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Review

Numerical simulations of gamma-ray burst explosions

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ABSTRACT

Gamma-ray bursts are a complex, non-linear system that evolves very rapidly through stages of vastly different conditions. They evolve from scales of few hundred kilometers where they are very dense and hot to cold and tenuous on scales of parsecs. As such, our understanding of such a phenomenon can truly increase by combining theoretical and numerical studies adopting different numerical techniques to face different problems and deal with diverse conditions. In this review, we will describe the tremendous advancement in our comprehension of the bursts phenomenology through numerical modeling. Though we will discuss studies mainly based on jet dynamics across the progenitor star and the interstellar medium, we will also touch upon other problems such as the jet launching, its acceleration, and the radiation mechanisms. Finally, we will describe how combining numerical results with observations from Swift and other instruments resulted in true understanding of the bursts phenomenon and the challenges still lying ahead.

1. Introduction

Numerical simulations have played a major role in the understanding of gamma-ray burst (GRB) studies in the past decade. Even though it is difficult to find a precise moment at which it all begun, the growing evidence of association between long-duration GRBs and core-collapse supernovae in the late 1990s (Woosley, 1993; Galama et al., 1998; Paczynski, 1998; Bloom et al., 1999) arguably played a major role in supporting the need for theoretical tools that could go beyond the approximations of spherical symmetry and/or top-hat jets. Numerical simulations are now used as a major tool in many aspects of the GRB phenomenology.

First, numerical methods are used to understand the properties of the progenitor. Binary compact mergers are heavily studied as short GRB progenitors (Rosswog, 2007; Giacomazzo and Perna, 2012; Giacomazzo et al., 2013; Rosswog et al., 2013) and massive, fast spinning stars and their core-collapse are investigated as potential long GRB progenitors (Woosley and Heger, 2006a, 2006b; Yoon et al., 2006). Numerical simulations are also used to understand the jet launching from a compact object, either a black hole or a magnetar (McKinney and Narayan, 2007a, 2007b; Harikae et al., 2009, 2010; Komissarov and Barkov, 2009; McKinney and Blandford, 2009; Nagataki, 2009; Taylor et al., 2011; Janiuk et al., 2013; McKinney et al., 2013). Subsequently, numerical simulations are used to model the dynamics of both magnetized (Bucciantini et al., 2009, 2012) and unmagnetized jets (MacFadyen and Woosley, 1999; Aloy et al., 2000; Zhang et al., 2003, 2004; Mizuta et al., 2006; Mizuta and Aloy, 2009; Morsony et al., 2007, 2010; López-Cámara et al., 2013; Mizuta and Ioka, 2013). Numerical simulations are finally used to model the prompt emission phase (Pe'er et al., 2006; Lazzati et al., 2009, 2011a, 2013; Lazzati and Begelman, 2010; Mizuta et al., 2011; Vurm et al., 2011; Lundman et al., 2013, 2014; López-Cámara et al., 2014; Chhotray and Lazzati, in press) and, eventually, the afterglow (van Eerten et al., 2011; De Colle et al., 2012a, 2012b; van Eerten and MacFadyen, 2012, 2013).

In this review we will concentrate on the hydrodynamical aspect of simulations, focusing on the interaction between the jet and the progenitor star and its consequences for the jet dynamics, propagation, and radiation mechanism. We refer the reader to the above references for a more complete discussion of the various numerical techniques and physical problems addressed.

2. Inside the star: ploughing through

Hydrodynamical (HD) simulations of relativistic jets inside massive stars have played a major role in our understanding of the GRB phenomenology. They are based on the assumption that somehow the central engine – being a black hole or a magnetar – is capable of producing a jet with the adequate luminosity and entropy. The jet has to propagate through a star that is mostly unchanged

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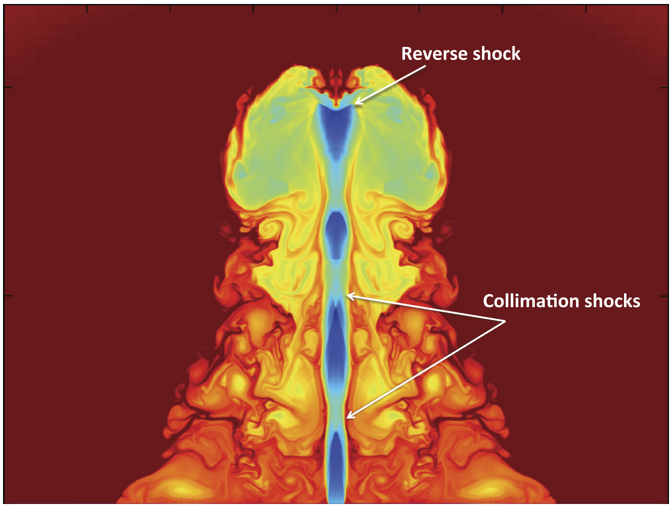

Fig. 1. False-color rendering of a relativistic jet expanding in the core of a massive star. Red colors show high-density while blue colors show low-density regions. The reverse shock that decelerates the jet material and the tangential collimation shocks are indicated. The forward bow-shock propagating in the interstellar matter is not shown. Adapted from Lazzati et al. (2012). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

since core-collapse, its free-fall time being longer than the typical GRB duration at radii beyond $\sim 10^9$ cm from the star's center. More controversial is the jet composition at the jet's base, i.e. the inner boundary of the simulation. Most simulations are HD and ignore the presence of magnetic fields. This is a good approximation as long as the magnetization is low. Since most jet launching mechanisms are heavily based on strong magnetization, such an assumption has unclear validity. Simulating unmagnetized jets, on the other hand, makes it possible to satisfy the requirement of very high resolution in the boundaries between the relativistic outflow and the surrounding star, a resolution that can be achieved only with adaptive mesh techniques.

