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Short Gamma-Ray Bursts as Manifestation of Collisions of Primordial Black Holes with Stars

B.E. Zhilyaev[1,2]

[1] Main Astronomical Observatory NAS of Ukraine, 27 Akademika Zabolotnoho, 03680, Kyiv, Ukraine
[2] International Center for Astronomical, Medical and Ecological Research, 27 Akademika Zabolotnoho, 03680, Kyiv, Ukraine

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1 Introduction

Gamma-ray bursts are the most powerful transient phenomena in the Universe. The BATSE survey data show that bursts are isotropically distributed. The gamma-ray burst durations range from milliseconds to hundreds of seconds, with a bimodal distribution of long bursts with $\Delta t \geq 2\,s$ and short bursts with $\Delta t \leq 2\,s$. The most plausible GRB progenitors suggested so far are expected to lead to a system with a central BH, NS-NS or NS-BH mergers, white dwarf - black hole mergers, hypernova or collapsars, and accretion-induced collapse. As mentioned by Meszaros (1999), the overall energetics from these various progenitors does not differ by more than about one order of magnitude. The measured gamma-ray fluences imply a total energy of order $10^{54}\,erg$ (isotropic) for GRB of cosmological origin, as results from high redshift observations. This is of the order of the binding energy of one solar rest mass. Note that there are only two dozen GRBs for which an estimate of the redshift is available. These have estimated either from absorption/emission lines in the optical afterglow or of host galaxies, or Fe emission lines in the afterglow X-ray spectra. Thus, only little more than 1% of GRBs have reliable cosmological origin, as results from observations. Different nature of long and short GRB follows from: (1) their duration distribution with the mean duration of 20 sec and 0.3 sec, respectively (Kouveliotou et al. 1993); (2) their different temporal properties, e.g. number and width of pulses in the light curve; (3) distributions of their gamma- ray spectra in the range $\sim 30 - 1800\ keV$ (Ghirlanda et al. 2003); (4) and, rather probably, the lack of any afterglow for short GRBs. Notice, only about 50% of the bursts display radio or optical counterparts. No redshift of short GRBs has been measured so far. These sources have not astronomical counterparts at other wavebands, too. Thus, the question of their cosmological origin remains controversial. Current models, such as the fireball shock model, the simple standard afterglow model, post-standard afterglow models, the relativistic blast wave model of gamma-ray bursts provide an interpretation of the major features of these objects, reproduce the properties of their light curves, the afterglows in X-ray, optical and radio, gravitational radiation from progenitors (Meszaros, 1999, 2002; Kobayashi, Meszaros, 2003). At the same time, there still remain a number of mysteries, concerning progenitors, the nature of triggering mechanism, the transport of the energy, etc. In empirical studies GRBs have been subjected to straightforward statistical analysis to examine a crucial question of whether GRBs include a uniform population or are separated into different classes (Fishman, 1995; Mukherjee et al. 1998). Such an approach has the large heuristic force, but, unfortunately, had solved none physical tasks.

