Gamma-ray Bursts from Stellar Collapse

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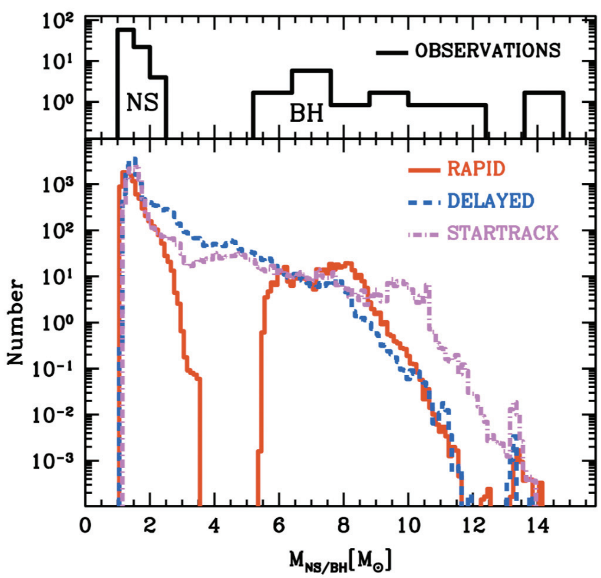
One of the leading models behind gamma-ray bursts postulates that these cosmic explosions are produced when a star collapses to form a black hole (BH). The subsequent accretion onto the BH produces the explosion. To understand these BH accretion disk gamma-ray burst (GRB) models, we must understand BH formation. We conducted a detailed study of BH formation, comparing our results with observed X-ray binary systems. Finally, these studies were applied to the recently observed Christmas burst.

Fig. 1. Number of compact remnants produced as a function of remnant mass. Those systems above two to three solar masses are BHs. The top panel shows the observed systems, the bottom panel shows our simulated results.



The leading model behind long-duration gamma-ray bursts (GRB) invokes the collapse of a massive star down to a black hole (BH) [1], but the exact details of this collapse and the exact progenitor remains unknown, with a host of progenitor possibilities [2]. To differentiate these progenitors, we must understand the details of BH formation and, to do this, we must understand stellar collapse. This year, we led a series of efforts to better understand BH formation and the progenitors of GRBs.

Stars are powered by fusion in their cores. Massive stars proceed through a series of core-burning phases, where the ashes of the previous phase become the fuel for the next phase. In this manner, the core burns hydrogen to helium, helium to carbon/oxygen, carbon to silicon, and silicon to iron. At this point, fusion of iron does not yield any additional energy. As the iron core increases in size, it ultimately becomes so massive that thermal and degeneracy pressure can no longer support the core and it collapses. The potential energy released in the collapse of the iron core of a massive star down to a neutron star (NS) is what powers type Ib/c and type II supernovae. However, in some stars the released energy is unable to drive a strong supernova explosion. In these cases, the proto-NS collapses to form a BH.

The fate of the collapsing star ultimately depends on the structure of the star. This year, we developed an analytic framework with which we are able to analyze stellar models and determine the fate of the collapsing stars and the final remnant mass of the collapsed core. By studying a large set of stars at collapse, LANL scientists developed correlations between the initial mass of a star and its final compact remnant mass after collapse [3]. With these correlations for both single and binary star systems, we were able to develop distributions of NS and BH masses in the galaxy that can be directly compared to observed distributions.

BH mass measurements rely on a complex combination of challenging observations of X-ray binaries (in quiescence, if they are transient) and of modeling of photometric and spectroscopic data. The uncertainties associated with these measurements are more significant than in the case of NSs. Early analysis argued that the measurements are consistent with a relatively narrow mass distribution [4] around seven solar masses. Recent analyses [5,6] have used the expanded current samples of BH measurements in both Roche-lobe-overflow and wind-driven X-ray binaries and proposed distributions to fit the observations (without quantitative consideration of selection effects). The statistically favored models have mass distributions that extend to high masses (~15–20 solar masses), depending on whether the wind-fed systems with more massive BHs (which are more uncertain) are included. Both studies conclude that there is clear evidence for a low-mass gap in the distribution, with no remnants found in between the maximum NS mass of about two solar masses and four to five solar masses. However, this field is still in a state of flux as new observations appear: observations of IGR J17081-3624 suggest that at least some low-mass BHs exist [7].

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Fig. 2. Artist's drawing of the Christmas burst showing the surrounding debris produced in our merger model.

These observed mass distributions are a select sample of the BHs in the universe. This sample is limited to those binary systems in which, after BH formation, the system is close enough to transfer mass from the companion to the BH, producing X-ray emission. These so-called "X-ray binaries" make up our observed mass distribution. To directly compare to our theoretical correlations with observations, we ran population synthesis models that evolved the stellar binaries until they became X-ray binaries. A comparison of theory and observation is shown in Fig. 1. Although the theory distribution still allows some systems within the range of two to four solar masses, we note that the recent observation of IGR J17081-3624 shows that some systems in the gap exist.

Although the primary factor in determining the fate of the star is the structure of the pre-collapse star, we have many uncertainties in the collapse that we must understand before we fully understand its fate. One of the most important is the role of the equation-of-state. With our computing time on the Turquoise network and using the SNSPH code [8], we were able to model the collapse of a 60-solar-mass start to times well beyond anything done to date. We are currently coupling the new Shen equation-of-state to the SNSPH code and we conduct detailed comparisons of this long run with a new run using this different equation-of-state. These comparisons will allow us to better quantify the importance of the equation-of-state on BH formation.

All of this work allows us to much better understand the BH-forming phenomenon that we observe in nature. We conclude with a discussion of one such example. On December 25, 2010, the Swift Burst Alert Telescope detected a GRB, one of the longest GRBs ever observed by Swift with a duration of over 2000 s (using the time in which 90% of the gamma-ray energy is released). The most surprising feature of this "Christmas burst" is the spectral energy distribution (SED) of its afterglow [9]. The X-ray SED is best modeled with a combination of an absorbed power-law and a blackbody (BB). The UV/optical/Near Infra-Red (UVOIR) SED can be modeled with a cooling and expanding BB model until 10 days post-burst, after which we observe an additional spectral component accompanied by a flattening of the light curve. This behavior differs from a normal GRB where the SED follows a power-law due to synchrotron emission created in shocks when the jet hits the interstellar medium.

Our studies of BH formation allowed us to quickly develop a plausible progenitor for this burst and we were able to develop a model that explained the observed features of this explosion. Our model, based on earlier work by Fryer and colleagues in the 1990s [10,11] invoked a compact object/main sequence merger just prior to the outburst. In essence, this model is an extreme version of the X-ray binaries we studied to understand the compact mass distribution. Instead of slowly accreting matter from its compact object, the compact object spirals into its companion's core. The subsequent accretion drives the powerful GRB explosion. The ejecta from the merger produce a shell responsible for many of the peculiar features of this explosion.

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