Gamma Ray Bursts: Near or Far?

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More than 3 years after the launch of the Burst and Transient Source Experiment (BATSE) on board National Aeronautics and Space Administration's (NASA) Compton Gamma Ray Observatory, researchers continue to debate the origins of the high-energy astrophysical phenomenon known as cosmic gamma ray bursts (GRBs). These enigmatic and unpredictable flashes of gamma ray energy provide a puzzle as controversial as any in modern astronomy. Over 1000 bursts have been detected to date by BATSE (Fig. 1), and although the initial stage of data analysis is past, arguments continue over how best to understand GRBs.

In the 18 years following their serendipitous discovery (*1*), GRBs were widely thought to be associated with neutron stars in our galactic disk, and a substantial amount of science was done to explain the detailed physics of GRBs in this context. After publication of the initial BATSE results (*2*), however, it was clear that the prevailing physical picture was in serious trouble. The gamma ray bursts detected by BATSE are isotropically distributed on the sky, with no significant quadrupole or dipole moment in any direction (*3*). Yet the bursts possess a brightness distribution that, for Euclidean space, implies a decreasing burst density at large distances. This combination effectively rules out the galactic disk as a possible home for the gamma ray burst population (*4*). Hartmann recently provided (*5*) an excellent overview of the evidence that supported the early galactic disk hypothesis, and its stark contrast to the observations of BATSE.

The galactic disk neutron star was a fertile foundation on which to build a wide range of detailed GRB models. However, without this physical setting, we are forced to step back and analyze the BATSE data from a somewhat different perspective, one less rooted in the detailed physical mechanisms of burst production and more focused on broad, simple characteristics of the data. By asking fundamental questions that can be effectively answered by BATSE, much can be learned about the nature of the gamma ray bursts, regardless of the details of how and in what environment they are created. The answers to many of these questions are beginning to yield compelling results.

One natural question to ask is, "How far away are the gamma ray bursts?" Although still uncertain to about 10 orders of magnitude, some recent progress has been made on this question regarding the possible distribution of bursts in a large galactic halo or corona. It is clear that such a corona, if it exists, must be very large. The solar system is offset 8.5 kpc from the center of the galaxy. This distance must be negligible compared with the size of the overall burst distribution in order to retain the appearance of isotropy in the GRB positions. As more bursts are detected and the constraints on isotropy are tightened through better statistics, the size of the required corona must be continually increased. Analyses of the first 1000 BATSE bursts show that a GRB population in a corona centered on the galaxy must be spherical and enormous, with bursts observed to distances of 300 kpc or more (6).

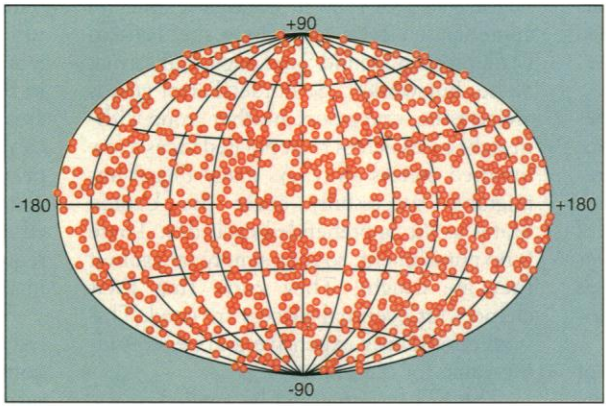

Fig. 1. The distribution of 1000 BATSE gamma ray bursts in galactic coordinates. There is no statistically significant deviation from isotropy in the distribution.

