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ON THE NATURE OF SOFT GAMMA REPEATERS

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ABSTRACT

Bursts from the soft gamma repeaters (SGRs) form a unique class in several respects. Temporal characteristics include short, 0.1 s, simple event profiles with very fast rise times. Event recurrence patterns are stochastic. Spectral shape is independent of burst intensity; neither spectral variability nor soft X-ray tails are observed. The ratios of burst peak fluxes for the three known SGRs is consistent with a Large Magellanic Cloud distance for 0526−66 and approximately galactocentric distances for 1806−20 and 1900+14. $A/A_{\rm max}$ and $V/V_{\rm max}$ tests imply that present instrumentation has sampled to the edge of the SGR population. The SGR source distribution and sparse population statistics are consistent with radio pulsars being the progenitors of SGRs, and the latter having short burst-active lifetimes.

A Large Magellanic Cloud distance for the 1979 March 5 superburst is allowed and the synchrotron self-absorption problem obviated if expansion and the observed spectral evolution are taken into account. The narrow, luminosity-independent spectra in 1806−20 bursts can be explained if the high photon flux is scattered by a dense pair plasma, destroying high-energy γ-rays, and converting soft X-rays by cyclotron resonant Compton scattering.

We present limits on the lack of persistent X-ray flux from all three SGR sources, and discuss other reported nondetections in the infrared, optical, and X-ray bands. In this connection we review previous arguments against proposed energy release mechanisms, including thermonuclear events, magnetic gating phenomena, and accretion events. Some models deriving the burst energy from neutron star quakes for source distances of tens of kiloparsecs are not excluded and appear plausible.

Subject headings: gamma rays: bursts — radiation mechanisms — stars: neutron

I. INTRODUCTION

From the source of the 1979 March 5 superburst, whose error box (Cline *et al.* 1982) lies within supernova remnant N49 in the Large Magellanic Cloud (LMC), at least 15 much less intense bursts were detected over a period of 4 yr by the KONUS experiments onboard *Veneras 11/12* and *13/14* (Golenetskii, Il'inskii, and Mazets 1984). The first smaller burst followed the March 5 superburst by 14 hr; no such bursts were detected by KONUS experiments for 6 months prior to March 5. The spectral characteristics of these smaller bursts are remarkably uniform: all burst spectra are consistent with a single characteristic energy of roughly 30 keV. Burst durations (FWHM) cluster near 100 ms and usually exhibit a decaying intensity. Two bursts extending to 1.5 s and 3.5 s have a distinctive "flat-topped" appearance. Fluences of the common bursts from the source of the March 5 superburst were too weak or too soft to be detected by other all-sky γ-ray burst experiments.

The KONUS *11/12* experiments also detected three bursts from a source at Galactic coordinates $l \simeq 47°$, $b \simeq 4°$ (Mazets, Golenetskii, and Guryan 1979). These bursts had spectral and temporal signatures essentially indistinguishable from the repeating soft bursts from the March 5 source. The peak intensity for the brightest burst from the second source was approximately an order of magnitude more intense than the brighter soft bursts from the March 5 source. The intervals between the three events were short, 10 and 33 hr. These recurring bursters are now referred to as soft gamma repeaters (SGRs) 0526−66 and 1900+14, respectively, although the bursts actually emit most of their energy in the hard X-ray range.

The repeating nature of a third SGR, 1806−20, was discovered by Hurley (1986) and Laros (1986). For a period of time 1806−20 was more prolific than the other two sources: Laros *et al.* (1987) reported approximately 110 bursts from 1806−20, detected by the *International Cometary Explorer* (*ICE*) from 1979 through 1984. The apparently higher level of burst activity in 1806−20 may be partly attributable to selection effects since the peak burst fluxes observed from 0526−66 were only a factor of 3 above the KONUS threshold, and weaker bursts would not have been detected. In addition, *ICE* had continuous coverage, i.e., the experiment did not require a trigger in order to record a burst. The pattern of burst repetition in 1806−20 appears stochastic, and burst fluences are uncorrelated with the preceding or following intervals between events. The highest peak fluxes are more than an order of magnitude greater than those from 0526−66. The 3 σ source error region, 2° long, overlies the Galactic plane near 10° Galactic latitude (Atteia *et al.* 1987).

