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Dieter Hartmann

George R. Blumenthal

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ANGULAR CLUSTERING PROPERTIES OF GAMMA-RAY BURSTS AND QUANTITATIVE CONSTRAINTS ON THEIR DISTANCES¹

DIETER HARTMANN AND GEORGE R. BLUMENTHAL

Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California at Santa Cruz

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ABSTRACT

We derive upper limits on the angular correlation function $w(\theta)$ of γ -ray bursts and show that these limits substantially constrain the sources to be very nearby or very distant. Since quiescent counterparts of γ -ray bursts have not as yet been unambiguously identified in any wavelength band, the γ -ray burst distance scale remains uncertain. Earlier work has shown that the angular distribution of γ -ray bursts on the celestial sphere is quite isotropic, with no evidence for a disk-like structure and no evidence for association with known galaxies or clusters. To test whether or not γ -ray bursts are associated with objects at great distance, we compare their clustering properties with those of known extragalactic populations, such as galaxies or galaxy clusters. We have determined the angular clustering properties of the sources in two recent γ -ray burst catalogs by calculating their two-point angular autocovariance function $w(\theta)$. The correlations of both data sets are consistent with $w(\theta) = 0$. Under the assumption that the underlying spatial correlation is a power law in radius, the derived upper limit on $w(\theta)$ can be used to constrain the correlation length and the characteristic survey depth of γ -ray burst catalogs. In particular, if the spatial correlation of γ -ray bursts resembles that of galaxies or galaxy clusters, present γ -ray burst catalogs must be complete to distances in excess of 100 Mpc. Alternatively, if γ -ray bursts are associated with a disk population within the Galaxy, then the upper limits on $w(\theta)$ constrain the sampling depth to less than two disk scale heights.

Subject heading: gamma rays: bursts

1. INTRODUCTION

About 100 γ -ray bursts brighter than $\sim 10^{-5}$ ergs cm⁻² s⁻¹ are observed annually. Since their discovery (Klebesadel, Strong, and Olson 1973) unambiguous positions have been obtained for ~ 200 of these. Searches at wavelengths other than γ -rays have not yet resulted in a convincing identification of quiescent counterparts. Furthermore, the angular distribution of γ -ray bursts on the celestial sphere is quite isotropic, showing no obvious association with galactic features (disk, bulge, globular clusters, and so on) or extragalactic features such as nearby galaxies or galaxy clusters. This lack of association with any known astronomical population has left the γ -ray burst distance scale undetermined. Proposed models range from galactic neutron stars to cosmic strings at cosmological distances, implying typical γ -ray burst luminosities between $\sim 10^{38}$ ergs s⁻¹, the Eddington luminosity of a $1 M_{\odot}$ neutron star, and $\sim 10^{50}$ ergs s⁻¹ if distances exceed ~ 100 Mpc. The duration of a typical γ -ray burst is of order of 1 s. For comprehensive discussions of the γ -ray burst phenomenon, see the recent reviews by Liang and Petrosian (1986), Hartmann and Woosley (1988), and Hurley (1988).

Statistical constraints on the spatial distribution of γ -ray bursts can be obtained from their angular distribution on the celestial sphere (e.g., Golenetskii *et al.* 1986; Atteia *et al.* 1987; Golenetskii 1988; Mazets *et al.* 1981; Mazets 1988; Hartmann and Epstein 1989), their cumulative brightness distribution “log N -log S ” (e.g., Mazets *et al.* 1981; Paczyński and Long 1988; Jennings 1988; Golenetskii 1988), and the $V/V_{\max}$ test (Schmidt, Higdon, and Hueter 1988; Hartmann, Gonzalez, and Hurley 1989). The results obtained from these methods suggest that the γ -ray burst distribution is consistent with isotropy and homogeneity. This implies that the sources are either very

nearby, e.g., a few neutron star scale heights, or at cosmological distances, well beyond the local supercluster (see, e.g., Epstein 1988; Hurley 1988; Epstein and Hurley 1988). To determine whether γ -ray bursts are of galactic or extragalactic origin (we are reminded of the “great debate” about the nature of the nebulae at the beginning of this century), data expected from future space missions such as GRO will be crucial. However, the data in hand already allow us to shed some light on this important question.

