THE DISTANCE SCALE TO GAMMA-RAY BURSTS

D. Q. Lamb

Department of Astronomy and Astrophysics, and Enrico Fermi Institute
University of Chicago, Chicago, IL 60637

ABSTRACT

We do not yet know the distance scale to gamma-ray bursts. Here I summarize observational results and theoretical calculations which provide evidence about the distance scale. First, I describe the recent discovery that many neutron stars have high enough velocities to escape from the Milky Way. These high velocity neutron stars form a distant, previously unknown Galactic "corona." This distant corona is isotropic when viewed from Earth, and consequently, the population of neutron stars in it can easily explain the angular and brightness distributions of the BATSE bursts. If this were all of the evidence that we considered, quite frankly, we could not distinguish between the cosmological and Galactic hypotheses. I contend that we can go further, by considering other important pieces of evidence.

I draw attention to the many similarities between soft gamma-ray repeaters, which are known to be high velocity neutron stars, and gamma-ray bursts. I point out that the source of the famous 1979 March 5 event, which is a high velocity neutron star 50 kpc away from us, demonstrates that high velocity neutron stars are capable of producing bursts which have the energy, the duration, and the spectrum of gamma-ray bursts. Finally, I comment that high velocity neutron stars in a distant Galactic corona can account for cyclotron lines and repeating, and naturally explain the absence of bright optical counterparts in gamma-ray burst error boxes, whereas all of these present major difficulties for cosmological models.

I conclude that when we consider all of the evidence, it adds up to a strong case for the Galactic hypothesis.

I. INTRODUCTION

Gamma-ray bursts continue to confound astrophysicists nearly a quarter century after their discovery (Klebesadel, Strong, and Olson 1973). Despite intense study by observers and theorists alike, no one knows for sure what they are, where they come from, or even whether or not they are a single phenomenon.

There are many reasons for this. The bursts occur at largely random times and come from largely random directions. We know their positions on the sky only approximately. They are a non-thermal phenomenon that exhibits a great diversity of time histories and a wide range of characteristic spectral energies. Furthermore, we know no quiescent counterparts of the bursts at radio, infrared, optical, ultraviolet, X-ray, or gamma-ray energies, and thus study of the bursts is isolated from the rest of astronomy and astrophysics. As a result, astronomers have been unable to bring the power of ground-based and space-based telescopes to bear on the questions of their nature and the distance scale to them. At present, those who study gamma-ray bursts have only the laws of physics and the properties of the bursts themselves to guide them.

II. THE CURRENT DEBATE

Before the launch of CGRO, most scientists thought that gamma-ray bursts came from magnetic neutron stars residing in a thick disk in the Milky Way (see, e.g., Higdon and Lingenfelter 1990, Harding 1991). Upper limits to the rate of faint bursts (e.g., Fishman et al. 1979) already implied that the cumulative brightness distribution of gamma-ray bursts must roll over at the faint end. Since a uniform distribution of sources in space requires that the brightness distribution of the bursts follow a power law with -3/2 slope, the rollover meant that gamma-ray bursts must be inhomogeneously distributed in space. Most scientists expected that BATSE would find that the sky distribution of faint bursts is concentrated in the Galactic plane, and would thus confirm that the burst sources lie in a Galactic disk roughly 2 kpc thick.

Instead, the data gathered by BATSE confirmed the existence of a rollover in the cumulative brightness distribution of gamma-ray bursts but showed that the sky distribution of the faint bursts is consistent with isotropy (see Figure 1) (Meegan et al. 1992, Briggs et al. 1995). The rollover in the cumulative brightness distribution and the isotropic sky distribution imply that we are at, or near, the center of the spatial distribution of burst sources and that the intrinsic brightness and/or spatial density of the sources decreases with increasing distance from us. Therefore the bursts cannot come from the Galactic disk.

While an origin for the bursts in the Oort Cloud of comets that exists around the solar system is not ruled out, this model suffers from a lack of any appealing physical mechanism and the likelihood that the Oort Cloud is not highly spherical. Consequently, the primary impact of the BATSE results was to intensify debate about whether the bursts are Galactic or cosmological in origin.

There is no overwhelming piece of evidence, no "smoking gun," which proves that the bursts are Galactic or cosmological. That is why we are having this commemorative debate. As is so often the case at the frontier of science, and as it was in the original "Great Debate," the evidence is circumstantial, even contradictory. Yet in the scientific process, each piece of evidence is weighed. Some pieces are given more weight, others less. And different scientists may give different weights to the same piece of evidence. But eventually, through the process of weighing-up the evidence, scientists reach a conclusion.

Paczyński (1995) focuses on the isotropic sky distribution of gamma-ray bursts. He describes the impact of the announcement that the sky distribution of the faint bursts is consistent with isotropy on him and on some others when it was made by the BATSE team in September 1991 (Meegan et al. 1992). The isotropy of the bursts on the sky is an important piece of evidence. The cosmological hypothesis is consistent with it. But the Galactic hypothesis is also consistent with it (see Figure 2). If this were all of the evidence that we considered, quite frankly we could not distinguish between the cosmological and

Galactic hypotheses. I contend that we can go further, by considering other important pieces of evidence, some of them very new. Indeed, since September 1991 many unexpected and important pieces of evidence have been discovered which bear strongly on the question of the distance scale to gamma-ray bursts. Of course the conclusion is not yet clear. But when we consider all of the evidence, I think you will see that it adds up to a strong case for the Galactic hypothesis.

