Mapana – Journal of Sciences
2023, Vol. 22, No. 2, *27-36*
ISSN 0975-3303 | https://doi.org/10.12723/mjs.65.3

Possible Alternate Scenario for Short Duration GRBs Invoking Dark Matter Objects

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Abstract

In recent works, we had discussed the possibility of primordial planets composed entirely of dark matter (DM) and considered this to be a possible reason for not detecting DM particles in the various ongoing experiments. It has been suggested that such primordial DM objects could have formed in the early universe. Here we look at these DM objects as possible candidates for short-duration gamma-ray bursts. This model has the advantage of eliminating the as-yet unresolved baryon load problem in the usual scenario. These could also provide a possible mechanism for the formation of sub-stellar black holes, distinct from the usual Hawking (primordial) black holes.

Keywords: short duration GRB; baryon load problem; dark matter objects; sub-stellar mass black holes

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1 Introduction

Short duration gamma-ray bursts (GRBs) are that gamma ray bursts that have a shorter duration (<0.2 to about 2s) and a harder spectrum as compared to the duration of 2 – 200s for long GRBs. Short GRBs are possibly due to the merger of two neutron stars, whereas the long GRBs are considered due to the collapse of very massive stars. The spectrum observed is harder because the objects merging to produce the GRB are more compact. In the case of short-duration GRB, the energy released is the binding energy of the neutron stars which is of the order of $\sim 10^{53} ergs$.

Most sources capable of impulsively releasing the $10^{53} ergs$ or more of energy required to power a GRB, however, contain so much matter around them that if the energy released were used to accelerate even a very small fraction ($\sim 10^{-3}$) of the baryons present, only a non-relativistic wind would result. This is known as the baryon-loading problem [1, 2]. It has been hoped that the geometry of the sources is such that at least some of the energy released is channeled along directions relatively free of baryons so that relativistic bulk motion and the ensuing beaming of radiation may occur along certain lines of sight. So far, this has not yet been fully demonstrated for any theoretical source of GRBs [3-5].

2 Dark matter objects

Here, we discuss a new class of objects made of pure dark matter particles. If these dark matter particles (of mass $m_D = 10GeV - 1TeV$) cluster and form gravitationally bound objects, these pairs of dark matter particles can annihilate throughout these objects. These dark matter particle-antiparticle pairs can undergo annihilation and produce high energy gamma rays, which could be detected. These high-energy gamma rays could be a signature of this new class of objects [6]. Dark Matter particles of several GeV rest masses, could gravitationally condense and form degenerate objects of planetary mass as discussed in recent papers [7-9].

The Chandrasekhar mass (upper limit) for these degenerate DM objects is given by:

$$M_{D(CH)} = \left(\frac{hc}{G}\right)^{\frac{3}{2}} \frac{1}{m_D^2} \qquad \ldots (1)$$

For a dark matter particle of mass $m_D \approx 100GeV$, this works out to be:

$$M_D \approx 10^{27}g = 10^{-6}M_{\odot} \qquad \ldots (2)$$

This is in accordance with the high-resolution N-body simulation, in standard Cold Dark Matter (CDM) paradigm consisting of particles with a mass of 100 – 1000GeV. The smallest dark matter object that formed in the early universe for the first time (microhalo) is $10^{-7} - 10^{-6}M_{\odot}$ [10, 11].