A distribution of this size is incompatible with many other pieces of evidence, however. The Large and Small Magellanic Cloud galaxies would be completely engulfed by such a large corona. Consequently, even a small amount of burst production in these galaxies would immediately be visible in the BATSE data as an excess of bursts in their respective directions. Given a corona this large, one would also expect an excess number of bursts from the direction of the nearest large spiral galaxy, M31, which (on the basis of its mass) should itself have a corona with nearly twice the burst production rate of our own. With no observed burst concentration in any of these directions, a caveat must be contrived to prevent these other galaxies from making GRBs, while the Milky Way makes a large number of them. The constraints are becoming uncomfortably tight on exactly what type of corona is needed to fit the observations. If each of the constraints (for example, on LMC and M31) cannot be satisfactorily explained, then coronal models are dead, according to some astronomers (*7*).

Another simple question is, "Do bursts repeat?" This must be answered with some care, partly because the uncertainty in each BATSE location is about 4°, so that a repeating source may not be localized to exactly the same place each time. Different types of repetition would also produce markedly different effects in the data. For example, 500 isotropically distributed burst sources each repeating once would produce quite a different angular distribution than an isotropic population of 500 burst sources with one repeating 501 times. Repetition may also be an important discriminator between gamma ray burst models. Early galactic disk models required repetition owing to the relatively small numbers of nearby neutron stars relative to the observed burst rate. Cosmological models, on the other hand, usually mandate a destruction of the burst environment during the release of nearly 10^{52} ergs, so repetition is unlikely unless two bursts can be shown to be gravitationally lensed events, thereby confirming a cosmological origin.

What is the maximum allowable fraction of the observed GRBs that could be repeaters, independent of the particular model of repetition? Many techniques can be used to address this quesiton, such as the two-point angular correlation function, or a nearest neighbor analysis. One such analysis of the first 260 BATSE bursts claims to find that gamma ray burst sources repeat on time scales of months with multiple repetitions from a substantial fraction of the BATSE bursts (8). Because of its modest statistical significance, however, this result has been met with cautious responses. Meegan, for instance, has expressed the concern that with so many people pouring over the data, it may be difficult to assess the statistical significance of each small but interesting indication (9).

Meegan and Hartmann have performed subsequent analyses of additional BATSE data to also search for repetition. Their recent works (*10, 11*) do not confirm the existence of repeating GRBs in the more ex-

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tensive BATSE data set, contradicting the previous claim of copious repeaters. These new results show that the BATSE data are in fact consistent with no-repeaters and state with 99% confidence that fewer than 20% of the bursts repeat, regardless of the repetition model.

A third interesting question to ask is, "What range of burst luminosity is revealed by the BATSE data?" The range of observed brightnesses exceeds a factor of 100. However, with no real knowledge of the spatial distribution, the luminosity function cannot be reliably extracted from the brightness distribution, and hence, the amount of energy released in the bursts cannot be determined. It was apparent from preliminary BATSE data, however, that the range of observed luminosity was likely to be small, at least for a Euclidean source distribution. This can be understood by visual inspection of the integral number versus brightness distribution. Bright GRBs are well known to follow the $-3/2$ power law indicative of spatial homogeneity (Fig. 2). At the dim end, however, the power law slope is about -0.8, indicating that the burst density decreases beyond some fixed but unknown distance. The transition region between these two slopes is very narrow, less than a factor of 10 in brightness. If the range of observed luminosity were broad, one would expect the curve to transition very slowly over a wide range of brightnesses, instead of breaking very abruptly from one region to the other.

This narrowness in observed luminosity can be quantified by studying the integral moments of the observed differential brightness distribution. These brightness moments are proportional to the moments of both the luminosity function and the radial distribution of observed bursts in Euclidean space (*12*). If one guesses a luminosity function for the GRBs, and hence its moments, it is straightforward to compute the moments of the corresponding radial distribution required to match the BATSE data. Moments of a positive-definite function are not independent quantities, however, and obey a general set of inequalities (*13*). For example, the second moment must be larger than or equal to the square of the first moment to insure a non-negative variance. If a set of radial distribution moments, derived from an assumed luminosity function and the BATSE data, violates these inequalities, one can conclude that the assumed luminosity function is incompatible with the data.

