HOW FAR AWAY ARE GAMMA–RAY BURSTERS?

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ABSTRACT

The positions of over 1000 gamma-ray bursts detected with the BATSE experiment on board of the Compton Gamma Ray Observatory are uniformly and randomly distributed in the sky, with no significant concentration to the galactic plane or to the galactic center. This is consistent with the previous, less precise experiments. The strong gamma-ray bursts have the intensity distribution consistent with the number density independent of distance in the Euclidean space. The weak gamma-ray bursts are relatively rare, indicating that either their number density is reduced at large distances or that the space in which they are distributed is non-Euclidean. In other words, we appear to be at the center of a spherical and bounded distribution of bursters. This is consistent with the distribution of all objects that are known to be at cosmological distances (like galaxies and quasars), but inconsistent with the distribution of any objects which are known to be in our galaxy (like stars and globular clusters). If the bursters are indeed at cosmological distances then a simple prediction follows: the weakest bursts should be redshifted, i.e. on average their durations should be longer and their spectra should be softer than the corresponding quantities for the strong bursts. There is evidence for both effects in the BATSE data.

At this time the cosmological distance scale is favored above the galactic one, but is not proven. A definite proof (or dis-proof) of the galactic distance scale could be provided with the results of a search for very weak bursts in the Andromeda galaxy (M31) with an instrument ~ 10 times more sensitive than BATSE.

If the bursters are indeed at cosmological distances then they are the most luminous sources of electromagnetic radiation known in the universe. At this time we have no clue as to their nature, even though well over a hundred suggestions were published in the scientific journals. An experiment providing ~ 1 arc second positions would greatly improve the likelihood that counterparts of gamma-ray bursters are finally detected. A new interplanetary network would offer the best opportunity.

1. INTRODUCTION

The information about the observed properties of gamma-ray bursts was provided by Dr. Fishman in his introductory paper. I shall summarize what I consider to be the most important for their distance scale. The observed distribution of gamma-ray bursts appears to be isotropic.

It is true that a number of researchers found small departures from perfectly uniform distribution by selecting various sub-samples of the bursts (e.g. Lamb & Quashnock 1994), but these small irregularities were not confirmed by the new data, and even the correctness of the original claim is in doubt (Rutledge & Lewin 1993). It is natural that any finite sample must exhibit some statistical fluctuations, giving evidence for things which are not, in fact, there. So far no specific suggestion of anisotropy survived the test of time. To the contrary, the more bursts are known the more isotropic their distribution appears, as the statistical fluctuations average out.

There was a lot of confusion in the 1980s about the correct way of measuring burst intensity. By "correct" I mean the way which would be proper to study their radial distribution. After some debate a consensus has been reached: the burst intensity has to be measured in the same units which are used to detect the bursts. Roughly speaking it is the number of photons detected in a time bin of a chosen duration. For example, if a burst is detected when the count of photons in one second intervals exceeds some threshold, then the peak count per second should be used as a measure of the burst intensity.

It is well known that if sources of any kind are uniformly distributed in a 3-dimensional Euclidean space then the number of sources, N, that appear to be brighter than some limit F is proportional to that limit in power -1.5, that is we have: $N \sim F^{-1.5}$. The reason is simple: the sources that appear a factor f brighter are a factor $f^{-0.5}$ farther away, and therefore they are detectable in a volume that is a factor $f^{-1.5}$ larger, and hence they are more numerous by a factor $f^{-1.5}$. For this relation to hold, the statistical properties of distant sources should be the same as the statistical properties of nearby sources, and the average number of sources per unit volume should be constant. This relation is observed to be approximately satisfied by the bright stars as well as by the bright galaxies, even though the nature of the two types of objects, as well as their distances, are very different.

The best statistics of bright gamma-ray bursts is provided by the instrument PVO – Pioneer Venus Orbiter, which was collecting information for 13 years, and registered over 200 strong bursts (Fenimore et al. 1992). The distribution of these bursts is well approximated with the relation $N \sim F^{-1.4}$, indicating that the sources of apparently strong, and presumably relatively nearby bursts, have a uniform number density out to some distance. The most sensitive instrument to date is BATSE, roughly 30 times more sensitive than PVO. The distribution of BATSE bursts may be approximated with the relation $N \sim F^{-0.8}$ (Meegan 1992), indicating that the number of apparently weak, and presumably distant bursts is relatively small, as if there were fewer of them at large distances, or if the space at some large distance was no longer Euclidean. The results from instruments with the sensitivity intermediate between PVO and BATSE is intermediate (Tamblyn & Melia 1993). In fact, when the PVO and BATSE bursts are combined, a gradual transition from a slope close to -1.5 on the bright end to -0.8 at the faint end becomes apparent (Fenimore et al. 1993). It appears that the results from all instruments provide a consistent view: the relatively nearby bursts are approximately uniformly distributed with distance, but beyond some distance the number density of bursters decreases, or the space becomes non-Euclidean.

It is very important to consider the two results together: the isotropic distribution in the sky with the apparent shortage of weak bursts in all directions. The conclusion is: we appear to be at the center, or near the center of a spherically symmetric and bounded distribution of gamma-ray bursters.

Another very important feature of a gamma-ray burst is its spectrum. The spectra are very broad, covering many decades of photon energies, extending in extreme cases to photons as soft as 1 keV, and in some cases to photons as hard as 18 GeV (Hurley et al. 1994). A typical spectrum may be approximated with a broken power law (Schaefer et al. 1992, 1994), and it is so broad that there is no doubt it is non-thermal. I think there is a consensus on this issue.

It is important to note that while it is relatively easy to make a model of a nearly thermal stellar spectrum, regardless of whether the star is radiating mostly in the infrared (like M-type giants and dwarfs), in the optical (as our sun), in the ultraviolet (as O-type stars), or even in the X-rays (as X-ray bursts). A thermal model is uniquely described with its temperature, and a few other well defined parameters. The situation is very different for any class of astronomical objects which have clearly non-thermal spectra, like quasars, radio pulsars, or gamma-ray bursts. There is no unique way to model such a spectrum and there is no consensus among the researchers which of the many models of any of the non-thermal sources is correct. Invariably, the models invoke free parameters and a lot of more or less ad hoc assumptions. While the quantitative models of thermal or nearly thermal sources may even be useful in estimating their distances, nothing of this sort is possible for any of the sources which have non-thermal spectra – the diversity of non-thermal models is limited only by the imagination of theoreticians who study them. I know of no example of a model of a non-thermal source to be successfully used to deduce its distance. Therefore, my conclusion is that currently there is no known way to use the observed spectra to deduce the distance to gamma-ray bursts.

But not everything is lost. Sometimes a spectrum can be used to deduce the distance even if we have no idea how the spectrum was formed: we just use the source as a light bulb, and the fact that it can be seen may be used for the distance estimate. The trick is that the matter between the source and the observer may absorb photons of some energy. For example, interstellar gas is very opaque to the ultraviolet and soft X-rays (cf. Paczyński 1991), while TeV photons cannot travel very far through the intergalactic radiation field (cf. Stecker et al. 1992). If the spectrum of a source located near the plane of our galaxy is found to extend into sub-keV domain than the source must be closer than about 1 kiloparsec from us (well within our galaxy), as otherwise the interstellar gas would prevent the soft photons from reaching us. If the spectrum is seen to extend above 1 TeV then the source cannot be at a distance larger than about 500 Megaparsecs as the intergalactic infrared radiation prevents super TeV photons from reaching us from a larger distance. It is possible that in the future such effects may help us to estimate the distances to gamma-ray bursters.

