ASTROPHYSICS

Gamma Ray Bursts

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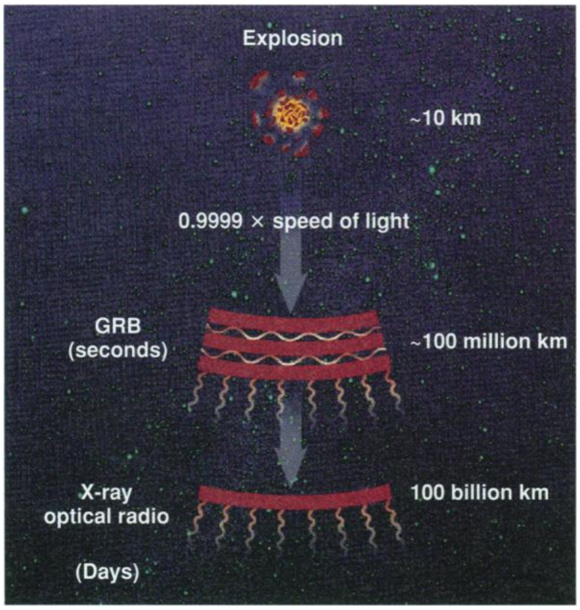
Gamma ray bursts (GRBs) have been an unsolved mystery in high-energy astrophysics for the last 30 years. Immediately after GRBs were discovered (*1*), scientists tried to understand the mechanism that causes these events and where they come from. Since then, many theories have been suggested to explain GRBs, which have durations spanning five orders of magnitude (ranging between a few milliseconds and minutes) and spectra that peak generally in the range of 0.1 to 1 MeV. Given these numbers, most theorists would think of processes occurring near neutron stars in our galaxy, many of which are known sources of rapidly varying, high-energy photon emission.

The picture changed markedly after the launch in April 1991 of the Compton Gamma Ray Observatory (CGRO). One of its experiments, the Burst And Transient Source Experiment (BATSE) was specifically designed to detect GRBs with unprecedented sensitivity and to measure the distribution of GRBs in space. As it turned out, the radiation from GRB sources had no preferred direction of arrival and no concentration on the galactic plane or at its center (*2*). Moreover, there was a dearth of very weak events, which indicated that the further out BATSE looked, the fewer events it detected: Apparently we had reached the end of the GRB distribution and we were right in its center. This is incompatible with a distribution of GRB sources near the Milky Way galaxy but easy to explain if GRBs originate from distances measured in gigaparsecs.

Taking burst strength as an average measure of the distance to the GRB source, further research on the BATSE database (currently of about 2000 GRBs) revealed additional hints for the cosmological distance scale: (i) stretching of the temporal structure of the weak bursts, suggesting the effect of expansion of the universe, albeit contested by some researchers (*3*), and (ii) a decrease in the peak energy in the GRB spectra as one goes from stronger to weaker bursts, again indicating a redshift effect (*4*). Theorists who insisted on galactic models had to push GRBs to an extended galactic halo to deal with data that set a relatively hard limit on the minimum distance of the GRB population of at least 200 kpc from the galactic center (to account for the lack of local concentrations).



Cosmological fireball. Gamma rays are produced in the explosion of a small astrophysical object, but they initially cannot escape the dense fireball. The explosion is not directly seen, but instead the fireball expands at a speed very close to that of light. The GRB is produced only after expansion of the fireball to a very large distance, on the order of 100 million km (comparable to the Earth-sun distance). If the burst occurs within a galaxy, then after expanding to a much larger radius (100 billion km), the fireball collides with the gas contained in the galaxy. This collision is expected to produce x-ray, optical, and radio radiation, arriving at a distant observer days and weeks after the GRB gamma rays (*12–14*). [Figure: courtesy of E. Waxman, Institute for Advanced Study, Princeton, New Jersey]

The next advance came with BeppoSAX, an Italian-Dutch satellite launched in 1996 and equipped with instruments that enabled fast and accurate localization to a few minutes of arc within hours after a burst. BeppoSAX contains a GRB monitor, two wide-field x-ray cameras, and a set of four narrow-field x-ray telescopes (NFTs). These detectors bore fruit in early 1997: on January 11 observers pointed large optical and radio telescopes at a GRB within hours after detection with BeppoSAX, and then again in several days in the hope of detecting a changing source. At the same time, the BeppoSAX scientists reoriented the satellite to use the NFTs for observations of low-energy x-rays in the same region, looking for the elusive x-ray counterpart of a GRB. After an improved position of the source was obtained several days later, the tally was disheartening—several radio and x-ray sources were found outside the permitted error region. Nothing was inside it.

On 28 February 1997 this procedure was repeated. After almost 30 years of futile searches, this time a fading counterpart was detected, both in the optical (*5*) and x-ray regions (*6*). Subsequent observations of the optical counterpart with the Hubble Space Telescope (HST) revealed that the original extended object that was detected with ground-based telescopes was two separate objects: a pointlike source and an extended "fuzz" (*7*). Both objects were too dim for an accurate identification of their nature with either the spectrograph of the powerful Keck telescope in Hawaii or the imaging power of HST. It seemed that the pointlike object was sitting at the edge of the "fuzz" and thus most likely was associated with it.

