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We describe observational evidence and theoretical calculations which support the high velocity neutron star model of gamma-ray bursts. We estimate the energetic requirements in this model, and discuss possible energy sources. we also consider radiative processes involved in the bursts.

INTRODUCTION

Gamma-ray bursts (GRBs) continue to confound astrophysicists nearly a quarter century after their discovery (1). Before the launch of CGRO, most scientists thought that GRBs came from magnetic neutron stars residing in a thick disk (having a scale height of up to ~ 2 kpc) in the Milky Way (2,3). The data gathered by BATSE showed the existence of a rollover in the cumulative brightness distribution of GRBs and that the sky distribution of even faint GRBs is consistent with isotropy (4,5). This rules out a thick Galactic disk source population, with (6) or without (7) spiral arms.

Consequently, the primary impact of the BATSE results has been to intensify debate about whether the bursts are Galactic or cosmological in origin. Galactic models attribute the bursts primarily to high-velocity neutron stars in a Galactic corona, which must extend one sixth or more of the distance to Andromeda ($d_{\rm M31} \sim 690$ kpc) in order to avoid any discernible anisotropy (8,9). Cosmological models place the GRB sources at distances $d \sim 1-3$ Gpc, corresponding to redshifts $z \sim 0.3 - 1$. A source population at such large distances naturally produces an isotropic distribution of bursts on the sky, and the expansion of the universe or source evolution can reproduce the observed rollover in the cumulative brightness distribution (10).

Within the context of this workshop, we focus on Galactic corona models involving high velocity neutron stars. A recent discussion of cosmological models may be found in, e.g., Blaes (11).

HIGH VELOCITY NEUTRON STARS

Only a few years ago scientists thought that neutron stars had velocities of 100 - 200 km s^{-1} (12). But recent studies show (13,14) 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 (14). 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; 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 $\sim$ 500 km s^{-1}, with $\sim 1/3$ of the neutron stars having transverse velocities $>$ 1000 km s^{-1} (14).

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 (15). 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 (13).

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} (13,16). These results have revolutionized our understanding of the spatial distribution of neutron stars in the Galaxy. Since the escape velocity from the Milky Way is $\approx$ 500 km s^{-1} in the solar neighborhood and $\approx$ 600 km s^{-1} in the Galactic bulge, where most neutron stars are born, all of these high velocity neutron stars will escape from the Milky Way. They form a distant, previously unknown "corona" around the Milky Way. This distant corona contains an ample population of sources which appear isotropic when viewed from the Earth.

THE GALACTIC CORONA

Prior to the launch of CGRO, many scientists believed it likely that gamma-ray bursts came from a thick Galactic disk. But, while a Galactic disk population was the most conservative and perhaps the most popular model (2,3), extended halo populations have also had a long and illustrious history (see, e.g., (17–20)). What did exist was a consensus that gamma-ray bursts come from magnetic neutron stars in the Galaxy. There were many reasons for this, several of which we describe below.

Following the discovery by BATSE that the faint bursts are distributed isotropically on the sky, Galactic halo and corona models found new flavor (see, e.g., (9,21–24)) as an attractive way of reconciling all of the evidence about GRBs which favors Galactic neutron stars with isotropy. However, these models were considered somewhat ad hoc, particularly by advocates of cosmological models, because no means of producing large numbers of neutron stars in an extended Galactic halo was known [see, e.g. (25)]. .

Consequently, the debate about whether GRBs 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., coalescing neutron star binaries or failed supernovae) 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 has given models a tremendous boost. Nevertheless, these models must answer several important questions:

- Can a Galactic corona of high velocity neutron stars account for the isotropic sky distribution and the rollover in the brightness distribution of GRBs seen by BATSE?
- Why do only high velocity neutron stars produce GRBs?
- Are GRBs beamed along the direction of motion of the neutron star or, if not, why is bursting activity delayed?
- Are there energy sources sufficient to power GRBs in such a model?
- Can the energy needed be released over 500 Myr or more?
- Can cyclotron lines formed in regions where the magnetic field is $\sim 2\times 10^{12} - 10^{13}$ G be produced by magnetic neutron stars in GRBs with luminosities $L_{\rm burst} \sim 10^{41} - 10^{43}$ erg s^{-1}?

We consider each of these questions below.