The bursts show a tremendous variety of intensity variation, the time structure and duration (cf. Fishman et al. 1994). In the past, the rapid time variability was thought to provide some limit on the distance to the sources. This is no longer so. It is well established that if the source expands ultra relativistically then the observed variability is compatible with any distance (Zdziarski et al. 1991). And there are at least two reasons to expect ultra-relativistic expansion of gamma-ray bursters located either in the galactic corona or at cosmological distances. First, at either distance scale, the luminosities are highly super-Eddington with the powerful radiation pressure driving relativistic expansion. Second, the observed spectra show no cut-off at the pair creation limit, implying the gamma-ray photons are streaming nearly radially from the "photosphere" out. This is equivalent to an ultra-relativistic flow.

It is my conclusion that at this time we have only one robust distance indicator for gamma-ray bursters: the apparently isotropic distribution of bursts in the sky combined with the evidence that the radial distribution is bounded at the same distance in all directions.

Following Hakkila et al. (1994) I shall use the term 'galactic corona' rather than 'galactic halo' for one of the currently popular distributions of gamma-ray bursters. The reason is that the required distribution is unlike any observed or theoretically proposed galactic halo. According to the most popular ideas of the galactic origin of the bursters they are related to the very high velocity neutron stars, which are claimed to have this novel type of distribution.

It is interesting to note that the two most popular distance scales are both extragalactic. The nearest galaxies, the Large and Small Magellanic Clouds, are at the distance of ~ 55 kiloparsecs. A few other galaxies are at about 100 kiloparsec. A typical coronal gamma-ray burst is believed to be at ~ 100 kiloparsecs, i.e. well into the intergalactic space. Of course, in the cosmological hypothesis the bursters are even farther away. The only justification to call the coronal distribution galactic rather than extragalactic is the origin of the bursters: in the coronal scenario they are thought to be ejected from our galaxy.

2. DISTANCE DETERMINATION IN ASTRONOMY

It is useful to recall how the distances are measured for various astronomical objects. This information can be found in any standard textbook. The simplest and the most direct method is the trigonometric parallax: a stellar position in the sky varies while the earth orbits the sun. With modern instruments stellar distance can be measured this way out to ~ 100 parsecs. This is a purely geometrical method.

A so called dynamical parallax is applicable to binaries for which spectroscopic orbits can be combined with the astrometric orbits. The geometry of orbital motion is measured in two ways, with spectroscopy and astrometry providing us with the linear and angular dimensions, respectively, and their ratio gives the distance to the binary.

Another purely geometrical method uses the apparent proper motions and radial velocities of a group of stars which cover a large area in the sky, like the Hyades cluster. A combination of the observed range of proper motions and radial velocities across the moving group allows the distance to be measured.

A purely geometrical method which works on a truly cosmological scale is based on gravitational lensing: the two images of a distant quasar are seen along the two different paths, and the light travel time is different along the two. If the brightness of the lensed quasar varies then the time lag between the observed variation of the two images is equal to the difference in the two path lengths divided by the speed of light. Other things being equal the time delay is proportional to the distance.

There are many simple but indirect geometrical methods known. If a new object appears to be associated with another, with a know distance, then the distance to the new source becomes known as well. An example is a BL Lac type object with a featureless spectrum observed to be at the center of a galaxy with a known redshift.

If a new source is found to be behind a known object then its distance must be larger. An example is another BL Lac object with the absorption lines in its spectrum observed to be at the same redshift as a galaxy which is seen in the same direction: the BL Lac object must be behind the galaxy.

A powerful method of distance determination is based on the observed distribution of sources – this is another purely geometrical approach, described in the next section.

The only physical method which works well deals with thermal sources which are optically thick, and therefore radiate like a black body, or like a somewhat distorted black body. The observed spectrum is used to estimate the surface temperature, and hence the surface brightness. The radial velocity variations in an eclipsing binary, or in a pulsating star, are used to measure the linear size of the star, and hence its area. The product of the area and the surface brightness is the intrinsic (absolute) stellar luminosity, while the apparent luminosity (the flux) can be measured directly. The ratio of the two is proportional to the square of distance. A popular techniques of this kind is known as Baade-Wesselink.

Many other methods exist, but they are usually related to those which have been described. However, no distance was ever reliably measured to any non-thermal source using any non-thermal models of its emission. Note, that gamma-ray bursts have very broad, non-thermal spectra. No clear association exists between the bursts and any other objects. Inspecting a long list of proven methods we find there is only one which is applicable to gamma-ray bursters: we have to use their observed distribution, as described in the following section.

3. DISTRIBUTIONS OF VARIOUS OBJECTS IN THE SKY

There are billions of stars, galaxies and other objects in the sky. There are hundreds of different types of objects known to astronomers. But there are only a few distinctly different types of distributions known. Almost every year a new class of objects is found. But a fundamentally new distribution has not been found in decades.

All objects known to exist in the inner solar system are strongly concentrated to the ecliptic: the orbits of all planets, asteroids, zodiacal dust, comets in the Kuiper belt. At larger distances, between our inner solar system and the closest stars, the only known objects are the comets in the Oort cloud. Their distribution is almost spherical, but not exactly: their shape is affected by the tidal disturbances of our galaxy (Clarke et al. 1994). If the bursts came from the Oort cloud, then we should have seen by now the effect of these tidal distortions in the sky distribution of the bursts, and we have not. The Oort cloud comets have yet another property that makes them unacceptable as candidates for gamma-ray bursts: their number density varies with the distance, and it is not uniform anywhere.

Once we get out of the solar system we encounter nearby stars, which are distributed more or less uniformly in space, apart from their tendency to 'cluster' in binaries and multiple systems. The distribution over the sky is almost isotropic, as shown in Fig. 1. Some apparent clustering is due to non-uniformity of the search procedure.

When the more distant stars are placed in the sky map their tendency to concentrate near the galactic plane becomes apparent: since Galileo we know that the Milky Way is made of stars. Among distant objects which are readily detected across the galaxy and which are related to stars of moderate mass are the planetary nebulae, the remnants of old red supergiants. A few thousand years ago the extended envelopes of those former supergiants flew away from their hosts at ~ 20 km/sec, and formed the ring like nebulae which are named "planetary". The ones older than a few thousand years expanded so much that they are too diffuse to see. The nuclei of the nebulae, former cores of red supergiants, are on their way to become white dwarfs. Planetary nebulae are very bright, and readily discovered out to large distances. Their concentration to the galactic plane demonstrates that they belong to the galaxy (cf. Figure 2).

What about the more violent, truly catastrophic stellar deaths known as supernova explosions? These blow huge bubbles in the surrounding interstellar medium forming nebulae known as supernova remnants. Their distribution in the sky is shown in Fig. 3, revealing a striking concentration toward the galactic plane.

There are also galactic halo objects in the astronomical inventory. The most extreme case of halo distribution known to date is offered by globular clusters. These are the oldest components of our galaxy, with nearly spherical distribution, reaching out to tens of kiloparsecs. Figure 4 shows their positions in the sky: a very strong concentration to the galactic center is striking. This is a general property of all known halo objects. Notice, that globular clusters are not distributed spherically around us, but they are almost spherically distributed around the galactic center. As we are 8 kiloparsecs away from the galactic center, we see them concentrated in that direction.

The more exotic objects, low mass X-ray binaries, show the same galactic pattern as shown in Fig. 5. These are neutron stars with solar type companions, and they clearly belong to our galaxy.