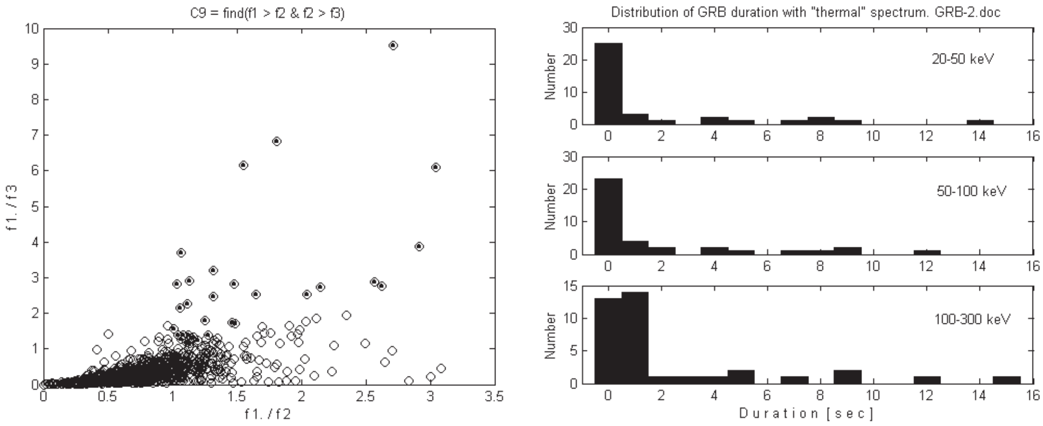

Fig. 1. Left: The colors of GRBs (a subclass C9, filled circles), defined by the ratio of fluences in BATSE channel 1 (20-50 *keV*) to channel 2 (50-100 *keV*) vs. channel 1 to channel 3 (100-300 *keV*), overlaid on a the color-color plot of all bursts detected (open circles).
Right: Histogram bar plots of the gamma-ray burst durations in seconds relative to the burst trigger time. The channels 1-3 from top to bottom. About two-thirds of bursts have a duration about one second, remaining third – up to about twenty seconds

2 The GRB sample and cluster analysis

We extract our data from the online database www.batse.msfc.nasa.gov/data/grb/catalog, which provides many properties of each burst from the BATSE 4b catalog. We consider three fluences, F1-F3, in the 20-50, 50-100, and 100-300 *keV* spectral channels, respectively, and three colors derived from the ratios of fluences, C12 = F1/F2, C13 = F1/F3, and C23 = F2/F3. We make use of the logical condition C9 = C12 >1 & C23 >1 to select a subclass of bursts with a particular spectral density function. One clearly sees from Equation (1) that the above logical condition picks out sources, noted by C9, with spectrum like the thermal deceleration radiation spectrum (bremsstrahlung). The subsequent analysis has quite proved validity of this assumption. The color-color plot of a subclass C9 is overlaid on a plot of all bursts from the BATSE 4b catalog. The bifurcation of the sample into two classes is easily seen in Fig 1 (left). This affords ground for considering GRBs of a subclass C9 in the frame of one physical model. The general idea of present work is that these GRB events may occur from collision of stars with primordial black holes.

PBHs have been claimed to be either interstellar objects suffering random collisions with chance stars at their way or members of the family like solar comets orbiting around parent stars. Entering a stellar atmosphere, PBH is supposed to produce the gamma-ray burst due to accretion. Its characteristics can be determined from a study of the GRB properties such as their fluences, colors, durations, etc.

The question of burst repetition remains controversial. Strohmayer et al. (1994) found from the sample of 260 BATSE catalog bursts that the level of uncertainty in BATSE burst locations limits a repeating fraction of less than $10 \div 15\,\%$ repeaters. The tightened inspection of gamma-ray burst repetition by analyzing the angular power spectrum of the BATSE 3B catalog of 1122 bursts showed that no more than 2% of all observed bursts can be labeled as repeaters (Tegmark et al. 1996). Furthermore, at 95% confidence, they conclude that the BATSE data are consistent with no repetition of classical gamma-ray bursts. Fig 2 from distributions of sources of the C9 class allows also to confidently conclude that these bursts were observed no more than once during 9 years of the BATSE mission. Secondly, the distribution in galactic coordinates shows that GRBs of a subclass C9 are isotropically distributed, in a statistical sense. Each burst comes from a random direction; no repeating events have been detected from precisely the same direction.

