TESTS AND CONSEQUENCES OF DISK PLUS HALO MODELS
OF GAMMA-RAY BURST SOURCES

I. A. SMITH
Department of Space Physics and Astronomy, Rice University, P.O. Box 1892, Houston, Texas 77251-1892; ian@spacsun.rice.edu
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ABSTRACT

The gamma-ray burst observations made by the Burst and Transient Source Experiment (BATSE) and by previous experiments are still consistent with a combined Galactic disk (or Galactic spiral arm) plus extended Galactic halo model. Testable predictions and consequences of the disk plus halo model are discussed here; tests performed on the expanded BATSE database in the future will constrain the allowed model parameters and may eventually rule out the disk plus halo model. Using examples, it is shown that if the halo has an appropriate edge, BATSE will never detect an anisotropic signal from the halo of the Andromeda galaxy. A prediction of the disk plus halo model is that the fraction of the bursts observed to be in the “disk” population rises as the detector sensitivity improves. A careful reexamination of the numbers of bursts in the two populations for the pre-BATSE databases could rule out this class of models. Similarly, it is predicted that different satellites will observe different relative numbers of bursts in the two classes for any model in which there are two different spatial distributions of the sources, or for models in which there is one spatial distribution of the sources that is sampled to different depths for the two classes. An important consequence of the disk plus halo model is that for the birthrate of the halo sources to be small compared to the birthrate of the disk sources, it is necessary for the halo sources to release many orders of magnitude more energy over their bursting lifetime than the disk sources. The halo bursts must also be much more luminous than the disk bursts; if this disk-halo model is correct, it is necessary to explain why the disk sources do not produce holotype bursts.

Subject headings: Galaxy: structure — gamma rays: bursts — stars: neutron

1. INTRODUCTION

In spite of the excellent data gathered by the Compton Gamma-Ray Observatory, the mystery of the locations and emission mechanisms of the gamma-ray burst sources remains unsolved. Since no quiescent counterparts of the bursters have been detected at any wavelength, one must attempt to solve these puzzles using the locations, brightnesses, and spectral and temporal features of the bursters themselves. The debate whether the sources are Galactic or cosmological continues. The existence of an extended Galactic halo has been strongly criticized. However, the hard 1979 March 5 burst from the soft gamma-ray repeater SGR 0525—66 suggests that it is physically possible for a source at a distance of 55 kpc to produce a classical gamma-ray burst.

The observations made by the Burst and Transient Source Experiment (BATSE) and by previous satellites suggest that gamma-ray bursts can be split into two classes (Diychkov et al. 1983; Norris et al. 1984; Dezalay et al. 1992; Kouveliotou et al. 1993; Lamb, Graziani, & Smith 1993; Lamb & Graziani 1994a, b). One class consists of bursts that tend to be longer, and may also be softer, and smoother on short timescales; the bursts in the other class tend to be shorter, and may also be harder, and variable on short timescales. The division of the bursts into two classes is not clean, and depends on the parameter(s) used to do so; this separation is complicated by the fact that the bursts show a wide range of spectral and temporal properties, allowing the signatures of two (or more) populations of sources to be blurred. The split of the bursts into two classes can be explained in two possible ways: (1) there are two separate spatial distributions for the burst sources; (2) there is one spatial distribution for the sources, but there are two different types of burst, or there is one type of burst that looks different when viewed from different angles.

Mao, Narayan, & Piran (1994) claimed that the short and long BATSE bursts have the same spatial distribution. However, BATSE is unable to detect all the short faint bursts because of the “fluence edge.” BATSE triggers on the number of integrated counts over three timescales: 1024, 256, and 64 ms. For very short bursts to trigger, their brightness must be greater than a certain level to compensate for their short durations, creating a cutoff edge for short faint bursts in the duration versus peak counts plot (Li et al. 1994; Petrosian, Lee, & Azzam 1994). Correcting for this steepens the $C_{\text{max}}/C_{\text{min}}$ curve for the short class of bursts so that the distributions for the short and long bursts may be significantly different. Until better statistics are available, it is not possible to determine if there is more than one spatial distribution for the sources. The possibility that there are two separate spatial distributions for the burst sources is investigated here, in particular using the disk plus extended Galactic halo model introduced in Smith & Lamb (1993; hereafter SL).

The possibility that there are two Galactic populations for the sources was first suggested by Lingenfelter & Higdon (1992). However, it was generally believed that the BATSE observations implied that only a few percent of the bursts could come from Galactic disk sources (Paczynski 1992a). This was disproved in SL, who showed that the observations are actually consistent with a large fraction of the sources being in the Galactic disk (at most $\approx 70\%$), with the rest in an extended Galactic halo of finite extent. To investigate the disk plus
extended Galactic halo model further, it is assumed here that the “long/smooth” class of bursts (~80% of the total) comes from halo sources, while the “short/variable” class of bursts (~20% of the total) comes from disk sources. In § 2 a particular combination of an exponential halo plus an exponential disk is considered, and this is used to show that the BATSE observations are consistent with this class of models. In particular, it is shown that BATSE will never detect an anisotropy from the halo of the Andromeda galaxy if the halo has an appropriate edge. Tests are outlined that can be performed on the data BATSE will acquire in the future that will constrain the allowed parameters more tightly. In § 3 it is shown that the disk-halo model predicts that the fraction of the observed bursts coming from disk sources should increase as the detector sensitivity increases. In § 4 the predicted $C_{\text{max}}/C_{\text{min}}$ distribution are shown for a detector that is much less sensitive than BATSE and for a detector that is much more sensitive than BATSE. Consequences of the model are discussed in § 5; in particular, the total number of disk and halo sources in our Galaxy, and their required birthrates, are calculated. This work expands on the discussion in Smith (1994a).

