Hard X-ray Bursts from Collapse of the Super Massive Stars

Maxim V. Barkov, 1,2,3 *
1Space Research Institute, 84/32 Profsoyuznaya Street, Moscow 117997, Russia
2Department of Applied Mathematics, The University of Leeds, Leeds, LS2 9JT, UK
3Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

ABSTRACT
The very first stars in the Universe can be very massive, up to $10^6 M_\odot$. They would leave behind massive black holes that could act as seeds for growing super massive black holes of active galactic nuclei. Given the anticipated fast rotation such stars would end their live as super massive collapsars and drive powerful magnetically-dominated jets. In this paper we investigate the possibility of observing the bursts of high-energy emission similar to the Long Gamma Ray Bursts associated with normal collapsars. We show that during the collapse of supercollapsars, the Blandford-Znajek mechanism can produce jets as powerful as few $10^{52}$ erg/s and release up to $10^{56}$ erg of the black hole rotational energy. Due to the higher intrinsic time scale and higher redshift the initial bright phase of the burst can last for about $10^5$ seconds whereas the central engine would remain active for about 10 days. Due to the high redshift the burst spectrum is expected to be soft, with the spectral energy distribution peaking at around 60 keV. The peak total flux density is relatively low, few $10^{-7}$ erg cm$^{-2}$ s$^{-1}$, but not prohibitive. The such events should be rear 0.03 year$^{-1}$, the observations needs long term program and could be done in future.

1 INTRODUCTION
The very first stars in universe were borned in the lack of heavy elements. It could leads to born of the super massive stars (SMS) [Bromm et al. 2002; Bromm & Loeb 2003, Santoro & Shull 2006; Devecchi & Volonteri 2009]. Such stars can be as massive as $10^6 M_\odot$, which will be referred to as Very Massive Stars (VMSs) are expected to collapse into black holes with very little mass loss [Fryer et al. 2001]. They would leave behind massive black holes (MBHs), which could play the role of seeds for the super massive black holes (SMBHs) of Active Galactic Nuclei (AGNs). The collapse of VMS were discussed recently in the paper [Komissarov & Barkov 2010].

Even more massive $3 \times 10^4 M_\odot < M < 10^6 M_\odot$ stars, which will be referred to as Super Massive Stars (SMSs) could be formed in more massive dark matter haloes with total mass $M \sim 10^8 M_\odot$, collapsed at $z \approx 10$ [Bromm & Loeb 2003; Begelman et al. 2006]. This stars do not reach the instability limit mass which is near $10^5 M_\odot$ and can be formed [Hoyle & Fowler 1963, Zeldovich & Novikov 1963, Bisnovatyi-Kogan et al. 1967, Wagner 1969]. The collapse of SMS can provide an alternative way of producing SMBHs.

There are two crucial differences between a normal collapsar and a supercollapsar. One is that instead of a proto-neutron star of solar mass the supercollapsars develop proto-black holes of tens of solar masses, within which the neutrinos from electron capture are trapped [Fryer et al. 2001, Suwa et al. 2007]. The other is that the accretion disks of supercollapsars are far too large and cool for the neutrino annihilation mechanism. This has already been seen in the numerical simulations of supercollapsar with mass $M = 300 M_\odot$ [Fryer et al. 2001]. Utilising the study of hyper-accreting disks by Beloborodov 2008 we find that at best the rate of heating due to this mechanism is

$$\dot{E} \approx 6 \times 10^{53} \dot{M}_0^{9/4} M_{h,6}^{-3/2} \text{ erg s}^{-1},$$

where $\dot{M}$ is the accretion rate and $M_h$ is the black hole mass. (Here and in other numerical estimates below we use the following notation: $\dot{M}_h$ is the mass accretion rate measured in the units of $10^3 M_\odot$ s$^{-1}$ and $M_h$ is the mass measured in the units of $10^4 M_\odot$.) Such low values have lead Fryer et al. 2001 to conclude that the magnetic mechanism is the only candidate for producing GRB jets from supercollapsars. In the following we analyse one particular version of the mechanism where the jets are powered by the rotational energy of the black hole via the Blandford-Znajek process [Blandford & Znajek 1977, Barkov & Komissarov 2008].

