Long GRBs and Supernovae from Collapsars

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Summary. Long duration gamma-ray bursts are associated with the death of massive stars as earlier observations and theoretical arguments had suggested. Supernova 2003dh observed with GRB030329 confirms this picture. Current progress in developing numerical special relativistic hydrodynamics codes with adaptive mesh refinement is allowing for high-resolution simulations of relativistic flow relevant for simulations of GRBs.

Long Gamma-Ray Bursts

Gamma ray bursts (GRBs) are the most luminous explosions in the universe, briefly out shining all other sources in the sky. As is well known, GRBs were discovered by military satellites in the late 1960s and have fascinated scientists ever since. We now believe that the common long variety of these bursts mark the death of stars many times more massive than our Sun (M $\gtrsim$20 $M_{\odot}$) and are the birth cries of rotating stellar mass black holes (or highly magnetized rapidly rotating neutron stars). The energetic supernova 2003dh, discovered on March 29, 2003 underneath the fading glare of a long GRB and widely discussed at this meeting, confirms this picture.

GRBs are defined as short ($\tau \sim$ 10s) non-thermal bursts of $\gtrsim$100 keV gamma rays. They exhibit diverse light curves but fall into two general classes defined by total durations above and below $\sim$ 2 s. Long GRBs have mean detected durations of 35 seconds, comprise roughly 2/3 of all the total GRB population and have softer spectra than their shorter duration cousins. Some vary on millisecond timescales, others shut off completely for a few seconds and then turn back on, some last over 2000 seconds. The rapid detected variability ($< 1\ \mu s$) and the large energy ($\approx 10^{52}$ erg) point to a stellar mass compact object as the "central engine" powering the GRB explosion. However, the duration of long GRBs is millions of dynamical times for such a dense object. Theoretical models must explain the discrepant timescales.

Among the many early theories attempting to explain GRBs was the emergence of a shockwave from a star during a supernova explosion. According to the collapsar model [4] some stars manage to produce asymmetric outflows traveling at 99.999% the speed of light. Such ultra-relativistic outflows are required to produce the non-thermal spectrum and rapid variability.

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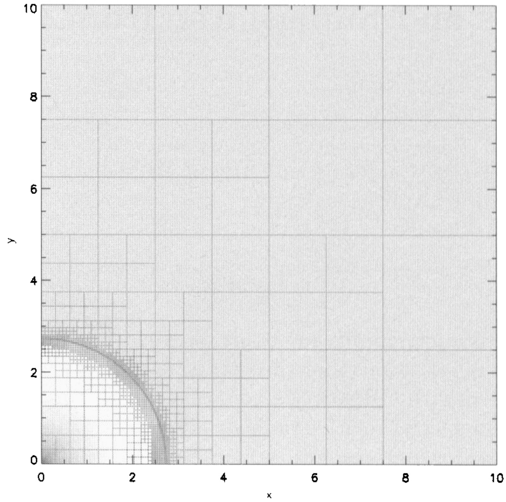

Fig. 1. Relativistic Blast Wave: Planar slice through a three-dimensional simulation of a spherical relativistic blast wave. Nine levels of adaptive mesh refinement were used to resolve the thin relativistically expanding spherical shell at radius 2.75. Each box is a block of $8 \times 8 \times 8$ zones. The Lorentz factor of the shell at this time is 120. The effective resolution of the simulation is 4096^3. It was run on 256 processors of the IBM SP Seaborg supercomputer at NERSC for twelve hours.

GRBs are now thought to be roughly ten times as energetic as supernovae in terms of the kinetic energy of the explosive outflow. A key question is why the explosion energy is concentrated in so little mass (10^{-5} solar masses) in a GRB instead of several solar masses in an "ordinary" supernova. In both cases much more energy (10^{53} ergs) may be released as neutrinos and yet more in gravitational waves. Understanding the total energetics of GRB explosions and the partitioning between the various channels (photon energies from gamma-rays to radio, neutrinos, gravitational waves) is critical to fully understanding GRBs.