2. EXPONENTIAL HALO PLUS DISK

2.1. The Model

In SL, examples of an infinite exponential disk combined with both a Gaussian halo and a standard “dark matter” halo were shown. With a “dark matter” halo, it is hard to fit the BATSE observations if $N_d/N_{\text{tot}} \gtrsim 0.2$, where $N_d$ is the number of bursts in the disk population and $N_{\text{tot}}$ is the total number of bursts observed. The reason is that it is difficult to generate the correct shape of the $C_{\text{max}}/C_{\text{min}}$ curve for the combined disk-halo model; the halo $C_{\text{max}}/C_{\text{min}}$ distribution cannot be made flat enough at small $C_{\text{max}}/C_{\text{min}}$ because halo sources continue to be observed at large distances (SL; Hakki et al. 1994a, b). Another problem with the “dark matter” halo is that bursts from sources in the halo of the Andromeda galaxy could be detected by BATSE, which could eventually produce an observable anisotropy (Hakki et al. 1994a, b). However, as will be shown later, the halo of the Andromeda galaxy will not be observed if the halo has an appropriate edge. Thus, while the standard “dark matter” halo is not currently ruled out by the BATSE observations, a halo that has an edge is preferable.

The functional form one should use for the spatial distribution of the halo sources is currently unknown, since the nature of the sources is not known. One possibility is to use models of the distribution of high-momentum neutron stars (for example, see Li & Dermer 1992; Hartmann et al. 1994; Podsiadlowski, Rees, & Ruderman 1994). However, a detailed model of the halo is not required here. As a simple example of a halo with an edge, an exponential halo will be used; an exponential Galactic halo model for the gamma-ray burst sources was first considered by Jennings & White (1980). The exponential halo has fewer free parameters than the Gaussian halo used in SL, which could also be used here. For the exponential halo, it is assumed that the sources are distributed spherically symmetrically about the Galactic center with number density distribution $n(R) = n_0 e^{-R/R_0}$, where $R$ is the distance of the source from the Galactic center. The sources are assumed to be standard candles with luminosity $L_\odot$, and the solar system is displaced a distance $R_0 = 8.5$ kpc from the Galactic center. The halo $\langle V/V_{\text{max}} \rangle$, $\langle \cos \theta \rangle$, and $\langle \sin^2 b \rangle$ can be calculated given $\tilde{r}$ and the distance $D_s$ to the faintest halo source that can be detected by a given instrument. Representative values of $D_s = 165$ kpc for BATSE and $\tilde{r} = 45$ kpc are used in the numerical calculations.

For the disk, it is assumed that the sources are standard candles with luminosity $L_d = L_\odot$ and that the disk number density distribution is $n(z) = n_0 e^{-|z|/z_0}$ with $n_0 \neq n_s$. The disk has infinite extent in the Galactic plane, $z_0$ is the disk scale height, and the distance to the faintest disk source that could be observed by the instrument will be called $D_d$. Given $D_d/z_0$, the disk $\langle V/V_{\text{max}} \rangle$ and $\langle \sin^2 b \rangle$ can be calculated. For the numerical calculations used here, $z_0 = 0.5$ kpc is chosen, as in SL. In SL, the fits to the BATSE data used a disk with $D_d/z_0 = 2/3$; here, a thinner disk with $D_d/z_0 = 2$ is chosen to highlight the differences this produces.

To compare with the BATSE data, $N_d = 39$ disk bursts and $N_s = 154$ halo bursts are used (i.e., 20.2% of the bursts come from disk sources); these are exactly the same numbers that were used for the “dark matter” halo plus disk example in § 4 of SL, allowing a direct comparison with the results here. Choosing a larger value of $N_d/N_{\text{tot}}$ would have little effect on the conclusions presented here; unlike the case for the “dark matter” halo, for the exponential disk plus halo model, there is no problem in having up to $\approx 1/2$ the bursts come from disk sources (SL).

Note that a detailed fitting of the BATSE data and expansive search of the available parameter space are not performed here; instead, the aim of this paper is to show that a representative model can explain the BATSE data, and to investigate the consequences of the model.