Constraining the nature of SGRs is difficult within the present observational picture, especially since no probable quiescent counterparts have been identified. However, if we consider SGRs as a class, then the available data are consistent with a single source morphology and energy release mechanism for all three SGRs. In § II we discuss the uniformity and uniqueness of SGR burst characteristics. We consider the distance question with regard to SGR celestial positions and ratios of maximum peak fluxes. We then discuss instrumental selection effects and estimate $V/V_{\max}$ and $A/A_{\max}$ ratios. We present X-ray upper limits on quiescent emission obtained with the *HEAO* A-1 experiment for all three SGR bursters in § III, and review the importance of other reported non-detections. In § IV spectral issues are addressed. The constraint discussed by Liang (1986) concerning synchrotron self-absorption in the March 5 superburst is obviated by consideration of spectral evolution and probable expansion of the emitting region. The narrow, luminosity-independent spectra and lack of spectral evolution of SGR bursts are explained in terms of resonant Compton upscattering at the cyclotron frequency ($\nu_B \sim 15$ keV) of soft X-rays by a dense pair plasma which also softens high-energy γ-rays. In § V we discuss likely progenitors for SGRs, review specific models in the context of an SGR class, and discuss possibly promising directions for further observations of SGRs.

II. A CLASS OF RARE SOURCES AT TENS OF KILOPARSEC DISTANCES

Although there are only three confirmed candidates for an SGR class, the relative uniformity and uniqueness of their known characteristics beg for attempts at constructing a self-consistent class picture. If all three SGR sources produce bursts by similar mechanisms, then certain models are less probable while others are favored. The extraordinary features of the March 5 superburst from 0526−66 appear to exclude it from consideration as an SGR burst (Cline 1981). Still these features should also be consistently explained within the framework of an SGR class. In particular, the γ-ray production and energy release mechanisms of the March 5 superburst and SGR bursts would be expected to be related. This connection is discussed in § V.

a) SGR Class Attributes

Several attributes isolate SGR bursts from other high-energy transients: (1) The burst recurrence patterns are stochastic, and the repetition time scale can be very short (Laros *et al.* 1987; Kouveliotou *et al.* 1987). In contrast, type I (thermonuclear) X-ray bursters and type II X-ray bursts from the "rapid burster" exhibit nonstochastic recurrence patterns which suggest specific energy release mechanisms (Lewin and Joss 1983). Optical flashes seen on archival plates in or near the error boxes of classical γ-ray bursters suggest recurrence (see Schaefer and Cline 1985), but this possibility remains unconfirmed since no simultaneous optical and γ-ray event has been observed. (2) The vast majority of time-resolved SGR events from all three sources have durations, $\tau_{\rm dur}$, which cluster near 100 ms, as illustrated in Figure 1. Most of the roughly 100 events from 1806−20 detected by *ICE* fall within one 0.5 s bin; the proportion of event profiles which overlap into two time bins is consistent with a peak in the duration distribution near 100 ms (J. Laros, private communication). Some shorter SGR bursts from 1806−20 ($\tau_{\rm dur} < 16$ ms) have been reported by Atteia *et al.* (1987). Generally, instrumental thresholds for detection discriminate against these shorter duration events—the true distribution may not be sufficiently well represented below durations of 30 ms (Kouveliotou *et al.* 1989). (3) All SGR bursts exhibit nearly identical spectral shapes in the common energy range where measured, e.g., above 30 keV (Mazets, Golenetskii, and Guryan 1979; Golenetskii, Il'inskii, and Mazets 1984; Atteia *et al.* 1987). This is in contrast to classical γ-ray bursts which have power output peaks at MeV energies and to X-ray bursts which exhibit quasi-blackbody spectra with $kT \sim$ 1–2 keV. (4) For the longer SGR bursts, no spectral variability is observed whenever measurements have been possible. The *Solar Maximum Mission*'s Hard X-Ray Burst Spectrometer (*SMM*/HXRBS) detected the most intense of the 1806−20 bursts seen by *ICE* as well as a second intense burst 0.8 s later. Figure 2*a* shows the two halves of the first burst (128 ms intervals) and the second burst, all of which had identical spectra within errors (Kouveliotou *et al.* 1987). Similarly, in two longer, flat-topped bursts from 0526−66, presumably the only bursts observed by KONUS instruments from this source in which a search for spectral differences could be performed, no spectral variability was found on a time scale as short as 0.5 s (Golenetskii, Il'inskii, and Mazets 1984). In contrast, classical γ-ray bursts show marked spectral softening across pulse structures (e.g., Norris *et al.* 1986) and X-ray bursts evolve throughout the event (e.g., Tawara, Kii, and Hayakawa 1984). (5) SGR bursts observed with 16 ms or better time resolution exhibit a very rapid rise (unresolved in 50% of bursts). A third HXRBS event, recorded with the high time resolution memory, shows that SGR bursts can have extremely short rise *and* decay times, less than 5 ms (Fig. 2*b*). The rise times of SGR bursts (and sometimes the total durations) are comparable to the fastest microstructure observed in classical γ-ray bursts (Laros *et al.* 1985). Figures 2*a* and *b* also illustrate the presence of an apparently distinct component of low-level emission associated with the three bursts seen by HXRBS.