Observable GRBs occur roughly once every 10 million years per galaxy. X-ray observations indicate that GRBs are beamed to about 1% of the sky so the true rate is higher: one per 100,000 years per galaxy. Since the supernova rate is about one per 100 years per galaxy, roughly 1/1000 supernova make a GRB. A key question is what special circumstances cause the star to make a GRB. It may be the formation of a black hole, a highly magnetized neutron star (magnetar) or a supermassive spinning neutron star.

Collapsars

The collapsar model proposes [4] that some rotating massive stars, more than about 25 times the mass of the Sun, fail to explode in the ordinary

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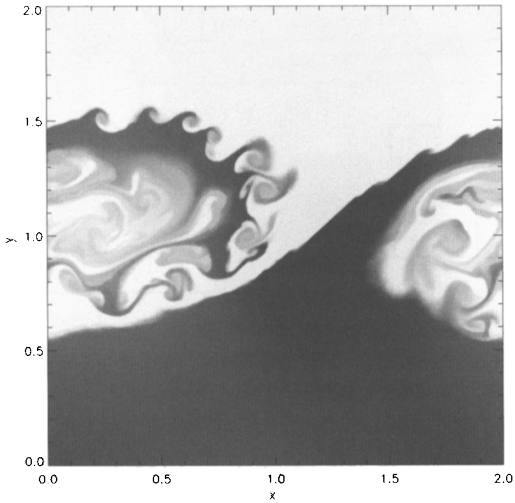

Fig. 2. Relativistic Kelvin–Helmholtz Instability: A mildly relativistic shearing layer with velocity 0.25 c and density 1 above and velocity -0.25 c and density of 5 below and a sinusoidal vertical velocity perturbation.

way thought to produce normal neutron stars. Instead the core of the star collapses to form a black hole. If the star is spinning sufficiently rapidly when it collapses, the gas in the star swirls into the new black hole by forming an accretion disk. The release of gravitational energy is thought to power a jet-like outflow along the rotational axis of the star. In addition the disk may sustain magnetic fields capable of extracting rotational energy directly from the black hole. Since gas falls immediately along the rotation axis where there is no centrifugal barrier, the polar regions of the star drain quickly into the black hole. As accretion disk energy is deposited in this low density channel by magnetic processes, perhaps aided by neutrino annihilation, a fast beamed outflow forms. The stellar gas remaining along the poles is shock heated and much of it is pushed sideways. Eventually the jet breaks out of the star and accelerates to ultra-relativistic speeds (See Fig. 1). Much of the gas attempting to accrete is expelled from the accretion disk since it can not cool. This outflowing gas and shockwaves from the jet explode the star. The collapsar model predicts an exploding star with every long GRB. Since hot gas flowing out in the star can form ^{56}Ni, some of these stellar explosion should be observable as supernovae beneath the glare of the fading optical counterpart of the GRB. Furthermore the star must have been small in radius when it died so that the relativistic jet can escape the star while it is still being powered by the accretion disk. Such a star should appear as a Type Ib/c supernova. SN2003dh was indeed of this type.

It is also possible that an highly magnetized rapidly spinning neutron is formed. This magnetar may act like a supercharged pulsar that accelerates a

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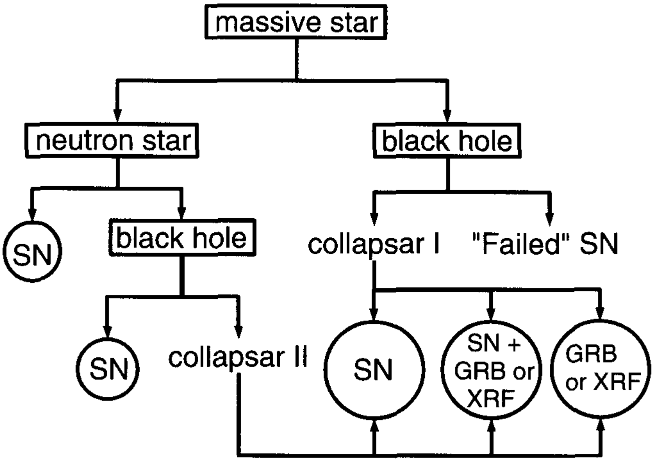