This paper is an extension our previous work Komissarov & Barkov 2010 here we investigate properties of collapse of VMS. In this paper we estimate temporal structure of the SMS collapse and predict the observational evidence of this process.
2 PHYSICAL MODEL

Let’s look for this problem. SMS should be fully convective and have rigid rotation. In our simple calculations we neglect aspherical shape of fast rotation SMS.

We assume the radius SMS before collapse as 640 $\frac{GM}{c^2}$ (Zeldovich & Novikov 1971; Shapiro & Teukolsky 1983; Shibata & Shapiro 2002). We can derive the undimensional critical parameter of rotation for SMS with $3 \times 10^4 M_\odot < M < 10^6 M_\odot$ as $J_0 < (M/10^6 M_\odot)^{1/4}$. Numerical simulations of SMS collapse show formation of massive BH and accretion disk. Follow the works (Shibata & Shapiro 2002) we know spin parameter of BH. Let us express the current radius and disk accretion time can be estimated from maximum disk and radius of the disk. It is easy to see that disk accretion time can be expressed as

$$ t_d = \frac{2R_d}{3v_r} \approx \frac{14}{9\alpha} \sqrt{\frac{R_d^3}{GM}}. $$

Using continuity equation $\dot{M} = -4\pi R v_r \rho$ and expressing $\dot{M}$ we get

$$ \rho \approx \frac{3\sqrt{14}}{16\pi} \frac{D M_s}{R^{3/2} R_d^{3/2}}. $$

\[2\] and \[3\] we get

\[3\]

The energy release depend on spin parameter of BH $a$, mass fraction of the disk and radius of the disk. It is easy to see

\[P \approx \frac{3\sqrt{14}}{56\pi} \frac{DGM_s^2}{R^{5/2} R_d^{3/2}}. \text{ (6)}\]

magnetic field pressure should be the same order as gas one $B^2/8\pi \approx P$, follow the work (Tout & Pringle 1996), we can estimate large scale poloidal magnetic field $B_p \approx B_s H/R$, so

$$ B_p \approx \frac{3^{1/2} 2^{3/4}}{7^{3/4}} \sqrt{DGM_s} \frac{R^{3/4}}{R_d^{3/4}}. $$

After last marginally stable orbit the large scale magnetic field could be accreted to BH with gas from accretion disk, the similar approach is described in Reynolds et al. (2006).

$R_{ms}$ is the radius of the marginally stable orbit (Bardeen et al. 1973),

$$ R_{ms} = r_g \sqrt{(3 - Z_2 + [(3 - Z_1)(3 + Z_1 + 2Z_2)]^{1/2})}. $$

$$ Z_1 = 1 + (1 - a^2/M^2)^{1/3}[(1 + a/M)^{1/3} + (1 - a/M)^{1/3}]. \text{ (8)}$$

$$ Z_2 = (3a^2/M^2 + Z_1^{1/2}). $$

To estimate magnetic flux on the horizon of BH we should substitute 6 into 11 and 3

$$ \Psi = 2\pi B_s R_{ms} \approx 2\pi \frac{3^{1/2} 2^{3/4}}{7^{3/4}} \frac{R_{ms}^{3/4} \sqrt{DGM_s}}{R_d^{3/4}}. \text{ (9)}$$

the energy realise of Blandford-Znajek mechanism ((Blandford & Znajek 1977)) could be expressed as

$$ E_{BZ} = \frac{1}{6c} \left( \frac{\Psi \Omega}{4\pi} \right)^2. \text{ (10)}$$

