or mixed pair of compact stellar objects—neutron stars or black holes—that have been orbiting each other for 10^8 or 10^9 years.

Among the few otherwise plausible alternatives, magnetar disruptions—catastrophic magnetic rearrangements of very young neutron stars—are excluded because the short GRBs, with energies exceeding 10^{48} ergs, are too energetic. Furthermore, their stel-

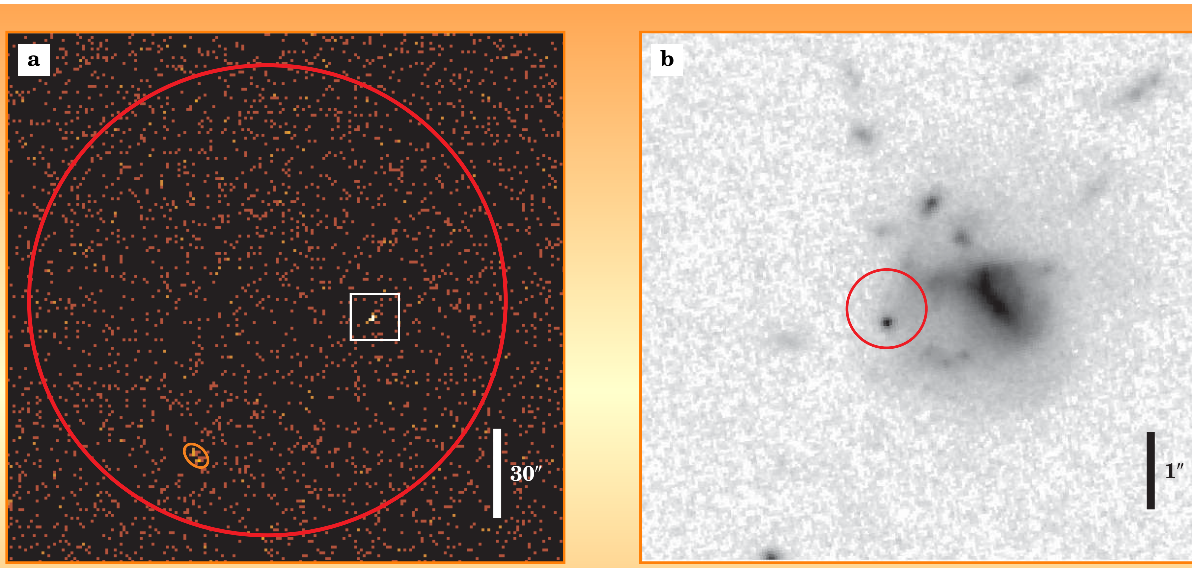

Figure 1. Pinpointing the short gamma-ray burst of 9 July 2005. **(a)** On the x-ray field image taken three days later by the *Chandra* orbiter, the red circle indicates the initial localization by the *HETE* satellite. The bright point source in the box is *Chandra*'s image of the burst's afterglow. The known x-ray source in the orange oval provides a positional reference. **(b)** A superposition of optical images from the *Hubble Space Telescope* in the weeks after the burst pinpoints the afterglow to a fading point source (within the red *Chandra* localization circle) just inside an irregular spiral galaxy that appears gray. Extended darker areas of the galaxy outside the circle are regions of active star formation. (Adapted from ref. 4.)

lar neighborhoods are too geriatric to harbor magnetars (see PHYSICS TODAY, May 2005, page 19). The old-star populations also argue against the supernova origin of short GRBs, as does the brevity of the bursts and the absence of optical evidence of associated supernovae.