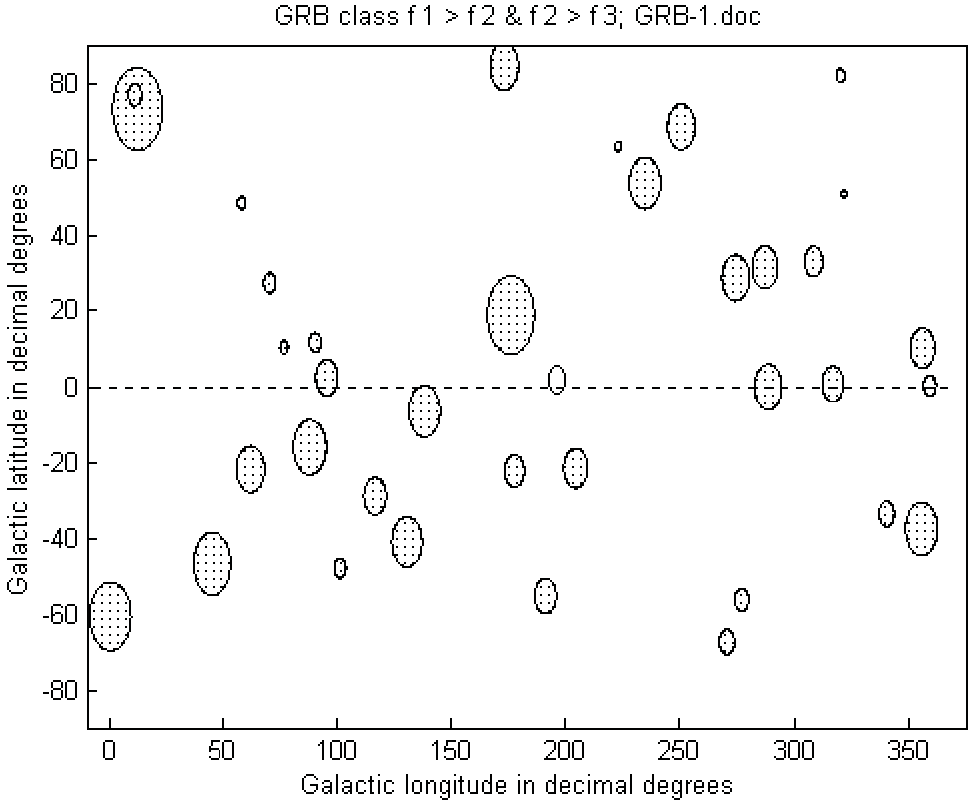

Fig. 2. The distribution in galactic coordinates with positional error ellipses shows that GRBs of a subclass C9 are isotropically distributed, in a statistical sense. Bursts come from a random direction; no coincident events have been detected from just the same direction. One repeating at the top left we treated as a random coincidence

3 Radiation processes with primordial black holes

A primordial population of black holes is thought was created in the early Universe. PBH had formed due to the collapse during the radiation era before $\sim 10^{-4}\,s$ since the beginning of the Universe. They could grow up to horizon mass of about $1\,M_{\odot}$. The moment of PBH formation t_0 depends on its starting mass (Zeldovich, Novikov, 1966), $t_0(s) \sim GM/c^3 \sim 2 \cdot 10^{-39}\,M(g)$, where the time is in seconds, the mass in grams. The hypothesis of PBHs formation near the cosmological singularity from density and metric fluctuations validated through numerical calculations by Novikov et al. (1979). PBH of less than $\sim 10^{15}\,g$ should have evaporated by now through the Hawking process. It appears that PBH with mass of $\sim 10^{15}\,g$ are now the most plentiful. Observations place an upper limit on an average space density of such PBHs about of $10^4\,ps^{-3}$. But if PBHs are clustered into galaxies, the local density can be greater by a factor exceeding 10^6 (Page, Hawking, 1976; Wright, 1996). This provides an upper limit of about $n_{BH} \sim 4 \cdot 10^{-46}\,cm^{-3}$ in the Galaxy (Chapline, 1975; Wright 1996). From this about one PBH we may expect to find in our solar system on average. This opportunity was investigated by Zhilyaev (2003) in details.

Observations of the Hawking radiation from the globular clusters can provide observational signature of PBHs. Gravitationally captured PBH haloes around the globular clusters were considered by Derishev, Belyanin, (1999). EGRET observations of the gamma-ray luminosity above 100 MeV of five nearby massive globular clusters placed, however, only the upper limits on the total mass of PBHs and their

