Cannonballs in the context of Gamma Ray Bursts:

Formation sites

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Abstract

We investigate possible formation sites of the cannonballs (CB, as described by Dar & De Rújula 2004) in the gamma ray bursts context by calculating their physical parameters, such as density, magnetic field and temperature close to the origin. Our results suggest that CBs can only be formed as instabilities (knots) within magnetized jets from hyperaccreting disks. These instabilities would most likely set in beyond the light cylinder where flow velocity with Lorentz factors as high as 2000 can be achieved. Our findings challenge the CB model of GRB if these indeed form inside core-collapse supernovae (SNe) as suggested in the literature; unless hyperaccreting disks and the corresponding jets turn out to be a natural outcome in core-collapse SNe.

Introduction

We explore the propagation and evolution of CBs in order to estimate their conditions at the formation sites. The CB parameters (density, magnetic field and temperature) are integrated backwards to the plausible source from the distance where the CBs become transparent to their enclosed radiation, as described by Dar & De Rújula (2004). We assume that CBs expand with constant expansion velocity, $v_{\rm exp} = c/\sqrt{3}$, and that the CBs move with constant Lorentz factor $\Gamma_{\rm CB}$. This implies that the ratio between CB radius and the distance it has travelled remains constant. We stop the backward integration when the density reaches nuclear saturation density or when the temperature become larger than 10^{12} K.

Model and Results

We have studied 8 cases of CBs with different Lorentz factors ($\Gamma_{\rm CB}$) and total number of baryons ($N_{\rm CB}$) per CB:

	$\Gamma_{\rm CB}$	$N_{\rm CB}$
Case 1	1.0×10^2	10^{49}
Case 2	1.0×10^2	10^{50}
Case 3	1.0×10^2	10^{51}
Case 4	1.0×10^3	10^{49}
Case 5	1.0×10^3	10^{50}
Case 6	1.0×10^3	10^{51}
Case 7	2.0×10^3	10^{49}
Case 8	2.0×10^3	10^{50}

- The density as a function of distance travelled is given by the assumption that CBs expands with a constant velocity and move with a constant speed. The density is shown in Fig. 1.
- The magnetic field strength is estimated from equipartition condition, $v_{\rm A} \simeq v_{\rm s} = \frac{c}{\sqrt{3}}$, or $B \propto R_{\rm CB}^{-3/2}$ and is shown in Fig. 2.

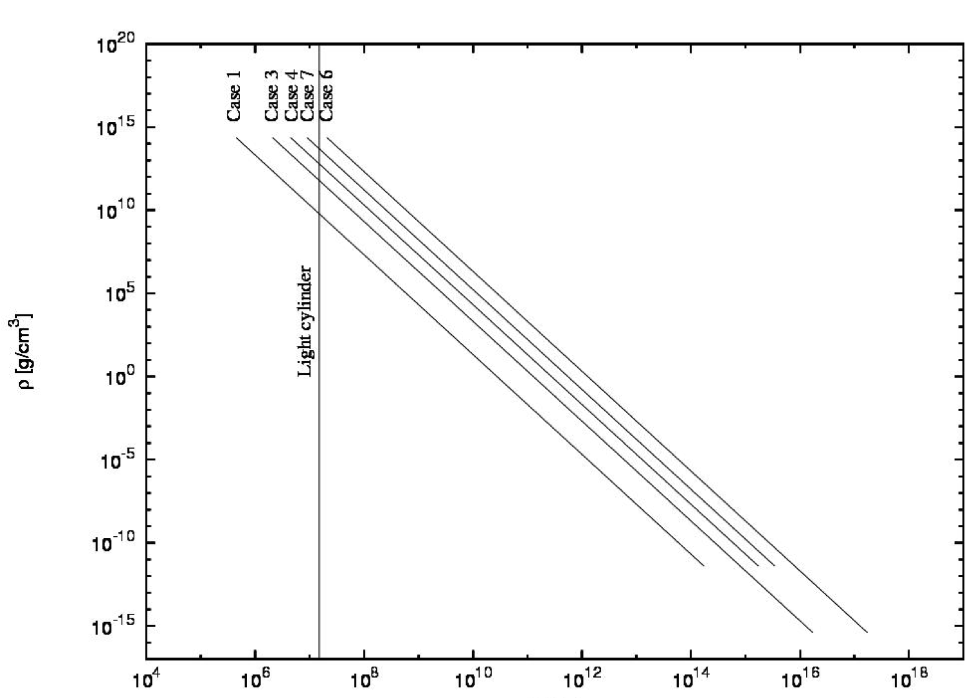

Fig 1: The density vs distance from origin for the different CB cases.