Ingredients in High Velocity Neutron Star Models

We have calculated detailed models of the spatial distribution expected for a population of high-velocity neutron stars born in the Galactic disk and moving in a Galactic potential that includes the bulge, disk, and a dark matter halo. All earlier studies of which we are aware that included these components of the gravitational potential employed the potential given by Miyamoto and Nagai (26). For studies of high-velocity neutron stars, it is essential to use a potential that is realistic out to very large distances. We find that the Miyamoto and Nagai (26) implies the existence of an extended disk, far beyond the observed Galactic disk. Approximately $\approx 20\%$ of the mass lies outside $r = 20$ kpc, whereas in more realistic exponential disks less than 4% of the mass lies outside 20 kpc.

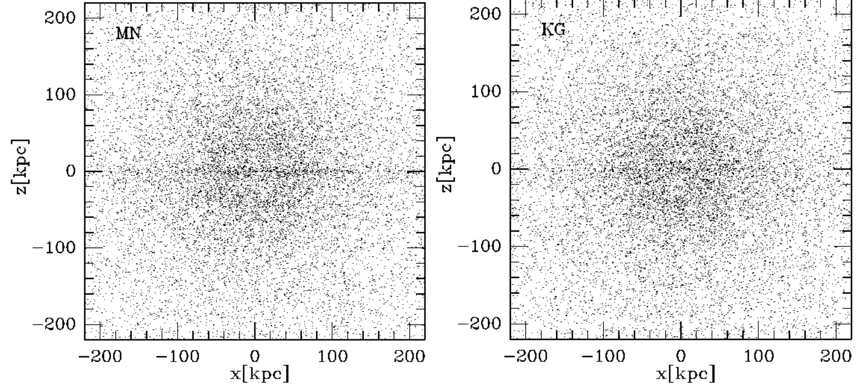

FIG. 1. Distribution of neutron stars with an initial kick velocity of 1000 km s^{-1} found using the Miyamoto and Nagai (1975) potential (left panel) and using the Kuijken and Gilmore (1989) potential (right panel). Note the increased concentration of stars in an extended disk due to the focusing described in the text.

The focusing effect of such a disk can be seen by calculating the ratio of the z components of the force using the Miyamoto and Nagai (26) potential to the force due to a point mass for $r \gg a, b, z$:

$$\frac{F_z^{MN}}{F_z^{PM}} = 1 + \frac{a}{(b^2 + z^2)^{1/2}}, \tag{1}$$

where a, b are parameters describing the Miyamoto and Nagai potential. Typically $a \approx 4$ kpc, $b \approx 0.2$ kpc, so that $F_z^{MN}/F_z^{PM} \rightarrow \approx 20$ as $z \rightarrow 0$. The use of the Miyamoto and Nagai (26) potential distorts the orbits of neutron stars whose initial velocity vectors lie in or near the plane of the disk, and leads to an anisotropic spatial distribution that is entirely an artifact of the unrealistic disk potential (see Figure 1).

We therefore use the mass distribution and potential given by Kuijken and Gilmore (27). Details of our calculation are given in (28).

Sky and Brightness Distributions of Bursts

Our detailed dynamical calculations 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 GRBs (Figure 2) [see also (23,29,30)].

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). A spread in neutron star kick velocities, in neutron star ages at which bursting behavior begins, or in the burst luminosity function tends to produce a cumulative peak flux distribution with a slope of -3/2, the value expected for a uniform spatial distribution of sources which emit bursts that are "standard candles." Figure 3 shows that a spread of less than a factor

