PERSPECTIVES: ASTROPHYSICS

The Challenge of Gamma Ray Burst Observations

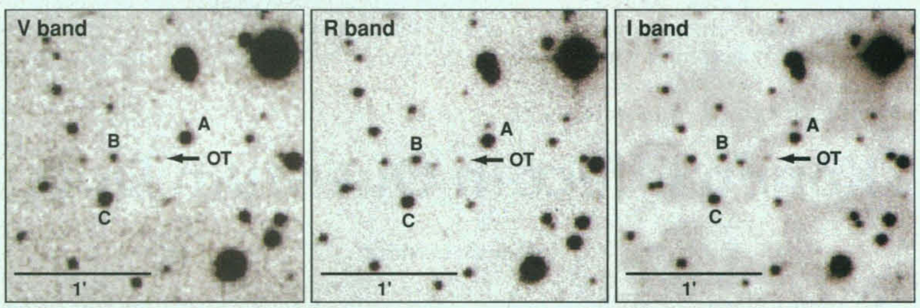
Peter J. T. Leonard

It is fair to say that there has been more progress in gamma ray burst (GRB) research in the past 16 months than during the previous 30 years. Until late February 1997, the main conclusion that could be drawn, based on observations primarily from the Compton Gamma Ray Observatory (*1*), was that GRB sources probably lie at cosmological distances well outside our galaxy. Now, with optical and radio follow-up observations of 11 GRBs, localized mainly by the BeppoSAX X-ray satellite (*2*), even the most die-hard critics now concede that GRBs originate from well beyond our galaxy, ruling out a multitude of models. Also, the fitting of theory to observations has provided precise quantitative estimates of the energy of the GRB fireballs and new knowledge about the physical conditions of the space into which they are expanding. This "bonanza" of observational results, as Gerald Fishman (NASA/Marshall Space Flight Center) described it at the 192nd meeting of the American Astronomical Society (*3*), has the theorists responding with updated cosmological GRB models, some of them entirely new.

At the meeting, ten observers presented cutting-edge results from an impressive armada of telescopes, none of which had even seen a GRB or afterglow 2 years ago (see figure). George Djorgovski (California Institute of Technology) presented his case that the 14 December 1997 GRB originated in a star formation galaxy with a redshift of 3.4. The implied electromagnetic energy release is 3×10^{53} ergs, assuming isotropic emission (versus beamed), which implies an amazingly powerful GRB mechanism. Djorgovski suggests that most GRBs occur in large-redshift galaxies and that, if we try hard enough, all host galaxies will be found. He believes that large amounts of interstellar extinction in the hosts may explain the unseen transients. Extinction may also provide an explanation for the "new no-host" problem, as it was called by Mark Metzger (California Institute of Technology), namely the surprising lack of bright host galaxies, via cases where afterglows are seen through holes in the gas and dust that otherwise shroud the hosts.

Titus Galama (University of Amsterdam) presented a beautiful piece of work, in which he deduced the energy of the fireball of the 8 May 1997 GRB and the physical conditions of the medium into which it expanded. The comparison was made between multiwavelength (x-ray to radio) observations taken 12.1 days after the GRB and the recently refined theory for the synchrotron emission from relativistic electrons that smash into an external medium. The predicted emission has spectral breaks that migrate to lower frequencies with time, and a multiwavelength observational snapshot fit to the spectrum combined with the apparent flux and a distance estimate (z = 0.835 for this particular GRB) can provide the advertised information. The (isotropic) energy of the fireball was found to be 3.7×10^{52} ergs, which is more than expected for a GRB produced by objects with masses similar to that of the sun. The estimated electron density of 0.035 cm^{-3} suggests fairly normal conditions in a galaxy, as opposed to those in a star formation region or far out in the halo of a galaxy.

