Quiescence and late time activity in collapsars due to critical angular momentum distributions

Diego Lopez-Camara

ABSTRACT

Even thought a large amount of long gamma ray bursts (LGRBs) present quiescent periods, their origin remains unclear. In this talk, it is shown how different angular momentum distributions, as a function of the stellar radius), can lead to neutrino luminosity variability and the possibility of quiescent epochs in LGRBs.

1. Introduction

Collapsing massive stars produce Supernovae (SN) and are linked to the production of Long Gamma Ray Bursts (LGRBs), providing clues to the progenitors and their environments. A key ingredient is the stellar rotation rate, impacting the energy release and outcome of the event following the implosion of the iron core. Stellar evolution considerations have shown that it is non-trivial to have rapid rotation, as mass loss and magnetic fields conspire to reduce the pre-SN angular momentum.

Many studies of neutrino cooled accretion relevant for collapsars have considered specific rotation laws that guarantee by a large margin the formation of a centrifugal disk, because the angular velocity is assumed to be nearly Keplerian, or because the absolute value of the angular momentum given implies a circularization radius much larger than the radius of the innermost stable circular orbit. However, the distributions of specific angular momentum considered were constant in the equatorial plane. This is unrealistic, as the specific angular momentum increases outwards in the core and envelope, with marked transitions at the boundaries between different shells.

Here we explore how the distribution of angular momentum as a function of radius can affect the qualitative properties of the accretion flow, and hence the neutrino luminosity, accretion rate and energy release. We pay particular attention to the form and rate of change of rotation in the star with radius, and show that state transitions may in principle produce observable consequences in LGRBs relevant to variability and quiescent periods.

1 Instituto de Ciencias Nucleares, UNAM, Apdo. Postal 70-543, México D.F. 04510, MEXICO
Woosley & Heger’s (2006) 1D pre-SN models were taken as the initial conditions. The correspondent distributions were mapped to two dimensions assuming spherical symmetry, and the iron core was condensed onto a point mass at the origin representing a BH, producing a pseudo-Newtonian potential. The evolution is subsequently followed with the same numerical code used in Lopez-Camara et al (2009).

2. State transitions.

The general trend in the distribution of specific angular momentum in pre-SN models is for a rise through the core and envelope. We thus initially considered angular momentum which increased linearly as a function of the stellar radii ($J(R)$). When $J(R)$ increased very slowly the result was a quasi-radial inflow (QRI); on the other hand, for a rapidly increasing $J(R)$ an accretion disk around the BH was produced. Interestingly, cases which increased linearly -but in neither of the two previous regimes-, this is: an intermediate linearly increasing case, allowed momentary appearance of a torus, which was accreted after a delay of $\sim 0.1$ s by the BH.

Since neighboring shells in pre-SN cores exhibit strong jumps in the $J(R)$ superimposed on an increasing function of radius. To explore how this feature affects the flow properties in the collapsing star, we considered a constant background distribution just below the critical value to produce the accretion disk around the BH ($J_{\text{crit}}$), and two narrow spikes with $J(R)$ well above $J_{\text{crit}}$. The resulting neutrino luminosity is shown in Figure 1. It is clear that multiple spikes in the distribution of specific angular momentum lead to clear transitions between the “quasi-radial” low-$L_\nu$ and “disk” high-$L_\nu$ state, with durations and delays correlated to the form and normalization of $J(R)$.

For the cases when the newly formed accretion disk had more than a third of the mass inside the QRI envelope which is falling onto it (case referred as: $\mu \geq 1/3$), then the initial disk absorbs the impact of the infalling shell and survives. Thus, when a second spike would approach the still existing disk it would simply add to the preexisting activity, leaving no place to quiescent periods. This is illustrated in the bottom panel of Figure 2. On the other hand, for cases when the disk has less than a third of that which is present inside the QRI envelope (case referred as: $\mu \leq 1/3$), then the accretion disk would be destroyed within a dynamical time scale. With this, when a second spike would reach the centrifugal barrier, a new disk would be created, persisting as long as the inflow has sufficient rotation (upper panel in Figure 2), and a quiescent epoch would be present.

The correspondent time scales can be estimated as the correspondent free fall time
Fig. 1.— Neutrino luminosity for the case where $J(R)$ has a constant background with two superimposed spikes.

for each shell, thus for the case when there is a quiescent period, the initial active period lasts approximately between 1 and 3 second, while the quiescent period lasts from 1 to 15 seconds (depending on the preSN characteristics), prior to the main burst. The corresponding neutrino luminosities would be: $L_\nu \simeq 10^{51}$ erg s$^{-1}$ for the quiescent period, and $L_\nu \simeq 10^{51}$ erg s$^{-1}$ for the active periods.

3. Discussion

We wish to stress that while we have presented the neutrino luminosity as a measure of energy output, it is by no means the only one possible, and should be viewed here as a proxy for central engine activity, like the mass accretion rate (with which it is closely correlated). One could equally use $\dot{M}$ or the power output through magnetic fields as a measure of the ability to drive relativistic outflows. Our numerical scheme is geared towards appropriate handling of thermodynamics and the neutrino emission, so it is natural to rely on these properties when making quantitative statements.

We note that just as not all LGRBs exhibit this behavior, clearly not all progenitors are capable of producing such state transitions. Whether this can power precursor activity is another matter, requiring the initial episode of accretion to create a low density polar funnel in the star, which remains to be studied in the near future.
Fig. 2.— The density and velocity field for the different scenarios.