The particular Galactic model that many scientists are now studying is motivated by the discovery that many neutron stars are born with such high velocities that they escape from the Galaxy (see Figure 3). These neutron stars form a distant, previously unknown Galactic "corona". This distant corona contains an ample population of sources which appear isotropic when viewed from Earth, and can therefore easily account for the angular and brightness distributions of the BATSE bursts. The soft gamma-ray burster phenomenon shows that high velocity neutron stars can produce burst-like behavior. Indeed, the famous 1979 March 5 event shows that high velocity neutron stars can produce an event which has the energy, duration, and spectrum of a gamma-ray burst. The Galactic corona model has the attractive feature that it naturally accounts for the many similarities between gamma-ray bursters and soft gamma-ray repeaters, which we know are high velocity neutron stars. In addition, the model easily explains the rapid time variability of many bursts, cyclotron lines, repeating, and the lack of bright optical counterparts.

On the other hand, the cosmological models that many scientists are studying, such as coalescing neutron star binaries and failed supernovae, face severe difficulties in explaining cyclotron lines, repeating, the lack of bright galaxies in the error boxes of bright bursts, and even the energies of the bursts.

Let us now pick up the story of the Galactic hypothesis with the discovery that many neutron stars have very high velocities.

III. HIGH VELOCITY NEUTRON STARS

Only a few years ago scientists thought that neutron stars had velocities of 100 - 200 km s^{-1} (see, e.g., Lyne, Anderson, and Salter 1982). But recent studies show (Lyne & Lorimer 1994; Frail, Goss, & Whiteoak 1994) that as much as 50% of neutron stars have velocities $v > 800$ km s^{-1}. These velocities are so high that these neutron stars escape from the Galaxy and produce a distant, previously unknown Galactic "corona."

The evidence that many neutron stars have high velocities comes from two independent directions. In the first case, long-wavelength radio observations have discovered that many young radio pulsars are associated with young ($t_{\rm age} < 10^4$ yrs) supernova remnants (Frail, Kassim, and Weiler 1994; Frail, Goss, and Whiteoak 1994). Sometimes the young pulsar lies within the shell-like supernova remnant; sometimes it is passing through the shell, as the spectacular radio image of the "duck" supernova remnant and pulsar PSR1757-24 reveals (see Figure 4); and sometimes the young pulsar is associated only with a comet-like "plerion," or filled remnant. In every case the pulsar lies far from the center of the remnant. These offsets imply median transverse velocities ~ 500 km s^{-1}, with $\sim 1/3$ of the neutron stars having transverse velocities > 1000 km s^{-1} (see Figure 5) (Frail, Goss, and Whiteoak 1994). Optical observations of bow shocks have also shown that some older pulsars have transverse velocities > 800 km s^{-1} (see, e.g., Cordes, Romani, and Lundgren 1993).

In the second case, a new model for the electron density in the Milky Way and a greater understanding of an important observational bias that affects the determination of pulsar velocities has dramatically increased the velocities inferred for older pulsars. The new electron density model shows that the distance to, and therefore the transverse velocity of, nearby pulsars was underestimated by about a factor of two in previous models. The observational bias that affects the determination of pulsar velocities arises because young radio pulsars are born close to the Galactic plane, and move rapidly away from it if their velocity is high. After some time, the pulsars that remain within detectable range are mostly those with small velocities. The strength of the bias is illustrated by the fact that the mean of the distribution of transverse velocities is 345 ± 70 km s^{-1} for pulsars with spindown ages $\tau < 3$ Myr, whereas it is 105 ± 25 km s^{-1} for pulsars with $\tau \gtrsim 70$ Myr.

Recent studies that incorporate these discoveries yield median neutron star total velocities $\langle v \rangle_{\rm median} \sim 600$ km s^{-1}, with as many as half of all neutron stars having velocities $v > 800$ km s^{-1} (Lyne and Lorimer 1994; Chernoff 1995).

These results have revolutionized our understanding of the spatial distribution of neutron stars. Since the escape velocity from the Galaxy is ≈ 600 km s^{-1} in the Galactic bulge, where most neutron stars are born, and ≈ 500 km s^{-1} in the solar neighborhood, all of these high velocity neutron stars will escape from the Milky Way. They form a distant, previously unknown "corona" around the Milky Way (see Figure 6). This distant corona contains an ample population of sources which appear isotropic when viewed from the Earth.