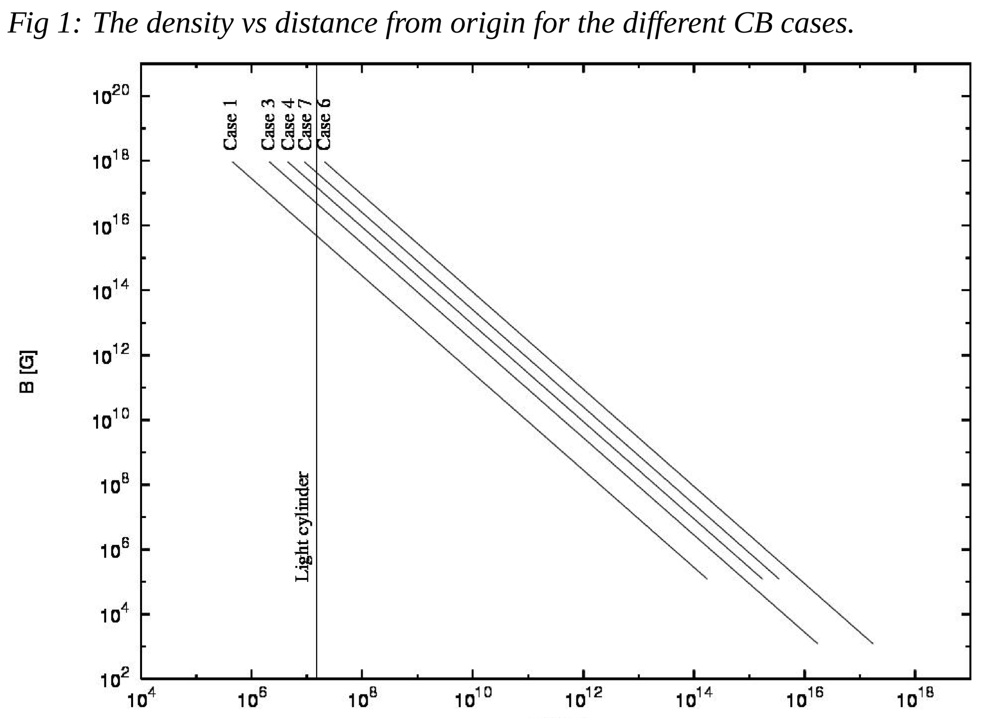

Fig 2: The magnetic field strength vs distance from origin for the different CB cases.

Case 1

The remaining CB parameter is the temperature, which we compute using the energy equation:

$$E_{\rm rad} + E_{\rm th} + E_{\rm mag} = E_{\rm tot}$$

where:

- Radiation energy:

$$E_{\rm rad} = aT^4 \frac{4}{3}\pi R_{\rm CB}^3$$

- Magnetic energy:

$$E_{\rm mag} = \frac{B^2}{8\pi}\frac{4}{3}\pi R_{\rm CB}^3 = \frac{M_{\rm CB}c^2}{6}$$

- Gas thermal energy:

$$E_{\rm th} = 3N_{\rm CB}kT$$

where $a = 7.5657\times10^{-15}\,{\rm erg\,cm^{-3}\,K^{-4}}$ is the radiation constant, $k = 1.3807\times10^{-16}\,{\rm erg\,K^{-1}}$ is Boltzmann's constant and T is the temperature.

We assume equipartition between magnetic, radiation and gas thermal energies at the source, and therefore take the total internal energy in the CB to be three times the magnetic energy.

