Constraints on the Galactic Corona Models of Gamma-Ray Bursts From the 3B Catalogue

Tomasz Bulik[1,2] and Donald Q. Lamb[1]

[1] *Department of Astronomy and Astrophysics*
University of Chicago
5640 South Ellis Avenue, Chicago, IL 60637

[2] *Nicolaus Copernicus Astronomical Center*
Bartycka 18, 00-716 Warsaw, Poland

We investigate the viability of Galactic corona models of gamma-ray bursts by calculating the spatial distribution expected for a population of high-velocity neutron stars born in the Galactic disk and moving in a gravitational potential that includes the Galactic bulge, disk, and a dark matter halo. We consider models in which the bursts radiate isotropically and in which the radiation is beamed. We place constraints on the models by comparing the resulting brightness and angular distributions with the data in the BATSE 3B catalog. We find that, if the burst sources radiate isotropically, the Galactic corona model can reproduce the BATSE peak flux and angular distributions for neutron star kick velocities $\gtrsim 800$ km s^{-1}, source turn-on ages $\gtrsim$ 20 Myrs, and BATSE sampling distances 130 kpc $\lesssim d_{\max} \lesssim$ 350 kpc. If the radiation is beamed, no turn-on age is required and agreement with the BATSE data can be found provided that the width of the beam is $\lesssim 20°$.

I. INTRODUCTION

Gamma-ray bursts (GRB's) continue to confound astrophysicists nearly a quarter century after their discovery (1). Before the launch of CGRO, most scientists thought that GRB's came from magnetic neutron stars residing in a thick disk (having a scale height of up to ~ 2 kpc) in the Milky Way (2). The data gathered by BATSE showed the existence of a rollover in the cumulative brightness distribution of GRB's and that the sky distribution of even faint GRB's is consistent with isotropy (3).

Galactic models attribute the bursts primarily to high-velocity neutron stars in an extended Galactic halo, which must reach one fourth or more of the distance to M31 ($d_{\mathrm{M31}} \sim 690$ kpc) in order to avoid any discernible anisotropy (4–6). Cosmological models place the GRB sources at distances $d \sim 1 - 3$ Gpc, corresponding to redshifts $z \sim 0.3 - 1$; a source population at such large
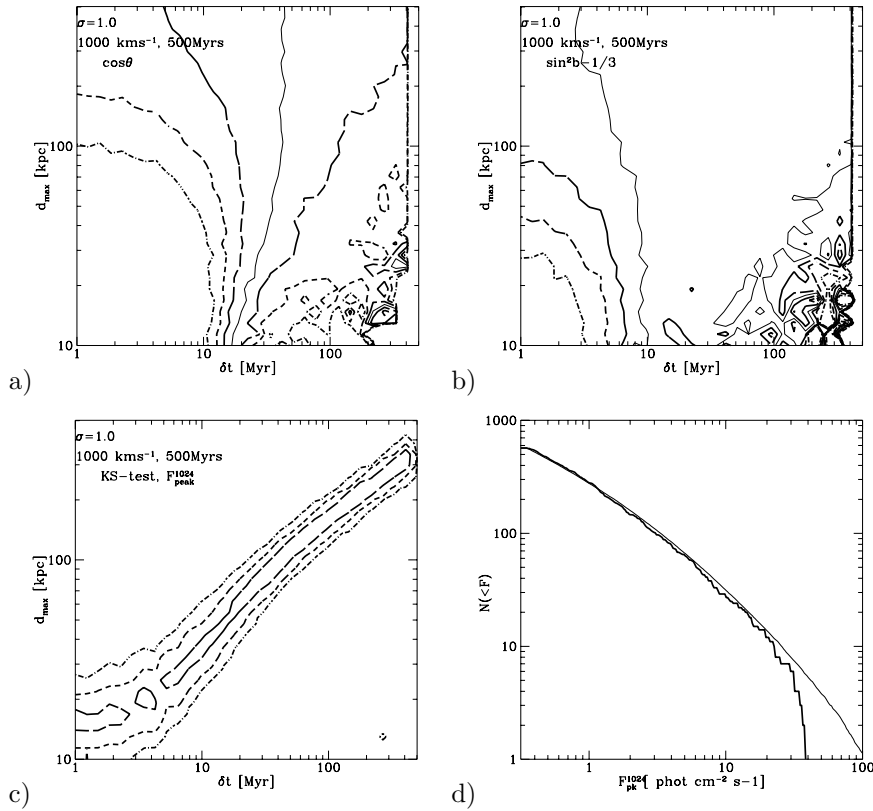
FIG. 1. Comparison of a Galactic halo model in which neutron stars are born with a kick velocity of 1000 km s^{-1}, have a burst-active phase lasting $\Delta t = 5 \times 10^8$ years, and a luminosity function with width $\sigma = 1.0$, with a self-consistent sample of 570 bursts from the BATSE 3B catalogue. Panels (a) and (b) show the contours in the (δt, d_{max})-plane along which the Galactic dipole and quadrupole moments of the model differ from those of the data by $\pm 1\sigma$ (solid lines), $\pm 2\sigma$ (dashed line), and $\pm 3\sigma$ (short-dashed line) where σ is the model variance; the thin line in panels (a) and (b) show the contour where the dipole and quadrupole moments for the model equals that for the data. Panel (c) shows the contours in the (δt, d_{max})-plane along which 32%, 5%, and 0.4% of simulations of the cumulative distribution of 570 bursts drawn from the peak flux distribution of the model have KS deviations D larger than that of the data. Panel (d) shows brightness distribution of a model with $\delta t = 30$ Myrs and $d_{max} = 80$ kpc and the BATSE data.