here $\Omega = \Omega_h/2$ the angular velocity of field lines, where $\Omega_h = a/2[1 + \sqrt{1 - a^2} c^2]/GM_{BH}$ is angular velocity of BH (Komissarov 2008), $a = J_{BH}/M_{BH}^2$ is dimensionless spin parameter of BH. Let us express the current radius and disk radius in $r_g$ units as $r_{ms} = R_{ms}/r_g$ and $r_d = R_d/r_g$, substituting 3 to 10 we get

$$ E_{BZ} \approx \frac{14}{3156} \frac{a^2 r_{ms}^{3/2}}{(1 + \sqrt{1 - a^2})^2 G} \frac{c^5 D}{r_g^{3/2}}. \text{ (11)}$$

The energy release depend on spin parameter of BH $a$, mass fraction of the disk and radius of the disk. It is easy to see
that all dependence from 0.5 < a < 1 is very weak (0.7 ± 1.4) so for our continue estimations we can assume it as 1. The expression will be shown as

\[ \dot{E}_{\text{BZ}} \approx 0.0012 \frac{c^5}{G} \frac{D}{r_d^{3/2}} \] (12)

3 RESULTS

We use the method which is described in the paper Barkov & Komissarov (2010) to calculate accretion disc fraction and accretion time scales. The accretion disk which formed for spin parameters of the star 0.5 < J_s < 0.97 have longer life time (see fig. 4 left panel) then free-fall time

\[ t_{ff} = \sqrt{\frac{2R_s^2}{9GM_s}} \] (13)

Parameter D depends on star angular momentum. We interporate our numerical model for polytropes (γ = 4/3) star with good accuracy in the range 0.5 < J_s < 0.97 by simple formula

\[ \log_{10} D = -3.3J_s^2 + 7J_s - 4.9 \] (14)

For J_s < 0.5 the accretion disk mass is negligible and D ≪ 1.

The accretion disk has maximum of matter distribution near radius R_d ≈ 25 ± 50r_g and it is a wick function of J_s (see fig. 4 right panel). To simplify our estimations we put R_d ≈ 40r_g. But accretion could be 3 ± 10 times longer (see fig. 4 left panel) or you can find scaling for self similar solution in the work of Beloborodov (2008).

The accretion disk time we can estimate as

\[ t_d \approx 1M_{s,6}\alpha_{-1}^{-1} \text{day} \] (15)

Using the mass accretion rate of fig. 4 we can check if the neutrino cooling needs to be included in the model. Under the conditions of the supercollapsars’s disk its cooling is dominated by pairs. Using the well known equation for this cooling rate (e.g. Yakovlev et al. 2001) we can compare the cooling time with the accretion time at a given radius. The result is

\[ \frac{t_d}{t_{cool}} \approx 10^{-5} \alpha_{-1}^{-9/4} (R/R_g)^{-13/8} M_{5/4}^5 M_\alpha^{-3/2} \] (16)

Thus, except for the very inner part of the disk, the neutrino cooling is indeed inefficient.

The complicated magnetic field topology can lead to strong degradation of energy release, the energy flux could be 10 times lower (Barkov & Baushov 2009). Over factor which can decrease magnetic flux on horizon is runaway of magnetic field if it became to strong (Gumenschev 2008). We will introduce the magnetization parameter in our formula β which could be order 0.1.

Here, we assumed that the whole of the disk is accreted by BH, following the original ADAF model. However, it has been argued that this model has to be modified via including the disk wind (ADIOS (Advection Dominated Inflow Outflow Solution) model, Blandford & Begelman 1999), which implies a mass loss from the disk and a smaller accretion rate compared to Fig. 4. While the arguments for disk wind are very convincing, the actual value of mass loss is not well constrained. We can estimate the effectiveness of accretion as following \( \eta \equiv M/M_{\text{init}} \approx (r_{in}/r_{out})^p \), here \( r_{in} \approx r_{m,6} \approx 5r_g \), \( r_{out} \approx 100r_g \) the radius of effective nuclear dissociation and \( p \approx 0.75 \). In the end we have \( \eta \approx 0.1 \).