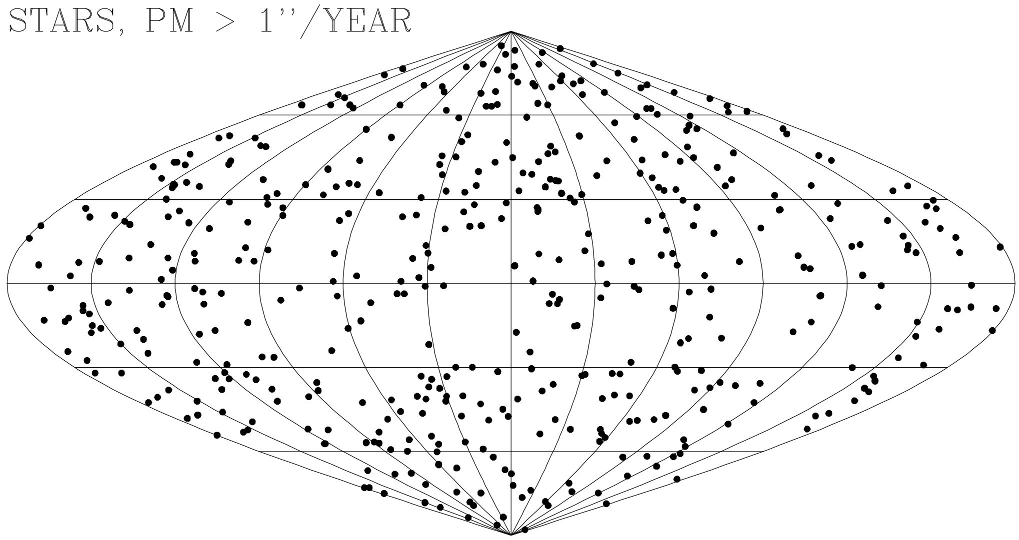

Fig. 1.— The distribution of the 528 nearby stars is shown in galactic coordinates. The data were obtained from the CDS in Strasbourg (I/87A) and it is based on W. J. Luyten (1976). These are stars with the proper motion in excess of one second of arc per year. The distribution is approximately isotropic and random. Some apparent clustering is due to non-uniform sky coverage of the search for the high proper motion stars.

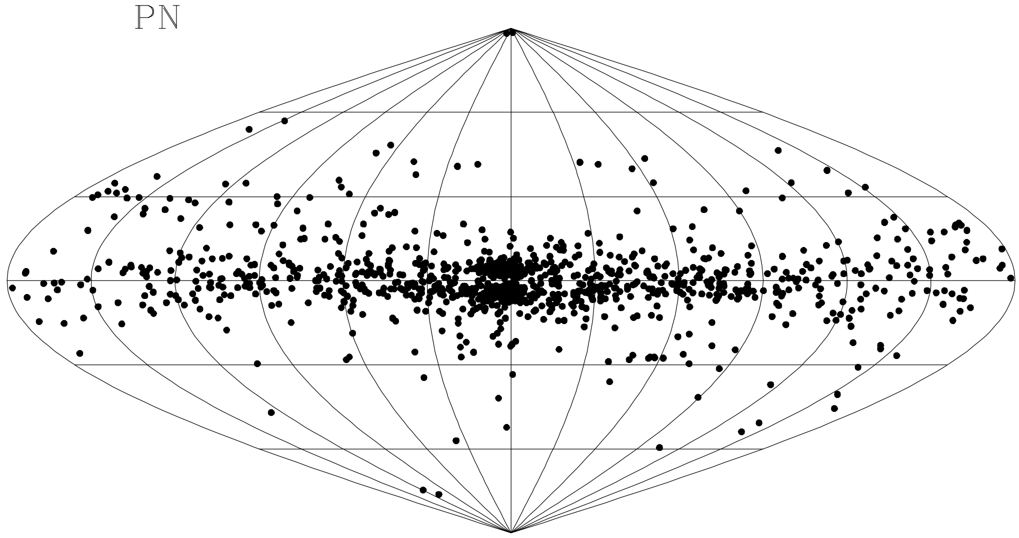

Fig. 2.— The distribution of the 1143 galactic planetary nebulae (PN) is shown in the galactic coordinates. The data was obtained from the CDS in Strasbourg (V/84) and it is based on A. Acker et al. (1992). Notice the strong concentration of objects toward the galactic plane, typical for the distribution of distant stars.

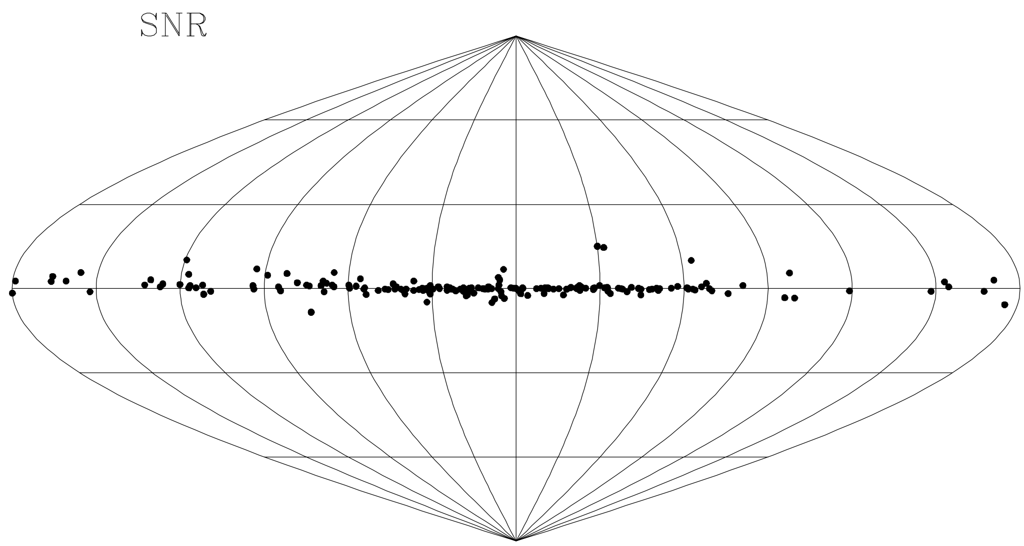

Fig. 3.— The distribution of the 182 galactic supernova remnants (SNR) is shown in galactic coordinates. The data were obtained from the CDS in Strasbourg (VII/163) and it is based on D. A. Green (1994). Notice the strong concentration toward the galactic plane of these galactic disk objects.

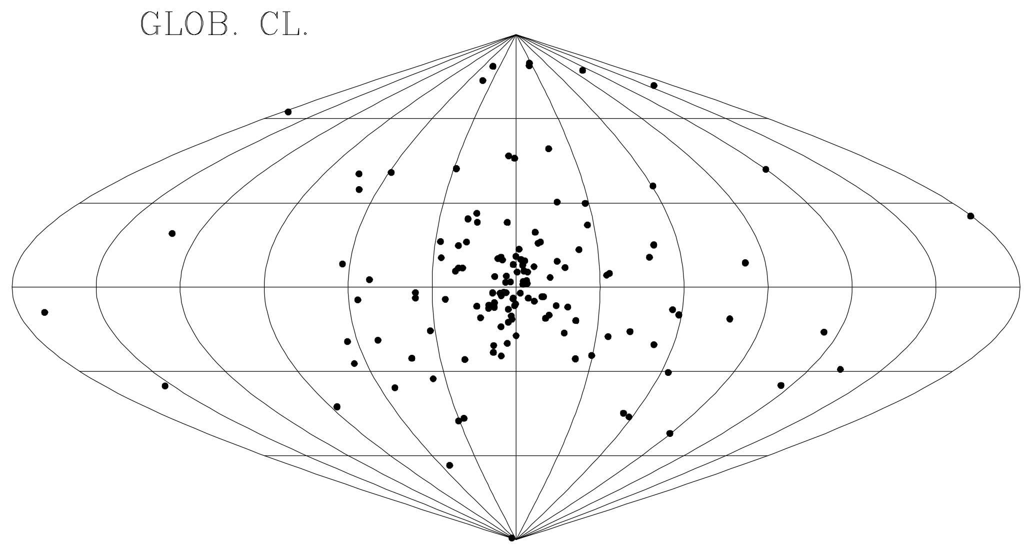

Fig. 4.— The distribution of the 160 galactic globular clusters (GLOB. CL.) is shown in the galactic coordinates. The data was obtained from the CDS in Strasbourg (VII/103) and it is based on R. Monella (1985). Notice the strong concentration toward the galactic center of these typical galactic halo objects.