- The total internal energy in the CB is thus:

$$E_{\rm tot} = 3\times E_{\rm mag} = 4.5\times10^{47}{\rm erg}\left(\frac{M_{\rm CB}}{10^{27}{\rm g}}\right)$$

- The resulting temperature is shown in Fig. 3.

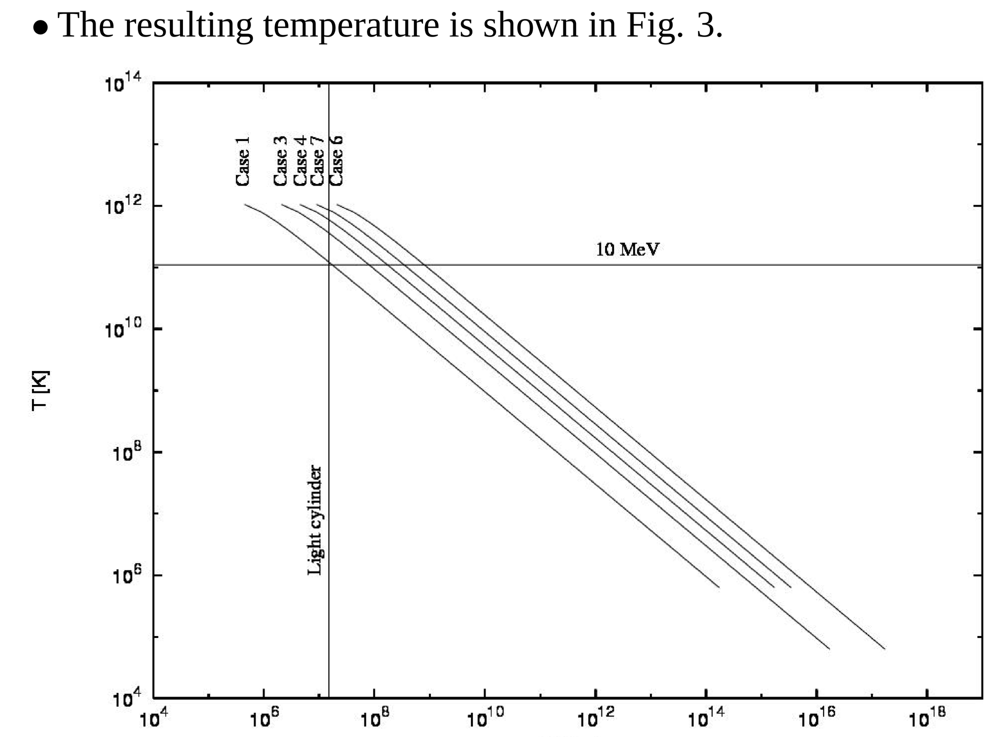

Fig 3: The temperature vs distance from origin for the different CB cases using the simple energy equation.

Summary

- The CB parameters at the source for cases 1-4 are $\rho = 10^9 - 10^{13}{\rm g/cm^3}$, $B = 10^{15} - 10^{17}$ G and $T = 10^{11} - 10^{12}$ K. These, as we show in the section below are reminiscent of conditions in hyperaccretion disks.
- Extreme CB cases (Case 6-8) can be ruled out as they reach nuclear saturation density and $T = 10^{12}$ K beyond the light cylinder (Fig. 4).

Case 2

In this case we include degeneracy pressure and neutrino effects during the evolution and expansion of the CBs. The new energy equation becomes:

$$E_{\rm rad} + E_{\rm th} + E_{\rm mag} + E_{\rm deg} = E_{\rm tot}$$

where the expressions for the degeneracy, radiation and gas thermal energies are defined in Popham et al. (1999) as:

- Degeneracy energy:

$$E_{\rm deg} = 3KM_{\rm CB}\left(\frac{\rho}{\mu_e}\right)^{1/3}$$

- Radiation energy:

$$E_{\rm rad} = \frac{11}{4}\frac{aT^4}{\rho}M_{\rm CB}$$

- Gas thermal energy:

$$E_{\rm th} = \frac{3}{2}RTM_{\rm CB}\frac{1+3X_{\rm nuc}}{4}$$

$$X_{\rm nuc} = 30.97\left(\frac{\rho}{10^{10}{\rm g/cm^3}}\right)^{-3/4}\left(\frac{T}{10^{10}{\rm K}}\right)^{9/8}\times\exp\left(-6.096\times\frac{10^{10}{\rm K}}{T}\right)$$

- The total energy is $E_{\rm tot} = 3E_{\rm mag} + E_\nu$, where E_ν is the neutrino energy. For simplicity the neutrinos are released in a sudden burst at a stage during the integration when the neutrino cooling is insignificant. This is seen as a jump in the temperature graph below.
- Two types of neutrino cooling can occur, neutrino emission due to pair annihilation:

$$\dot{q}_{\nu,\bar\nu} \simeq 5\times10^{33}\left(\frac{T}{10^{11}{\rm K}}\right)^9\ {\rm ergs\ cm^{-3}\ s^{-1}}$$

and neutrino losses due to the capture of pairs on nuclei:

$$\dot{q}_{\rm eN} = 9.0\times10^{33}\left(\frac{\rho}{10^{10}{\rm g/cm^3}}\right)\left(\frac{T}{10^{11}{\rm K}}\right)^6 X_{\rm nuc}\ {\rm ergs\ cm^{-3}\ s^{-1}}$$

E_ν is the sum of these integrated over time. For simplicity the neutrinos are released in a sudden burst at a stage during the integration when the neutrino cooling is insignificant. This is seen as a jump in the temperature (Fig. 4 below).

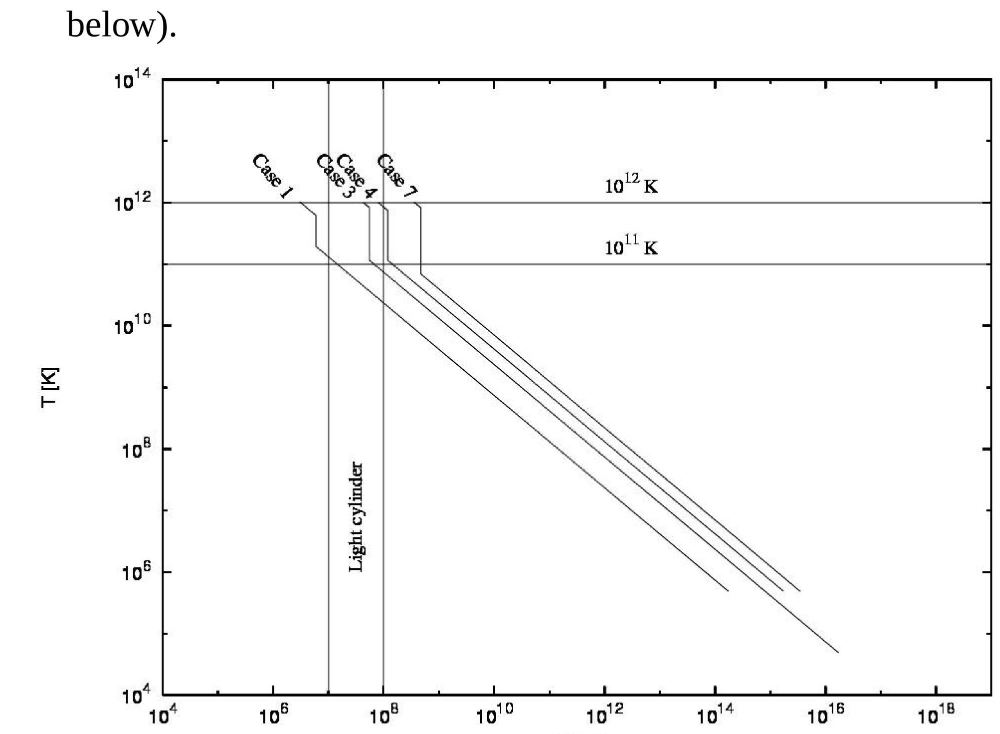

Fig 4: The temperature vs distance from origin for the different CB cases, using an energy equation taking pressure degeneracy and neutrino cooling into account.