The size of these objects is given by (for the usual degenerate gas configuration; thermal energy not being relevant)

$$M_D^{\frac{1}{3}}R = \frac{92h^2}{Gm_D^{\frac{8}{3}}} \qquad \ldots (3)$$

For the $10^{-6}M_{\odot}$ object the size works out to be:

$$R \approx 10^5\ cm \qquad \ldots (4)$$

The corresponding velocity of the DM particles in the interior of these objects is given by,

$$v = \frac{h\, n^{\frac{1}{3}}}{m_D} \qquad \ldots (5)$$

where the internal number density $n \approx 10^{24}/cc$. Therefore, we have

$$v \approx 10^3\ cm/s \qquad \ldots (6)$$

The annihilation rate is $\sim n^2\sigma v = 10^{15}/cc/s$ … (7)

We assume the standard wimp cross-section, $\sigma \approx 10^{-36}cm^2$. Over the entire volume, the annihilation rate is then given by, $\int_0^R n\,(r)^2\sigma v(4\pi r^2)dr$. The volume of the object (from equation (4)) is $(10^5)^3$cc. Therefore, the total number of annihilations over the volume is $\approx 10^{30}$/s. The annihilation of the dark matter particles takes place according to [12, 13] (The enhancement due to formation of Wimponium [14] is given in reference [15]):

$$D + \underline{D} \rightarrow 2\gamma \quad \dots (8)$$

Here, $D, \underline{D}$ refer to the corresponding particles and antiparticles.

For dark matter particles of mass $100GeV$, each gamma photon has energy of 50 $GeV \approx 0.1ergs$. Hence the total energy radiated per second is:

$$E \approx (10^{30})\,(0.1) = 10^{29}\ ergs/s \quad \dots (9)$$

The total number of dark matter particles (of mass $m_D \approx 100GeV$) present in the $10^{-6}M_\odot$ object is:

$$\frac{M_D}{m_D} \approx 10^{49} \quad \dots (10)$$

If there are $\approx 10^{30}$ annihilations per second, then the lifetime of these DM objects is:

$$t_{life} \approx 10^{19}s \quad \dots (11)$$

As we see from the above result, the life span of these objects consisting predominantly of $m_D \approx 100GeV$ dark matter particles is more than the age of the universe. Only about 10% of the mass of these objects would have evaporated in the Hubble time so that such objects can still be detected by their gamma-ray flux. The flux from these objects at $1kpc$ is given by:

$$f_{1kpc} = \frac{10^{29}}{4\pi(3\times10^{21})^2} \approx 10^{-15} ergs/cm^2/s \quad \dots (12)$$

These objects need not necessarily be confined to the galactic centre. They can be formed in the halos as well as over the galactic volume (in principle). Similarly, we can estimate the flux from such an object one parsec away as, $f_{1pc} \approx 10^{-9} ergs/cm^2/s$. This implies that on Earth, about 300 photons will be detected by a meter square detector over a year. The absence of such a flux enables constraints to be placed on the population abundance of such objects [16].

Observation of globular cluster M13 using MAGIC telescope sets an upper limit on the high energy gamma-ray emission at $< 5.1 \times 10^{-12} ergs/cm^2/s$ [17]. The $100GeV$ DM particles annihilate to produce gamma photons of $\approx 0.1ergs$. The flux of these gamma photons from M13 at $\sim 7kpc$ is:

$$f \approx 2 \times 10^{-16} ergs/cm^2/s \qquad \dots (13)$$

Equation (13), along with the results from [17] can set constraints on the number of these DM objects in the cluster M13.

These size, lifetimes, and flux will depend on the DM particle mass. The above analysis is done for $m_D \approx 100GeV$. Table 1 gives these observable parameters for different DM particle masses.

Table 1 Size of the DM objects, their lifetimes, and flux (at different distances) from such objects for different DM particle masses

$m_D\ (GeV)$	$R\ (cm)$	$t_{life}\ (s)$	$f_{1kpc}\ (ergs/cm^2/s)$	$f_{1pc}\ (ergs/cm^2/s)$
10	6×10^5	10^{16}	10^{-10}	10^{-4}
100	10^5	10^{19}	10^{-15}	10^{-9}
250	3×10^3	10^{21}	10^{-19}	10^{-13}
500	10^3	5×10^{22}	10^{-21}	10^{-15}
1000	10^3	3×10^{23}	10^{-21}	10^{-15}

3. Admixture of baryonic matter and DM

If an equal amount of baryonic matter collapses along with the dark matter to form these objects, then the baryonic matter will be heated up to a temperature T, according to:

$MR_gT = 10^{48} ergs$ … (14)

This gives $T \approx 10^{12}K$, R_g being the universal gas constant.