Fig. 3. Flowchart: Evolutionary paths leading to stellar explosions. SN = supernova explosion. GRB = Gamma-ray burst and XRF = X-ray flash.

magnetically dominated flow. In both scenarios, the jet may be composed of extremely relativistic particles which manage to escape the star and travel far away before internal collisions dissipate energy and emit the gamma-rays we observe. Alternatively, the outflow may be magnetically dominated plasma with few particles that dissipates energy through plasma instabilities. A combinations of particles and magnetic fields is also possible. A key question is the degree to which instabilities can mix material into the jet.

Ni Production

It is important to note that models for long GRBs must explain the large amount of ^{56}Ni observed in the explosion. The Type Ibc supernovae observed so far shine principally because of radioactive decay of the Ni. In the collapsar models this Ni is though to be produced from gas that is ejected from an accretion disk [4]. The jet itself is not hot enough to synthesize the Ni and does not contain very much mass.

Relativistic Blastwaves

Recent fundamental progress in understanding the physics of GRBs and their environment has resulted from detailed comparison between observed light curves and theoretical models for relativistic blast waves e.g., [3]. The data to be obtained by the SWIFT satellite requires accurate theoretical models of GRB jet dynamics to address fundamental questions:

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How do relativistic jets spread as they decelerate? What is the lateral dynamics of the post shock material? How do multi-dimensional dynamical effects alter a structured jet? How do multi-dimensional jets interact with various external mass distributions: stellar wind, constant density, clumpy medium? How does late-time or slower ejecta interact with the decelerated blast wave when it catches up? What is the structure of refreshed shocks when they occur? Are relativistic blast waves stable to small perturbations? Can they disrupt on an outflow timescale?

All of these questions are critical for accurate modeling of SWIFT GRB data.

Code Development

Recent progress has been made developing high-order special relativistic hydrodynamics code using adaptive mesh refinement (AMR) to allow high resolution simulation of GRB jets in two and three dimensions [1, 7]. With sufficient development we will be capable of fully resolving relativistic blast waves relevant for GRBs in multi-dimensional computer simulations. With the code, we perform fully resolved multi-dimensional simulations of a jetted relativistic blast wave from the ultra-relativistic phase, described by the Blandford-McKee solution [2], to the trans-relativistic spreading phase as swept up ambient medium decelerates the flow (Figure 1). Comparison of synchrotron emission to be calculated from our simulations with afterglow light curves from SWIFT GRBs will constrain jet structures and test analytic treatments of relativistic fluid dynamics.

Preliminary tests have shown that we have sufficient resolution (effective resolution of 4096^3 and higher) in three dimensions using Cartesian coordinates (avoiding coordinate singularities). AMR is ideally suited to this problem because relativistic blast waves form extremely thin structures requiring resolution of $\delta r/r \lesssim 1/4\Gamma^2$ but are not volume filling. We fully resolve the thin shells (sometimes referred to as pancakes in the GRB community) as they propagate, but use coarser resolution in the smooth regions in front of and behind the blast wave.

Previous studies have treated the jet evolution with various one-dimensional simplifications to the dynamics. There has been some work done in 3D but it is with diffusive hydro schemes and were very far from the resolution required to resolve the jet structure. This problem requires the resolution achievable with high order algorithms with adaptive mesh refinement on massively parallel super-computers.

The code already runs in three-dimensions and runs on massively parallel computers at NERSC. Our project is at a critical juncture because so much has been accomplished in a short time of collaborative work. Our project will benefit enormously from several sustained visits where the team can work collaboratively.