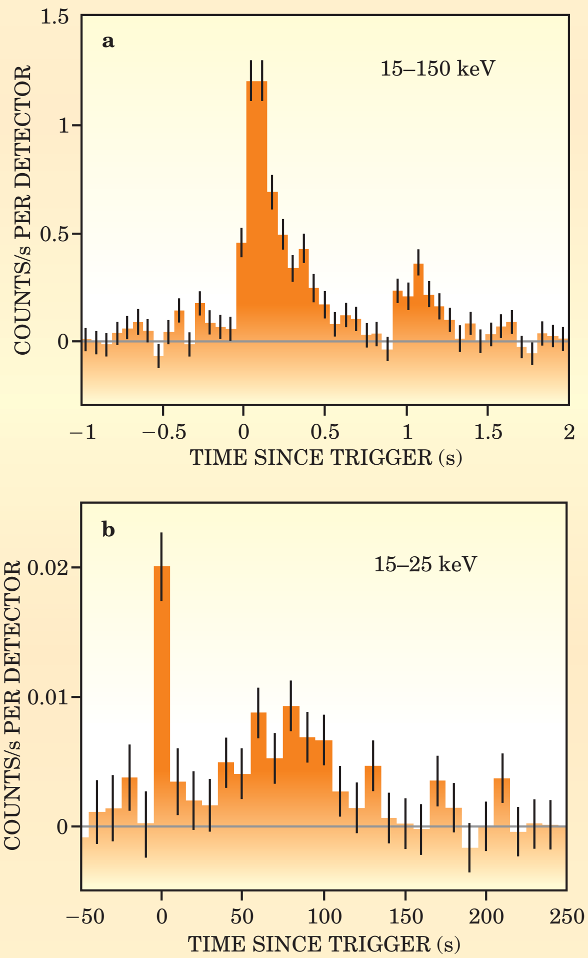

Figure 2. Emission of hard and soft gammas from the short 24 July burst, as recorded by the Burst-Alert Telescope aboard the *Swift* orbiter. BAT is an imaging array with thousands of detector elements. **(a)** Within the first two seconds, the record of gammas with energies up to 150 keV shows two prominent short peaks. **(b)** In addition to those initial peaks, the record of soft gammas (up to 25 keV) detected over the first four minutes shows an additional faint, broad enhancement centered near 80 s. (Adapted from ref. 5.)

Swift and *HETE*

Why have astrophysicists had to wait until this year for the localization of short bursts? Whereas a short GRB typically lasts only a fraction of a second, long bursts usually continue for tens of seconds. The first, and crudest, directional information from a GRB comes from a gamma-burst detector aboard an orbiting satellite. The longer the burst's duration, the better the initial localization, which serves to point x-ray and optical telescopes in roughly the right direction for successive refinement. The transient afterglows they see can, in the best cases, locate the source to within 0.1 arcsecond.

Since 1997, the Italian–Dutch *BeppoSAX* orbiter and NASA's *High Energy Transient Explorer (HETE)*, in conjunction with followup observations of afterglow by larger telescopes, had localized more than a hundred long GRBs—but not a single short one—to their host galaxies.

The launch of NASA's *Swift* satellite last November began a new observational era. Among *Swift*'s principal purposes was the prompt localization of short GRBs. To that end, it carries an x-ray telescope (XRT) that can be slewed in less than a minute to point toward a GRB recorded by BAT, the orbiter's wide-field burst-alert gamma telescope. Such prompt response, it was hoped, would allow the XRT to detect and locate a rapidly fading x-ray afterglow with sufficient accuracy to direct much bigger orbiting and ground-based telescopes to the appropriate patch of sky.

The 9 May short GRB, the first and weakest of the three, was recorded by *Swift* and analyzed by a team led by Neil Gehrels (NASA Goddard Space Flight Center).[1] Over the following days, bigger telescopes scrutinized the local region of sky defined by the handful of x-ray photons recorded by the XRT in two hours after the 40-ms gamma burst. They found no longer-lasting afterglow at x-ray, optical, or radio wavelengths. But the XRT localization, by itself, identified the probable host as a large elliptical galaxy at redshift $z = 0.22$. That implies a distance of about 3 billion light years. The average redshift of the long GRBs localized since 1997 is ten times larger.

The two short GRBs discovered in July were brighter and therefore more informative than their May predecessor, even though their redshifts imply that all three were about equally distant. The 9 July short GRB was discovered and localized by the *HETE* team, led by George Ricker of MIT.[2] The five-year-old *HETE* satellite carries both gamma and x-ray detectors, but it does not have *Swift*'s rapid-slewing capability. By a stroke of fortune, however, *HETE*'s x-ray imagers were pointing in just the right direction to localize the burst.

In addition to the 100-ms hard-gamma peak, *HETE* recorded a surprising broad second peak of x rays that lasted for more than 100 seconds. Because that extended peak was too faint to have been detected by the earlier GRB satellites, it doesn't compromise the designation of the burst as a classic short-duration GRB.

The ultimate localization that pinpointed the 9 July burst unambiguously to a quiet corner of an old spiral galaxy at $z = 0.16$ resulted from a symbiosis between the initial *HETE* localization and afterglow measurements over succeeding days by the orbiting *Chandra X-Ray Observatory*, ground-based telescopes, and the *Hubble Space Telescope* (see figure 1).[3,4]

Collimation

The burst's light curve—the record of how afterglow fades with time—observed by *HST* yields two important conclusions. First, it convincingly precludes the existence of a supernova associated with the GRB. And second, a sudden steepening of the light curve after a week suggests that the 9 July GRB's emission of radiation and relativistic ejecta is collimated into a narrow jet with opening angle about 15°. Such an abrupt change in light-curve slope is taken to be a relativistic effect of light generated by a narrow cone of high-speed ejecta slowing down in the ambient medium.

There is abundant evidence of the collimation of long GRBs. If most short bursts are similarly collimated, the relative observed brightness for a given distance straightforwardly implies that the short bursts release at least a hundred times less energy in gammas than do the long bursts. And it implies that there are many more short GRBs out there than the small fraction that happen to be beamed toward us.

