because melt flows out of the mantle too fast to build up lateral variations in melt concentration and so density. Alternatively, the viscosity of the shallow mantle may be so high as to slow dynamic flow.

The asymmetry in the pattern of inferred partially molten mantle may be related to asymmetric spreading of the ridge (*3*). The Pacific Plate on the west side of the ridge is moving about twice as fast to the west, in the hot-spot reference frame, as the Nazca Plate is moving to the east. The mantle to the west appears to be hotter than the mantle to the east, based on the slower rate of subsidence of the ocean floor with age on the west side of the ridge. The combination of asymmetric spreading and lateral variations in mantle thermal structure may mean that most upwelling and melting take place on the west side of the ridge.

The more sharply defined lateral variation observed in conductivities compared with the variation in seismic velocities may reflect the fact that electromagnetic and seismic methods measure different things. Evans *et al.* (*1*) note that as melt gets out from the mantle, the melt fraction may drop below the point at which the melt pockets are interconnected. There may be enough melt in the mantle to the east of the ridge to lower the seismic velocities but not enough to affect the conductivity. Geodynamic models treating melt fractions retained in mantle upwelling below an asymmetrically spreading ridge are now being carried out by several groups.

The results reported by Evans *et al.* will spark much effort to refine and test competing models for lateral flow of melt toward the ridge axis (*5*). Studies of slices of oceanic crust and mantle pushed up on land and exposed in complexes called ophiolites are drawing more attention from people interested in understanding how melt gets out of the mantle. There is encouraging improvement in petrologic and geochemical methods for estimating how fast melt flows through the solid mantle matrix and how fast that matrix moves up.

An interesting offshoot problem involves the origin of axial highs along fast spreading mid-ocean ridges such as the part of the East Pacific Rise where the experiment was conducted. One can argue that these narrow highs, which look like a fairly continuous dorsal fin along thousands of kilometers of ridge axis, are the longest topographic feature on our planet for which the basic mechanism of formation is disputed. The first models for this feature involved a deep root of low-density, probably melt-rich region below the axis. The MELT Experiment does not show the existence of such a root so other explanations are now being sought (*6*).

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PERSPECTIVES: ASTROPHYSICS

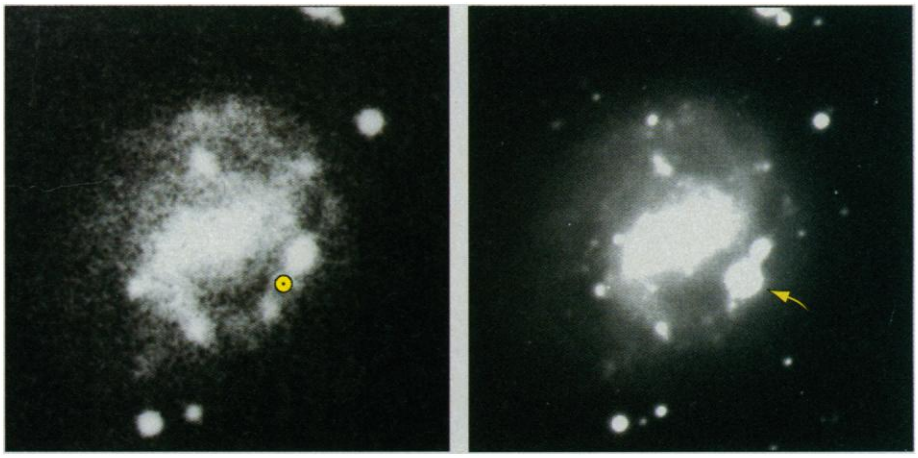
From Gamma-Ray Bursts to Supernovae

Jan van Paradijs

Gamma-ray bursts (GRBs) (*1*) are energetic astronomical events that last from tens of milliseconds to tens of minutes, with energies of up to 1 million electron volts. During the peaks of the brightest events, their flux is similar to that of the brightest stars that are visible to the naked eye. First observed in 1967, GRBs have been the focus of the recent Burst and Transient Source Experiment (BATSE) on the Compton Gamma-Ray Observatory (CGRO) (*2*). These new observations confirm earlier indications that the bursts are uniformly spread out over the sky and exclude the possibility that they occur in our galaxy, as previously thought by most astrophysicists. The wealth of new data is providing clues to the origin of these events and, in a striking twist, reviving an old idea (*3*) that links GRBs to supernovae (*4*) .