2.2. Comparison with BATSE Observations

The values of $\langle V/V_{\text{max}} \rangle$, $\langle \cos \theta \rangle$, and $\langle \sin^2 b \rangle$ for the disk, halo, and combined disk plus halo of § 2.1 are given in Table 1. The values for the combined model are all easily consistent with the BATSE observations; $\langle V/V_{\text{max}} \rangle = 0.321 \pm 0.013$ for 520 bursts, $\langle \cos \theta \rangle = 0.031 \pm 0.021$, and $\langle \sin^2 b \rangle = 0.326 \pm 0.011$ for 743 bursts (Meegan et al. 1994). A relatively thin disk was used in this example, and Table 1 shows that $\langle \sin^2 b \rangle = 0.2932$ obtained using $D_d/z_0 = 2/3$ in SL. For an isotropic distribution of bursts on the sky, the value of $\langle \sin^2 b \rangle = 0.2932$ would be a 3 σ deviation from isotropy for 67 disk bursts, while $\langle \sin^2 b \rangle = 0.2932$ would be a 3 σ deviation from isotropy for 497 disk bursts. This illustrates how future BATSE observations will constrain the allowed values of $D_d/z_0$ for the disk sources. A combination of $\langle V/V_{\text{max}} \rangle \leq 0.4$ and $\langle \sin^2 b \rangle = 1/3$ for the “disk” class of bursts would be strong evidence against them coming from disk sources.

The predicted brightness of the bursts can be compared with either the observed $C_{\text{max}}/C_{\text{min}}$ flux, or fluence distribution.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Disk</th>
<th>Halo</th>
<th>Disk + Halo</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\langle V/V_{\text{max}} \rangle$</td>
<td>0.4566</td>
<td>0.2844</td>
<td>0.319</td>
</tr>
<tr>
<td>$\langle \cos \theta \rangle$</td>
<td>0.0</td>
<td>0.0627</td>
<td>0.050</td>
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<tr>
<td>$\langle \sin^2 b \rangle$</td>
<td>0.2242</td>
<td>0.3321</td>
<td>0.310</td>
</tr>
</tbody>
</table>

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tions; a detailed fitting of the BATSE observations is not required here, and for illustrative purposes the \( C_{\text{max}} / C_{\text{min}} \) distribution from the 1024 ms timescale will be used. The criteria explained in § 3 of SL were used to obtain the \( C_{\text{max}} / C_{\text{min}} \) distribution for 193 BATSE bursts. (From the 241 bursts in the First BATSE Catalog, we deleted those whose \( C_{\text{max}} / C_{\text{min}} < 1 \) and those whose peak rate is "undetermined" on the 1024 ms timescale, which leaves 193 bursts.) Figure 1 shows this and the \( C_{\text{max}} / C_{\text{min}} \) distribution for the combined exponential halo plus disk (solid curve); it can be seen that there is a reasonable agreement. Note that no attempt has been made to optimize the fit to the BATSE data, since that is not the aim of this paper: to do so requires fully incorporating the observational selection effects, including the variation in \( C_{\text{min}} \) and accounting for the random sampling of the source population which affects the distance to, and hence the brightness of, the brightest bursts (Smith 1994b). The latter effect also strongly affects the shape of the \( C_{\text{max}} / C_{\text{min}} \) distribution at large values of \( C_{\text{max}} / C_{\text{min}} \), so that the deviations between the model and the data curves are not important (Smith 1994b). See Loredo & Wasserman (1993) for a Bayesian approach to the problem of fitting the burst observations.

The model curve shown in Figure 1 assumes that there is no temporal variation in \( C_{\text{min}} \). Smith (1994b, 1995) demonstrated the effect of different \( C_{\text{min}} \) variations on an extended exponential halo model (similar results apply to the combined disk plus halo model). It was found that to produce the BATSE \( C_{\text{max}} / C_{\text{min}} \) distribution including a varying \( C_{\text{min}} \) requires a larger observing distance (relative to the scale height of the halo) than for a constant \( C_{\text{min}} \); however, the observations can still be fitted (see Band 1992 and Hartmann & The 1993 for related discussions on \( \langle V / V_{\text{max}} \rangle \).

The largest value of \( C_{\text{max}} / C_{\text{min}} \) for the disk bursts is 16 (this is slightly higher than the value of 13 found for the thicker disk in § 4 of SL). There are 14 halo bursts brighter than the brightest disk burst: if it is possible to distinguish between the disk and the halo bursts (for example, because of their duration, or variability), a firm prediction of the disk plus halo model is that the very brightest bursts should have temporal and spectral behaviors characteristic of the halo class of bursts. Kouveliotou et al. (1993) showed that the short and long bursts in the first BATSE catalog have the same range of peak fluxes over 64 ms. However, since there are only a few bright bursts in the smaller (in number) class, this result is currently unreliable. Using Monte Carlo techniques, it was shown in Smith (1994b) that there can be a large variation in the shape of the brightness distribution and the magnitude of its values for the brightest \( \sim 10 \) bursts; statements based on the brightness of the brightest bursts in a population must be made with extreme caution. Until a larger sample of bursts exists for the smaller (in number) class, it is not possible to draw firm conclusions on the range of fluxes of the two classes; however, if future BATSE observations show that the range of fluxes is the same for the two classes, this would rule out the disk plus halo model.