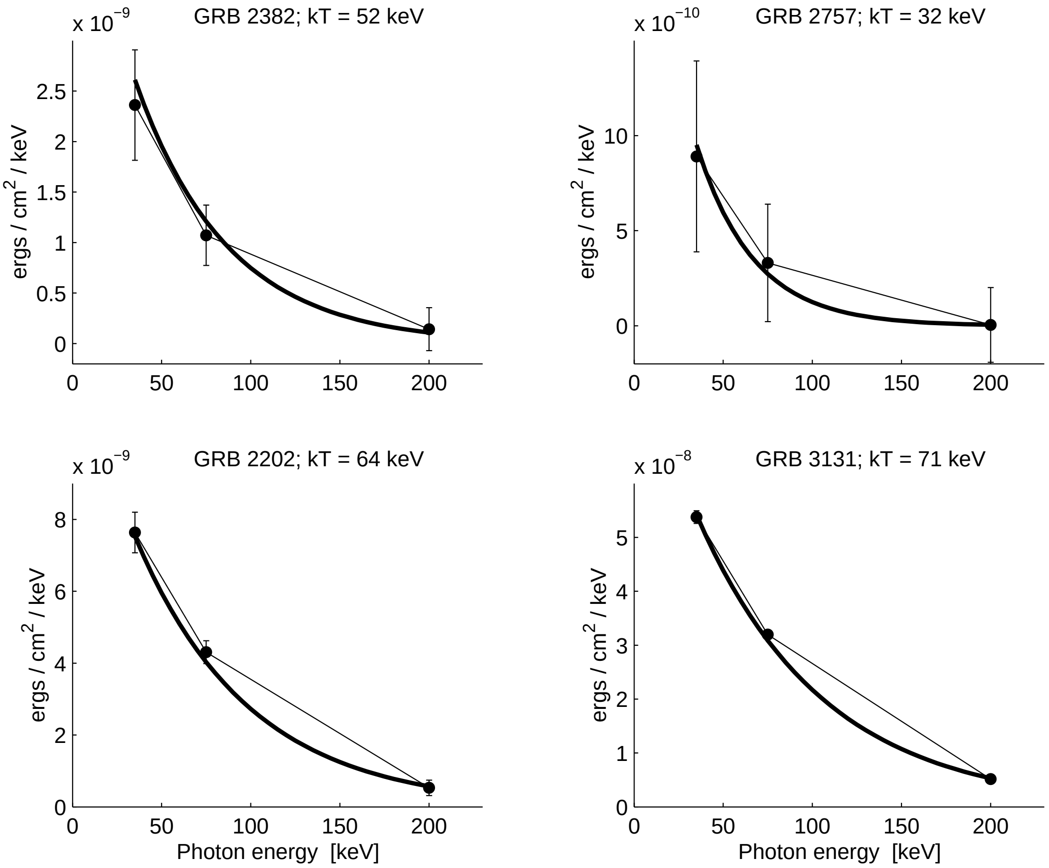

Fig. 3. Some of GRB spectra (all fluences and their errors) and their thermal bremsstrahlung model fits (heavy lines). Equation (1) was used to derive fits for the temperature of the bursts

mass fraction in these clusters $\sim 10^{-6}$. Notice, all the mentioned estimates refer to marginal PBH with mass of $\sim 10^{15}\,g$. The number density of PBH of greater mass up to $\sim 1M_{\odot}$ is one of the most discussing topics of advanced cosmology. Observations of microlensing events towards the Large Magellanic Clouds reveals that the event rate is well above expectation from 'known' stars in the Galactic halo. The durations of events lead to the lens masses estimate of roughly $0.3 \div 0.7$ solar mass, which is a significant puzzle at present. Sutherland (1999) noted an extraordinary solution of the problem, e.g. possibly primordial black holes.

3.1 GRBs with the thermal bremsstrahlung spectrum

In a reference frame, in which the small-mass BH and the target star are initially at rest, the impact speed is equal to the escape speed v_e. To a first approximation this is true for the BH with nonzero initial speed. So, for a solar type star the BH would arrive at the surface with the speed of about $600\,km\,s^{-1}$, for a giant star its value would be about $350\,km\,s^{-1}$ (Allen, 1973). From this a characteristic time Δt for GRB sources can be derived, apart a small numerical factor, $\Delta t \sim L/v_e$, where L is the distance for which atmospheric attenuation of gamma rays becomes substantial. To avoid excessive attenuation in stellar photosphere for photons with energies between $10\,keV$ and $100\,MeV$ the burden of overlying material must amount to $\sim 10\,g\,cm^{-2}$ (Hillier, 1984). For a Sun-like star and a typical giant star these correspond to altitudes $\sim 300\,km$ and $\sim 7000\,km$, respectively, above the photosphere level with optical depth of unity. So, one may expect a characteristic time Δt for GRB sources to be 0.5 and 20 seconds for a Sun-like star and a giant star, respectively. Note, as follows from Fig 1 (right), histogram plots of the gamma-ray burst durations of a subclass C9 display that about two-thirds of bursts have duration about one second, remaining third - up to about twenty seconds. The energy spectrum of the radiation from GRB depends on the characteristics of the source itself. Since the observed gamma-ray spectrum is below $0.511\,MeV$, the threshold for the pair production, the fireball is expected with the luminosity not much above than Eddington limit. Such a spectrum can produce an optically thin plasma with thermal bremsstrahlung. The flux leaving the fireball on account of thermal bremsstrahlung is given by (Allen, 1973; Hillier, 1984)