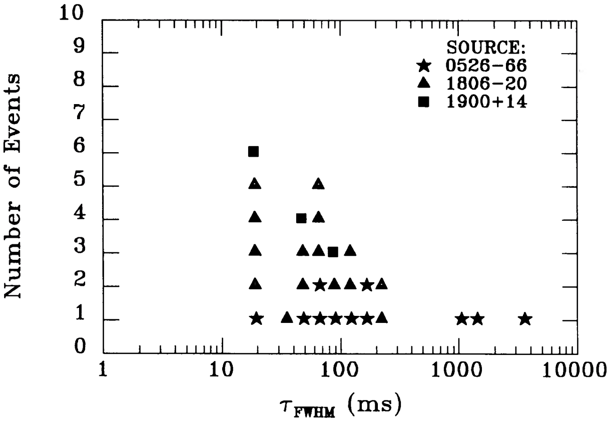

FIG. 1.—Binned duration histogram of SGR events observed with time resolution ≤128 ms. Events with temporal profiles where $\tau_{\rm FWHM} \sim 16$ ms are not resolved. SGR 0526−66 events: Mazets and Golenetskii (1981) and Golenetskii, Il'inskii, and Mazets (1984); SGR 1900+14 events: Mazets, Golenetskii, and Guryan (1979); SGR 1806−20 events: Atteia *et al.* (1987) and Kouveliotou *et al.* (1987).

Thus, SGR burst characteristics appear to be sufficiently uniform and distinct from those of other high-energy transients to merit consideration as a class. The question then arises: Are the burst energies from the three sources consistent with a single luminosity function? This brings us to consider what the source distribution and burst fluxes imply about SGR distances.

b) Celestial Distribution and SGR Distances

A self-consistent picture of an SGR class appears to be reinforced when the celestial distribution, maximum peak flux per source, probable source ages, and likely progenitors are considered. As suggested by Cline, Kouveliotou, and Norris (1987), the projected SGR distribution is similar to that of the high-density Population I regions of the Galaxy and the LMC.