We have calculated the angular clustering properties of the positions given in two recent γ -ray burst catalogs (Golenetskii *et al.* 1986; Atteia *et al.* 1987). If γ -ray bursts are indeed extragalactic and trace either the galaxy distribution (Prilutskii and Usov 1975; Usov and Chibisov 1975; Atteia and Hurley 1986; McBreen and Metcalfe 1988) or the large-scale structure of the universe (Goodman 1986; Paczyński 1986, 1987, 1988; Babul, Paczyński, and Spergel 1987) the angular correlations of γ -ray bursts should exhibit a similarly pronounced correlation as that observed for galaxies and clusters of galaxies (Peebles 1980; Groth and Peebles 1977; Fall 1979; Hewett 1982; Davis and Peebles 1983; Bahcall and Soneira 1983). Similarly, if the γ -ray bursts arise from a disk-like galactic population, then one expects significant nonzero angular correlations if the sources are sampled out to a distance of several disk scale heights.

This paper is organized as follows. In § II we discuss the basic properties of the method. The results obtained for the two γ -ray burst catalogs are discussed in § III and the conclusions are presented in § IV.

II. METHOD

The angular autocovariance function $w(\theta)$ is defined in the following manner. Consider an ensemble of points distributed on the sky. Then for any given point, the probability dP (averaged over the ensemble) of finding a second point at an

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angular separation θ and within the solid angle $d\Omega$ is given by (Limber 1953; Peebles 1973)

$$dP = n[1 + w(\theta)]d\Omega, \quad (1)$$

where n is the mean number of ensemble points per steradian. Clearly, $w(\theta)$ is a measure of the deviation from Poisson probabilities. In practice, the autocovariance function is evaluated by rewriting equation (1) as

$$1 + w(\theta) = \frac{\mathcal{N}_p}{\mathcal{N}_{pp}}, \quad (2)$$

where $\mathcal{N}_p$ is the number of ensemble pairs having angular separation in the interval $(\theta, \theta + d\theta)$, and $\mathcal{N}_{pp}$ is the number of pairs in a purely Poisson ensemble of points with separation in the same interval. We shall use equation (2) to evaluate the autocovariance function of γ -ray bursts. To evaluate the uncertainties in $w(\theta)$, we assume Poisson errors in the pair counts. That is, we take

$$\frac{\delta w}{1 + w(\theta)} = \frac{1}{\sqrt{\mathcal{N}_p}}. \quad (3)$$

This error estimate is known to underestimate the uncertainty in real samples (Peebles 1973; Kaiser 1986).

Based on the observed isotropy of γ -ray bursts and the wide field of view of burst detectors, it appears justified to assume that the observations cover the complete sky with approximately uniform coverage. If this assumption does not hold, boundary corrections must be used to determine the autocovariance function (e.g., Sharp 1979; Hewett 1982). In contrast to galaxies, γ -ray bursts are not point-like sources. The localization accuracy for γ -ray bursts, $\Delta\theta$, is typically less than but of order of one degree (e.g., Golenetskii *et al.* 1986; Atteia *et al.* 1987). The effect of the finite sizes of the "error boxes" on $w(\theta)$ can be neglected as long as we consider only angles large compared to $\Delta\theta$.

III. RESULTS

Following the procedure outlined in § II we have calculated the angular autocovariance function $w(\theta)$ for two recent compilations of γ -ray burst locations.

The first data set (hereafter referred to as the "Network catalog") is a catalog of 84 γ -ray bursts which occurred between 1978 September 14 and 1980 February 13 (Atteia *et al.* 1987). The burst events were detected by the interplanetary network, consisting of experiments aboard the near-Earth spacecrafts *Vela 5A*, *5B*, *6A*, *6B*, *Prognos 7*, *SMM*, and *Helios 2*, the *International Sun-Earth Explorer (ISEE 3)* at the Lagrange point L_1 between the Earth and the Sun, the *Pioneer Venus Orbiter (PVO)* in orbit around Venus, and the Franco-Soviet Signe experiments aboard *Venera 11* and *12*. Burst localization was possible for 80 out of the observed 84 events. The locations, derived from arrival-time analysis, are given as single error boxes, double error boxes, or annuli of location. Typical "error box" sizes are less than but of order of 1 square degree. The published time histories and localizations of the KONUS experiment (Mazets *et al.* 1981) were used to complete or refine the interplanetary network localizations. In this paper we only consider the 54 single error boxes and neglect their finite sizes (§ II). The galactic distribution of these sources is shown in Figure 1.