This energy corresponds to gamma-ray frequencies. Since the mass which is heated up is $\sim 10^{-6} M_{\odot}$, in this scenario, the 'baryon load' problem seems ameliorated as the relativistic kinetic energy corresponds to a Lorentz factor of $\sim 10^2 - 10^3$. The time scale of the gamma ray burst here is given by:

$t_{burst} = \sqrt{\frac{R^3}{GM}} \approx 0.01s$ … (15)

This indeed corresponds to the duration of a short GRB.

The matter will expand to $> 10^9 m$ in a few seconds. Depending on the ambient medium, there could be afterglows. The expansion would cause a lowering of the temperature, resulting in the production of X-rays, UV, etc., that is, radiation of successively longer wavelengths over longer intervals of time, as in the usual scenario.

Peak wavelength would scale with the expansion time scale as roughly $\lambda \sim t^{-1}$, so that a few days after the initial burst, the wavelength would be in the ultraviolet to the visible range but with an intensity far less (by a factor of 10^4) than the initial burst luminosity. As in this scenario, magnetic fields are not expected to be present [6], and the radiation would not be polarised like in some GRB sources.

This could be an alternative scenario for short duration sub-luminous gamma-ray bursts. Again, in this scenario, unlike in some other models of short duration GRBs we do expect much lower fluxes of neutrinos and gravitational waves to be simultaneously emitted (for details, see ref. [6, 8]). This could be another distinct signature of this model.

4 Formation of sub-stellar mass black holes

An additional consequence of this model could be the formation of sub-stellar mass black holes, distinct from Hawking primordial black holes. If the mass of these DM objects exceeds the limit given by equation (3), they will collapse to form black holes of size given by:

$$R_S = \frac{2GM}{c^2} \approx 1cm \qquad \dots (16)$$

(For DM particles of mass $m_D \approx 100GeV$)

The energy released during the collapse is given by:

$$E = \frac{GM^2}{R} \approx 10^{48} ergs \qquad \dots (17)$$

Collapse of such DM objects could also be a source of gravitational waves if they even have a slight departure from spherical symmetry (while collapsing) [18].

It is to be noted that these dark matter objects can also form binary systems, with each of them having, for instance, a mass of $10^{27} g$ and size of $10^5 cm$ $10^5 cm$ (following equations (2) and (4)). If their separation is about ten times their size, then the period P is given by:

$$GMP^2 = 4\pi^2 R^3 \qquad \dots (18)$$

Or $P \approx 1s$

This implies that the merger of these objects could also lead to short duration GRBs of period $\sim 1s$. This scenario could also be a source of gravitational waves, different from those produced by neutron star mergers because they will not be accompanied by electromagnetic radiation since dark matter does not couple with radiation [18]. As in the case of NS mergers, much of the collapse energy is radiated in the form of gravitational waves.

If these binary systems are present at a distance of say $20Mpc$, the corresponding strain at earth due to gravitational radiation emission from them is:

$$h = \frac{2GE}{rc^4} \qquad \dots (19)$$

where $E \approx 10^{48} ergs$ is the energy released. The strain then becomes:

$$h \approx 3 \times 10^{-27} \qquad \dots (20)$$

The strain due to gravitational radiation emission from these binaries at different distances from Earth is given in table 2.

Table 2 Strain on the gravitational wave detectors from binary DM objects vs. their distance from Earth.

Distance (r)	Strain (h)
$20Mpc$	3×10^{-27}
$10kpc$	6×10^{-24}
$1kpc$	6×10^{-23}
$1pc$	6×10^{-22}

As can be seen, this strain is within the sensitivity of either LIGO [19] or future gravitational wave detectors such as LISA [20].