All these galactic objects: low mass X-ray binaries, globular clusters, supernova remnants, planetary nebulae and stars, have been detected in the nearby galaxies. This is a general property of all known galactic objects: none of them is specific to our galaxy only, all of them are also found in other galaxies, provided they are luminous enough to be detectable.

The distribution of nearby galaxies is shown in Fig. 6. Their clustering is very strong. In fact, almost all nearby galaxies are members of the Virgo cluster. Looking farther out we find that the more distant galaxies are still clustered but their overall distribution becomes more and more uniform. However, no optical or infrared survey has been deep enough to demonstrate directly that the distribution becomes truly homogeneous and isotropic. This is possible with radio surveys which detect very luminous and very rare radio galaxies and quasars. Because of their enormous radio power these objects are detected at truly cosmological distances, and even the brightest sources show an isotropic and random distribution over the sky, as presented in Fig. 7. Also, a sky map of over 60,000 radio sources is available as a beautiful poster from the National Radio Astronomy Observatory, based on the observations done by Gregory & Condon (1991). The majority of radio sources is distributed isotropically and randomly over the sky, and their distances are cosmological. A subset of radio sources is strongly concentrated to the Milky Way, and these belong to our galaxy.

Let us summarize our findings. Among the many types of objects there are only two which satisfy the condition that they are random (not clustered) and isotropic: these are the distributions of the nearby stars and the very distant extragalactic objects. Any intermediate distance scale reveals either the galactic structure or the local signature of the large scale structure of the universe. No exception is known! Of course this is nothing new. This was pointed out many times in the past (cf. van den Berg 1983, Paczyński 1991, and references therein). Now we are ready to consider the distribution of gamma-ray bursts.

Prior to the launch of the Compton Gamma Ray Observatory it was already known that the gamma-ray bursts were distributed isotropically over the sky (Atteia et al. 1987). Their positions were measured using the interplanetary network of detectors. It was known that the isotropic and random distribution in the sky was compatible with only two distance scales at which other objects have been observed to have such distribution: one smaller than $\sim$ 200 parsecs, and the other one larger than $\sim$ 100 Megaparsecs, but nothing in between. The radial distribution of the bursters was expected to be uniform approximately out to the thickness of the galactic disk in the first case, and approximately out to the Hubble distance in the second case. These two vastly different distance scales could be readily distinguished if very weak, and therefore very distant bursts could be detected. In the galactic hypothesis the sources more distant than $\sim$ 200 parsecs were expected to be concentrated to the galactic plane, while in the cosmological hypothesis arbitrarily distant bursters were expected to remain isotropic.

What was known about the radial distribution of gamma-ray bursters in the pre-BATSE era? Initially there was a terrible confusion about the distribution of burst intensities. For some reason it was customary to present diagrams with the number of bursts as a function of so called

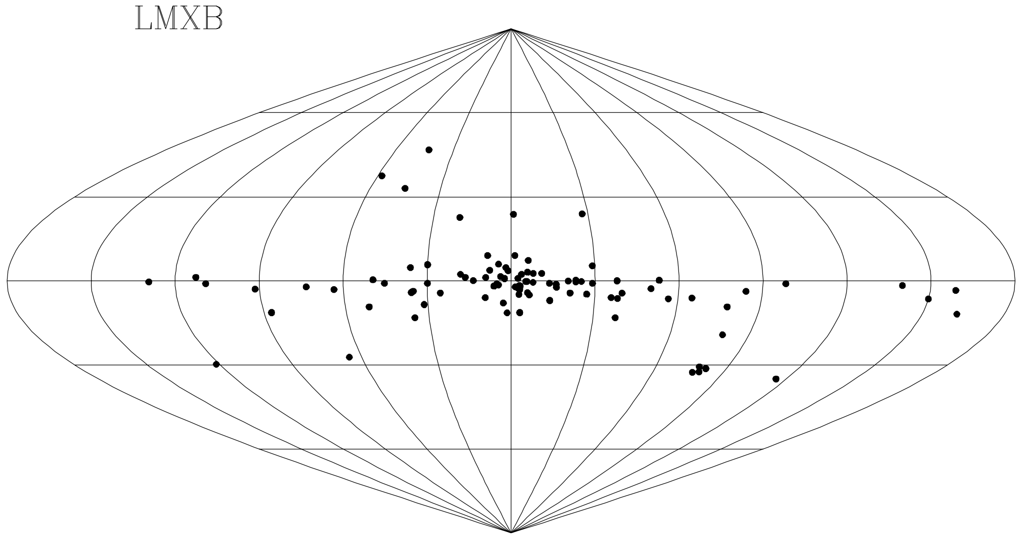

Fig. 5.— The distribution of the galactic low mass X-ray binaries (LMXB) is shown in galactic coordinates. The data were obtained from J. van Paradijs (1995). Notice the concentration toward the galactic center and toward the galactic plane.

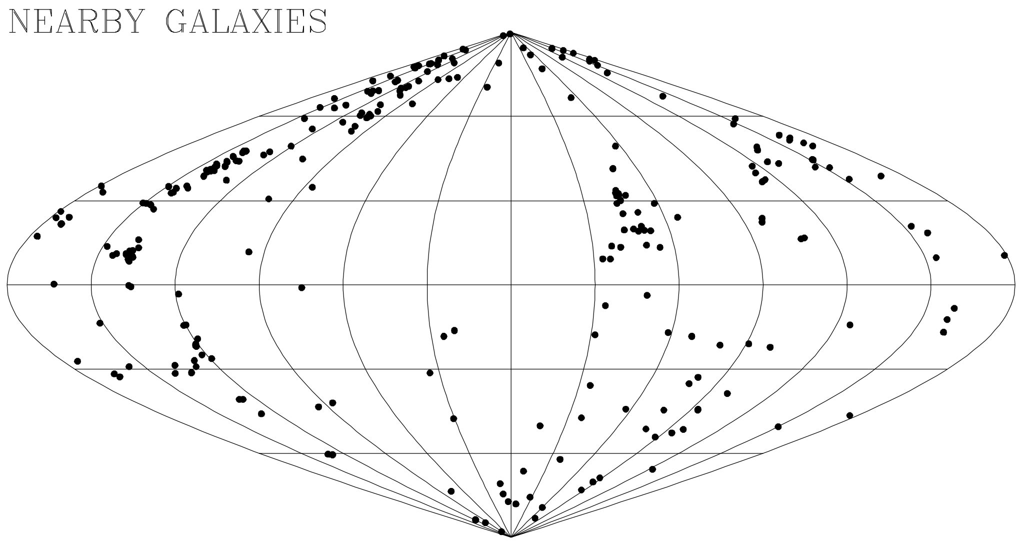

Fig. 6.— The distribution of the 276 nearby galaxies in shown in galactic coordinates. The data were obtained from the CDS in Strasbourg (VII/161) and it is based on K.-H. Schmidt, T. Boller, & A. Priebe (1993). Notice the highly irregular distribution concentrated on the nearby Virgo cluster.

"fluence", the total energy received from a given burst in all photons over the full duration of the burst. However, the bursts were detected not by measuring their fluence but rather by measuring the maximum count rate of photons in some restricted energy range. Therefore, fluence had very little to do with the burst detectability, and the distribution of the bursts according to their fluence should have never been used to make any inferences about the radial distribution of the bursters. Most unfortunately it was used for just this purpose during a whole decade. As very few bursts had low fluence it seemed that the observed distribution was bounded. One might think that this incorrect use of the observed fluence misled everybody to think that the bursters were at cosmological distances. Amazingly, only very few reached that conclusion, among them were Prilutskii & Usov (1975) and Paczyński (1986).

A few years ago a number of investigators realized that not the fluence but the peak photon count rate should be used to study the space distribution (Mazets 1986, Paczyński & Long 1988, Schmidt et al. 1988). Once the correct measure of burst intensities was adopted it became apparent that there was no clear evidence for the "edge" effect in the pre-BATSE data: the bursters were distributed uniformly not only over the whole sky but also in distance. Therefore, there was no way to choose which of the two distance scales was correct, galactic or cosmological. Nevertheless, the galactic origin was favored by almost everybody on the basis of models to be discussed in the next section of this paper.