Using (12) now we can estimate The maximum possible energy realise rate is

\[ \dot{E}_{\text{BZ}} \approx 1.7 \times 10^{51} \beta_{-1} D_{-1} \text{erg s}^{-1} \] (17)

dhere \( D_{-1} = D/10 \), \( \beta_{-1} = \beta/0.1 \) and \( \beta_{-1} = \beta/0.1 \). The remarkable property of disk dynamo supported BZ is undependable from mass of the progenitor. It is mostly depend only from SMS angular momentum (14). Higher angular momentum – longer and brighter event (see fig. 4 left panel).

The total power of such event is enormous \( E_{\text{tot}} \approx t_d \times \dot{E}_{\text{BZ}} \approx 10^{56} \text{ergs} \). This energy is enough to sweep away the protogalaxy with baryonic mass \( \sim 10^8 M_\odot \).

Taking into account jet collimation, we can expect very bright sources, which could be detected from very large cosmological distance.

4 DISCUSSION

SMS can be borne only in very early stages of star formation (\( z \approx 10 \)), the observational time should be

\[ t_d = (1+z)t_d \approx 10 \text{ days} \] (18)

Due to large z the spectra should be shifted to Hard X-Ray. If our analogy with short-hard gamma ray burst (GRB), but it is most probable is merging of two compact stars, accretion disk formation and collimation of the jet produced by strong wind from the disk. Here we may expect the similar behaviour. The same collimation properties leads us to opening angle 0.1 rad. Put the factor dilution \( A \sim 10^{-3} \).

Let us estimate brightness of such burst. For \( z \approx 10 \) and Cosmological parameters \( \Omega_m = \Omega_k + \Omega_m = 1 \) and \( \Omega_k = 0.72 \), \( \Omega_L = 0.28 \) (Komatsu et al. 2006) luminosity distance will be \( d_L \approx 3.2 \times 10^{29} \text{ cm} \) (Mukhanov 2005), so flux on the earth should be

\[ F = \frac{\dot{E}_{\text{BZ}}}{4\pi d_L^2} \approx 1.3 \times 10^{-7} \text{ erg cm}^{-2} \text{ s}^{-1} \] (19)

here \( c_{e,-1} = c_e/0.1 \) is conversion coefficient of Blandford-Znaek flux to radiation. SMS were formed first in gas clouds with mass \( \sim 10^8 M_\odot \). Follow the work (Begelman et al. 2006) we can estimate the density of SMS at \( z = 10 \) as \( n_{mb} \sim 0.01 Mpc^{-3} \).

We can estimate the rate of such events in analogy to work Komissarov & Barkov (2010). Let us assume, for the sake of simplicity, that all supercollapsars go off simultaneously at cosmological time \( t_c \) corresponding to \( z = 20 \) (a moderate spread around this redshift will not significantly change the result). In flat Universe the observed time separation between events occurring simultaneously at \( r_0 \) and \( r_0 + dr_0 \), where \( r_0 \) is the comoving radial coordinate, is

\[ dt = c dr_0 \]

The corresponding physical volume within one steradian of the BAT’s field of view, is

\[ dV = a^3(t_c) r_0^2 dr_0 \]

where \( a(t_c) = (1+z)^{-1} \) is the scaling factor of the Universe at \( t = t_c \) (in the calculations we fix the scaling factor via
the condition \(a(t_o) = 1\). \(r_0\) and \(t_e\) are related via \(r_0 = r_L(1 + z)^{-1}\). Putting all this together we find the rate to be

\[
 f_c = A \frac{C n_{\text{inh}} r_L^2}{(1 + z)} \approx 0.03 A \frac{n_{\text{inh}}}{10^{-2}} \text{yr}^{-1}.
\]

(20)

This events should rear and the long term observations program could reveal them.