Taking \( z_0 = 0.5 \) kpc, all the observed disk source would be within \( D_{\text{L}} = 1 \) kpc of the Earth. The radial structure of the Galactic disk will produce a small effect in this case, for example, to \( \langle \cos \theta \rangle_{\text{d}} \), which is ignored here; a detailed study using different radial structures for the Galactic disk has shown that the dipole anisotropy is important only if the sampling distance is comparable to the distance to the Galactic core (Hakkila et al. 1994a). Assuming the gamma-ray emission in the burst is isotropic for both the disk and halo sources, the ratio of the burst luminosities \( L_{\text{b}} / L_{\text{d}} = 2.7 \times 10^5 \); if the local disk neutron star sources have a luminosity of \( L_{\text{n}} \sim 10^{37} \) ergs s\(^{-1}\), the halo sources would have a luminosity \( L_{\text{h}} \sim 3 \times 10^{41} \) ergs s\(^{-1}\).

Dividing the bursts into three equal-sized groups of the brightest, intermediate, and faintest, \( \langle \sin^2 b \rangle_{\text{d}} = 0.26, 0.314, 0.290 \) and \( \langle \cos \theta \rangle = 0.056, 0.051, 0.043 \), respectively. There is little difference in these values, a behavior that agrees with the BATSE observations. For this example, the value of \( \langle \sin^2 b \rangle_{\text{d}} \) for just the disk bursts gives a tighter constraint on the allowed disk parameters than \( \langle \sin^2 b \rangle_{\text{h}} \) for the faintest 1/3 bursts. Although there are more bursts in the faint set, the inclusion of the approximately isotropic halo bursts significantly dilutes the deviation from isotropy.

2.3. Andromeda Halo

A potential problem with the "dark matter" halo is that it has infinite spatial extent. Therefore, it is possible that one could see an anisotropy from the halo bursts of the Andromeda galaxy (Hakkila et al. 1994a, b). Hakkila et al. (1994a, b) applied an artificial cutoff to the "dark matter" halos at the tidal radii of the Andromeda and Milky Way galaxies, but found that there could still be a signal from Andromeda given a large enough number of BATSE bursts. However, assuming a cutoff at \( \sim 250 \) kpc from the Caldwell & Ostriker (1981) halo models, the Andromeda galaxy would not be detected (Higdon & Lingenfelter 1994a, b).

An anisotropy from Andromeda will not be detected during the lifetime of BATSE if the halo has an appropriate edge, which is the case for the exponential halo example considered here. To show this, assume that the Milky Way and Andromeda galaxies both have exponential halos. For simplicity, it will be assumed that the two halos have the same scale height \( h = 45 \) kpc and the same central number densities \( n_0 \), although it is easy to consider other cases if necessary. The solar system...
is displaced a distance 8.5 kpc from the Milky Way Galactic center, and will be taken to be displaced a distance 670 kpc from the center of the halo of the Andromeda galaxy. As in § 2.1, the distance to the faintest halo source that can be detected by BATSE is taken to be \( D_h = 165 \) kpc. The ratio of the number of halo bursts observed from sources in the Milky Way galaxy to the number of halo bursts observed from sources in the Andromeda galaxy per unit time is found to be \( N_{\text{MW}}/N_{\text{And}} = 9.2 \times 10^4 \). This means that of the first \( 10^5 \) bursts observed by BATSE, only one would come from an Andromeda galaxy source. Many more bursts would have to be seen before a significant anisotropy could be detected. This illustrates that BATSE will never detect an anisotropy from the Andromeda galaxy if the halo has an appropriate edge: the detection of an anisotropy in the direction of Andromeda would indicate that the extended Galactic halo has a distribution that resembles the "dark matter" form.

The above calculation for the detectability of Andromeda used a halo that is appropriate for fitting the BATSE observations in the disk plus halo model. The same conclusions hold for pure halo models of the burst sources (i.e., no disk component). To illustrate this, consider the exponential halo of Smith (1994b, 1995): using \( r = 50 \) kpc and \( D_h = 170 \) kpc gave brightness and spatial distributions that are consistent with the BATSE observations. Assuming that Andromeda has a halo with the same parameters, it is found that of the first \( 3 \times 10^4 \) bursts observed by BATSE, only one would come from an Andromeda source. Again the important conclusion is that BATSE would never detect an anisotropy from Andromeda.

2.4. Characteristic Features of Brightest Bursts

The separation of the bursts into two classes is complicated by the fact that the bursts show a wide range of spectral and temporal properties, allowing the signatures of two (or more) populations of sources to be blurred. To determine if there is more than one population of burst, one needs an uncontaminated sample of one of the types of burst, so that its characteristic features can be discovered. If the disk plus halo model is correct, the necessary "clean" sample is given by the very brightest bursts that the theory predicts should come from the halo sources. A careful analysis of the spectral shapes and variabilities of the brightest BATSE bursts is encouraged to look for characteristic features.