$$I_\nu = 5.44 \cdot 10^{-39} \cdot Z^2 \cdot gNN_e/\sqrt{T} \exp(-h\nu/k/T), \quad erg\,cm^{-3}\,s^{-1}\,sterad^{-1}\,Hz^{-1} \tag{1}$$

where Z is the charge of particles, g is the Gaunt factor, $N = N_e$ is the number density of ions and electrons. The summarized power of the fireball integrated along the line of sight is

$$I_\nu = 1.44 \cdot 10^{-27} \cdot \sqrt{T} \cdot Z^2 \cdot EM, \quad erg\,s^{-1}, \tag{2}$$

where EM is the volume emission measure

$$EM = \int NN_e dV = 0.85 \cdot N_e^2 V \tag{3}$$

For cosmic abundances and uniform density $EM = 0.85 \cdot N_e^2 V$, where V is the fireball volume (Ness, 2004). As proposed, the fireball extent corresponds to roughly the run of gamma rays at energies between $\sim 10\,keV$ and $\sim 100\,MeV$ in stellar atmosphere, i.e. the atmospheric depth where the mass along the line of sight reaches $\sim 10\,g$. Adopting typical values of N_e from Allen (1973), we may evaluate the fireball radius for a Sun-like star from 300 to $1000\,km$. The fireball radius in the atmosphere of a typical giant star is about 20 times larger. For the total optical depth of the fireball for Thomson scattering we may write

$$\tau \simeq \sigma_T N_e L \tag{4}$$

where σ_T is the cross-section for Thomson scattering. With the values of N_e and L mentioned above the optical depth are $0.2 \ldots 0.6$ and ~ 4 for the Sun and for a typical giant, respectively. Thus, we can suspect, that the condition of low optical depth is held approximately true. Fig 3 shows some of GRB spectra and their thermal bremsstrahlung model fits. Equation (1) can be used to derive fits for the temperature of the bursts. Equation (2) leads to (isotropic) energy estimate. Thus, a model fit leads to the temperature estimates in the range 30 to $70\,keV$. E.g., in GRB 2757 a model fit leads to a temperature estimate of $T = 32 \pm 3\,keV$ and to a power estimate of $1.5\,10^{35}\;erg\,s^{-1}$, for a solar type star and by order of magnitude greater for a giant star. If the BH luminosity is taken to be the Eddington limit

$$L_c = 3\,10^4 L_\odot M_{BH}/M_\odot \tag{5}$$

then a typical fluence in BATSE channel 1 ($20 - 50\,keV$) of $F1 \sim 5\,10^{-7} erg\,cm^{-2}\,s^{-1}$ should correspond to the distance of source of about 50 parsecs. This leads to the BH mass estimate of $\sim 0.002 M_\odot$ for a Sun-like star and by order of magnitude greater for a giant star. Thus, the PBH mass may amount from some thousandth to some hundredth parts of the solar mass.

From the burst rate related to a new subclass of GRB discussed above formal number density of BH can be calculated. Let number densities are n_{BH} and n for the BH and target stars respectively. Then the encounter rate of BH per unit volume can be written:

$$\Gamma = n_{BH}\, n\, v\, \sigma, \;\; cm^{-3}\, s^{-1} \tag{6}$$

The values of $\lg(n)$ for giants, main sequence stars and white dwarfs are: -3.2, -1.2, $-2.3\; ps^{-3}$, respectively, according to Allen (1973). By the adoption of the mean values of the stellar radius r equal to 10, 1 and 0.01 in solar units for the above targets the weighted values of n and r are: $n = 0.069\, ps^{-3}$, $r = 1.01\, R_{\odot}$. Let adopt the number density $n \simeq 0.069\, ps^{-3}$, the cross section for closest encounter $\sigma = \pi\, R_{\odot}^2$ and the mean stellar velocity of $\sim 100\, km\, s^{-1}$. Then for an average rate of bursts $\Gamma \approx 4\, yr^{-1}$ we can expect n_{BH} of order $3\, 10^{15}\, ps^{-3}$, assuming uniform distribution. The enormous amount of this estimate disagrees with the uniform distribution and forces to conclude that PBH should be clustered around stars forming the gravitationally binding systems.