Distances to GRBs were measured for the first time in 1997, after the detection of long-lived x-ray, optical, and radio wavelength afterglows of GRBs (*5*). The ability to measure these afterglows was the direct consequence of the rapid availability of accurate GRB positions, measured with the wide-field camera on the Italian-Dutch satellite BeppoSAX. Many afterglows were found in faint host galaxies, and redshift determinations (which reflect the expansion of the universe) unambiguously established that the distance scale is cosmological (that is, GRBs come from very far away in space and time) (*6*).

GRBs are by far the most luminous photon emitters in the known universe, with peak luminosities of up to several 10^{52} erg/s (that is, 10^{19} solar luminosities). Their optical afterglows are also extraordinarily luminous. For instance, at its redshift of 0.835, the peak magnitude of the optical afterglow of GRB970508 corresponds to an optical luminosity about two orders of magnitude higher than that of a luminous type Ia supernova, one of the brightest extra–solar system objects in the sky. Even brighter was GRB990123, the only GRB for which optical emission was



Before and after. The galaxy ESO 184-G82 several years before the supernova 1998bw (**left**) and within a day of gamma-ray burst GRB980425 (**right**), which occurred at or near (**arrow**) SSN1998bw. [The circle in the left panel indicates the future position of SN1998bw.]

CREDIT: T. J. GALAMA; PUBLISHED IN (*10*)

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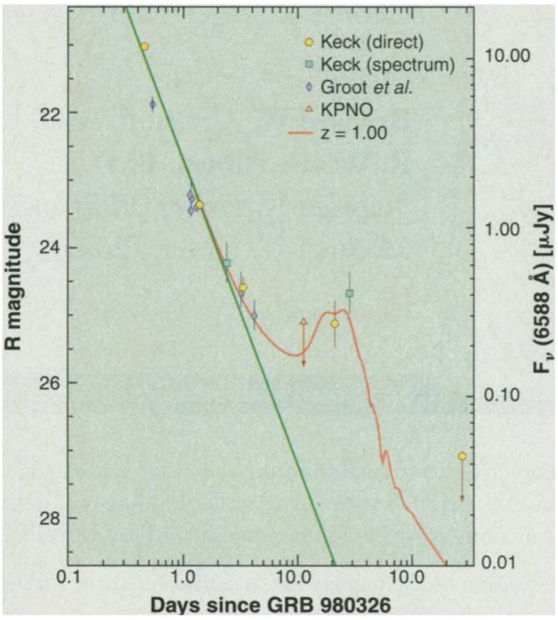
detected simultaneously with the gamma-ray emissions; for a brief moment, this optical emission became as bright as 10 million type Ia supernovae (*7*).

The ability to determine the location of and distance to a GRB and observe its burst and decay in detail at a variety of different wavelengths has allowed astronomers to test GRB models. An early model, developed long before the present observations, proposed that GRBs were caused by a shock wave emerging from the photosphere of a supernova (*3*). However, this model was soon discarded, as the GRB discovery paper already showed that there was no known correlation of GRBs with observed supernovae. Now after detailed studies of several GRBs in the late 1990s have revealed more information, theorists propose a connection between GRBs and supernovae.