IV. THE GALACTIC CORONA

Paczyński (1995) gives the impression that prior to BATSE there was a firm consensus that gamma-ray bursts came from magnetic neutron stars in a thick Galactic disk. While a Galactic disk population was the most conservative and perhaps the most popular model (Higdon and Lingenfelter 1990, Harding 1991), extended halo populations have also had a long and illustrious history (see, e.g., Fishman 1978, Jennings and White 1980, Jennings 1994, Shklovski and Mitrofanov 1985, Atteia and Hurley 1986). What did exist was a consensus that gamma-ray bursts come from magnetic neutron stars in the Galaxy. There were many reasons for this, which I describe below.

Following the discovery by BATSE that the faint bursts are distributed isotropically on the sky, Galactic halo and corona models found new favor (see, e.g., Brainerd 1992, Li and Dermer 1992, Smith and Lamb 1993) as an attractive way of reconciling all of the evidence about gamma-ray bursts which favors Galactic neutron stars with isotropy. However, these models were considered somewhat ad hoc, particularly by advocates of cosmological models.

Consequently, the debate about whether the bursts are Galactic or cosmological in origin was characterized as one between those who advocated objects which we know produce burst-like phenomena (high velocity neutron stars; see below) but which were not known to have the necessary spatial distribution (extended Galactic halo) *vs.* those who advocated objects which we do not know can produce burst-like phenomena (e.g., failed supernovae and coalescing neutron star binaries) but were known to have the necessary spatial distribution (cosmological).

The subsequent discovery that many neutron stars have velocities high enough to escape from the Milky Way and form a Galactic "corona" has given these models a tremendous boost. Detailed dynamical calculations of the motions of high velocity neutron stars moving in the gravitational potential produced by the bulge, disk, and dark matter halo of the Galaxy show that a distant corona of high velocity neutron stars can easily account for the isotropic angular distribution and the brightness distribution of gamma-ray bursts (Li and Dermer 1992; Li, Duncan, and Thompson 1994; Podsiadlowski, Rees, and Ruderman 1995; Bulik and Lamb 1995).

This is illustrated in Figures 7 and 8, which show the sky distribution and the brightness distribution for a typical set of parameter values (e.g., neutron star velocity $v = 1000$ km s^{-1}, onset of the burst-active phase at a neutron star age $\delta t = 30$ Myr and lasting $\Delta t = 500$ Myr; the BATSE sampling distance $d_{\max} = 200$ kpc).

In high-velocity neutron star models, the slope of the cumulative peak flux distribution for the brightest BATSE bursts and the PVO bursts reflects the space density of the relatively small fraction of burst sources in the vicinity of the Sun ($d \lesssim 50$ kpc). Therefore any spread in neutron star kick velocities, neutron star ages at which bursting behavior begins, the rate of bursting as a function of age, or the burst luminosity function tends to produce a peak flux distribution to -3/2, the value expected for a uniform spatial distribution of sources which emit bursts that are "standard candles." Figure 9 shows that a spread of less than a factor of 10 in the luminosity function, which is consistent with everything we know about gamma-ray bursts, is sufficient to produce agreement with not only the BATSE, but also the PVO, brightness distribution of bursts (Bulik and Lamb 1995). Beaming along the direction of motion of the neutron star can also reproduce both brightness distributions (Li, Duncan, and Thompson 1994).

The Galactic corona model predicts subtle anisotropies as a function of burst brightness, which are a signature of the model and may offer a means of verifying or rejecting it (Li, Duncan, and Thompson 1994; Podsiadlowski, Rees, and Ruderman 1995; Bulik and Lamb 1995). There is tantalizing evidence that such anisotropies exist (Quashnock and Lamb 1993; Lamb and Quashnock 1994), but these need confirmation using larger, self-consistent data sets.

It has often been stated that Andromeda, a bright galaxy similar to our own Milky Way and lying only 700 kpc away, imposes a severe constraint on extended halo models (Hakkila et al. 1994; Hartmann 1994). This is true, however, only if one assumes that the burst sources are distributed like the dark matter in the halo and that the dark matter halo extends to arbitrarily large distances (Smith and Lamb 1993, Smith 1995). However, we know that the dark matter halo can actually extend only 1/3 - 1/2 the distance to Andromeda because of tidal disruption.

A similar statement has been thought to be true for corona models because in such models Andromeda must produce its own "wind" of high velocity neutron stars. Some of these will travel toward us, and when they produce gamma-ray bursts, BATSE should detect them.

However, Andromeda imposes no constraint if the bursts are beamed along the direction of motion of the neutron star, as some models posit (Li and Dermer 1992; Li, Duncan, and Thompson 1994). Then only the rare neutron star whose motion is almost directly toward us would be visible to BATSE. The few resulting bursts from Andromeda would always be swamped by bursts from the many high velocity neutron stars born in the Milky

Way and moving away from us.

Even if the bursts radiate isotropically in all directions, detailed dynamical calculations of the motion of neutron stars in the combined gravitational potential of the Milky Way and Andromeda show that an excess of bursts toward Andromeda is not detected until one samples distances $d_{\rm max} \sim 500$ kpc from Earth (see Figure 10) (Podsiadlowski, Rees, and Ruderman 1995; Bulik, Coppi, and Lamb 1995). Thus there is ample parameter space (BATSE sampling distances $d_{\rm max} \approx 100 - 500$ kpc) for a population of sources in the Galactic corona.