Time-averaged spectral fitting of the brighter bursts has not found any universal fit (Schaefer et al. 1992; Band et al. 1993). However, splitting the bursts into smaller time intervals and studying the spectral evolution may be a more promising way to reveal characteristic features. Spectral evolution studies from previous satellites have found a range of behaviors (Hurley et al. 1992). In preliminary work, Kargatis et al. (1993) studied the rapid spectral evolution of three of the BATSE bursts: one of these was an overwite, and the other two are the first and fourth brightest bursts over 1024 ms in the first BATSE catalog. Kargatis et al. (1993) found that there was a correlation between the flux and hardness in the decay phase of the burst; a study of more of the bright BATSE bursts is underway to discover if this is a characteristic feature of the halo bursts (see also Ford et al. 1994).

Another possible characteristic feature of the halo bursts is high-energy gamma-ray emission; several of the bright BATSE bursts have also been detected by COMPTEL and EGRET. Winkler et al. (1993) reported COMPTEL observations of more than 20 bursts, 16 of which are in the first BATSE catalog and are not overwrites. Of these 16, six have \((C_{\text{snr}}/C_{\text{min}})_{1024} > 10\). Schneid et al. (1993) presented EGRET observations of six bursts, three of which are in the first BATSE catalog; these are the first, second, and fourth brightest BATSE bursts measured on the 1024 ms timescale. This high-energy emission could be a generic feature of the halo bursts.

A motivation for retaining a class of sources in the disk is that the formation of cyclotron lines is easier for nearby neutron star models (Lamb, Wang, & Wasserman 1990). If stable cyclotron lines cannot be produced by sources in the extended Galactic halo, this implies that BATSE should not detect cyclotron lines in the very brightest bursts.

3. \( N_h/N_{\text{tot}} \) FOR DIFFERENT DETECTOR SENSITIVITIES

A consequence of the disk plus halo model is that the fraction of the bursts that are observed to come from "disk" sources \( N_h/N_{\text{tot}} \) depends on the sensitivity of the burst detector. This is illustrated in Figure 2, which plots \( N_h/N_{\text{tot}} \) as a function of the maximum distance that a detector can see halo sources \( D_h \), i.e., of the detector sensitivity. The solid curve is for the exponential halo plus disk used in § 2, while the dashed curve is for the "dark matter" halo plus disk used in § 4 of SL. For the standard "dark matter" extended Galactic halo (Brainerd 1992), the source number density distribution is given by \( n(R) = n_0 [1 + (R/R_0)^2] \). For the example is § 4 of SL, \( D_d/\bar{z}_0 = 2/3 \) was used for the disk, and for the "dark matter" halo \( R_0 = 8.5 \) kpc, \( R_o = 22.5 \) kpc, and \( D_h = 135.0 \) kpc were chosen.

To generate Figure 2, the spatial distributions for the sources are kept fixed, and \( D_h \) and \( D_d \) are varied. Because standard candles are used, the ratio \( D_h/D_d \) remains the same as at the BATSE sensitivity; \( D_h/D_d = 165 \) for the exponential halo example, and \( D_h/D_d = 405 \) for the "dark matter" halo example. The filled diamonds mark the halo observing distances used for the BATSE fits in the two examples. Note that since \( \bar{z}_0 \) only enters the ratio \( D_h/\bar{z}_0 \), the \( N_h/N_{\text{tot}} \) curves are independent of the value chosen for \( \bar{z}_0 \).

![Fig. 2.](image)

**Fig. 2.** \( N_h/N_{\text{tot}} \) as a function of the maximum distance that a detector can see halo sources for the exponential halo plus disk example (solid curve) and "dark matter" halo plus disk example (dashed curve). The filled diamonds are at the values of the parameters used to fit the BATSE data.
Figure 2 shows a firm prediction of the disk plus halo model: 
\( N_d/N_{\text{tot}} \) rises as the detector sensitivity improves. Note that the relative number of bursts in the two classes will change with 
the detector sensitivity for any two-population model in which 
the scale heights of the two populations are different; for 
extample, a combination of Galactic and cosmological populations (Katz 1994). The same is also true if there is only one 
spatial distribution for the sources and the sampling distance is 
different for the two classes of bursts.

It is predicted that if the disk plus halo model is correct, 
different satellites should see different relative numbers of 
"short" and "long" bursts. Since BATSE is the most sensitive 
gamma-ray burst detector flown so far, one would expect that 
it would most clearly see the split of the bursts into two classes 
(although it should be recalled that because of the "fluence 
edge," BATSE undersamples the short bursts relative to the 
long bursts: correcting for this raises \( N_{\text{short}}/N_{\text{tot}} \)). The results 
shown in Figure 2 assume that the different instruments are 
essentially the same, except for their distance sensitivity. In 
practice, the trigger criterion, energy range, energy sensitivity 
etc. for different detectors also affects the relative number of 
bursts seen in the two classes, especially if the two populations 
have different spectral and/or temporal properties. Table 2 lists 
the fraction of the bursts that were in the "short" class for 
several different satellites (derived from the papers listed in 
Table 2). It can be seen that the results are currently inconclusive; 
the number of bursts in some of the surveys is small, and 
the differences in the detector biases and sensitivities must be 
completely incorporated before a valid comparison can be made. In particular, it can be seen from Table 2 that the definition 
used for the boundary between the "short" and "long" 
bursts differs from experiment to experiment (\( T_{90} \) and \( T_{50} \) are 
defined as the time over which the integrated counts increase 
from 25% to 75% and 5% to 95%, respectively, of the total 
counts above background; the definition of the burst "duration" for each of the experiments is detailed in the refer-

ences in Table 2). However, by studying \( N_{\text{short}}/N_{\text{tot}} \) for the 
different satellites, it may be possible to rule out the two-
population models, and a careful reexamination of the old 
gamma-ray burst databases is encouraged. In particular, it 
would be useful to have complete catalogs for all the earlier 
experiments so that, for example, all the soft gamma-ray re-
peater events can be excluded from the analysis. It might 
be possible to account for some of the instrumental differences 
by studying which of the BATSE bursts would have been detected 
by the different experiments.