The results for the 8 May and 14 December 1997 GRBs have inspired the theorists to consider some extreme scenarios for the origin of the GRBs. Xiadong Shi and George Fuller (University of California, San Diego) proposed that a GRB will result from the final stages of the collapse of a massive (10^5 to 10^9 solar masses), compact, relativistic cluster of neutron stars into a supermassive black hole in distant galaxies. Black holes in this mass range are believed by most astronomers to power active galactic nuclei. The merger of the cluster into a black hole results in intense production of neutrino pairs. These neutrino pairs convert into an electron-positron plasma, which in turn annihilates into a GRB. This scenario works best when the cluster is rotating, so that there will be a baryon-free region along the rotating axis through which the gamma rays can easily escape. The Shi and Fuller model has no difficulty meeting the energy requirements of distant GRB sources and also predicts that GRBs mainly originate at redshifts of 2 to 3, where the quasars dominate and roughly where Djorgovski would prefer to put the GRB sources.



Now you see it.... Images in different wavelength bands (**left** to **right**) of the afterglow (arrow) of the GRB of 19 May 1998 taken the following day with the 1.3-m telescope at the MDM (Michigan-Dartmouth–MIT) observatory [red (R) and infrared (I) band images, 20 May 1998, 20:31 UTC] and the WIYN (Wisconsin-Indiana-Yale-National Optical Astronomy Observatories) 3.5-m telescope [visual (V) band image, 20 May 1988, 20:34 UTC]. This was the brightest known afterglow to date and would have been visible on the Palomar Sky Survey. OT, optical transient.

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At the opposite end of the scale are the merging neutron star pair models, which used to rank with the more extreme models for GRBs but are now among the least extreme models, being just barely able to do the job, if at all. To produce the observed gamma ray flux from a neutron star merger at cosmological distances, the emission needs to be strongly beamed into a narrow cone that covers only 10^{-4} to 10^{-2} of the sky. Peter Meszaros (Pennsylvania State University) stated at the meeting that there is no strong observational evidence either for or against beaming in GRBs, so merging neutron stars cannot be ruled out. Indeed, at least some beaming would appear to be inevitable, given that many models invoke the escape of radiation along an axis of symmetry, as well as highly relativistic bulk flows (Lorentz factors of 10^2 to 10^3).

Jay Salmonson and James Wilson (Lawrence Livermore National Laboratory) and Grant Matthews (Notre Dame University) presented a new version of the merging neutron star model for GRBs, in which the GRB is produced before the

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merger occurs. Relativistic hydrodynamic calculations indicate that induced heating will occur in the neutron stars, resulting in thermal energies of 10^{52} to 10^{53} ergs in each star. This causes intense neutrino pair production, and these pairs partially recombine to produce 10^{51} to 10^{52} ergs of a relativistically flowing electron-positron plasma. Annihilation of this plasma produces a GRB with a spectrum that peaks at 100 keV, similar to what is observed. The GRB lasts for tens of seconds. The process cuts off when a black hole (or holes) is formed from the neutron stars. Improved simulations are under way to refine these predictions.

Between the extremes set by the supermassive black hole formation model and the merging neutron star pair model is the "collapsar" model presented by Andrew MacFayden and Stan Woosely (University of California, Santa Cruz). In this scenario, runaway accretion onto the neutron star formed by a failed supernova event in a massive rotating star produces a black hole surrounded by an accretion disk with relativistic jets of matter emanating from the poles of the hole to produce a GRB. This theory is described in a recent issue of *Science* (*4*).

NASA has enthusiastically responded to these developments with plans for at least three missions to help unravel the GRB mystery. The focus in the near term is to provide accurate localizations for as many GRBs as possible. HETE-2 (High Energy Transient Explorer–2; the first was lost in November 1996) will be launched in 1999. If it is put into an equatorial orbit, then it will localize roughly 50 GRBs per year with 10–arc minute to 10–arc second accuracy, according to George Ricker (Massachusetts Institute of Technology). Proposals for an even better GRB localizer are now being reviewed by NASA in the form of a MID-sized EXplorer-(MIDEX) class mission. Farther down the road is the Gamma-Ray Large Area Space Telescope (GLAST), with a planned launch in 2005. This mission will be able to detect high-energy gamma ray photons with energies of up to 300 GeV from a variety of astrophysical sources, including GRBs, to help constrain the physics of the acceleration processes. Because GRBs are apparently the most energetic events in the universe, next to the Big Bang itself, then what we learn from future ground- and space-based observations of this phenomenon will likely extend our knowledge at the frontiers of physics and present an ongoing challenge to observers and theorists alike.