A larger sample of BATSE bursts or a more sensitive instrument might reveal an excess of bursts toward Andromeda. If so, this would constitute definitive evidence that the bursts are Galactic in origin. However, if no excess were detected it could be due to beaming of the bursts along the direction of motion of the neutron star and therefore could not be taken as definitive evidence that the bursts are cosmological in origin.

Where do we stand in weighing-up of evidence so far? Clearly, the cosmological and Galactic hypotheses are both consistent with the sky distribution and the brightness distribution of the BATSE bursts. Quite frankly, the two hypothesis are indistinguishable in this respect. Therefore we have to appeal to other evidence.

V. SOFT GAMMA-RAY REPEATERS

We have seen that a Galactic corona of high velocity neutron stars can easily account for the BATSE sky distribution and brightness distribution of gamma-ray bursts. Is there any evidence that high velocity neutron stars can produce burst-like behavior?

Yes, there is. Soft gamma-ray repeaters produce high energy transients whose durations overlap with those of gamma-ray bursts (see Figure 11), and whose characteristic spectral energies form a continuum with those of gamma-ray bursts (see Figure 12). The main distinction between soft gamma-ray repeaters and gamma-ray bursters is that the former have been clearly shown to repeat on time scales of days to years (Mazets et al. 1979, Laros et al. 1987, Atteia et al. 1987), whereas the latter have been thought not to repeat. But recently, a number of scientists have found strong evidence that gamma-ray bursters also repeat (Quashnock and Lamb 1993b, 1994; Wang and Lingenfelter 1993, 1995; Strohmayer, Fenimore, and Mirales 1994; Quashnock 1995). I will discuss the evidence for gamma-ray burst repeating in §IX.

Three soft gamma-ray repeaters are known. Two lie in the Galactic disk at distances of 10's of kpc (SGRs 1806-20 and 1900+14); the third lies in in the Large Magellanic Cloud in the halo of the Milky Way at a distance of 50 kpc. All three are associated with young supernova remnants (Evans et al. 1980, Kulkarni and Frail 1993, Kouveliotou et al. 1994, Murakami et al. 1994, Hurley et al. 1994). In two cases, the soft gamma-ray repeater lies far away from the center of the supernova remnant, implying a neutron star velocity of ~ 1000 km s^{-1} (Evans et al. 1980, Hurley et al. 1994). Clearly, high velocity neutron stars can produce burst-like behavior.

If gamma-ray bursts come from high velocity neutron stars in a distant Galactic corona, there are additional similarities between gamma-ray bursts and soft gamma-ray repeaters. Both have luminosities $L \sim 10^{41} - 10^{43}$ erg s^{-1}. Both also appear to have strong magnetic fields, as we discuss below. These similarities and the ones we discussed above suggest a physical or evolutionary relationship between soft gamma-ray repeaters and gamma-ray bursts. The unification of these two phenomena is a very attractive feature of the Galactic hypothesis.

VI. THE FAMOUS 1979 MARCH 5 GAMMA-RAY TRANSIENT

We have seen that high velocity neutron stars can produce burst-like behavior. Have high velocity neutron stars ever been seen to produce an event that looks like gamma-ray bursts? The answer is,"yes." The event is the famous 1979 March 5 gamma-ray transient, which I now discuss.

The source of this famous event is SGR 0526-66, which lies in in the Large Magellanic

Cloud in the halo of the Milky Way at a distance of 50 kpc. It is associated with the young supernova remnant N49 (Evans et al. 1980, Rothschild, Kulkarni, and Lingenfelter 1994) (see Figure 13). SGR 0526-66 lies far away from the center of the supernova remnant, implying a velocity greater than 1200 km s^{-1}.

Seventeen bursts have been observed from this source (Mazets et al. 1979, Golenetskii et al. 1984). The distribution of the durations of these bursts overlaps completely with that of gamma-ray bursts (see Figure 14). Let's take a look at the longest of these, the famous 1979 March 5 event itself.

Figure 15 shows the time history of the March 5th event. The burst had an intense spike which lasted ~ 0.2 s, followed by ~ 200 s of emission which exhibited an 8 s periodicity (Mazets et al 1979). The association with the supernova remnant N49 and the 8 s periodicity leave little doubt that this object is a neutron star. The existence of pulsations implies a strong magnetic field. The spectrum of the emission following the intense spike had a characteristic spectral energy $\langle E \rangle \approx 40$ keV, typical of soft gamma-ray repeater bursts.

What about the spectrum of the intense spike? Although nine different satellites observed the March 5th event (Evans et al. 1980), the intensity of the spike produced so-called "dead-time" and "pulse pike-up" effects which precluded reliable analyses of the spectrum. Recently, Fenimore et al. (1995) used the power of present-day computers to unravel these effects in the ICE and PVO instruments. They succeeded in accurately determining the spectrum of the spike. The answer? The spectrum of the spike looks just like that of a gamma-ray burst! The spike has a characteristic spectral energy ≈ 200 keV, with no soft component (see Figure 16).