Relativistic blast waves are ideally suited for AMR because they form extremely thin structures which do not necessarily fill the computational volume. To correctly solve for the dynamics of a relativistic blast waves it is necessary to resolve characteristic scales of $\frac{\delta r}{r} \lesssim \frac{1}{16\Gamma^2}$. For $\Gamma \sim 100$ this requires that zones of width $\delta r \lesssim 6.25^{-6} r$. To grid the entire volume with sufficient resolution would require $(1.6 \times 10^5)^n$ zones where n is the number of spatial dimensions.

Fig. 1 shows a thin spherical shell formed as a fireball deposited at the center expands. Most of the volume is smooth and well resolved with low refinement (large blocks).

Our simulations will be of sufficient quality that comparison with SWIFT light curves may allow for confirmation of the dynamics of relativistic shock waves. Preliminary tests on 512 processors of a parallel supercomputer (Seaborg at NERSC) confirm that we have more than sufficient resolution to resolve 3D.

Mixing

Compactness arguments require that GRB jets be ultra-relativistic during the gamma-ray emitting phase. This requires that they maintain an extremely large energy to mass ratio ($\eta \equiv \frac{E}{m} \gtrsim 100$) as they are born and propagate. A key unanswered question is whether or not GRB outflows can remain sufficiently clean or whether baryons will be mixed in to the flow lowering the maximum asymptotic Lorentz factor below the values required by observations. This problem is especially relevant for collapsars in which the jet must propagate through a star. Do shear instabilities and microscopic mixing processes load unacceptably large numbers of baryons into the jet? What is he the timescale for the mixing? Can pressure gradients and centrifugal barriers repel material from the jet core along the rotation axis? Some aspects of these questions are addressable with numerical simulation. AMR can be helpful for initial phases of evolution before inhomogeneities fill the simulation volume. Even then, our code is capable of simulating high resolution throughout the volume when run on massively parallel machines. Fig 2, shows a calculation of the relativistic Kelvin-Helmholtz instability. Such shear instabilities can be suppressed for ultra-relativistic flows. We can track mixing in these flows by adding multiple fluids to our calculations.

An important advance in the study of GRB physics is the development of new high resolution special relativistic hydrodynamics code using adaptive mesh refinement (AMR) [7]. These are the first codes capable of fully resolving relativistic blast waves relevant for ultra-relativistic GRB blastwaves in multidimensional computer simulations. It is now possible to perform the first fully resolved multidimensional simulations of a jetted relativistic blast wave from the ultra-relativistic phase, described by the Blandford-McKee solution, to the trans-relativistic spreading phase as swept up ambient medium decelerates the flow. Comparison of synchrotron emission to be calculated from these simulations with afterglow light curves from SWIFT GRBs will constrain jet structures and test analytic treatments of relativistic fluid dynamics.

Future simulations will be of sufficient quality that comparison with SWIFT lightcurves may allow for confirmation of the dynamics of relativistic shockwaves. Preliminary tests on 512 processors of a parallel supercomputer (Seaborg at NERSC) confirm that we have more than sufficient resolution to resolve 3D. Such calculations are critical for interpreting the detailed lightcurves of GRBs to be discovered by SWIFT.

Future Prospects

The present and future is bright for GRB research. The HETE-II satellite is currently in orbit contributing valuable localizations of GRBs including GRB030329. The SWIFT satellite is scheduled for launch this Spring (2004). The principle problem for observing GRBs has been the very fact that they release energy on rapid timescales. In order to the take full measure of the photon output of GRBs integrated over all wavelengths, it is necessary to observe the GRB rapidly with instruments tuned to a wide range of wavelengths. In addition to their gamma-ray emission much energy is released in the X-ray through radio bands. We need to detect GRBs from space (gamma-rays are absorbed by the atmosphere and don't reach Earth) and quickly determine accurate positions on the sky so that other satellites (HST Chandra) and Earth-based telescopes (Keck, VLT) can search for their emission. HETE is doing this now and SWIFT will soon. We can look forward to exciting new discoveries.

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