5 CONCLUSIONS

In spite of the significant progress in the astrophysics of Gamma Ray Bursts, both observational and theoretical, it may still take quite a while before we fully understand both the physics of the bursts and the nature of their progenitors. At the moment there are several competing theories and too many unknowns. Similarly, we know very little about the star formation in the early Universe. For this reason, the analysis presented above is rather speculative and the numbers it yields are not very reliable. Further efforts are required to develop a proper theory of supercollapsars and to make firm conclusions on their observational impact. The collapse of SMS could be one of the most powerful event in the universe. This event can destroy the seed cluster and form single SMBH. The expected very long duration of bursts and their relatively low brightness imply that a dedicated search program using the image trigger will be required. Such search would be useful even in the case of non-detection as this would put important constraint on the models of early star formation, GRB progenitors, and SMBHs.

ACKNOWLEDGMENTS

Author appreciated to Prof. S. Komissarov and F. Aharonyan for useful discussion. This research was funded by PPARC under the rolling grant “Theoretical Astrophysics in Leeds” (MVB). We appreciate for partial support the NORDITA program on Physics of relativistic flows.

REFERENCES

Bardeen J.M., Press W.H., Teukolsky S.A., 1972, ApJ, 178, 347
Barkov M.V., Komissarov S.S., 2008, MNRAS, 385, L28
Barkov M.V., Komissarov S.S., 2010, MNRAS, 401, 1644
Barkov M.V., Baushev A.N., 2009, arxive:0905.4440
Begelman M.C., Volonteri M., 2009, ApJ, 694, 302
Bisnovatyi-Kogan G.S., Zeldovich Ya.B., Novikov I.D., 1967, Soviet Astron, 11, 419
Blandford R.D. & Znajek R.L., 1977, MNRAS, 179, 433
Blandford R.D. & Begelman M.C., 1999, MNRAS, 303, L1
Bromm V., Coppi P.S., Larson R.B., 2002, ApJ, 564, 23
Bromm V., Loeb A., 2003, ApJ, 596, 34
Devecchi B., Volonteri M., 2009, ApJ, 694, 302
Fryer C.L., Woosley S.E., Heger A., 2001, ApJ, 550, 372
Hoyle F., Fowler W.A., 1963, MNRAS, 125, 169
Igumenshchev I., 2008, ApJ, 677, 317
Komatsu E., Dunkley J., Nolta M.R., Bennett C.L., Gold B. et al., 2009, ApJS, 180, 330
Komissarov S.S., 2008, arxive:0804.1912
Komissarov S.S., Barkov M.V., 2010, MNRAS, 402, L25
Mukhanov V., 2005, Physical Fundations of Cosmology, (Cambridge University Press)
Narayan R., Yi I., 1994, ApJ, 428, L13
Reynolds C.S., Garofalo D., Begelman M.C., 2006, ApJ, 651, 1023
Santoro F., Shull J.M., 2006, ApJ, 643, 26
Shakura N.I., Sunyaev R.A., 1973, A&A, 24, 337
Shapiro S.L., Teukolsky S.A., 1983, Black holes, white dwarfs, and neutron stars: The physics of compact objects (New York, Wiley-Interscience)
Shibata M., Shapiro S.L., 2002, ApJ, 572, L39
Suwa Y., Takiwaki T., Kotake K., Sato K., 2007, Publ.Astron.Soc.Jap., 59, 771
Tout C.A., Pringle J.E., 1996, MNRAS, 281, 219
Wagoner R.V., 1969, ARA&A, 7, 553
Yakovlev D.G., Kaminker A.D., Gnedin O.Y., Haensel P., 2001, Phys. Rep., 354, 1
Zeldovich Ya.B., Novikov I.D., 1965, Soviet Phys. Usp., 8, 522
Zeldovich Ya.B., Novikov I.D., 1971, Relativistic Astrophysics, Vol. 1 (Chicago: Univ. Chicago Press)