The second catalog (hereafter referred to as the KONUS catalog) consists of 160 locations obtained from the KONUS

experiment aboard the Soviet satellites *Venera 11–14* (Mazets *et al.* 1981; Golenetskii *et al.* 1988; Mazets 1988; Golenetskii 1988). The KONUS experiment on *Venera 11–12* was carried out from 1978 to 1980 followed by *Venera 13–14* in 1981–1983. In 827 days of observations a total of 343 γ -ray bursts were detected. Burst localization was obtained using arrival analysis in conjunction with the anisotropic detector response. Based on the KONUS experiments alone 143 single localizations were obtained. However, the final catalog contains 160 positions, out of which only 120 were derived from KONUS data exclusively; the remainder utilized data of the interplanetary network. The galactic distribution of these sources is also shown in Figure 1.

The two sets of data are not independent of each other because each has made use of information obtained from the other. For this reason we do not add the catalogs to obtain a larger data sample for statistical purposes, but rather analyze both data sets independently. We have calculated the angular autocovariance function $w(\theta)$ following the procedure outlined in § II. The results are shown in Figure 1. With more source positions, the KONUS catalog has better statistics and reaches to smaller angular scales. However, both catalogs separately are consistent with zero correlation. In each case only one data point was nonzero at more than the 1σ level. Taken together, the results indicate zero angular correlation over two orders of magnitude ($\theta \sim 1^\circ$ – 100°). As discussed in § II, the error bars shown in Figure 1 are underestimates of the true errors. We do not calculate $w(\theta)$ for angles smaller than 1° because the γ -ray burst positions are typically not determined to better than 1° .

One can use our observed upper limit on the angular autocovariance function to constrain models in which γ -ray bursts are associated with objects having observed nonzero correlations. This constraint is particularly straightforward in the case where these underlying spatial correlations have a power-law form:

$$\xi(r) = Ar^{-\alpha}. \quad (4)$$

Imagine that a survey extends out to some limiting distance D with a selection function $\phi(y)$, which is the probability that an object at distance yD will be included in the catalog. Then, if the underlying correlation function is given by equation (4) with $\alpha > 1$, the angular covariance function of the catalog is (Peebles 1980)

$$w(\theta) = \theta^{1-\alpha} \frac{AH(\alpha)}{D^{\alpha}E^2} \int_0^\infty dy y^{5-\alpha} \phi^2(y), \quad (5)$$

where

$$E = \int_0^\infty dy y^2 \phi(y) \quad (6)$$

and in terms of the gamma-function,

$$H(\alpha) = \frac{\Gamma(1/2)\Gamma(\alpha/2 - 1/2)}{\Gamma(\alpha/2)}. \quad (7)$$

Now, for simplicity, assume that the survey of γ -ray bursts is complete out to the limiting distance D . Then

$$\phi(y) = \Theta(1 - y), \quad (8)$$

where $\Theta(x)$ is the standard Heaviside function. Equation (6) then implies that $E = \frac{1}{3}$. For $\alpha = 2$, which is a commonly measured slope for the spatial autocovariance function, equation

FIG. 1.—The top row shows the galactic distribution of 54 single error box locations of γ -ray bursts detected by the interplanetary network (right; Atteia et al. 1987) and 160 localizations obtained from the KONUS experiment aboard the Soviet satellites *Venera 11–14* (left; Mazets et al. 1981; Golenetskii et al. 1986). The angular covariance functions $w(\theta)$ for both catalogs are shown below the maps. In comparison to the data of the interplanetary network of γ -ray burst detectors, the larger number of sources in the KONUS catalog allows a determination of $w(\theta)$ on smaller angular scales and with better statistics. However, both catalogs independently are consistent with zero correlation. Taken together, the observations suggest $w(\theta) = 0$ over two orders of magnitude in angle ($\theta^\circ \sim 1\text{--}100^\circ$). If the underlying spatial source correlation follows a r^{-2} power law in radial separation, it is useful to interpret the upper limits on the product $\theta w(\theta)$ (bottom row) in terms of a minimum sampling depth for γ -ray burst observations (see text).

(7) yields $H(\alpha) = \pi$, and equation (5) becomes

$$w(\theta) = \frac{9\pi A}{4D^2\theta}. \quad (9)$$

If γ -ray bursts are extragalactic and associated with galaxies, then they will have a nonzero spatial correlation function. If the number of burst sources per galaxy is a constant, then gamma ray bursts should actually have the same autocovariance function as galaxies. Davis and Peebles (1983) find the galaxy-galaxy covariance function to be well fitted by the form

$$\xi_{gg}(r) = \left(\frac{r_0}{r}\right)^\alpha, \quad (10)$$

where $\alpha \approx 1.8$, the correlation length $r_0 \approx 5h^{-1}$ Mpc, and h is the Hubble constant in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Using the approximation $\alpha \approx 2$ (which is consistent with the uncertainties in the data), equation (9) implies the angular covariance function

$$w(\theta) = \frac{9\pi}{4} \left(\frac{5h^{-1} \text{ Mpc}}{D}\right)^2 \frac{1}{\theta}. \quad (11)$$

One should note that our results are insensitive to the difference between slopes of $\alpha = 2$ and $\alpha = 1.8$ for the spatial covariance function.