The first issue numerical simulations have to address is the propagation of the jet inside the star. A known result is that the jet cannot expand conically and accelerate proportionally to the radius inside the progenitor star (Matzner, 2003). Early GRB simulations (MacFadyen and Woosley, 1999; Aloy et al., 2000) showed that the jet head propagates trans-relativistically, at few tens of per cent of the speed of light. This speed depends very weakly on the jet and star properties and a value $\beta_h = 0.25$ for the jet-head speed gives an accurate prescription for the propagation inside the star (Lazzati et al., 2012). A sub-luminal propagation speed also ensures that the jet is causally connected with the star and the star material that accumulates in front of the jet can move aside. Numerical results can be qualitatively reproduced by analytical models (Morsony et al., 2007; Bromberg and Levinson, 2007; Bromberg et al., 2011). Even the most advanced analytical models, however, assume cylindrical symmetry and do not include important effects such as vortex shedding, multiple tangential shocks, and turbulence. As a consequence, they cannot exactly reproduce some simulations detail and fail to precisely predict even the jet head expansion velocity inside the progenitor star (Lazzati et al., 2012).

One important consequence of a relatively slow jet propagation inside the star is the creation of a cocoon that surrounds the jet. An amount of energy

$$E_{\rm Cocoon} = L_j \left(t_{\rm bo} - \frac{R_\star}{c} \right) \sim L_j \frac{R_\star}{c\beta_h} = 10^{52} L_{j,51} R_{\star,11} \;\; {\rm erg} \qquad (1)$$

is deposited in the cocoon and, from the cocoon, is transferred to the star. L_j is the engine luminosity, $t_{\rm bo}$ is the jet breakout time,

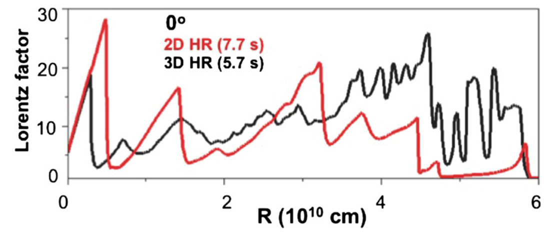

Fig. 2. Radial profile of the Lorentz factor of jets propagating in massive stars at the time of their breakout off the star's surface. Results from a 2D simulation (red) and a 3D simulation (black) are compared, showing how 3D produces a more complex profile due to the presence of multiple minor shocks rather than a few strong ones. Adapted from López-Cámara et al. (2013). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

$R_\star$ is the progenitor star's radius, and β_h is the jet's head propagation speed in units of the speed of light. $L_{j,51}$ and $R_{\star,11}$ are the luminosity and stellar radius normalized by 10^{51} erg s^{-1} and 10^{11} cm, respectively. Note that once the jet head has broken out on the star's surface, all the jet behind the head does exit the star, accounting for the $R_\star/c$ term in the equation above. The energy deposited in the cocoon is therefore enough to unbind the stellar material. However, because the jet deposits the energy in the star far from the core, the explosion might be darker than a normal core-collapse supernova (CCSN). This is due to the lack of newly synthesized ^{56}Ni, whose decay powers the light curve of "normal" CCSNe. The presence of jets, however, changes the energy distribution in the ejecta, producing explosions with fast ejecta that can explain bright radio emission in some supernovae (Lazzati et al., 2012).

A firm result of simulations, independent of the code and of the jet and star properties, is the complexity of the jet profile. The jet is characterized by the presence of multiple shocks (Fig. 1). There is a reverse shock that decelerates the expanding jet as a consequence of the bow shock at the jet's head. There are, however, several collimation shocks behind the reverse shock as well. These are tangential shocks that are produced by the interaction of the jet with the cocoon. As a consequence of the presence of collimation shocks the jet's Lorentz factor is not uniform behind the reverse shock, but it has a characteristic sawtooth shape (Fig. 2). A cartoon showing the various components of the jet–star interaction dynamics is shown in Fig. 3.

Initial simulations of the jet propagation were performed in cylindrical symmetry in two dimensions (MacFadyen and Woosley, 1999; Aloy et al., 2000; Morsony et al., 2007). More recently, full 3D simulations have become possible. They show interesting features and more complexity in the jet dynamics. One important limitation of 2D simulations is the "plug instability", an effect whereby any overdensity of ambient medium that accumulates ahead of the jet next to the axis is trapped and creates an obstacle. As a consequence the system develops two plumes of low-density, high-temperature material at large polar angles (see, e.g., Fig. 1 in Lazzati et al., 2010). This instability is seen in jets from both constant and variable engines (López-Cámara et al., 2014). 3D simulations have shown that the jet, instead, travel through the path of least resistance, its head moving round the polar axis to avoid over-densities in the progenitor star or induced by the bow shock itself (Zhang et al., 2004; López-Cámara et al., 2013). As a consequence, the collimation shocks are also reduced in size and intensity, producing a more complex structure and a smoother profile of the Lorentz factor (Figs. 2 and 4).

3. Outside the star: free expansion... almost

A second important stage of a GRB jet is its expansion once it has left the progenitor star. The jet is expected to be freely