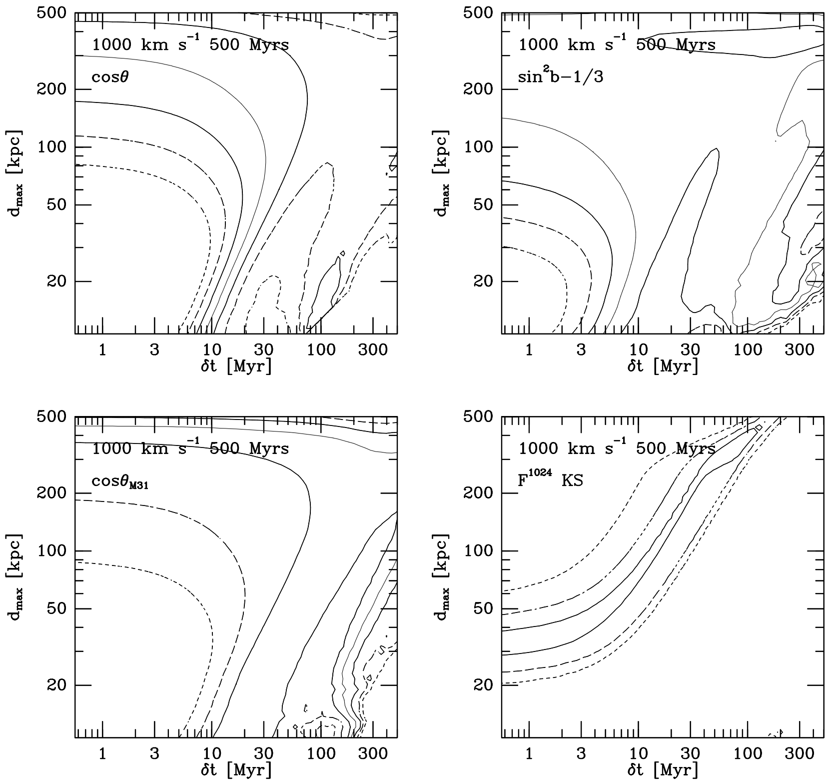

FIG. 2. Comparison of a Galactic corona model with the inclusion of M31 in which neutron stars are born with a kick velocity of 1000 km s^{-1} and have a burst-active phase lasting $\Delta t = 500$ million years with a carefully-selected sample of 285 bursts from the BATSE 2B catalogue. Panels (a), (b), and (c) show the contours in the (δt, $d_{\rm max}$)-plane along which the Galactic dipole, Galactic quadrupole moments, and dipole towards M31 of the model differ from those of the data by $\pm\ 1\sigma$ (solid lines), $\pm\ 2\sigma$ (dashed line), and $\pm\ 3\sigma$ (short-dashed line) where σ is the model variance; the thin line in panel (a)-(c) shows the contour where the dipole moment for the model equals that for the data. Panel (d) shows the contours in the (δt, $d_{\rm max}$)-plane along which 32%, 5%, and 4×10^{-3} of simulations of the cumulative distribution of 285 bursts drawn from the peak flux distribution of the model have KS deviations D larger than that of the data.

of 10 in the luminosity function, which is consistent with what know about GRBs, is sufficient to produce agreement with not only the BATSE, but also the PVO, brightness distribution of GRBs. Beaming along the direction of motion of the neutron star can also reproduce the combined BATSE and PVO brightness distributions (31,29).

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

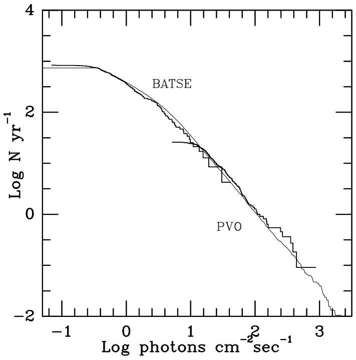

FIG. 3. Comparison of the brightness distribution of bursts from a Galactic corona of high velocity neutron stars (thin line) and the brightness distribution of both BATSE and PVO gamma-ray bursts (thick lines) (10).

of verifying or rejecting it (23,31,30,28).

It has often 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 (8). This is true, however, only if the halo extends to large distances (32). However, the halo of the Milky Way can extend only 1/3 - 1/2 of 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 produces its own "wind" of high velocity neutron stars. Some of these will travel toward us, and when they produce GRBs, BATSE should detect them.

However, Andromeda imposes little constraint if the bursts are beamed along the direction of motion of the neutron star, as some models posit (31,29). Then only the rare neutron star in the corona of Andromeda whose motion is almost directly toward or away from us would be visible. So long as the BATSE sampling depth $d_{\rm max} < 700$ kpc (the distance to Andromeda), the few bursts visible 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. Only if $d_{\rm max} > 700$ kpc, so that a large number of the neutron stars in the Andromeda corona whose motions are away from us are visible, would an excess toward Andromeda be detectable (33).

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 4) (30,33). Thus there is ample parameter space (BATSE sampling distances $d_{\rm max} \approx 100 - 500$ kpc) for a population of sources in a 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. Lack of an excess toward Andromeda would be compelling evidence that the bursts are cosmological in origin only if made by an instrument at least 50 times more sensitive than BATSE, given the possibility that the bursts are beamed along the direction of motion of the neutron star and current constraints on the Galactic corona model.