The masses of these sub-stellar mass black holes will depend on the mass of the dark matter particles constituting them, as given by equation (1). For different dark matter particle masses the black hole mass is given in table 3 (see also ref. [8]).

Table 3 Sub-stellar black hole mass for different DM particle mass

m_D (GeV)	M_D (g)
10	10^{29}
100	10^{27}
250	4×10^{25}
500	10^{25}
1000	3×10^{24}

These black holes will then evaporate due to the usual Hawking radiation with a lifetime given by:

$$t_{ev} = \frac{5120\pi G^2 M^3}{\hbar c^4} \quad \ldots (21)$$

For this lifetime to be of the order of the Hubble time, the mass of the black hole should be:

$$M \approx 10^{14} g \quad \ldots (22)$$

This implies that we would expect all of the above black hole masses (formed by the collapse of DM dominated objects) to be still present at the present epoch of the universe [21-23].

5 Conclusions

Here, we present an alternate scenario for short-duration gamma ray bursts due to the collapse of dark matter-dominated objects. This scenario successfully eliminates the baryon load problem. The remnant of these GRBs will be black holes of sub-stellar mass, which provides another mechanism for the formation of such black holes, apart from the usual Hawking black holes. This scenario could also be a novel source of gravitational waves, different from those produced by neutron star mergers in the sense that they will not be accompanied by electromagnetic radiation.

References

[1]. W Kluzniak *Astrophys. J.* **508** L29 (1998)

[2]. T Piran *Unsolved Problems in Astrophysics* (USA: Princeton Univ. Press) *ed*. J N Bahcall and J P Ostriker 343 (1997)

[3]. F Rasio and S L Shapiro *Astrophys. J.* **401** 226 (1992)

[4]. W Kluzniak and W H Lee *Astrophys. J.* **494** L53 (1998)

[5]. J R Wilson et al. *AIP Conf. Proc. 4, Gamma-Ray Bursts* (USA: AIP) *ed.* C A Meegan et al. 788 (1998)

[6]. C Sivaram and K Arun arXiv:0910.2306v1 [astro-ph.CO] (2009)

[7]. G Narain, J Schaffner-Bielich and I N Mishustin *Phys. Rev. D* **74** 063003 (2006)

[8]. C Sivaram and K Arun *Open Astron. J.* **4** 57 (2011)

[9]. C Sivaram, K Arun and O V Kiren *Astrophys. Space Sci.* **361** 230 (2016)

[10]. M S Delos *Phys. Rev. D* **100** 083529 (2019)

[11]. D Anderhalden and J Diemand *J. Cosmol. Astropart. Phys.* **2013** 009 (2013)

[12]. P Salati *Int. J. Mod. Phys.: Conf. Series* **30** 1460256 (2014)

[13]. D N Spergel et al. *Astrophys. J. Suppl. Ser.* **170** 337 (2007)

[14]. J March-Russell and S M West *Phys. Lett. B* **676** 133 (2009)

[15]. S Zioutask et al. *Science* **306** 1485 (2004)

[16]. S D M White *Cosmology and Large Scale Structure* (Netherlands: Elsevier) *ed*. R Schaeffer et al. 349 (1996)

[17]. H Anderhub et al. *Astrophys. J.* **702** 266 (2009)

[18]. C Sivaram, K Arun *Earth Moon Planets* **123** 9 (2019)

[19]. K Schmitz *J. High Energy Phys.* **2021** 97 (2021)

[20]. P Amaro-Seoane et al. *Classical Quantum Gravity* **29** 124016 (2012)

[21]. C Sivaram and K Arun arXiv:0911.1823v1 [astro-ph.CO] (2009)

[22]. O V Kiren, K Arun and C Sivaram *Adv. Space Res.* **68** 2050 (2021)

[23]. C Sivaram, K Arun and O V Kiren *Open Astron. J.* **7** 33 (2014)