The covariance function shown in Figure 1, based on the data of Golenetskii *et al.* (1986), gives a conservative upper limit $w(\theta) < 2/\theta^\circ = 0.035/\theta$. Hence, equation (11) yields

$$D > 71h^{-1} \text{ Mpc} \quad (12)$$

for γ -ray bursts associated with galaxies. Thus, if this association with galaxies is real, then the survey must be fairly complete out to 140 Mpc (for $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$), which corresponds to a total γ -ray burst energy of

$$E_\gamma = 1.2 \times 10^{50} \left(\frac{D}{100 \text{ Mpc}}\right)^2 \left(\frac{S}{10^{-4} \text{ ergs cm}^{-2}}\right) \text{ ergs}, \quad (13)$$

where typical observed fluences S are of order of $10^{-4} \text{ ergs cm}^{-2}$ (e.g., Hurley 1988). This is already large compared to the total γ -ray energy emitted by a typical Type II supernova event: $E(> 100 \text{ keV}) \sim 2 \times 10^{46} \text{ ergs}$ (e.g., Pinto and Woosley 1988). In the case of Type II supernovae, the energy is released over ~ 400 days. On the other hand, the γ -ray luminosities of active galaxies are typically of order of $L_\gamma \sim 10^{46} \text{ ergs s}^{-1}$ (Bassani and Dean 1983), implying amplification factors larger than 10^4 for models in which γ -ray bursts are caused by lensing of distant steady sources (McBreen and Metcalfe 1988; Paczyński 1986).

If the sources are optically thin to photon-photon pair creation, then the size of the γ -ray emitting region must exceed (e.g., Schmidt 1978; Epstein 1985 and references therein)

$$R \gtrsim 1.5 \times 10^{15} \left(\frac{D}{100 \text{ Mpc}}\right) \left(\frac{S}{10^{-4} \text{ ergs cm}^{-2}}\right)^{1/2} \text{ cm}. \quad (14)$$

Light travel time arguments then give a shortest time scale for temporal variability of order of $5 \times 10^4 \text{ s}$ for distances greater than 100 Mpc. Variability in the time structure of γ -ray bursts has been observed down to milliseconds; this time variability may even extend down to microseconds (Mitrofanov 1988), although the limits of instrumental resolution make this uncertain at the present time. In view of these difficulties, both opti-

cally thick and relativistic models have been considered to avoid these constraints (e.g., Paczyński 1986; Goodman 1986).

If the γ -ray bursts are instead associated with objects which are more spatially correlated than galaxies, then the catalogs must be complete to correspondingly greater distances than that given by equation (12). For example, if γ -ray bursts are associated with rich Abell clusters of galaxies, then the observed correlation length of such clusters is $\sim 25h^{-1} \text{ Mpc}$ (Bahcall and Soneira 1983), which suggests that the catalogs should be complete out to $\sim 350h^{-1} \text{ Mpc}$. This is a significant fraction of a Hubble radius $c/H_0 = 3000h^{-1} \text{ Mpc}$.

It is of course possible that γ -ray bursts are instead associated with extragalactic objects which are less clustered than galaxies. For example, in models of biased galaxy formation, the mass distribution in the universe is much less clustered than the galaxy distribution (Dekel and Rees 1987; Blumenthal 1988). So if γ -ray bursts were associated with "failed" galaxies which never initiated strong star formation, then one would expect them to have a small autocovariance function. However, if γ -ray bursts are at all associated with stellar evolution, then their correlations should be similar to the correlations of stars, which are well approximated by the galaxy-galaxy correlation function. Hence, the limit (12) is probably realistic.

We now consider the implications of the limits on $w(\theta)$ for local γ -ray burst models in which the sources are distributed in a disk having scale height H . For simplicity, assume that the source density distribution is an infinite, uniform disk with density falling exponentially with distance from the plane of the disk. With this geometry, we have generated catalogs of randomly placed disk sources such that the catalogs are complete out to radial distance D . For each catalog, the angular autocovariance function has been calculated. The results are shown in Figure 2 and compared to the autocovariance function obtained for the KONUS observations. We conclude from this figure that the survey depth of the γ -ray burst catalogs must be less than about two disk scale heights, $D \lesssim 2H$. Larger values of D/H would necessarily lead to strong positional autocorrelations on the sky.