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 GRBs, and whose characteristic spectral energies form a continuum with those of GRBs. The main distinction between SGRs and GRBs is that the former have been clearly shown to repeat on time scales of days to years whereas the latter have been thought not to repeat. But recently, a number of scientists have found significant evidence that GRBs also repeat (34–37).

Three soft gamma-ray repeaters are known. Two lie in the Galactic disk at distances of tens 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 (38–42). In two cases, the soft gamma-ray repeater lies far away from the center of the supernova remnant, implying a neutron star velocity of $\gtrsim 1000$ km s^{-1} (38,42) Clearly, high velocity neutron stars can produce burst-like behavior.

If GRBs come from high velocity neutron stars in a distant Galactic corona, there are additional similarities between GRBs and SGRs. 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 SGRs and GRBs. The unification of these two phenomena is a very attractive feature of the Galactic hypothesis.

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 GRBs? The answer is "yes." The event is the famous 1979 March 5 gamma-ray transient.

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 (38,43) 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 (44,45). The distribution of the durations of these bursts overlaps completely with that of GRBs.

The burst had an intense spike which lasted ~ 0.2 s, followed by ~ 200 s of emission which exhibited an 8 s periodicity (44). 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 SGR bursts.

Although nine different satellites observed the March 5th event (38), 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. (46) used the power of present-day computers to unravel these effects in the ICE and PVO instruments. They found that the spike has a characteristic spectral energy $\langle E \rangle \approx 200$ keV, with no soft component, like a typical gamma-ray burst.

Whether the 1979 March 5 event is a GRB or a unique event can be argued either way. But either way, it demonstrates that distant high velocity neutron stars in the Galactic halo can produce events that have the energy, the spectrum, and the duration of GRBs. This evidence strongly supports the high velocity neutron star model.

ENERGETICS

We take $F_{\rm peak} \sim 10^{-7}$ erg cm^{-2} s^{-1} as the typical peak energy flux of a BATSE burst. Then the typical burst luminosity is

$$L_{\rm burst} \sim 10^{41} \left(\frac{F_{\rm peak}}{10^{-7}\ {\rm erg\ cm^{-2}\ s^{-1}}} \right) \left(\frac{d}{100\,{\rm kpc}} \right)^2 {\rm erg\ s^{-1}}\ . \tag{2}$$

Taking 5 s as the average photon flux-to-energy flux conversion factor for BATSE bursts (10), the typical burst energy is

$$E_{\rm burst} \sim 5 \times 10^{41} \left(\frac{F_{\rm peak}}{10^{-7}\ {\rm erg\ cm^{-2}\ s^{-1}}} \right) \left(\frac{d}{100\,{\rm kpc}} \right)^2 {\rm erg}\ . \tag{3}$$

The rate of burst detection by BATSE corresponds to an all-sky rate $R_{\rm burst}^{\rm BATSE} \sim 800$ bursts yr^{-1}. Assuming a neutron star birth rate $R_{\rm NS} \sim 3 \times 10^{-2}$ yr^{-1}, each neutron star must produce a total number of bursts

$$N \approx R_{\rm burst}^{\rm BATSE}/(f_{\rm escape} R_{\rm NS}) \approx 8 \times 10^4 \left(f_{\rm escape}/0.3 \right)^{-1}\ , \tag{4}$$

during its burst-active phase, where $f_{\rm escape}$ is the fraction of neutron stars born with velocities high enough to escape from the Galaxy. Then the total supply of energy needed by each neutron star in the Galactic corona is

$$E \sim N(E_{\rm burst}/5 \times 10^{41}) \sim 10^{46}\ {\rm erg}\ , \tag{5}$$

Among possible energy sources are gravitational energy from accretion of planetesimals (47,48), crustal strain energy from spin down of the neutron star, and magnetic field energy stored in the interior of the neutron star (30). Below we discuss each possibility in turn.

Accretion

The gravitational energy released by accretion is

$$E_{\rm burst} = GM\,\Delta M_{burst}/R\,. \qquad (6)$$

Taking a neutron star mass $M = 1.4 M_\odot$ and radius 10 km,

$$\Delta M_{burst} \approx 10^{21} \left(E_{\rm burst}/5\times10^{41}\ {\rm erg}\right) {\rm g}\,. \qquad (7)$$

Then the total mass needed to power the GRBs from each neutron star is

$$M \approx N\Delta M \approx 10^{27} \left(E_{\rm burst}/5\times10^{41}\ {\rm erg}\right) {\rm g} \approx 10^{-6} M_\odot\,. \qquad (8)$$

This amount of mass can be supplied by a planetesimal.