The rate at which \( N_d/N_{\text{tot}} \) increases as \( D_s \) (and \( D_a \)) increases 
deeps on the rate at which new disk and halo sources are 
observed as the detector sensitivity improves. At large \( D_s \), the 
rise in \( N_d/N_{\text{tot}} \) is less steep for the "dark matter" halo plus disk 
example shown in Figure 2, because new halo sources continue 
to be observed at large distances in the "dark matter" halo. 
For \( D_s \) smaller than the BATSE observing distance, both disk 
and halo sources are no longer detected as \( D_a \) decreases, and 
the \( N_d/N_{\text{tot}} \) curves flatten.

A reanalysis of the values of \( N_d/N_{\text{tot}} \) for different satellites 
may conclude that these values are essentially the same. If so, 
this will be very hard to explain in terms of the two-population 
model, because it is difficult to flatten \( N_d/N_{\text{tot}} \) sufficiently at 
small \( D_a \). In principle, there are two ways to flatten \( N_d/N_{\text{tot}} \):

1. Make the halo sources be as homogeneous as possible, so 
that reducing \( D_s \) leads to a large reduction in the number of 
observed halo sources. However, to generate the shape of the 
observered BATSE \( C_{\text{max}}/C_{\text{min}} \) distribution requires \( D_s \) at 
the BATSE sensitivity to be several times the scale height of the 
halo distribution. Therefore, the \( N_d/N_{\text{tot}} \) curve cannot be 
significantly flattened in this way.

2. Make the disk distribution be as thin as possible; 
reducing \( D_s \) for a thin disk results in a smaller reduction in 
the number of observed disk sources than for a thick disk where 
the sources are more homogeneous. This is illustrated in

### Table 2

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( N_{\text{short}}/N_{\text{tot}} )</th>
<th>Definition of Short</th>
<th>Remarks</th>
<th>Reference</th>
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<tr>
<td>BATSE</td>
<td>58/222 (26%)</td>
<td>( T_{90} &lt; 2 \text{ s} )</td>
<td>First catalog data</td>
<td>Kouveliotou et al. 1993</td>
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<td>PHEBUS</td>
<td>17/66 (26%)</td>
<td>( T_{90} &lt; 2 \text{ s} )</td>
<td>No correction for &quot;fluence edge&quot;</td>
<td>Terekhov et al. 1994</td>
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<td>ISEE 3</td>
<td>6/21 (29%)</td>
<td>Duration &lt; 1 \text{ s}</td>
<td>Sensitive in 100 keV to 100 MeV range, so may miss some soft, halo bursts</td>
<td>Norris et al. 1984</td>
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<tr>
<td>SIGNE-2M</td>
<td>11/48 (23%)</td>
<td>Duration &lt; 0.25 \text{ s}</td>
<td>Very small database</td>
<td>Diychkov et al. 1983</td>
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<td>SIGNE 13/14</td>
<td>28/171 (16%)</td>
<td>( T_{50} &lt; 0.6 \text{ s} )</td>
<td>Removed 1979 March 5 burst</td>
<td>Kargatis et al. 1994</td>
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<td></td>
<td></td>
<td></td>
<td>Histogram in Figure 1(a) of Kargatis et al. (1994) erroneously contains 172 bursts: 1982b May 25 burst with ( T_{90} = 4.5 \text{ s} ) should not have been included</td>
<td>Kargatis et al. 1994</td>
</tr>
<tr>
<td>KONUS 11/12</td>
<td>8/136 (6%)</td>
<td>Duration &lt; 1 \text{ s}</td>
<td>Bursts with duration ( T &lt; \text{ trigger integration time} ), have threshold approximately ( \propto 1/T ), so missed some short bursts</td>
<td>Mazets et al. 1982</td>
</tr>
<tr>
<td>KONUS 13/14</td>
<td>9/81 (11%)</td>
<td>Duration &lt; 1 \text{ s}</td>
<td>Removed SGR bursts</td>
<td>Golenetskii et al. 1987</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Localized bursts</td>
<td>Golenetskii et al. 1987</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Removed SGR bursts</td>
<td>Golenetskii et al. 1987</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>More sensitive than KONUS 11/12 for short bursts, but similar trigger problems</td>
<td>Golenetskii et al. 1987</td>
</tr>
<tr>
<td>PVO</td>
<td>49/225 (22%)</td>
<td>Equivalent time width &lt; 1 \text{ s}</td>
<td>Triggered PVO bursts</td>
<td>Chuang 1990</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SGR bursts not removed</td>
<td>Chuang 1990</td>
</tr>
</tbody>
</table>
4. \(C_{\text{max}}/C_{\text{min}}\) FOR DIFFERENT DETECTOR SENSITIVITIES