It was expected that BATSE, with its very high sensitivity, should resolve the distance puzzle. Its huge detectors were tested in balloon flights during which ~ 60 events should have been detected if their distribution followed the $N \sim F^{-1.5}$ law. Instead only three were recorded (Meegan et al. 1985). It was clear that the new detectors were so sensitive that they reached the "edge" of burst distribution, but with only three events nothing could be said about the sky distribution. BATSE was designed to have not only very high sensitivity, but also to be able to locate the bursts with a precision of a few degrees. Therefore, it should be very easy for the BATSE to check if the weak bursts are concentrated to the galactic plane or are they isotropic, thereby definitely solving the puzzle of their distance. Or so it seemed.

On September 23, 1991 the first results about the sky distribution of weak bursts from the BATSE were presented at Annapolis, Maryland. Their sky distribution was isotropic, yet the distribution of intensities was approximately $N \sim F^{-0.8}$, a clear indication that the instrument could see beyond the region filled uniformly with the bursters (Meegan et al. 1992). At the instant the critical viewgraphs were shown, a large fraction of the audience accepted them as a clear evidence of the cosmological distance scale. Many participants of that historic conference changed their opinion because no concentration of the weak sources to the galactic plane was apparent in the BATSE data, even though it was expected by almost all of them. Nevertheless, some 50% of researchers have not changed their minds.

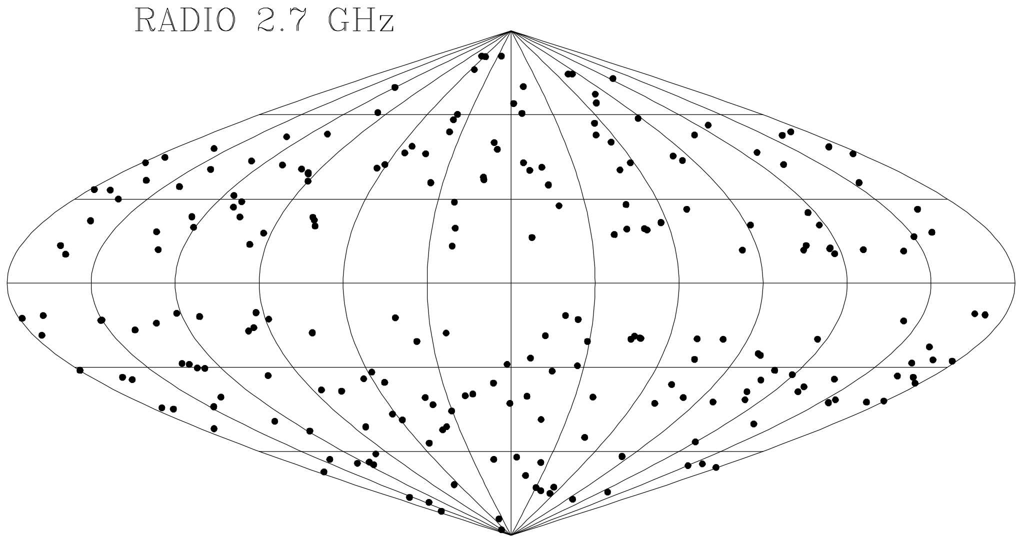

Fig. 7.— The distribution of the 233 strongest 2.7 GHz extragalactic radio sources in shown in galactic coordinates. The data were obtained from Wall & Peacock (1985). These sources are associated with very distant galaxies, and they are apparently distributed isotropically and randomly in the sky. Sources in the 'zone of avoidance' close to the galactic equator are not shown to avoid confusion with the large number of galactic sources.

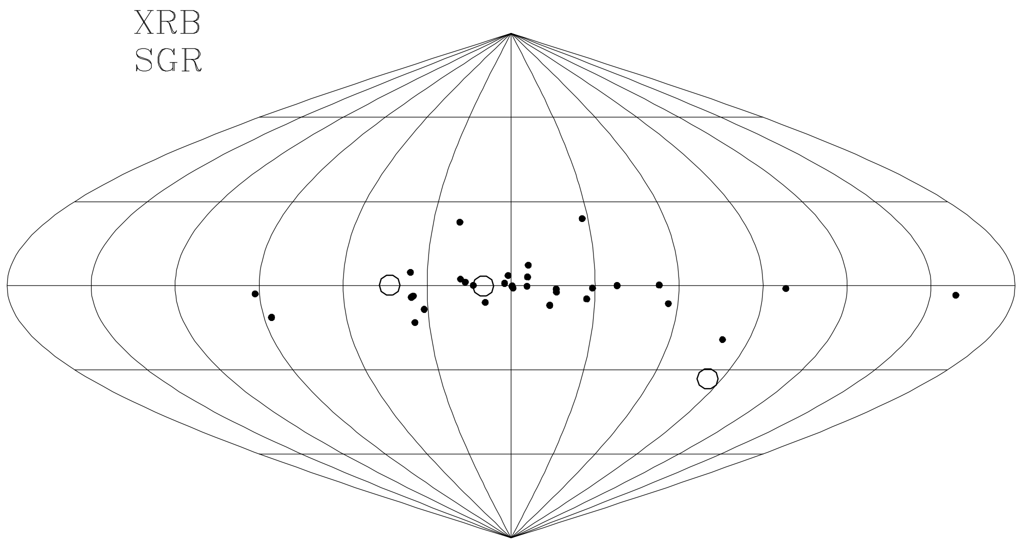

Fig. 8.— The distribution of the galactic X-ray bursters (XRB – filled circles) and the three known soft gamma repeaters (SGR – open circles) is shown in galactic coordinates. The data were obtained from J. van Paradijs (1995). Notice the strong concentration of sources toward the galactic plane and the galactic center.

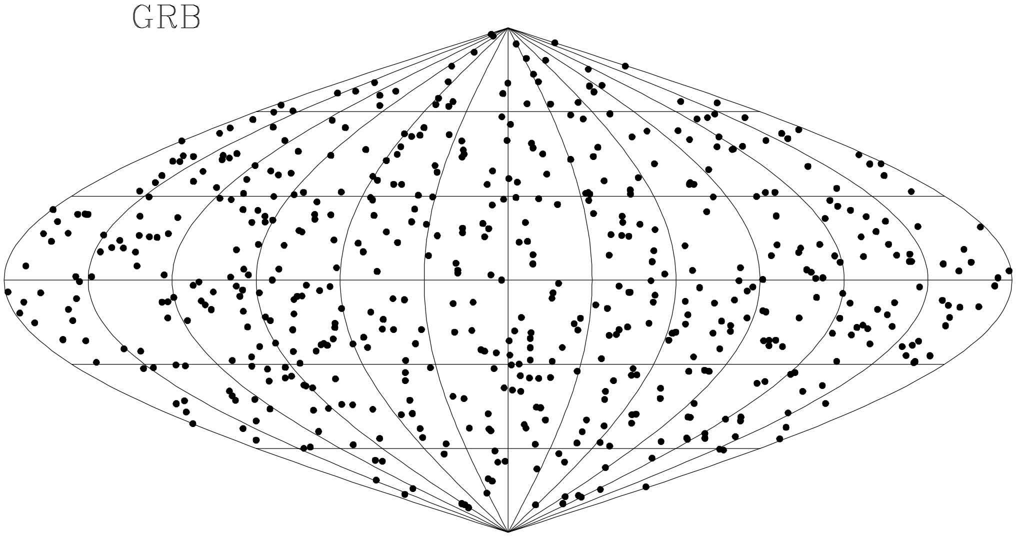

Fig. 9.— The distribution of the 585 gamma-ray bursts (GRB) from the second BATSE catalog in shown in galactic coordinates. The data were obtained from GRONEWS at Goddard Space Flight Center. Notice the random and isotropic distribution of sources over the sky.