The application of this methodology to bursts in Euclidean space shows that at least 80% of the bursts observed by BATSE are drawn from a range of luminosity that does not exceed a factor of about 6 (*14*). This narrow range is remarkable by itself when compared with the distributions of many other observed burst properties such as duration, which span several orders of magnitude. Independent analyses with different techniques, notably that of Ulmer and Wijers (*15*), also arrive at this rather interesting conclusion.

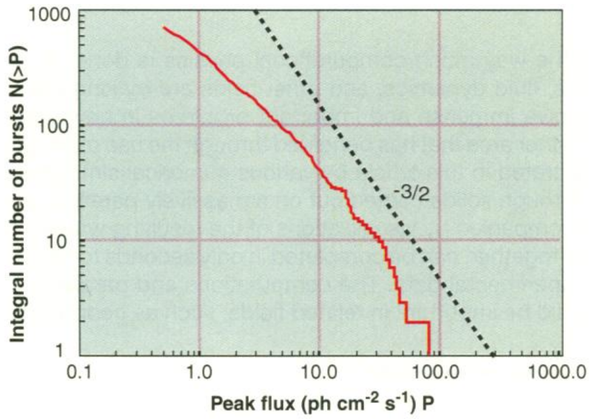

Fig. 2. The integral number versus brightness distribution of 687 gamma ray bursts with peak flux ≥ 0.5 photon cm^{-2}s^{-1}. The combination of Euclidean spatial inhomogeneity with the isotropy of Fig. 1 is unlike any known population of galactic objects.

Because the previous result is derived assuming GRBs in Euclidean space, we ask another question: "What if GRBs are cosmological? Does the previous result still hold?" Norris and colleagues have recently analyzed the time profiles of bursts observed by BATSE and claimed to find time-dilation effects that indicate the dimmest BATSE bursts are located at redshifts of $z \sim 2$ (*16*), thereby adding some support to the notion that bursts are cosmological.

By assuming a particular cosmology and burst distribution, one can utilize the BATSE brightness distribution moments to deduce moments of the candidate luminosity function. As before, if these derived luminosity moments violate the moment inequalities, the assumed cosmology and burst distribution are incompatible with the data. Such an analysis not only confirms the well-known agreement between the BATSE brightness distribution and a cosmological distribution of nonevolving mono-luminous bursts to a redshift of $z \sim 1$ (*17, 18*), but also indicates that a wide range of observed luminosity is possible for nonevolving cosmological bursts only in the context of an accelerating universe, driven by a positive cosmological constant Λ (*19*). The concept of a universe that accelerates as it expands is not a comfortable one for most astronomers.

Emslie, however, believes there is an escape (*20*). If the cosmological burst population is evolving, then the requirement of a narrow luminosity range may be relaxed either by placing a higher rate density of bursts at suitable redshifts, or by making bursts at such redshifts more luminous as a group. In fact, if the time-dilation results (*16*) are correct, some form of density or luminosity evolution that increases with redshift is required for $\Lambda = 0$ cosmologies to explain both the BATSE brightness distribution and the $z \sim 2$ limiting redshift (*21*).

Indeed, we have learned a great deal simply by asking fundamental questions of the BATSE data. The data are consistent with no repeating sources, and only a small fraction of the overall population can possibly repeat. A galactic disk population cannot simultaneously produce the observed angular isotropy and Euclidean spatial inhomogeneity. A galactic corona must be so large that the coronae of nearby galaxies should also be observed. The observed range of luminosity is narrow unless the bursts are cosmological and (i) the universe is accelerating ($\Lambda > 0$), or (ii) the gamma ray bursts are a moderately evolving population. If accurate, the recently measured limiting redshift of $z \sim 2$ requires evolving cosmological bursts or $\Lambda > 0$ to also explain the observed brightness distribution. Strict application of Occam's razor leads clearly in the direction of a cosmological origin for these events; however, this does not constitute a proof that bursts are at cosmological distances. Obtaining a definitive answer to the question of gamma ray bursts will require more data, more time, and more analyses.

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