The disk plus halo model has no difficulties in generating \(C_{\text{max}}/C_{\text{min}}\) distributions that are consistent with the observations made by detectors that were less sensitive than BATSE. For example, Figure 3a shows the \(C_{\text{max}}/C_{\text{min}}\) distribution for the exponential halo plus disk example of §2 observed by a detector that is identical to BATSE in all respects except that it is a factor of 10 less sensitive, i.e., it can detect sources to a distance 1/(10)\(^{1/2}\) that of BATSE. To compare with Figure 1, \(N_{\text{tot}} = 193\) is used in Figure 3a; the less sensitive detector will require more time than BATSE to see this number of bursts. At large \(C_{\text{max}}/C_{\text{min}}\), the distribution tends toward a \(-3/2\) power law. At small \(C_{\text{max}}/C_{\text{min}}\), the deviation from the \(-3/2\) power law is far less pronounced than it is at the BATSE sensitivity.

The values of \(\langle V/V_{\text{max}}\rangle\), \(\langle \cos \theta \rangle\), and \(\langle \sin^2 b \rangle\) for the disk, halo, and combined disk plus halo for this less sensitive detector are given in Table 3. As expected, \(\langle V/V_{\text{max}}\rangle\) for the combined disk plus halo is larger for the less sensitive detector than it is for BATSE (the values of \(\langle V/V_{\text{max}}\rangle\) are larger for both the disk and halo components). The values of \(\langle \cos \theta \rangle\) and \(\langle \sin^2 b \rangle\) for the combined disk plus halo are similar to the values at the BATSE sensitivity; \(\langle \sin^2 b \rangle\) is closer to 1/3 for the less sensitive detector because \(N_d/N_{\text{tot}}\) is smaller for this case, and the disk is effectively more homogeneous. These results are consistent with the observations made by earlier satellites (Higdon & Lingenfelter 1994a, b); for example, \(\langle V/V_{\text{max}}\rangle = 0.46 \pm 0.02\) for Pioneer Venus Orbiter (PVO) (Hartmann et al. 1992).

Figure 3b shows the \(C_{\text{max}}/C_{\text{min}}\) distribution for the exponential halo plus disk example of §2 observed by a detector that is identical to BATSE in all respects except that it is a factor of 25 times more sensitive, i.e., it can detect sources to a distance 5 times farther than BATSE. Again \(N_{\text{tot}} = 193\) is used, and the radial dependence of the disk number density is ignored for simplicity; these results are for illustrative purposes only. For only 193 bursts, the curve does not reach a \(-3/2\) power law at large \(C_{\text{max}}/C_{\text{min}}\). At small \(C_{\text{max}}/C_{\text{min}}\), the curve steepens because the disk bursts begin to dominate; this is a firm prediction of the disk plus halo model, if a sensitive enough detector is ever flown. Paczyński (1992b) was concerned that attempts to fit the BATSE observations using the disk plus halo model would produce \(C_{\text{max}}/C_{\text{min}}\) curves similar to Figure 3b. However, to get a curve of this form requires \(N_d/N_{\text{tot}} \gtrsim 0.8\), which is much larger than is needed to fit the BATSE observations.

The values of \(\langle V/V_{\text{max}}\rangle\), \(\langle \cos \theta \rangle\), and \(\langle \sin^2 b \rangle\) for the disk, halo, and combined disk plus halo for this more sensitive detector are given in Table 4. The value of \(\langle V/V_{\text{max}}\rangle\) for the combined disk plus halo is larger for the more sensitive detector than it is for BATSE, because \(\langle V/V_{\text{max}}\rangle_d\) must be between 0.4 and 0.5, and the disk bursts dominate. The value of

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**TABLE 3**

| Average Quantities for Example of Exponential Halo plus Disk for Less Sensitive Detector |
|---------------------------------|--------|--------|----------------|
| Quantity                        | Disk   | Halo   | Disk + Halo   |
| \(\langle V/V_{\text{max}}\rangle\) | 0.4841 | 0.4366 | 0.440         |
| \(\langle \cos \theta \rangle\)  | 0.0    | 0.0620 | 0.058         |
| \(\langle \sin^2 b \rangle\)    | 0.2952 | 0.3315 | 0.329         |

**TABLE 4**

| Average Quantities for Example of Exponential Halo plus Disk for More Sensitive Detector |
|---------------------------------|--------|--------|----------------|
| Quantity                        | Disk   | Halo   | Disk + Halo   |
| \(\langle V/V_{\text{max}}\rangle\) | 0.4077 | 0.0098 | 0.353         |
| \(\langle \cos \theta \rangle\)  | 0.0    | 0.0628 | 0.009         |
| \(\langle \sin^2 b \rangle\)    | 0.0563 | 0.3322 | 0.094         |

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<sin^2 b) for the combined disk plus halo is much smaller than 1/3 for the more sensitive detector because of the dominance of the disk bursts, which for B_d > z_0 are close to the thin-disk limit of <sin^2 b> = 0. Note that, in practice, a radial dependence for the disk number density distribution can make <cos \theta> ≠ 0.