Whether the 1979 March 5 event is a gamma-ray burst or a unique event can be argued either way. But in either case, it demonstrates that distant high velocity neutron stars in the Galactic halo can produce events which have the energy, the spectrum, and the duration of gamma-ray bursts. This evidence weighs heavily on the side of the Galactic hypothesis.

VII. CYCLOTRON LINES

Almost fifteen years ago Mazets et al. (1981, 1982) reported seeing single lines in the spectra of gamma-ray bursts at low energies ($E \lesssim 70$ keV). Later Heuter (1988) reported single lines at low energies in the spectra of two bursts seen by HEAO-1 A4. However, the statistical significance of the lines was modest.

More recently, equally-spaced lines were seen by *Ginga* in the spectra of three bursts (Murakami et al. 1988, Fenimore et al. 1988, Graziani et al. 1992, Yoshida et al. 1992) with high significance (Fenimore et al. 1988; Graziani et al. 1992a,b, 1993; Freeman et al. 1995a,b). Figure 17 shows the lines seen in two of the bursts. The line features in these three bursts have been studied extensively, and there is no doubt that they exist.

Lines have not been definitively seen by BATSE (Palmer et al. 1994), but this fact does not strongly contradict earlier observations (Teegarden et al. 1993, Fenimore et al. 1993, Band et al. 1994).

Similar line features are seen in the spectra of accretion-powered pulsars, which are known to be magnetic neutron stars (se Figure 18). The equally-spaced lines seen in gamma-ray bursts and accretion-powered pulsars are easily explained in terms of cyclotron resonant scattering in a strong magnetic field (Makashima and Mihara 1992).

Magnetic neutron stars in the Galactic corona appear able to produce cyclotron lines even though the luminosities of the bursts greatly exceed the so-called Eddington luminosity at which radiation pressure and gravity balance. Cyclotron lines may form, for example, in a relativistic wind flowing out from the magnetic poles of the neutron star (Miller et al. 1991), or at magnetic equator where hot plasma is trapped by magnetic field (Lamb 1982; Katz 1982, 1994).

In contrast, producing cyclotron lines is a difficult problem for cosmological models. While no quantitative calculations have been done, the violent release of $\sim 10^{52}$ ergs of energy which is required to power cosmological bursts would seem to preclude the formation of cyclotron lines lasting tens of seconds. "Femtolensing" has been proposed (Stanek, Paczyński, and Goodman 1993, Ulmer and Goodman 1994) but requires a very small source whereas gamma-ray burst emission at cosmological distances requires a large source.

Thus the existence of cyclotron lines is weighty evidence favoring the Galactic hypothesis.

VIII. REPEATING

Recently, a number of scientists have found significant evidence that gamma-ray bursts repeat on time scales of days to months (Quashnock and Lamb 1993, 1994; Wang and Lingenfelter 1993, 1995; Strohmayer, Fenimore, and Mirales 1994; Quashnock 1995). Such behavior is similar to the behavior of soft gamma-ray repeaters, as we described earlier.

Repeating sources appear as clusters of bursts on the sky because the positions of the bursts are known only to about 7° (see Figure 19). The evidence for repeating has come from nearest-neighbor (Quashnock and Lamb 1993, 1994) and angular-temporal correlation (Wang and Lingenfelter 1993, 1995) analyses of the first BATSE catalog, and a model comparison study using the same catalog (Strohmayer, Fenimore, and Mirales 1994). Brainerd et al. (1994) investigated numerous possible systematic effects and concluded that the results of these groups is not due to instrumental effects.

Studies of the second BATSE catalog have not confirmed repeating (Brainerd et al 1995; Meegan et al. 1995; Quashnock 1995) but this is expected given the limitations in the second BATSE catalog due to the failure of the tape recorders on board the Compton Observatory (Wang and Lingenfelter 1995; Quashnock 1995; Quashnock and Lamb 1995). A likelihood analysis of the first and second BATSE catalogs, in fact, shows that the odds favoring repeating is as large in the second catalog as in the first, showing that inclusion of the second year of data (which was badly affected by loss of the tape recorders) neither strengthens nor weakens the evidence in favor of repeating. NASA and the BATSE team have worked hard to surmount the difficulties stemming from the loss of the tape recorders, and it is expected that the third BATSE catalog will provide a true test of the repeating hypothesis.

Repeating is naturally expected, even required, in high velocity neutron star models of gamma-ray bursts, since the total number of neutron stars in the Galactic corona implies that each must burst 10^4 times or more in its lifetime in order to account for the number of bursts seen per year (Podsiadlowski, Rees, and Ruderman 1995; Lamb, Bulik, and Coppi 1995).

In contrast, cosmological models face severe difficulties in accounting for repeating. The amount of energy needed to power the bursts is so large that in the most widely studied models, such as coalescing neutron stars and failed supernova, it requires the destruction of the source.

Hence, repeating clearly favors the Galactic hypothesis; but we will assign it only modest weight, pending confirmation of it using the data in the third BATSE catalog.