References

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PERSPECTIVES: CONDENSED MATTER PHYSICS

Kondo Effect in Quantum Dots

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A simple picture of electrons in metals would suggest that the resistivity should decrease straightforwardly as the temperature is lowered. Yet for certain metals, the resistivity goes through a minimum and starts to rise as they are cooled. This peculiar behavior, discovered over 60 years ago, has come to be called the Kondo effect after Jun Kondo, who in 1964 gave the first correct explanation of this effect in terms of magnetic impurities (*1*). About a decade ago, three groups of theorists (*2–4*) predicted that the effect would also manifest itself in the low-temperature transport of electrons through a quantum dot. Recently, Goldhaber-Gordon and colleagues at the Massachusetts Institute of Technology (MIT) and the Weizmann Institute of Science (*5*) announced the first observation of the predicted effects. On page 540 of this issue, Cronenwett and co-workers at Delft University of Technology (*6*) report on more detailed results.

Both groups conducted their studies on single-electron transistors made by depositing metal gates over a two-dimensional electron gas formed in a GaAs/AlGaAs heterostructure. Applying a negative voltage to these gates depletes the regions below them, creating a small dot, or an atom-like box for electrons, coupled by tunneling to two separate two-dimensional electron gases acting as source and drain leads (see figure).

Many experimenters have investigated the source-to-drain current I_{sd} of such single-electron transistors as a function of the voltage V_{sd} between the leads (*7*). Especially interesting is a plot of linear conductance $G = I_{sd}/V_{sd}$, with V_{sd} kept very small, as a function of the voltage V_g on the dot. The result is a series of periodically spaced peaks, each indicating the change in the number of electrons N in the dot by one (see figure). Understanding electron transport through single-electron transistors is facilitated by the introduction of a function $D_{loc}(E)$, called the local density-of-states, representing the spectrum of energy required to add an electron to the dot. The energy required to add an electron to an empty dot is E_1, the energy of the lowest spatial state of the dot. A second electron, with a spin of the opposite direction, goes into the same spatial state, but its addition costs a larger energy $E_1 + U$, where U is the Coulomb repulsion energy between the two electrons. Because a third electron can no longer enter the E_1 state, it enters the next available spatial state with energy E_2. Taking account of the Coulomb interaction with the first two electrons, its addition requires an energy $E_2 + 2U$. Continuing this, we see that $D_{loc}(E)$ has peaks at $E = E_1$, $E_1 + U$; $E_2 + 2U$, $E_2 + 3U$; and so forth, which occur in pairs as indicated by the semicolons. (The peak widths are finite because of finite escape time onto the leads.) Two peaks within a pair are separated by U, whereas the separation between different pairs, corresponding to different spatial states, is larger. Note also that in the region covered by each pair, N is odd and the dot is magnetic (spin 1/2), whereas, between the pairs, N is even and the dot is nonmagnetic (spin 0).

When a voltage V_g is applied to the dot, $D_{loc}(E)$ is replaced by $D_{loc}(E - eV_g)$, where e is the electron charge. Each time one of the peaks of $D_{loc}(E - eV_g)$ lines up with the Fermi level E_F of the leads, a peak shows up in G, and these peaks are also clustered into pairs. Outside these peaks, G vanishes because electron tunneling into or out of the dot requires finite energy and is impossible. This so-called Coulomb blockade in single-electron structures is well established by experiments and is also reproduced in (*5*) and (*6*) at temperatures much greater than 100 mK.

What is remarkable about the MIT-Weizmann and Delft experiments is that, as the samples are cooled further, the inner shoulders of each pair of peaks in $G(V_g)$ broaden and are enhanced, whereas no broadening is seen outside of the pairs where the dot is nonmagnetic. This is what theories (*2–4*) predicted to be a signature of the Kondo effect in dot systems.

The Kondo effect is essentially a screening of the dot (or impurity) spin by nearby free electrons and so takes place

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