A GRB on 2 April 1997 provided us with one more x-ray counterpart, but nothing in the optical or radio wavelength range. An event on 8 May 1997 made up for it, however. Not only were an x-ray and an optical counterpart detected (*8*), but this time Keck obtained a spectrum, which for the first time provided a concrete limit of the distance scale of a GRB: from spectral absorption lines (*9*), it was estimated that the source was at least at a distance corresponding to a redshift, z, of 0.835, or ~4 Gpc away. The next question to answer was what was the optical counterpart? The HST observations did not reveal anything more than a pointlike object at the direction of the source. Nothing like a galaxy was seen, which raised the possibility that the absorber (which provided the lines in the spectrum) was a dense cloud in our line of sight. New spectral measurements a week later revealed an emission line at exactly the same redshift of 0.835 (*10*). This line is associated with star formation in galaxies and became visible after the illuminating source (the burster) be-

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came fainter. This indicated that the line originated from a faint galaxy, perhaps a dwarf galaxy—very small, faint objects that abound in the universe. We do not know their exact distribution because they are difficult to observe beyond a certain distance. Another surprise from the GRB on 8 May was that this time the Very Large Array of radio telescopes in New Mexico detected a radio counterpart that also seemed to be variable (*11*). This was the first radio emission detected from a GRB.

What is the theorist's take on all this? Currently favored is an expanding fireball model with all its variants (*12, 13*). This model (see figure) describes the radiation of a fireball that is produced at the site of a GRB by some mechanism (such as merging neutron stars in distant galaxies) in terms of the time scales necessary for the radiation to escape from the originally dense bulge of the hot and expanding plasma. The x-ray data indicate that the plasma cools at a rate inversely proportional to the time interval (t^{-1}) since the GRB; the theory concurs. The optical light curves observed so far are not similar. The February event showed only a decay, whereas the May one exhibited two peaks before it decayed with a t^{-1} relation.

What is the prospect of the field and what is next? In what may be a new era in high-energy astrophysics we must answer questions such as, what is, if any, the correlation between GRB intensity and intensity of emission in other wavelengths? Does the geometry of the emitter change with wavelength? If so, are there GRB counterparts for which the gamma rays were never detected because they were not directed towards us? Is there a "typical" optical light curve of a GRB, as there seems to be a "typical" x-ray one?

After 30 years we find ourselves just starting to unravel the GRB enigma. In addition to the BeppoSAX instruments, the recent, successfully tested rapid scanning of BATSE GRB error regions with NASA's Rossi X-ray Timing Explorer (RXTE) has now also produced x-ray counterparts. In a few years approved and proposed missions such as HETE and BASIS may increase the suite of instruments available to find GRB counterparts. And as our counterpart sample increases, we may be able to establish the GRB origin and probe to deeper cosmological distances to the early stages of the universe.

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SEMICONDUCTOR DEVICES

Closer to Coherence Control

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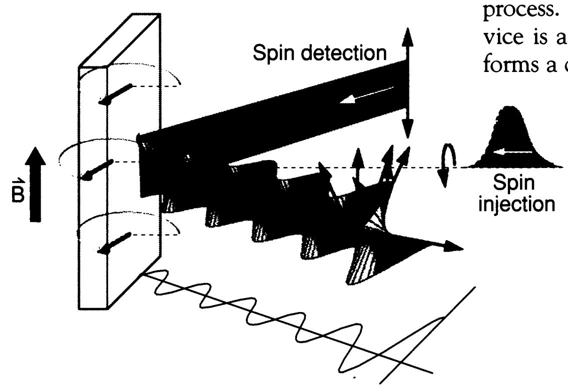
Any basic digital electronic device involves two states, the famous 0 or 1 of binary logic. As the device is made smaller and smaller, the quantum nature of the system begins to appear. In quantum mechanics, we attach a probability to the occupation of each state. In addition, we are interested in the phase difference of the wave functions of these two states when the system is excited from one state to the other. This additional quantum property is known as coherence, and the dynamics of coherence is much studied in quantum optics. The problem with semiconductors, however, is that the optical coherence lasts no more than a few picoseconds, and only when the system is much cooler than the liquid nitrogen temperature. Neither condition enhances the prospects for building a coherent semiconductor device. Nevertheless, an exploration of coherent spin states for a quantum device has begun. The concept of coherence between two spin states was in fact borrowed by quantum optics. As reported on page 1284 of this issue, Kikkawa *et al.* (*1*) have induced the coherence between the two spin states of the optically excited electron and have discovered an environment which does not disturb this coherence for several nanoseconds, which persists even at room temperature. This is a necessary first step in the exploration of coherent spin dynamics in a semiconductor.



Effect of light. On the right, a light pulse is shown with an electric vector rotating in the sense of the purple arrow. On impinging on the crystal on the left, it excites electrons with spins pointing in the propagating direction of light. Like a gyroscope, the magnetic field **B** tries to bring the electron spin to alignment but only succeeds in making the spins precess about the magnetic field as shown by the yellow circles. The electron spin dynamics is monitored by a beam of light whose polarization initially lies in the vertical plane. The plane of polarization is rotated on reflection depending on the electron spin direction (Kerr rotation). The result is recorded as a function of time as shown by the damped sinusoidal trace below.

Coherent quantum devices are important not just because they contain one more piece of information but because they preserve quantum properties in a chain of such devices without the interference of observations except at the preparation and at the end of the process. For example, if each elementary device is a logic gate, then the chain of gates forms a quantum computer. Remarkable research in quantum computation theory (*2*) has shown that such a computer could factorize a large integer much faster than the traditional computer. A logic gate consisting of a trapped ion or an atom passing through an optical cavity has been demonstrated to work (*2*). The decoherence time is long (microseconds), but the devices work at very low temperatures, so a long chain of such devices is impractical.

Researchers then turned to ensembles of atoms or electrons carrying spins (*3*): because the spins are "up" or "down," they form a kind of natural binary logic. The attempt to incorporate spin in electronics has been stimulated by the ability to inject spin-polarized electrons from a ferromagnetic material to a semiconductor (*4*) or metal (*5*). But rather than being coherent devices, these spin transistors still have classical two-state properties. Kikkawa *et al.* (*1*) use a more conventional method of producing electron spins in semiconductors by optically exciting the electron with a specific spin di-

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