distances naturally produces an isotropic distribution of bursts on the sky. In addition, studies show that the expansion of the universe can reproduce the observed rollover in the cumulative brightness distribution e.g., (7).

Recent studies (8,9) have revolutionized our understanding of the birth velocities of radio pulsars. They show that a substantial fraction of neutron stars have velocities that are high enough to produce an extended halo around the Milky Way like that required by Galactic halo models of GRBs (10).

Detailed studies of the spatial distribution expected for high-velocity neu-

tron stars born in the Galactic disk (6,11) show that there is a large region in the parameter space where galactic models are consistent with the data from the 2B catalogue. The aim of this work is to re-evaluate this models in the light of the BATSE 3B catalogue.

II. MODELS

We have calculated detailed models of the spatial distribution expected for a population of high-velocity neutron stars born in the Galactic disk and moving in a Galactic potential that includes the bulge, disk, and a dark matter halo.

We use the mass distribution and potential (12) which includes a doubly exponential disk, a bulge, and a dark matter halo (6). The circular velocity v_c and the Galactic disk lead to characteristic angular anisotropies as a function of burst brightness which provide a signature, and therefore a test, of high-velocity neutron star models.

We assume that the neutron stars are born with the local circular velocity $v_c \approx 220$ km s^{-1} of the Galactic disk and an isotropic distribution of initial kick velocities v_{kick} ranging from 200 to 1200 km s^{-1}. We follow the resulting orbits for up to 3×10^9 years. Given that current knowledge of v_{kick} is poor, we adopt a Green's-function approach: we calculate the spatial distribution of neutron stars for a set of kick velocities (e.g., $v_{\text{kick}} = 200, 400, ..., 1200\,\text{km s}^{-1}$).

We consider a model in which the bursts are standard candles, i.e. $L = \delta(L - L_0)$, and also models with the log-normal luminosity function with some width, $P(L, L + dL) \approx \exp(-(\log(L/L_{av})/\sigma)^2)dL/L$. We denote d_{av} the distance to an average burst. If the width of the luminosity function is small than d_{av} tends to d_{max} - the sampling distance. We parametrize the burst-active phase by a turn-on age δt and a turn-off time Δt, and assume that the rate of bursting is constant throughout the burst-active phase; i.e., the burst rate $r = $ const for $\delta t \leq t \leq \Delta t$ and 0 otherwise. The high-velocity neutron star model then has the following parameters: v_{kick}, δt, Δt, BATSE sampling depth d_{max}, and the width of the luminosity function σ. We also consider a beaming mode (10) in which bursting occurs in a cone with width θ_b along the initial kick velocity of a neutron star. Such models do not require a turn-on delay .