4. THEORETICAL MODELS

When Ruderman (1975) presented his review of the newly discovered gamma-ray bursts at the Texas Symposium he noted there were more theories than the total number of bursts known at the time. This was a golden era for theorists: almost anything could be proposed. Ruderman noted that among all those speculations one was clearly missing: nobody had yet proposed that the bursts were caused by comets made of antimatter falling into white holes. Almost everything else was. In his recent reviews Nemiroff (1994a,b) compiled a list of over one hundred different theories. One does not have to know much about the subject to realize that if there is one correct theory of the bursts then all but one are wrong. One may continue this reasoning to note that if 99 out of 100 hundred published theories are wrong then most likely all 100 are wrong. In other words, the multitude of proposals is the weakness and not the strength of the field. All theories of gamma-ray bursts ever presented were speculative, yet, they served a useful purpose by exploring so many diverse possibilities.

Over the years people got tired with the original unrestricted freedom and a consensus emerged that gamma-ray bursts were some energetic phenomena on the surfaces of nearby neutron stars. There might have been a rational reason: the discovery of X-ray bursts which had some similarity to gamma-ray bursts. The story of X-ray bursts is one of the most spectacular success stories in modern astrophysics: a reasonable quantitative theory was developed within a year or two of their discovery, and it looks as good now as it did more than a decade ago (Joss &

Rappaport 1984). What made that success possible?

First, the sky distribution of X-ray bursts as shown in Fig. 8 instantly reveals their galactic origin and firmly sets their distance scale at about 8 kiloparsecs. Their spectra are thermal, very closely approximated by the Planck curve. The peak luminosity is $\sim 10^{38}$ ergs per second, while the peak temperature is $\sim 2 \times 10^7$ K. According to the last two numbers the radius of the source is ~ 10 kilometers. All this makes sense: 10 km is the radius of a neutron star, and 10^{38} erg/sec is the Eddington luminosity of a neutron star. A simple yet accurate model of a nuclear explosion followed. Also, the optical companion stars were found for many X-ray bursters. These companions provided the source of fresh nuclear fuel for the explosions.

The similarity between the X-ray bursts and the gamma-ray bursts is limited. Both have duration of the order of seconds. Both emit hard photons. So, one might relate them, at least initially. But then, there are mostly differences. The X-ray burst have thermal spectra that peak at about 6 keV. Gamma-ray bursts have very broad non-thermal spectra extending all the way from 1 keV to 10^7 keV. X-ray bursts show a clear concentration to the galactic center, while gamma-ray bursts have isotropic sky distribution, as shown in Fig. 9. All X-ray bursts have similar intensity variation: fast rise and exponential decay, with a simple correlation between the peak intensity and the burst duration, while there is nothing regular about the intensity variation of gamma-ray bursts. X-ray bursts are known to repeat, while gamma-ray bursts either do not repeat or repeat very rarely.

A fair analogy of the similarities and differences between X-ray and gamma-ray bursts is offered by the similarities and differences between the stars and quasars. The stars and the quasars are unresolved sources of optical radiation, and at least some stars and some quasars are variable. Yet the stars have thermal spectra and are concentrated to the galactic plane and the galactic center, while the quasars have very broad, mostly non-thermal spectra and are distributed isotropically over the sky. Quantitative stellar models exist, and there is not much controversy except for some details. The models of stellar atmospheres are very well described with just a few parameters, the most important being the effective temperature. At this time there are many competing models of quasar emission, none of them really quantitative. Even the geometry of quasar structure is not known, except for rather crude description in terms of the so called "unified models". It is generally believed that there are supermassive black holes at the centers of quasars, but no proof exists, and none is in sight. There is no agreement about the origin of quasars, how long they live, and how they die. Recently, it has been found that many of them are not at the centers of galaxies, as it was generally believed just a year ago (Bahcall et al. 1994, 1995).

It is interesting to analogize the star – quasar comparison with the X-ray burst – gamma-ray burst comparison. It is well established that X-ray bursters are ordinary neutron stars emitting thermal spectra with the effective temperature $\sim 2 \times 10^7$ K. It is equally well established that gamma-ray bursts, just like quasars, have very broad non-thermal spectra, and there is no direct evidence they have anything to do with any stars.

There are also three soft gamma repeaters known, and all three are associated with supernova remnants: two in our galaxy, and one in the Large Magellanic Cloud, as shown in Fig. 8 (cf. Kulkarni et al. 1994, Murakami et al. 1994, Vasisht et al. 1994, and references therein). These three objects were suggested to be neutron stars with ultra strong magnetic fields, in the range $10^{14} - 10^{15}$ gauss (Duncan & Thompson 1992). Their peak luminosity is $\sim 10^{42}$ ergs per second (Kouveliotou et al. 1987, and references therein). The spectra look almost thermal, with most energy radiated at $\sim$ 30 keV (Golenetskii et al. 1984, Paczyński 1992c, Fenimore et al. 1994), which is a factor $\sim$ 5 higher than the peak of thermal spectra of X-ray bursts, and completely different than the broad non-thermal spectra of gamma-ray bursts, which extend to GeV energies (Hurley et al. 1994, and references therein). The soft gamma repeaters are super-Eddington events, $\sim 10^3$ times more luminous than X-ray bursts. The relation to gamma-ray bursts is unclear. A possible link is provided by the unique March 5, 1979 event (GB790305b) which is related to the repeater SGR 0526-66 in the Large Magellanic Cloud, and which had a peak luminosity in excess of 10^{45} ergs per second (Mazets et al. 1982, Fenimore et al. 1995, and references therein).

As their name implies the soft gamma repeaters repeat. Their intensity variations are very simple: a rapid rise followed by a rapid decline, with no large fluctuations. Their spectra, their intensity variations, their repetition and their sky distribution make them somewhat similar to X-ray bursts, but very different from gamma-ray bursts.

The discovery of X-ray bursts contributed to the popularity of the galactic neutron star hypothesis for gamma-ray bursts, but very soon the latter acquired the life of its own. At any particular time some types of models were fashionable. A few years later the old models were out of fashion, and some new models would be popular. There were common ingredients to most of them: magnetized neutron stars and some source of free energy that was to be released very rapidly. There were starquakes and comets falling onto the surface, phase transition deep under the surface, and nuggets of quark matter. And no consensus ever emerged as to the actual source of energy, or the physical process responsible for the observed emission.

Some spectral features in some bursts were interpreted as cyclotron lines or annihilation lines (Higdon & Lingenfelter 1990, and references therein). There was a lot of excitement when double lines were reported by the GINGA experiment (cf. Murakami et al 1992): two or three gamma-ray bursts had absorption lines at 20 keV and at 40 keV present for a small fraction of the burst's duration. These were interpreted as the fundamental and the first harmonic cyclotron lines in a field of 2×10^{12} gauss. Sophisticated models were developed to explain the lines in terms of neutron stars located at a distance $\sim$ 100 parsecs, just right for the popular paradigm.

There was also a modest variety of models developed in the past for gamma-ray bursters at cosmological distances, i.e. at $\sim$ 1 Gigaparsec (cf. Higdon & Lingenfelter 1990, Paczyński 1991, 1992, and references therein), and there were even more of those developed following BATSE's discovery of isotropy and inhomogeneity of the distribution (cf. Mészáros et al. 1994, and references therein). Perhaps the colliding neutron stars became the most popular cosmological model. Their main virtue was that they helped many researchers to overcome their prejudice against the cosmological distance scale, but it remains to be seen if they have any relation to the real bursters. I cannot stress more strongly that the validity of the colliding neutron star scenario has nothing to do with the distance scale – if it turns out to be irrelevant for gamma-ray bursters the case for cosmological distance scale will not be affected at all.