Crustal Strain Energy

The rotational energy in a neutron star at birth is

$$E_\Omega \approx \frac{1}{2} I\Omega^2 \approx 3\times10^{47}\,(P/0.3\,{\rm s})^{-2}\,{\rm erg}\,. \qquad (9)$$

However, only a fraction of this energy can be stored in the neutron star crust and released at much later time is (30)

$$E_{\rm strain} \approx 0.5\,\mu\,\theta^2_{\rm max}\,4\,\pi\,R^2\,\Delta R_{\rm crust}\,, \qquad (10)$$

where $\theta_{\rm max}$ is the maximum strain the crust can withstand before braking, R is the radius of the neutron star and ΔR is the thickness of the crust. Taking $\mu \approx 3\times10^{29}$ dyne cm^{-2}, $\theta_{\rm max} \approx 10^{-2}$, and $\Delta R_{\rm crust} \approx 0.1R \approx 10^5$ cm, the maximum strain energy that the crust can store is

$$E_{\rm strain} \approx 2\times10^{43} \left(\frac{\mu}{3\times10^{29}\,{\rm dyne\,cm^{-2}}}\right) \left(\frac{\theta_{\rm max}}{10^{-2}}\right)^2 \left(\frac{R}{10^6\,{\rm cm}}\right)^2 \left(\frac{\Delta R_{\rm crust}}{0.1R}\right) {\rm erg}\,. \qquad (11)$$

This energy is much smaller that given by equation 5. Thus the strain energy that can be stored in the neutron star crust as it solidifies while the neutron star is rotating rapidly appears unable to supply the total energy needed to power the bursts in the Galactic corona model.

Magnetic Field Energy

We know from accretion-powered pulsars and rotation-powered pulsars that the surface fields of most neutron stars lie in the range $B_s \sim 10^{11} - 10^{13}$ G. We have virtually no knowledge about the internal magnetic fields of neutron stars. If the internal field exceeds 10^{16} G, then superconductivity is quenched and the total energy stored in the internal magnetic field is

$$E^{\rm normal}_{\rm magnetic} \approx \frac{4\pi}{3} R^3 \frac{B^2}{8\pi} \approx \frac{1}{6} R^3 B^2 \approx 10^{49} \left(\frac{B}{10^{16}\,{\rm G}}\right)^2 {\rm erg}\ . \qquad (12)$$

If the internal magnetic field is less than 10^{16} G, it is expected that the interior of the neutron star will be superconducting. Then the total energy stored in the internal magnetic field is (30)

$$E^{\rm super}_{\rm magnetic} \approx \frac{1}{6} R^3 B B_c \approx 10^{49} \left(\frac{B}{6\times 10^{13}\,{\rm G}}\right) \left(\frac{B_c}{10^{16}\,G}\right) {\rm erg}\ . \qquad (13)$$

However, the energy stored in the interior magnetic field might then be released on the time scale,

$$\tau_{\rm spindown} \approx 10^7 P^2 (B/10^{12}\,{\rm G})^{-2}\,{\rm yr} \ll 5\times 10^8\,{\rm yr}\ , \qquad (14)$$

if the spin vortices in the superfluid drag the magnetic flux tubes toward the surface of the neutron star (49). Thus, if the interior of the neutron star is superconducting, the amount of energy stored in the interior magnetic field is sufficient to power the bursts in the Galactic corona model but may be released over a period of time much less than the required lifetime of such sources.

If magnetic field instabilities stress the neutron star crust, then from equation 11 above, the energy released would be (30)

$$E_{\rm strain} \approx 2\times 10^{42} \left(\frac{\mu}{3\times 10^{29}\,{\rm dyne\,cm^{-2}}}\right) \left(\frac{\theta}{10^{-3}}\right)^2 \left(\frac{R}{10^6\,{\rm cm}}\right)^2 \left(\frac{\Delta R_{\rm crust}}{0.1R}\right) {\rm erg}\ , \qquad (15)$$

which is about right for GRBs.