III. COMPARISON BETWEEN MODELS AND DATA

We compare the models with a carefully-selected data set that is self-consistent (6). We use only bursts that a) trigger on the 1024 ms timescale, and have $t_{90} > 1024$ ms, b) have F_{pk}^{1024}, the peak flux in 1024 ms, since we adopt it as the brightness measure. c) have $F_{\text{pk}}^{1024} \geq 0.35$ photons cm^{-2} s^{-1} in order to avoid threshold effects (7,13). We also exclude overwriting bursts and MAXBC bursts. The 3B catalogue contains 570 bursts satisfying the
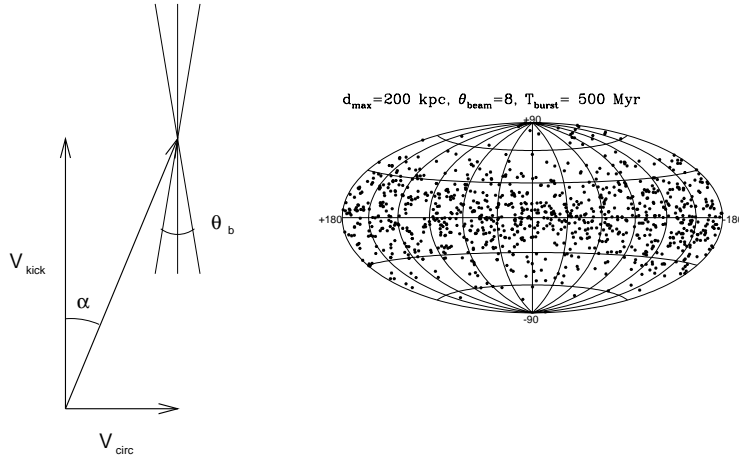
FIG. 2. The left panel shows the lower limit on the beaming angle θ_b. A star with the kick velocity V_{kick} perpendicular to the disk plane also has a galactic circular velocity V_{circ} in the plane, however, it is bursting along the direction of V_{kick}. If the angle α is larger than θ_b the bursts will never be seen by an observer in the Galaxy, relatively close to the birthplace of the neutron star. The right panel shows a skymap for $v_{kick} = 10^3$ kms^{-1}, and $\theta_b = 8°$.

above criteria; this set of bursts has Galactic dipole and quadrupole moments $\langle\cos\theta\rangle = 0.018 \pm 0.0241$, and $\langle\sin^2 b - \frac{1}{3}\rangle = -0.011 \pm 0.012$, and $\langle\cos\theta_{M31}\rangle = 0.0078 \pm 0.0241$.

We test the viability of Galactic halo models by comparing the Galactic dipole and quadrupole moments, $\langle\cos\theta\rangle$ and $\langle\sin^2 b - 1/3\rangle$, of the angular distribution of bursts for the model with those for the above set of bursts, using χ^2. We have also compared the peak flux distribution for the model with that for the above set of bursts, using the KS test.

These comparisons do *not* provide estimates of model parameters (i.e., they do not yield parameter confidence regions), but are meant only to be a rough "goodness-of-fit" guide to models which should be tested using a more rigorous approach like the maximum likelihood method.

In Figure 1 we present the results for a Galactic halo model in which neutron stars are born with a uniform single velocity 1000 km s^{-1} turn-off time $\Delta t = 5\times10^8$ yrs, and a log-normal luminosity function with $\sigma = 1.0$. As an example, in the model with $\delta t = 100$ Myrs and $d_{ave} = 170$ kpc the expected dipole and quadrupole moments are $\langle\cos\theta\rangle = 0.0033$ and $\langle\sin^2 b - 1/3\rangle = -0.0046$, after correcting for the BATSE exposure. This values are extremely close to those expected for isotropy.

The beaming model (10) fits the data when the beaming angle $\theta_b \approx 20°$, and the constraints on the BATSE sampling distance are similar to the case of isotropic emission. An interesting feature of the beaming model is that θ_b is bounded on both sides. The upper limit is due to the galactic anisotropy seen for young neutron stars because of their birth places. The lower limit is

due to the galactic rotational velocity which leads to lack of bursts in galactic polar directions when the beaming angle is too small. The lower limit is approximately $\tan\theta_b > v_c/v_{kick}$, see Figure 2.

Comparisons of this kind show that the high-velocity neutron star model can reproduce the peak flux and angular distributions of the bursts in the BATSE 3B catalogue for neutron star kick velocities $v_{\rm kick} \gtrsim 800$ km s^{-1}, burst turn-on ages $\delta t \gtrsim 20$ million years, and BATSE sampling depths 130 kpc $\lesssim d_{\rm max} \lesssim 350$ kpc. It is clear from this comparison that global isotropy comparisons will not yield the answer to the question of the origin of gamma-ray bursts.

In high-velocity neutron star models, the slope of the cumulative peak flux distribution for the brightest BATSE bursts and the PVO bursts reflects the space density of the relatively small fraction of burst sources in the solar neighborhood. The standard candle models reproduce the BATSE peak flux distribution but they are unable to explain the $-\frac{3}{2}$ slope observed for the PVO bursts. The luminosity function "fills" the void near us with distant bright bursts which appear as isotropic, nearby bursts. Moreover, increasing the width of the luminosity function allows to relax the constraint on the burst turn-on time δt.

M31 provides a strong constraint on the BATSE sampling distance $d_{\rm max}$ (4). We have investigated the effects of M31 within the framework of the high-velocity neutron star model described above by including the distortion of the Galactic halo potential due to M31, as well as the spatial distribution of burst sources emanating from M31. The results of this work are summarized in these proceedings (14).

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