A possibility that gamma-ray bursters may be in the extended galactic corona was proposed many times in the past (Fishman et al. 1978, Jennings & White 1980, Jennings 1992, Shklovski & Mitrofanov 1985, Atteia & Hurley 1986). The popularity of the corona was intermediate between the galactic disk and cosmology, pretty much as the distance involved was also intermediate. Until recently no serious attempts were made to build physical models for the corona. Today, those who like the galactic origin relate gamma-ray bursters in the extended corona to the very high velocity neutron stars ejected from the galactic disk (Duncan & Thompson 1992, Li & Dermer 1992, Podsiadlowski et al. 1995). In this scenario the bursters are thought to be at the distance ~ 100 kiloparsecs.

More work was done on models bursting in the galactic disk, i.e. at ~ 100 parsecs, than on all other models combined. However, this distance scale is no longer considered acceptable. Next in number are cosmological models at ~ 1 Gigaparsec. Finally, there are the galactic corona models at ~ 100 kiloparsecs. The relevance, or rather irrelevance of all these models to the determination of the distance scale to real gamma-ray bursters will be discussed in the next section.

5. DISCUSSION

Following the BATSE's discovery the old galactic disk paradigm was practically eliminated as it was in a direct conflict with the observed distribution. The two competing distance scales emerged: one was the galactic corona and the other was cosmological. The nature of the arguments leading to these two possibilities was (and still is) very different.

There is no evidence in the BATSE (or any other) data which would point to the galactic corona as the site of gamma-ray bursters. The proposed distribution is unprecedented in that there is no other observed population of sources in that region. It requires the bursters to have constant space density out to a distance of at least 30 kiloparsecs away from the center, so that our 8 kiloparsec offset from the center would not be noticed. A typical burster is now supposed to be at ~ 100 kiloparsecs, a factor of 1,000 farther away than in the old galactic disk paradigm, and therefore it has to be $\sim 10^6$ times as luminous. All models ever developed for the disk paradigm are useless, including the models that so nicely explained the spectral lines reported by the GINGA team. The main problem faced with all coronal models is the need to explain their distribution, or more precisely how gamma-ray bursters come to be in an area where nothing else is. It is paradoxical that the galactic distribution proposed for the bursters is designed so as to erase any trace of the galactic origin in the observed distribution.

Ever since the extended corona was first proposed as the site for gamma-ray bursters the emphasis was on the radial extent and sphericity, hence the popularity of the very high velocity neutron stars which can go out as far as we please. But the really difficult problem with the coronal idea is not its outer extent, but the size of its inner core, the region over which the number density of the bursters has to be uniform, independent of location (Paczyński 1991, Hakkila et al. 1994, and references therein). In order not to see our 8 kiloparsec offset from the galactic center that core must be at least 30 kiloparsec in radius. In spite of the many papers written about the coronal models I am not aware of a satisfactory explanation of the extent of this uniform density region. The observed isotropy of the strong bursts (Atteia et al. 1987) combined with the observed radial uniformity of the PVO bursts (Fenimore et al. 1992, 1993, and references therein) demands that there is a region around us which has a constant number density of gamma-ray bursters. If that region is in our galaxy it must be at least 60 kiloparsecs in diameter. This is the most serious problem faced by any galactic corona model.

The nature of the problem is twofold. First, there is nothing else observed to have so extended constant density volume. Second, the galactic mass is concentrated to its center and this makes it very difficult, perhaps impossible, to design a theoretical distribution which could be made and kept uniform within such a big sphere.

The observed distribution is automatically satisfied if we adopt cosmological distance scale: all objects detectable at cosmological distances are distributed isotropically in the sky, and the number density of all of them appears to decrease at sufficiently large distances as a consequence of the redshift. The uniform density region in almost any cosmological scenario is a few Gigaparsec in extent. The observed distribution is the most important argument for the cosmological distance scale to gamma-ray bursters.

There are plenty of models, or rather very schematic scenarios for either distance scale. As the sources are clearly non-thermal the diversity of models is limited only by the skill and imagination of theoreticians. This is not a unique situation. To the contrary: this is a typical situation. It is pretty much the same with all other non-thermal sources, like radio pulsars or quasars, even though we know the distance to those objects. Once we have to abandon the constraints of thermal equilibrium and feel free to add magnetic fields, turbulence, relativistic particles, and other "high energy" ingredients, it is next to impossible to come up with a unique and highly quantitative description of what is going on. This is not to say that we should not try to invent new non-thermal models. In the process we find a large variety of interesting possibilities, and perhaps at some point we shall find a testable model which will turn out to be correct. I do not expect this to happen as long as we do not know for sure how far away the bursters are, and therefore we do not know what the energy requirements are. I am not aware of a single case in the history of astrophysics in which a distance to any non-thermal source was reliably established using any non-thermal emission models. Unfortunately, even when the distance is known it is still difficult or impossible to decide which non-thermal model is correct.

The distribution of radio pulsars in the sky, as well as the effect of the interstellar medium on the propagation of pulsar emission, revealed their distance almost instantly. Yet, we still do not have a quantitative model for their radio and gamma-ray emission. The distance to quasars was found when their emission line spectra revealed their redshifts, and some of them were found at the centers of galaxies. However, even though there is no longer a significant dispute over their distance, we still do not have a quantitative model of their non-thermal emission which extends from long wave radio to GeV gamma-rays. Of course there are plenty of models of radio pulsar and quasar emission, but none of them is generally accepted, and no consensus is in sight after three decades of hard work.

Perhaps the most devastating argument against using models to determine the distance scale is the history of gamma-ray bursts. As far as I can see the galactic disk origin with its distance scale of ~ 100 parsecs has been practically abandoned in spite of the fact that most theoreticians used to be convinced it was correct. More models were developed, and more theoretical papers were written for the distance of ~ 100 parsecs, than for all other distances combined. Yet, those models developed over almost two decades had to be abandoned because of the BATSE observations. In spite of so many very diverse possibilities no bursts were convincingly found to be at ~ 100 parsecs. I do not think the quality of models developed for the distance of ~ 100 kiloparsecs or ~ 1 Gigaparsec is any higher than was the quality of the disk models: none is nearly good enough to be really trusted. I am not aware of any reason why the physics of the new models is superior to the physics of the old models. My conclusion is that the models of gamma-ray bursters as currently available are useless for distance determination. Each model is designed to work at some particular distance, be it 100 parsecs, 100 kiloparsecs, or 1 Gigaparsec. In fact there are many competing models for every possible distance. Even when the distance is finally established by model independent means we still shall not know which model, if any, is correct, as is still the case for quasars.

How can one determine the distance if one does not know what it is that one tries to determine the distance to? In fact, this is how astronomy usually works. The stars were known for millenia and they were used for variety of purposes, from navigation to astrology, while nobody knew what they were, or even how far away they were. About 150 years ago the distance to the first star, 61 Cygni, was measured using the Earth's motion around the sun (Bessel 1838). Gradually, not only many stars had their distances measured, but also the size of the Galaxy was estimated. Still, it was not known what makes the stars shine, and no quantitative stellar models existed. Finally, some 60 years ago the energy of the stars was explained in terms of thermonuclear reactions and the first quantitative stellar models were built, often refining the distance.

When a new class of objects is discovered it is a standard procedure to estimate the distance from the observed distribution. It is always clear that if the sources are concentrated to the galactic plane or the galactic center then their distances must not be very different from a kiloparsec. If the distribution is isotropic then they must be either very close, at ~ 100 parsecs, or very far, more than ~ 100 Megaparsecs away. Often new types of objects, or even a diffuse background which may not be resolved into sources, are separated into galactic and extragalactic components on the basis of their sky distribution. The same procedure can be applied to gamma-ray bursts. And the verdict is: the distance scale seems to be cosmological. Has this been proven? Certainly not. Gamma-ray bursts are so enigmatic that in fact they may be a manifestation of an entirely unknown phenomenon, they may be events on an unknown and unprecedented type of objects, with a new and unprecedented distribution in space. We must have a truly firm determination of their distance before we may hope to understand what they are and how they burst.