IX. ORPHANS

Several studies report that the durations of faint bursts and the widths of their peaks are factor of two longer than for bright bursts (Norris et al. 1994; Davis et al. 1994; Fenimore et al. 1995b). However, Mitrofanov et al. (1993, 1994) find no difference in the widths of the peaks of faint and bright bursts.

The reported time stretching of a factor of two has been interpreted as due to cosmological time dilation. However, the difference is not uniquely a signature of cosmological time dilation, and therefore of a cosmological origin for the bursts. The difference can be intrinsic to the bursts, be due to correlations among other burst properties, or arise from the inhomogeneous spatial distribution of sources.

Moreover, when the spectral energy dependence of the peak width is carefully taken into account, the reported time stretching of a factor of two requires that the burst sources lie at a redshift $z \approx 6$, if one attributes the difference to cosmological time dilation (see Figure 20) (Fenimore and Bloom 1995). The bursts would then originate before the first generation of stars or galaxies; in other words, they would be "orphans." Furthermore, consistency with the observed brightness distribution of bursts and an origin at $z \approx 6$ requires strong source evolution; then the -3/2 slope of the brightness distribution of bright bursts is coincidental. It is then no longer evidence that the spatial distribution of nearby sources is uniform, and that nearby space is Euclidean.

Alternatively, the sources could lie at redshifts $z = 0.1 - 1$, but then at least 70% of the reported difference in the widths of the peaks of faint and bright bursts must be intrinsic to the burst. This raises the question: if 70%, then why not all? This is a particularly relevant question, given we know that more intense spikes are narrower than less intense spikes within individual bursts.

Consequently, the reported time stretching is neither evidence for nor against the cosmological or Galactic hypotheses.

X. THE LACK OF BRIGHT OPTICAL COUNTERPARTS

Using the time-of-flight of gamma-ray bursts across the solar system, the Interplanetary Network of burst detectors has derived accurate locations for a number of bright bursts (see, e.g., Hack et al. 1994). Optical searches of these error boxes often show no bright object within them (Schaefer 1992, 1994). As examples, I show in Figures 21 and 22 the Interplanetary Network error boxes for GB790406 and GB791116. The brightest object in the first error box is 24.7 magnitudes in B (Motch et al. 1985), while the brightest object in the second error box is 21 magnitudes in B and R (Schaefer 1992).

The lack of bright optical counterparts for these bright bursts is easily explained if gamma-ray bursts come from high velocity neutron stars in the Galactic corona, since source distances of 100 - 500 kpc and the small surface area of neutron stars imply extremely faint emission in quiescence.

In contrast, the lack of bright optical "host" galaxies in the Interplanetary Network error boxes of bright bursts is poses a severe difficulty for cosmological models. The gamma-ray burst brightness distribution implies that these bright bursts lie nearby, at redshifts $z \approx 0.1 - 0.2$; any bright galaxy in the error box should be easily visible. Their absence rules out cosmological models involving either active galactic nuclei or a normal population of galaxies (Schaefer 1992, 1994; Woods and Loeb 1995). It is even questionable that the rate of gamma-ray bursts can be proportional to the amount of blue light (Woods and Loeb 1995). This is a problem for the most popular cosmological models, which involve the coalescence of neutron star binaries (Paczyński 1986, Goodman 1986; Eichler et al. 1989; Narayan, Piran, and Shemi 1991; Paczyński 1991; Piran, Narayan, and Shemi 1992; Narayan, Paczyński, and Piran 1992; Piran 1994) and failed supernovae, since in them the burst rate would be expected to be proportional to the amount of blue light (Paczyński 1992).

Thus the lack of bright optical counterparts strongly favors the Galactic hypothesis.

XI. FUTURE PROSPECTS

The study of gamma-ray bursts and soft gamma-ray repeaters is advancing rapidly, as the many recent discoveries discussed by Fishman (1995), Paczyński (1995), and myself make clear. However, as I stated in the Introduction, there are many reasons why the answer to the question of the distance scale to gamma-ray bursts still eludes us. Below I mention several key observations that might help answer the question.

Sky distribution. Our ability to detect or place upper limits on any anisotropies in the burst sky distribution, especially as a function of burst brightness, will increase slowly but steadily as BATSE detects more bursts. Confirmation of significant Galactic dipole and/or quadrupole moments as a function of burst brightness, or overall, would provide definitive evidence that the bursts are Galactic. Further limits on any angular anisotropy will constrain, and might rule out, the Galactic hypothesis. However, the limits that BATSE will be able to achieve are not likely to be definitive, since the angular distribution of bursts from the distant Galactic corona can be very isotropic.

Detection of a concentration of bursts toward Andromeda, either by BATSE, by lengthy (> 20 days) X-ray (2-10 keV) observations using imaging X-ray telescopes (Yoshida, Ogasaka, and Murakami 1994), or a scintillation counter experiment with > 10 times the BATSE sensitivity would provide definitive evidence in favor of the Galactic hypothesis. However, the absence of any concentration toward Andromeda could not be taken by itself as definitive evidence against the Galactic hypothesis, since the bursts might well be beamed along the direction of motion of the neutron stars (Li, Duncan, and Thompson 1994). Then only the rare neutron star whose motion is almost directly toward us would be visible to BATSE. The few resulting bursts from Andromeda would always be swamped by bursts from the many high velocity neutron stars born in the Milky Way and moving away from us.