Most models that favor a local origin of γ -ray bursts invoke neutron stars. Evidence for this paradigm stems from a diverse set of theoretical and observational considerations (e.g., Woosley 1984; Liang and Petrosian 1986; Epstein 1988; Hartmann and Woosley 1988; Hurley 1988; Mazets 1988). It is now widely recognized that neutron stars are a likely product of the evolution of massive stars ($M \gtrsim 10 M_\odot$; e.g., Woosley 1987; Woosley and Weaver 1986), so that their birthplaces are predominantly near the galactic plane. Typical velocities of order of 100 km s^{-1} lead to the rapid migration away from the galactic disk and the population of a halo extending to $\sim 10 \text{ kpc}$. In order to obtain a more accurate constraint in the context of galactic neutron star models of γ -ray bursts, one needs to calculate the spatial distribution function of neutron stars based on a realistic galactic mass model (Hartmann, Epstein, and Woosley 1989).

IV. CONCLUSIONS

Fifteen years after the discovery of γ -ray bursts, their spatial distribution remains a persistent mystery. No unambiguous identification has been found at any wavelength band. A recent workshop on the statistical properties of γ -ray bursts (summarized in Epstein and Hurley 1988) considered two distinct approaches to the γ -ray burst mystery which are now

FIG. 2.—The angular autocovariance function obtained from γ -ray burst observations of the KONUS experiment (circles) aboard the satellites *Venera 11–14* (Golenetskii *et al.* 1986; Golenetskii 1988; Mazets *et al.* 1981; Mazets 1988) is compared to those expected for exponential disk distributions (solid and dotted lines). The curves are labeled by the sampling depth in units of the disk scale height. The observations indicate that the KONUS catalog can be complete to distances less than about two scale heights if γ -ray bursts are associated with a disk population of objects.

being pursued: their $\log N - \log S$ distribution and a qualitative estimate of the degree of isotropy. Since then, the $V/V_{\max}$ test has been suggested (Schmidt, Higdon, and Hueter 1988) as an independent test of the source homogeneity. The statistical evidence obtained from these approaches indicates that γ -ray bursts are either very close (kiloparsec scale) or very far (megaparsec scale). It is generally, but not universally, believed that γ -ray bursts originate on or near galactic neutron stars. However, viable models exist that place the sources at cosmological distances. In order to test extragalactic models in which γ -ray bursts trace the large-scale structure of the universe and local models with disk geometry, we have calculated the angular autocovariance function of two recent γ -ray burst catalogs containing a total of ~ 200 unambiguous source positions. We find that the data are consistent with zero correlation on angular scales between 1° and 100° .

If the spatial correlation function of γ -ray bursts resembles that of galaxies or galaxy clusters, the present observations must be complete to distances exceeding ~ 100 Mpc. For photon energies above ~ 100 keV, this implies emitted energies much larger than those expected from Type II Supernovae or active galaxies. Although the present data are not yet sufficient to rule out some or all of the proposed extragalactic models, they do begin to severely constrain them. Improved limits will be obtained from ~ 200 additional localizations expected to result from the ongoing reduction of interplanetary network data obtained between 1981 and 1984 (K. Hurley, private communication). Theoretical models that invoke correlated

extragalactic populations need to be compared with the observed angular correlation of γ -ray bursts. A test of string models of γ -ray bursts will become more meaningful when simulations of string evolution give reliable estimates of their underlying correlation function. The calculations of Turok (1985) suggested that the observed correlations among rich clusters of galaxies can be explained by cosmic strings. However, the simulations of Bennet and Bouchet (1988) seem to suggest that such correlations may be washed out (see also Peebles and Silk 1988).

Last, but not least, we emphasize that $w(\theta)$ is also a useful tool for testing local γ -ray burst models that invoke more standard galactic populations such as neutron stars (Hartmann, Epstein, and Woosley 1989). Assuming an infinite disk with a source number density that decreases exponentially in one dimension, we have used the upper limits on $w(\theta)$ to show that present γ -ray burst catalogs do not sample the sources to distances larger than about two scale heights.

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DIETER HARTMANN and GEORGE R. BLUMENTHAL: Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California at Santa Cruz, Santa Cruz, CA 95064