What can be done to to prove the distance scale? Some steps have already been taken. The cosmological distance scale is suggested by the fact that the observed distribution is not only isotropic but also appears to be bounded. The latter effect comes about because the distant sources are supposed to be redshifted. If they are redshifted we should look for additional observational consequences, of which at least two are promising. First, the redshift affects not only the wavelength of every photon but also the apparent duration of every burst (Paczyński 1992, Piran 1992). Second, the spectra are not strict power laws, they are somewhat curved. Therefore, a redshifted spectrum should appear somewhat softer (Paczyński 1992). The time dilation effect was apparent in some correlations, but the possibility of the redshift interpretation was not noticed for a while (Kouveliotou et al. 1992, Paciesas et al 1992). Recently, both effects were reported to be present in the data (Lestrade et al 1992, Norris et al. 1994, 1995, Nemiroff et al. 1994, Wijers & Paczyński 1994) at approximately 4 σ level. Some doubts remain (Mitrofanov et al. 1994, Band 1994b, Fenimore & Bloom 1994) and it will take some time until the consensus is reached on the presence or absence of the effect, and on its interpretation. At this time the case for the presence of the cosmological redshift effect in the weak BATSE bursts looks promising, but it is not proven yet. The case for cosmological redshift will be stronger when the two methods, the time dilation and the spectral softening, are shown to agree.

What about a variety of arguments advanced against the cosmological distance scale? Let me list some of the more common. The lines reported by the GINGA experiment, and previously claimed by the KONUS as well as some other experiments, are a common objection to the cosmological distances. I think the reality of the lines is far from proven. Only two fully algorithmic searches were done for the lines: one for the SMM data (Messina & Share 1992), the other for the BATSE data (Palmer et al. 1994), and no line was found in either of the searches. All lines ever claimed were found using subjective human judgement, and at best a posteriori statistical analysis was performed.

Let us suppose the lines turn out to be real. There is no unique way to interpret them. For example, at least three papers were written pointing to gravitational femtolensing as a possible cause if the bursters are at cosmological distances (Gould 1992, Stanek et al. 1993, Ulmer & Goodman 1995). This explanation was never pushed very hard because the confidence in the reality of the lines is not very high. Why spend time explaining something which may not exist? In any case, the only models explaining the lines in terms of cyclotron absorption required the bursters to be at $\sim$ 100 parsecs (cf. Lamb 1992, and references therein). None of those models can be adapted to work at either galactic corona or cosmological distance scales, as the bursting material is expected to expand relativistically in either of those two cases. If the lines are proven to exist a new explanation and new models have to be developed for any of the two distance scales currently under consideration. The lines, even if they exist, will not resolve the galactic corona vs cosmology controversy.

Huge energies required by cosmological gamma-ray bursts are often pointed out as a problem. This argument was often used in the past against the extragalactic distance to M31 and the cosmological distance to quasars. A term “supernova” was even invented many decades ago to ridicule the possibility that a stellar explosion observed in M31 as S Andromedae might be as powerful as required by the supposedly extragalactic origin. Today we know that supernovae are indeed very powerful, that M31 is another galaxy, outside of our own, and cosmological distances to the quasars are no longer seriously disputed.

I think it might be useful to point out that in astronomy “large” is not less plausible than “small”. In fact, many types of objects and events are known to be possible only if they are “astronomically large”. For example, it is well established that thermonuclear burning of hydrogen may be sustained in a self-gravitating object only if its mass is larger than $\sim 10^{32}$ grams. The only known neutrino bursts, those from supernovae, are on a scale of $\sim 3 \times 10^{53}$ ergs, all released within ~ 10 seconds. Everything we know in our universe is very low on energy compared with the Big Bang. Incidentally, the term “Big Bang” was also invented to ridicule the concept. Therefore, the energetics of gamma-ray bursts is not a distance indicator and cannot be used against them being at cosmological distances.

The repetition is well established for the X-ray bursts and for the soft gamma repeaters (all three of them) but it is a controversial issue for gamma-ray bursts (cf. Band 1994a, and references therein). The repetition, if established, will be very important for the understanding of gamma-ray bursts, but it has no relation to the distance scale as long as we do not know what the gamma-ray bursters really are. For example, Ostriker (1992) thinks the bursters are at cosmological distances and he expects them to repeat.

A common feature of all anti-cosmological arguments is that all of them are model dependent. The author(s) always have some specific model in mind when a claim is made that the model could not possibly give rise to a burst at a distance of a few Gigaparsecs. And usually the argument is correct, but only for that particular model, or for a particular set of models. There never was a proof that no model could possibly produce a burst at any specific distance scale. Also, there never was a model that could quantitatively demonstrate that it must produce a burst. Notice, that even though so many sophisticated models were developed for the distance scale of ~ 100 parsecs, we have no observational evidence that there are any events of the type described with those models. My conclusion is: we have to admit we do not know what gamma-ray bursters are and we do not know what makes them burst. Therefore, if we want to determine their distance we must use a model independent method. And this is perfectly normal: this is how distances are established in astronomy.

There is a complication with the cosmological distance scale which should be mentioned here. All types of objects observed at cosmological distances, quasars, galaxies, and clusters of galaxies, are known to evolve: their typical luminosity and their number density observed at large redshifts are different than local. The population of gamma-ray bursters may also evolve. If there were no bursters in the early universe, then the observed distribution appears bounded because there are no bursters at large distances, and not because the redshift made the distant bursters very dim, and pushed them below the detection threshold. In this case the weakest BATSE events could be relatively nearby, and their redshifts may be too small to measure. What is interpreted as a redshift might instead be a consequence of evolution. This is a rather ugly possibility, but unfortunately it cannot be ruled out as long as we do not understand gamma-ray bursters. The case for cosmological redshift will be stronger when the time dilation and the spectral softening are found to be consistent with each other.

6. CONCLUSIONS

There is a strong evidence that gamma-ray bursters are at the cosmological distances, but there is no rigorous proof yet. The most important question we can ask at this time is: how can one distance scale or another be proven? Note, that all types of objects known to exist in our galaxy are always found in other galaxies as soon as the detectors are sensitive enough to uncover those objects at extragalactic distances. Therefore, we may have full confidence that if the known gamma-ray bursts are associated with our galaxy there should also be gamma-ray bursts associated with M31, which is the nearest giant spiral, pretty much like our own (Atteia & Hurley 1986). This issue cannot be resolved by the BATSE, at least not yet (Hakkila et al. 1994), but a new experiment with ~ 10 times BATSE's sensitivity should resolve the issue (Harrison et al. 1994). If a concentration of very weak bursts towards M31 is detected we shall have to accept the fact that the BATSE bursters are in the corona of our Galaxy, establishing a new type of a distribution of astronomical objects. If no signature of M31 is found we shall have to accept the cosmological origin of the bursts. I hope that all participants of this debate agree with my assessment of the decisive role of the experiment aimed at M31. Note, that extending the observed luminosity function of gamma-ray bursts to the level 10 below the current BATSE limit is almost certain to be interesting in its own right: if the bursters are in the galactic corona we shall find where the corona is truncated; if they are cosmological we shall find them at larger redshifts and they may turn out to be useful for cosmology.

The current situation may be summarized as follows:

1. We do not know what gamma-ray bursters are or what makes them burst.
2. We have strong evidence that gamma-ray bursts are at cosmological distances.
3. We have no evidence for any other distance scale.

4. We have no evidence against cosmological distance scale.

5. We do not have a proof that the bursters are at cosmological distance.

6. An experiment ~ 10 times more sensitive than BATSE will definitely determine the distance scale by comparing the number of the weakest bursts towards M31 with the number in any other direction.

7. An experiment providing ~ 1 arc second positions would greatly improve the likelihood that counterparts of gamma-ray bursters are finally detected. This may be a critical step towards the determination of the nature of the bursters. A new interplanetary network would offer the best opportunity to achieve this goal.

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