RADIATIVE PROCESSES

Pair Fireballs

Our discussion of pair fireballs follows that of Mészáros (50). A compactness parameter $\tau_{\gamma\gamma} \approx (L_{burst}\sigma_T/4\pi r c \epsilon_\gamma \Gamma^2) \lesssim 1$ is required for photons to be observed above an energy ϵ_γ, where r is the radius of the source and Γ measures the relativistic velocity. For $r \approx R$, $\tau_{\gamma\gamma} \gg 1$ at $\epsilon_\gamma \approx 1$ MeV unless $\Gamma \gtrsim 10^4$. This result suggests that the initial stages of pair fireball in a gamma-ray burst is optically thick.

If so, we expect that the sudden release of the energy that powers the burst will produce a trapped fireball in the region of closed magnetic fields lines in the neutron star magnetosphere and a mildly relativistic wind from the regions of open field lines at the magnetic poles (see Figure 5). This picture is similar in many respects to the soft gamma-ray repeater model of Thompson and Duncan (68).

The energy required in a solid angle θ is

$$E_{\text{burst}} \approx 10^{41} \left(\frac{F_{\text{peak}}}{10^{-7}\,\text{erg}\,\text{cm}^{-2}\,\text{s}^{-1}} \right) \left(\frac{d}{100\,\text{kpc}} \right) \theta^2\,\text{erg} \; . \qquad (16)$$

Pair production occurs if $\epsilon_\gamma > 4(m_e c^2)^2 \epsilon_t^{-1} \alpha^{-2}$, where ϵ_t is the lab frame target photon energy and α is the relative angle between the two photons.

Causality implies $\alpha \lesssim \Gamma^{-1}$, or $\Gamma^{-1} \lesssim \alpha \lesssim 2 m_e c^2 (\epsilon_t \epsilon_\gamma)^{-1/2}$, and

$$\epsilon_\gamma \lesssim 10^4 (\epsilon_t/\text{MeV})^{-1} (\Gamma/10^2)^2\,\text{MeV} \; . \qquad (17)$$

This implies relativistic expansion and therefore beaming. How large might Γ be? In AGN, an initial value (near the central source) as large as $\Gamma \sim 10^4$ is often assumed. If the wind is powered by Compton scattering, a value $\Gamma \approx 10$ or so is expected.

If $(E_{\text{burst}}/\delta m_{\text{burst}} c^2) \lesssim 1$, where δM_{burst} is the amount of baryonic matter entrained in the outflow, then the wind will be subrelativistic due to baryonic poisoning.

Cyclotron Lines

Almost fifteen years ago Mazets et al. (51,52) reported seeing single lines in the spectra of GRBs at low energies ($E \lesssim 70$ keV). Later Hueter (53) 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 (54–57) with high significance (55,56,58). 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 (59), but this fact does not strongly contradict earlier observations (60).

Similar line features are seen in the spectra of accretion-powered pulsars (61), which are known to be magnetic neutron stars. The equally-spaced lines seen in GRBs and in accretion-powered pulsars are easily explained in terms of cyclotron resonant scattering in a strong magnetic field (62,63).

Magnetic neutron stars in the Galactic corona appear able to produce cyclotron lines even though the luminosities of the bursts might 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 (64), or at the magnetic equator (58) where hot plasma is trapped by the magnetic field (65–68).

CONCLUSIONS

Detailed dynamical calculations show that a distant Galactic corona of high velocity neutron stars can easily account for the isotropic angular distribution and the brightness distribution of GRBs. Gravitational potential energy from accretion and magnetic field energy seem the most promising sources of energy which are capable of powering bursts from such a population of neutron stars.

In a GRB hot plasma will likely flow from the polar cap in a relativistic wind, but will be trapped at the magnetic equator by the magnetic field. Cyclotron lines might form in either region.

Future Prospects

Below we mention several key observations that might confirm or refute the hypothesis that the GRBs come from a distant Galactic corona of high velocity neutron stars.

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, or by a more sensitive experiment would constitute definitive evidence that the bursts are Galactic in origin. Lack of an excess toward Andromeda would be compelling evidence that the bursts are cosmological in origin only if made by an instrument at least 50 times more sensitive than BATSE, given the possibility that the bursts are beamed along the direction of motion of the neutron star and current constraints on the Galactic corona model

Cyclotron lines. Other spectroscopy instruments are now operating (TGRS and Konus on Wind) or will soon be flown (e.g., 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 the *Compton Gamma-Ray Observatory.* It is therefore expected that the third BATSE catalogue will provide an excellent opportunity to test the repeating hypothesis. Confirmation of repeating would doom most cosmological models.