There are at present two main models for GRBs. In the first, two compact stars (such as a neutron star and a black hole) coalesce (*8*). In the second, the core of a presumably very massive star collapses, leaving behind a black hole surrounded by a solar mass accretion disk (*9*). In this second, so-called collapsar model, the GRB is produced by a relativistic jet that pierces through the exploding star along its rotational axis. In addition to the fast GRB, a much slower (~10^4 km/s) outflow is produced, giving rise to thermal emission from an expanding photosphere, that is, a supernova. If this model is correct, one would thus expect a (relatively weak) supernova to be apparent in the afterglow light curve of GRBs.

The first direct evidence for a connection between GRBs and supernovae came from observations of GRB980425, which occurred on 25 April 1998 (see figure on previous page). The BeppoSAX satellite determines an area called the error box, in which a GRB must have occurred. The error box for GRB980425 also contained a supernova, SN1998bw, located in a spiral arm of galaxy ESO 184-G82 (*10*). This galaxy lies at a distance of ~40 megaparsecs from Earth, cosmologically speaking just around the corner from the Milky Way. GRB980425's energy budget was quite small, a factor of ~10^5 smaller than that of normal GRBs. The probability of finding a supernova as bright as SN1998bw that would explode within a day of the burst inside the error box of GRB980425 is on the order of 10^{-4}, and thus a physical association between the two seemed likely (*10*). Some researchers have rejected the association, because of the presence of a faint x-ray source in the GRB error box (which does not coincide with the supernova) that could be the GRB afterglow. But a recent analysis of this x-ray source by Pian *et al.* (*11*) shows that it is unlikely to be a GRB afterglow.

Independent of its association with the GRB, SN1998bw was a remarkable event.



Afterglow. R-band light emission of GRB980326 as measured by various sources superimposed on a relatively faint supernova light curve (red) at a redshift of about 1, which fits the data well.

CREDIT: J. BLOOM

It is by far the most luminous supernova observed to date at radio wavelengths, and its properties indicated the presence of a mildly relativistic outflow at about 90% the speed of light (*12*). It has been classified as a type Ic supernovae; that is, hydrogen and helium are absent in its spectra. Such supernovae are believed to have lost their hydrogen- and helium-rich envelope in a strong stellar wind or as a result of mass transfer in a binary star. The optical light curve and spectra of SN1998bw indicate that the exploding star was a CO star of about 10 solar masses, whose core collapse probably left a black hole. The amount of radioactive ^{56}Ni produced in the event has been estimated to be ~0.75 solar masses, an order of magnitude higher than that of typical type Ic supernovae, with a total explosion energy of several 10^{52} ergs (*13*).

A recent study (*14*) has been able to fit the decay properties of GRB980425 and SN1998bw with a model similar to the collapsar model.

Recently, evidence for a second GRB coinciding with a supernova was found in the case of GRB980326 (*14*). Several weeks after the burst, the afterglow brightened by a factor of 60, compared with the extrapolation of the early power law decay (see figure on this page). Afterward, the flux decay continued, showing that the flattening of the light curve does not reflect the steady light of a host galaxy. Bloom *et al.* (*14*) successfully modeled the light curve of GRB980326 with a combination of a power law afterglow and the light curve of SN1998bw, redshifted to about 1. The very steep afterglow decay of GRB980326 can be explained by a blast wave propagating in the wind of a massive star.

A similar connection between GRBs and supernovae was recently suggested (*15*) for the optical light curve of GRB970228, the first GRB to be optically identified. In this case, the redshift is known, and the only free parameter in the fit to the light curve is the exponent of the power law component. Chevalier and Li (*16*) have shown that after subtraction of the supernova contribution, the light curve of GRB970228 is also steep and best explained by an explosion in a massive stellar wind, lending further support to the association between GRBs and supernovae.

The exciting consequence of these recent studies is that at least some GRBs, and perhaps all of them, originate from the core collapse of very massive stars. The supernova connection provides a direct link between GRBs and crucial events in the evolution of massive stars and galaxies. This framework for describing GRBs promises a rapid increase in our understanding of this violent phenomenon.

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