Cyclotron lines. Other spectroscopy instruments will soon be flown (e.g., TGRS on Wind, Konus on Wind, HETE, Konus on Spectrum X-Gamma, etc.) which will search for lines. Further confirmation of the existence of cyclotron lines would provide strong evidence in favor of the Galactic hypothesis.

Repeating. The new bursts in the third BATSE catalog are not expected to suffer from the same limitations which afflicted bursts in the second year of observations due to failure of the tape recorders on-board tape recorders. It is therefore expected that the third BATSE catalogue will provide a fair test of repeating hypothesis.

Counterparts. If quiescent counterparts were found, they would likely provide the most immediate and powerful information about the distance scale to gamma-ray bursts. But the chance of finding counterparts is unclear, particularly if the bursts come from distant high velocity neutron stars in the Galactic corona. The BATSE GROCSE network is providing approximate positions of bursts in real-time for ground-based searches.

HETE will provide more accurate (few arcsecond to few arcminute) positions in real-time for ground-based searches. Missions have been proposed (e.g., BASIS and ETA) which would produce 1" burst positions; these missions would definitively answer the question of repeating and determine whether or not the bursts have visible counterparts at other wavelengths.

Serendipitous discovery. The discovery of gamma-ray bursts was serendipitous and many of the most important advances in the field have come from unexpected discoveries. Thus, if history is any guide, the distance scale to gamma-ray bursts will most likely be established through some entirely unexpected or serendipitous discovery.

XIII. CONCLUSION

I have summarized observational results and theoretical calculations which provide evidence about the distance scale. First, I described the recent discovery that many neutron stars have high enough velocities to escape from the Milky Way. These high velocity neutron stars form a distant, previously unknown Galactic "corona." This distant corona is isotropic when viewed from Earth, and consequently, the population of neutron stars in it can easily explain the angular and brightness distributions of the BATSE bursts. If this were all of the evidence that we considered we could not distinguish between the cosmological and Galactic hypotheses. I contended that we can go further, by considering other important pieces of evidence.

I drew attention to the many similarities between soft gamma-ray repeaters, which are known to be high velocity neutron stars, and gamma-ray bursts. I pointed out that the source of the famous 1979 March 5 event, which is a high velocity neutron star 50 kpc away from us, demonstrates that high velocity neutron stars are capable of producing bursts which have the energy, the duration, and the spectrum of gamma-ray bursts. Finally, I commented that high velocity neutron stars in a distant Galactic corona can account for cyclotron lines and repeating, and naturally explain the absence of bright optical counterparts in gamma-ray burst error boxes, whereas all of these present major difficulties for cosmological models.

I conclude that when we consider all of the evidence, it adds up to a strong case for the Galactic hypothesis (see Table 1).

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TABLE 1

Comparison of evidence for ($\surd$) and against ( ) the cosmological and Galactic hypotheses.

EVIDENCE	COSMOLOGICAL	GALACTIC
Isotropy and Brightness Distribution	$\surd$	$\surd$
Similarities of SGRs & GRBs		$\surd$
Famous 1979 March 5 Event		$\surd$
Cyclotron Lines		$\surd$
Repeating		$\surd$
Time Stretching	—	—
No Bright Optical Counterparts		$\surd$

FIGURE CAPTIONS

Figure 1. Sky map of the first 1005 gamma-ray bursts observed by BATSE. Of these, 485 are from the second BATSE catalog and have positional uncertainties of about 7°. The remainder have preliminary positions or are affected by gaps in the telemetry stream, and have more uncertain positions. (From Briggs et al. 1995.)

Figure 2. Sky map of 1005 bursts from a Galactic corona of high velocity neutron stars. This map demonstrates that a non-cosmological population of objects can also account for the BATSE sky distribution of gamma-ray bursts. (After Bulik and Lamb 1995.)

Figure 3. Side view of the Milky Way. The Galactic bulge and disk are clearly visible; the dark lane along the plane of the Galaxy is the result of dust. Also shown are the Sun, the globular clusters which surround the Galactic disk, and the trajectories of high velocity neutron stars which are escaping from the Milky Way. These high velocity neutron stars form a previously unknown Galactic "corona." The corona contains an ample population of neutron stars which appears isotropic when viewed from Earth. Many scientists believe that this population of distant neutron stars is the source of gamma-ray bursts.

Figure 4. False-color radio image of the supernova remnant G5.4 – 1.2 and the young radio pulsar PSR 1757-24. The pulsar has a velocity of at least 1300 - 1700 km s^{-1} away from the plane of the Galaxy. Pulsars like this reach a distance of 100 kpc in about 70 Myr, and form a distant, previously unknown halo of neutron stars around the Milky Way. (After Frail, Kassim, and Weiler 1994.)