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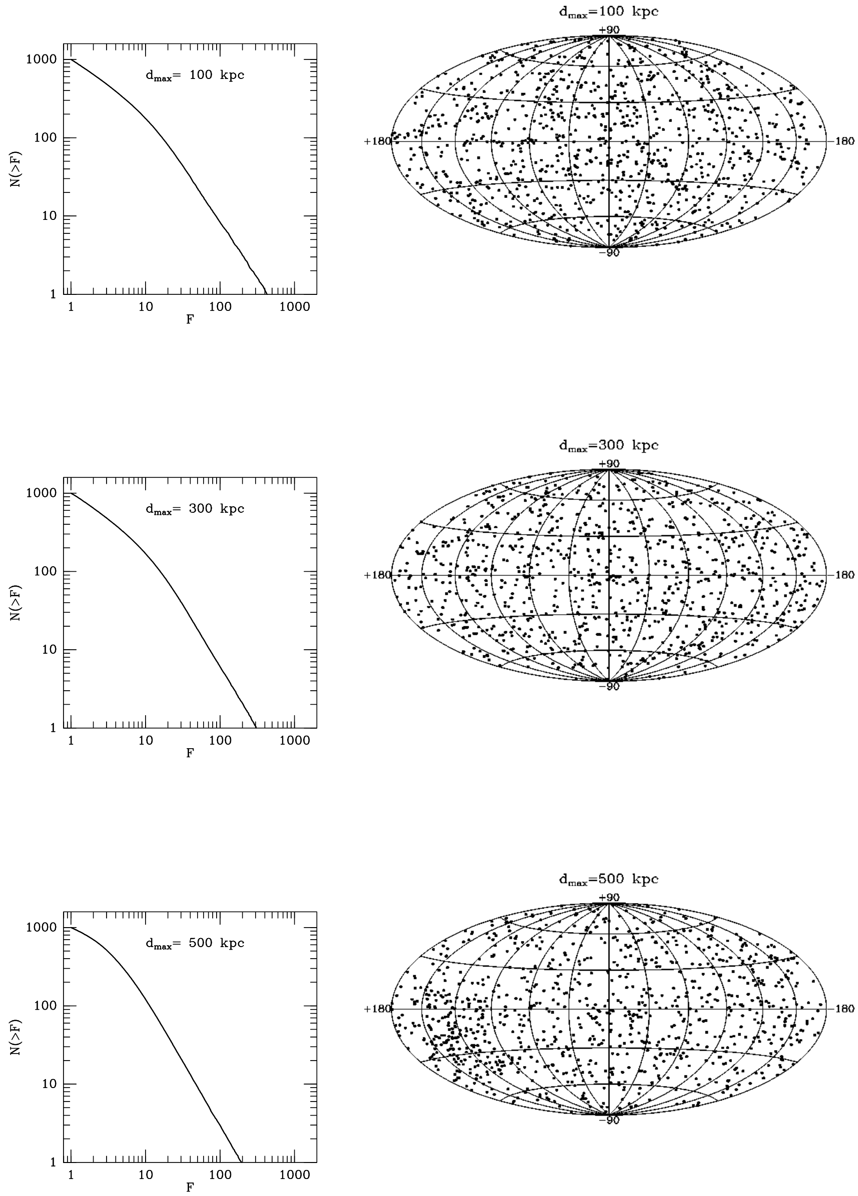

FIG. 4. Sky distribution and brightness distribution of bursts from a Galactic corona of high velocity neutron stars for BATSE sampling distances $d_{\max} = 100$, 300, and 500 kpc. Note that an excess of the bursts appears only when $d_{\max} = 500$ kpc.

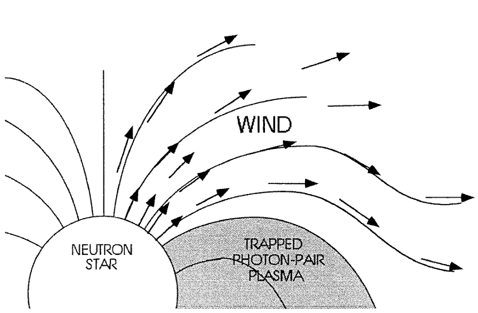

FIG. 5 Neutron star magnetosphere, showing the region at the magnetic pole where super-Eddington luminosities may drive a relativistic pair wind, and the region at the magnetic equator where super-Eddington luminosities may create a trapped pair fireball (68).