4 PBHs in the light of the comet paradigm

PBH in the vicinity of stars may be found either in consequence of captures processes or incorporation during the formation of stars from interstellar clouds. The binding systems may result, in particular, from tidal capture and exchange encounters (Johnston, Verbunt, 1996). Tidal capture occurs when a PBH transfers some of its kinetic energy to tides in another star during a close passage, and enough tidal energy is dissipated to bind the PBH in orbit around its captor. An exchange encounter occurs when a PBH ejects one of the stars in a binary in a close encounter, and takes its place. However, these processes are efficient only with a quite massive PBH mainly in globular clusters, where the average distance between stars is relatively small. The incorporation of PBHs during the formation of stars and other gravitationally bound objects was analyzed by Derishev, Belyanin (1999). The detailed description of a gravitational incorporation requires exact calculations of the collapse dynamics. Two of the simplest cases were analyzed. These authors argued that in the free-fall contraction relationship between the PBH number density and the average one remains constant. PBHs become trapped inside a protostar. In the case of an adiabatic contraction an appreciable fraction of PBHs forms the gravitationally captured haloes around the protostar.

We may use the comet paradigm to understand various aspects of the PBH phenomenon. As in the solar system, small-mass PBHs orbiting other stars may resemble solar comets in both their dynamical history and orbital evolutions over long periods of time. Their behavior, in terms of celestial mechanics, may be similar to that seen in solar comets. The idea of distant reservoirs of comets known as the Oort cloud, the Edgeworth-Kuiper belt, Centaurs and Jupiter-family comets may be appreciable to other star systems with PBH companions. It appears that in terms of orbits the comet analogue may be appreciable in unmodified form. Stress some essential features of the comet paradigm. (1) No more than 18 percent of comets have a period less than 20 years. The others do not follow perfect elliptic or hyperbolic orbits. Their orbital evolution may be typically chaotic due to gravitational perturbations by the giant planets. None of comets is coming from outside the solar system. They form a gravitationally bound halo around the Sun. (2) Comet collisions with the Sun and planets are ordinary events in solar system history. For example, the Kreutz sungrazing group of comets shows extraordinarily small perihelion distances (Bailey, 1992). So, the orbit of comet Ikeya-Seki passed in perihelion at a distance from the center of the Sun of only 1.67 times its radius. Remember also the collision of comet Shoemaker-Levy 9 with Jupiter in July 1994. On the analogy of the sungrazing group of comets, one can clearly see some PBHs as 'stargrazers' in other stellar systems. Thus, in terms of orbits we can suppose all these features to be also inherent gravitationally bound PBH around other stars. All these appear to support the view that PBH collisions with the parent star may be quite frequent events in its history. In this context one may expect that some short GRBs are observable signatures of primordial black holes in the Universe.

5 Conclusion

To summarize, some GRB progenitors can be related to primordial black holes, which have formed the gravitationally captured haloes around stars like the family of solar comets. PBHs are relic of a hot matter in the early Universe. They could be captured during the formation of stars from interstellar clouds. PBHs may be randomly injected from distant reservoirs similar to the Oort cloud or the Edgeworth-Kuiper belt in the solar system. These objects can undergo a complex orbital evolution process, driven by secular resonances, and by a sequence of close encounters with planets. Eventually, they can collide with the central star or can be ejected from the star system. PBHs are the engines driving gamma-ray bursts when collide with the parent stars. They can exhibit the main qualitative features of GRBs. Entering a stellar atmosphere, PBH can produce the gamma-ray burst due to accretion with a duration from a few tenths of second to a few seconds. Adopting the Eddington luminosity for PBH, a thermal bremsstrahlung model fits leads to the temperature estimates in the range of some tens keV and to the power estimate of $10^{35\div36}$ $erg\, s^{-1}$. Their masses are estimated in the range from thousandths to hundredths of the solar mass. These burst sources are found to be isotropically distributed on the sky and are seen from a distance up to 50 parsecs.

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