The 24 July event, detected by

Swift,[5] provides a striking look at details of the compact-object merger that presumably triggered it. Figure 2 shows BAT's record of gammas detected in the first few minutes. A hard-gamma spike at 0.1 s is followed by softer-gamma emission with a second prompt peak at 1.1 s and a faint late enhancement—similar to the one *HETE* found—centered at about 80 s.

The burst's x-ray afterglow, recorded by *Swift*'s XRT and eventually by *Chandra*, allowed ground-based telescopes to find optical and radio afterglows and confirm that the host was an old elliptical galaxy at $z = 0.26$ with very little star formation.[6]

Surpisingly, the steady fading of the x-ray afterglow after the first two seconds was interrupted by three flare-ups. The first, similar to HETE's unexpected finding, peaked at about one minute, and the last came six hours later. "Such an extended scenario of activity is hard to reconcile with model simulations of a fast, clean merger of two neutron stars," says Gehrels. Instead, the *Swift* team argues, the episodic flaring may well indicate the stretching, breaking, and piecemeal consumption of a neutron star by a black-hole partner several times its mass.

The supernova scenario explains why long GBRs should be strongly collimated. But compact-object merger models are less clear about collimation of short GRBs.[7] Evidence from the 24 July burst is contradictory: A break in the slope of the infrared light curve[6] a day after the burst suggests collimation with an opening angle of about 10°. But the apparent absence of a corresponding break in *Chandra* x-ray data casts doubt on that collimation.

If the short GRBs are generally not collimated, then their energy output in gammas is not very much less than the 10^{51} ergs typical of the long GRBs. Such high energies are not obviously inconsistent with merger models. If, as now seems likely, the short GRBs are indeed caused by mergers of compact objects, their collimation is an important issue for estimating the rate at which an upgraded LIGO gravitational-wave detector should expect to detect signals from such mergers.

Happily the localization of three short GRBs in just three months holds out the hope that astrophysicists will be able to confront their merger scenarios with many more bursts in the near future. In fact, a very faint short GRB, detected by *Swift* on 13 August, has been tentatively localized to a cluster of galaxies at a redshift of 0.7, much farther away than its three predecessors.

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Order Parameter of the Chiral Potts Model Succumbs at Last to Exact Solution

Exact solutions are prized because they can be used to compare theory with simulation and experiment without ambiguity. Finding them has sometimes proved arduous.

"The statistical theory of phase changes in solids and liquids involves formidable mathematical problems." Thus Lars Onsager began his 1944 magnum opus on the two-dimensional Ising model. As if to justify his opening line, he filled the 43 pages that followed with the exposition of a new algebra and the derivation of a crystal's specific heat, partition function, and critical temperature.[1]

The Ising model started life in 1925 as a simple one-dimensional quantum mechanical model of ferromagnetism. Each spin in a chain interacts with its two nearest neighbors and aligns with them, or not, depending on the interaction energy, the temperature, and chance.

Onsager generalized the Ising model to two dimensions, but his 1944 paper didn't address what was in a sense the model's original raison d'être: a solution for the spontaneous magnetization or its dimensionless equivalent, the order parameter M. He conjectured a solution in 1949. Three years later, C. N. Yang set out to prove it.[2] After working six months on the longest calculation of his life, Yang wrote up his analysis and gave, in equation 96, an expression of alluring simplicity:

$$M = (1 - T^2)^{1/8},$$

where T represents a dimensionless temperature.

Now, in an effort that lasted 15 years, Rodney Baxter has solved the order parameter of a further generalization of the Ising model known as the chiral Potts model.[3] Baxter retired three years ago from the Australian National University in Canberra. Although the physical and mathematical implications of his solution aren't clear yet, its derivation, says Fred Wu of Northeastern University in Boston, represents "one of the greatest feats in the field of exactly solved models."

Scalar and chiral

In 1952, Cyril Domb asked his graduate student Renfrew Potts to tackle an Ising model in which the spins point not just up or down, but also in $N - 2$ equally spaced directions in between. Potts derived a duality relation between the model's low- and high-temperature behavior for $N = 2$, 3, and 4. But no one has found a general solution. Only at the critical temperature have the model's properties been calculated.

In 1974, Wu and Y. K. Wang added a further generalization to what became known as the Potts model: a dependence of the interaction energy on direction. The need for such a model became clear a few years later when experimenters began looking at the melting and freezing of atomic monolayers on crystalline surfaces.

As the temperature drops in those systems, the liquid layer orders itself into domains that either line up with the substrate structure or follow the layer's own ordering. At certain concentrations, equilibrium phase transitions occur between those so-called commensurate and incommensurate phases.

The theorists who tried to understand those transitions, among them Stellan Östlund, David Huse, and Michael Fisher, developed and explored so-called chiral versions of the 2D Potts model in which the interaction between neighboring spins differs depending on whether the neighbors lie on the x- or y-axis of the lattice. As first formulated, the models success-