Figure 5. Histogram of pulsar transverse velocities derived from associations between young radio pulsars and young supernova remnants. Half have transverse velocities > 600 km s^{-1} and are escaping from the Galaxy; these produce an ample population of sources which appear isotropic when viewed from the Earth. (From Frail, Goss, and Whiteoak 1994.)

Figure 6. Color picture of high velocity neutron stars streaming away from the Milky Way, as viewed by an observer outside the galaxy. (After Bulik and Lamb 1995.)

Figure 7. Sky map of 1005 bursts from a Galactic corona of high velocity neutron stars and sky map of the first 1005 BATSE bursts. It is impossible to tell the two maps apart, demonstrating that cosmological sources are not the only distant objects that can account for the BATSE sky distribution of gamma-ray bursts. (After Bulik and Lamb 1995.)

Figure 8. Brightness distribution of bursts from a Galactic corona of high velocity neutron stars and brightness distribution of the bursts in the second BATSE catalog. It is impossible to tell the two distributions apart, demonstrating that cosmological sources are not the only objects that can account for the BATSE brightness distribution of gamma-ray bursts. (After Bulik and Lamb 1995.)

Figure 9. Comparison of the brightness distribution of bursts from a Galactic corona of high velocity neutron stars (thin line) and the brightness distribution of both BATSE and PVO gamma-ray bursts (thick lines) (from Fenimore et al. 1993). (After Bulik and Lamb 1995.)

Figure 10. Sky distribution and brightness distribution of bursts from a Galactic corona of high velocity neutron stars for BATSE sampling distances ranging from 100 – 600 kpc. (After Bulik, Coppi, and Lamb 1995.)

Figure 11. Comparison of the durations of soft gamma-ray repeater bursts and gamma-ray bursts. Soft gamma-ray repeaters are known to be high velocity neutron stars that lie at distances of 10's of kpc.

Figure 12. Comparison of the hardness ratios (i.e., characteristic spectral energies) of soft gamma-ray repeater bursts and short (< 1 s) gamma-ray bursts. Soft gamma-ray repeaters are known to be high velocity neutron stars that lie at distances of 10's of kpc. (After Kouveliotou 1993.)

Figure 13. False-color X-ray image of the supernova remnant N49 in the Large Magellanic Cloud, which lies at a distance of 50 kpc from us. Superimposed on the image is the error box for SGR 0526-66, the source of the 1979 March 5 gamma-ray transient and sixteen recurrences of it. The error box lies far away from the center of the supernova

remnant, implying that the neutron star has a velocity greater than 1200 km s^{-1}. There is little doubt that the 1979 March 5 event came from a high velocity neutron star 50 kpc away from us. (After Rothschild, Kulkarni, and Lingenfelter 1994).

Figure 14. Comparison of the durations of the 17 bursts from SGR 0526-66 and gamma-ray bursts. SGR0526-66 is a high velocity neutron star 50 kpc away from us.

Figure 15. Time history of the famous 1979 March 5 gamma-ray transient. The association with the supernova remnant N49 and the 8 s periodicity leave little doubt that this object is a neutron star. The existence of pulsations implies a strong magnetic field. (After Mazets et al. 1979.)

Figure 16. Comparison of the spectrum of the initial spike of the famous 1979 March 5 gamma-ray transient and the spectra of gamma-ray bursts. The March 5th event demonstrates that neutron stars $\sim$ 100 kpc away are capable of producing gamma-ray bursts. (After Fenimore, Klebesadel, and Laros 1995.)

Figure 17. Photon number spectra of GB870303 and GB880205. The equally-spaced lines are seen in other neutron star sources and are easily explained as cyclotron scattering in a strong magnetic field. (After Fenimore et al. 1988 and Graziani et al. 1992.)

Figure 18. Photon number spectra of four accretion-powered pulsars. Notice the equally-spaced lines, which are similar to those in gamma-ray bursts. (After Makishima and Mihara 1992.)

Figure 19. Sky distribution of those bursts in the first BATSE catalog which have another burst within 5°, highlighting the evidence for gamma-ray burst repeating. Repeating sources appear as clusters of bursts on the sky because the positions of the bursts are known only to about 7°. (From Quashnock and Lamb 1994.)

Figure 20. Time dilation versus redshift z predicted for gamma-ray bursts, assuming that the bursts are cosmological. If the reported time stretching of a factor of two were attributed to cosmological time dilation, the sources would have to lie at a redshift $z \approx 6$ and they would be orphans. If they were to lie closer, most of the reported time stretching

would have to be intrinsic to the source. (From Fenimore and Bloom 1995.)

Figure 21. Interplanetary Network location for GB790406 showing the absence of any bright galaxy in the error box. (After Motch et al. 1985.)

Figure 22. Interplanetary Network location for GB791116 showing the absence of any bright galaxy in the error box. The bright object near the lower left hand boundary of the error ellipse and the faint object inside and toward the upper right hand boundary of the error ellipse are nearby stars. (After Schaefer 1992.)