Formation sites

- CB conditions at the source derived from our calculations seem to favor hyperaccretion disks. Conditions in hyperaccretion disks (Popham et al. 1999): $\rho\sim10^{12}{\rm g/cm^{-3}}$, $T\sim10^{11}$ K, $B\sim10^{14}-10^{15}$ G, comparable to the conditions found for case 1-4 at the light cylinder.
- However, if CBs form within the hyperaccretion disk, acceleration to Lorentz factors of the order 1000 seems a major challenge.
- The most likely scenario is for CBs to form as instabilities in jets from hyperaccretion disks. In this case the disk material has already been accelerated to $\Gamma > 1000$ by the time it reaches the light cylinder (Fendt & Ouyed 2004).
- Disk-jets become cylindrically collimated beyond the light cylinder (Fendt & Memola 2001). Knot generating instabilities occur as jets collimate (Ouyed et al. 1997), and CBs could form as instabilities beyond the light cylinder.

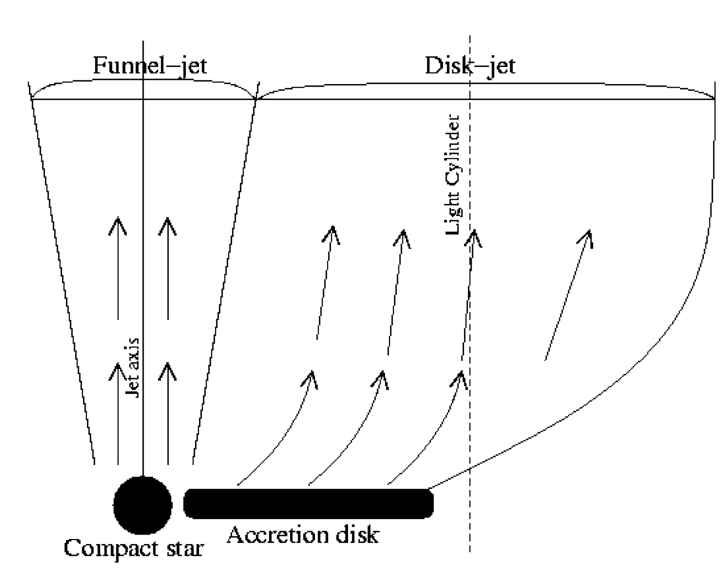

Fig 5: Illustration of Funnel-jet and Disk-jet. The funnel-jet is launched from a region close to the compact star. The disk-jet is launched from the accretion disk.

- To a first order, instabilities related to Alfvén crossing time can develop on timescales

$$t_{\rm ins} = t_{\rm A} = \frac{2R_{\rm jet}}{v_{\rm A}},$$

where $R_{\rm jet}$ is the radius of the disk-jet. For $1R_{\rm lc} < R_{\rm jet} < 10R_{\rm lc}$ ($R_{\rm lc}$ is the radius of the light cylinder), we arrive at $t_{\rm ins}\sim1-10$ ms which would imply the plausible formation of blob of matter as massive as $M_{\rm ins} = t_{\rm ins}\dot{M}_{\rm jet}\sim 10^{-8}-10^{-7}M_\odot$. This can be compared to the typical CB mass of the order $M_{\rm CB} = 10^{-7}M_\odot$.

- Funnel jets are ultra-relativistic low-density jets (De Villiers et al. 2005). Although instabilities occur in funnel-jets, the instabilities have much lower densities than required for CBs (De Villiers et al. 2005). Fig. 5 shows an illustration of funnel-jets and disk-jets.

Conclusion

The CB model for GRB (Dar & De Rújula 2004) requires that all (or almost all) core collapse SNe will produce CBs to explain frequency of GRBs. If CBs form in disk-jets from hyperaccretion disks as our results indicate, this means that hyperaccretion disks must be a natural outcome in core collapse SNe to accommodate the CB model. –This remains to be confirmed.

References

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