5. BIRTHRATE OF DISK AND HALO SOURCES

To show some of the consequences of the disk plus halo model, the total number of disk and halo sources in our Galaxy and their required birthrates will now be calculated.

Assuming the disk sources are distributed with axial symmetry about the Galactic center, the total number of disk bursts that occur in the whole Galaxy per unit time is N_{d,\theta} = \int_{\theta}^{\theta_\max} 2\pi \rho d\phi \int_{z=0}^{z_\max} n(\rho, z) dz. As an example, the simple disk of \S 2 will be used here, assuming there is no radial dependence out to a cutoff at radius \rho_c; using a more realistic n(\rho, z) does not change the result significantly. For this exponential disk, N_{d,\theta} = 2\pi \rho_c^2 z_0 n_d.

Assuming the halo sources are distributed with spherical symmetry about the Galactic center, the total number of halo bursts that occur in the whole Galaxy per unit time is N_{h,\theta} = \int_{\theta}^{\theta_\max} 4\pi R^2 n(R)dR. As an example, the exponential halo of \S 2 is used here, which gives N_{h,\theta} = 8\pi R^2 n_h. (Note that extending the integral to infinity does not greatly overestimate the number of halo bursts; all but 1% of the bursts occur inside \R = 8.4R.)

The ratio (N_{h,\theta}/N_{d,\theta}) is a typical example, the disk plus exponential halo model of \S 2 gives (n_h/n_d) = 5.4 \times 10^{-6}. Assuming \rho_c = 15 kpc, one finds (N_{h,\theta}/N_{d,\theta}) = 0.0117; similarly, other disk and halo examples give (N_{h,\theta}/N_{d,\theta}) \sim 10^{-2} to 10^{-3}. This shows that the number of halo bursts that occur in the whole Galaxy per unit time is a small fraction of the total number of bursts that occur in the whole Galaxy per unit time.

N_{h,\theta} and N_{d,\theta} are the number of halo and disk bursts in the whole Galaxy per unit time, which are not the same as the number of active halo and disk sources in the Galaxy at a given time: a given number of bursts could be produced by many sources that burst only once over their bursting lifetime, or by a few sources that burst many times over their lifetime. The ratio of the number of active (i.e., still capable of bursting) halo sources to the number of active disk sources in the whole Galaxy at a certain time is given by (N_{h,\theta}/N_{d,\theta}) B_d/B_h \Gamma_t/\Gamma_h, where B_d and B_h are the number of bursts each halo and disk source produces over its lifetime, and \Gamma_t and \Gamma_h are the bursting lifetimes of the halo and disk sources, respectively (for simplicity, it is assumed there is no variation in these quantities from source to source). The observed fluxes of the halo and disk bursts are roughly comparable, yet the observed halo sources are far more distant than the observed disk sources; this means the ratio of the luminosities of the halo and disk bursts L_{h}/L_{d} \gg 1 (L_{h}/L_{d} \sim 10^{-2} for typical disk plus halo examples). It might therefore be expected that a disk source would burst more often than a halo source, so that (B_d/\Gamma_d) \gg (B_h/\Gamma_h). However, this would imply that the number of active halo sources in the Galaxy is not a small fraction of the total number of active bursters.

If it is assumed that the Galaxy is in a steady state in which sources are born and die at the same rate, then the ratio of the birthrate of the halo sources to the birthrate of the disk sources is given by (N_{h,\theta}/N_{d,\theta}) (B_d/B_h). The mechanism by which the halo sources are born is not known. However, it is generally believed that the birthrate of the halo sources is small compared to the birthrate of the disk sources (Hartmann et al. 1992; Hartmann et al. 1994; although see Fabian & Podoslakowski 1993 for a model where this is not the case). For this to be true, it is necessary that B_d \ll B_h; this would require that the halo sources release much more energy over their bursting lifetime than the disk sources, which constrains the possible models for the disk and halo bursters.

If the disk bursts are more tightly beamed than the halo bursts, then (N_{h,\theta}/N_{d,\theta}) is reduced by a factor (f_d/f_h), where f_d and f_h are the fractions of the sky covered by the beams for the disk and halo bursters, respectively. However, the ratio of the luminosities (L_{h}/L_{d}) would then have to rise by a factor (f_h/f_d).

For the disk plus halo model to be correct, it is necessary to explain why the bursting process is different for the halo and disk sources. It is also necessary to explain why disk sources do not produce halo-type bursts (Hartmann et al. 1994). It is possible that the high velocity of the halo sources (Eichler & Silk 1992; Li & Dermier 1992), perhaps in conjunction with a strong magnetic field (Duncan, Li, & Thompson 1993), makes the halo sources different from those in the disk. Alternatively, the halo sources could be formed in the protogalaxy (Hattori & Terasawa 1993), while the disk sources are significantly younger. The fact that the halo sources accrete less material from the interstellar medium may also distinguish them from the disk sources.

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