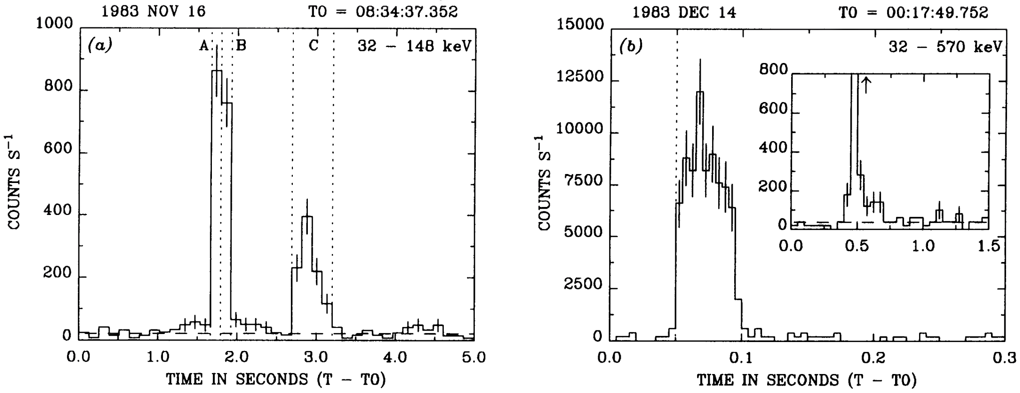

FIG. 2.—Time profiles of two intense events from SGR 1806−20 detected by *SMM*/HXRBS. (*a*) The spectra of intervals A, B, and C are indistinguishable (128 ms resolution). The first pulse (A + B) is the most energetic event observed from 1806−20 (90% occulted by HXRBS shield). The first and second pulses (possibly one event) have the shortest separation of all events detected by *ICE* from 1806−20. (*b*) The event rise and decay are unresolved with 5 ms resolution. The dotted line corresponds to the beginning of the single off scale 50 ms accumulation in the inset. A possibly distinct component of low-intensity emission is evident in both (*a*) and (*b*). Dashed lines indicate background levels. Adapted from Kouveliotou *et al.* (1987).

In Figure 3 we make a narrower comparison, between SGRs and X-ray pulsars. There is a marked concentration toward the Galactic plane and Magellanic Clouds for both sets of objects. SGRs 1900+14 and 1806−20 are within 4° of the plane. The fraction of the sky including the Magellanic Clouds and the region within 5° of the plane is less than 0.1. The *a posteriori* probability of finding all three sources within these regions is less than 10^{-3}.

As noted by Kazanas and Ellison (1986) at least three additional, relatively soft spectrum bursts were recorded by KONUS instruments (Mazets and Golenetskii 1981) which tend to support the hypothesis of association with Population I objects at several kiloparsec distances. The Galactic latitudes of the sources are −2°, −25°, and −16°. However, these events do not really fit the paradigm: the characteristic energies obtained from fits employing Gaunt factors are $kT \sim 60$–70 keV in each case (Norris 1983); no repeated outbursts were observed, and the event durations were many seconds in each case.

A celestial distribution similar to that of the X-ray pulsars in Figure 3 would be plotted for active radio pulsars, whose scale heights are a few hundred pc (Manchester 1987), if they were visible to distances of a few tens of kiloparsecs. The SGR distribution thus resembles the distributions of two candidate progenitor populations, which can have magnetic fields as high as a few times 10^{12} G. Recent theoretical and observational results indicate that the total magnetic field may decay more slowly than previously believed (Kulkarni 1986; Sang and Chanmugan 1987). Decay by a factor of 2 may occur on a time scale of 10^7 yr. During this interval an extinct radio or X-ray pulsar can attain a scale height of $10^3 \times (v_z/100 \text{ km s}^{-1})$ pc. For 1900+14, at 4° from the Galactic plane, a distance of 10 kpc corresponds to a scale height of 700 pc. Hence, the hypothesis that radio or X-ray pulsars are the progenitors of SGRs is consistent with the distribution and scale heights of non–LMC SGRs, magnetic fields strong enough to account for the 8 s periodicity in the March 5 superburst, and the interpretation of the turnover in spectra from 1806−20 as resonant Compton scattering in a 10^{12} G field (see § IV).

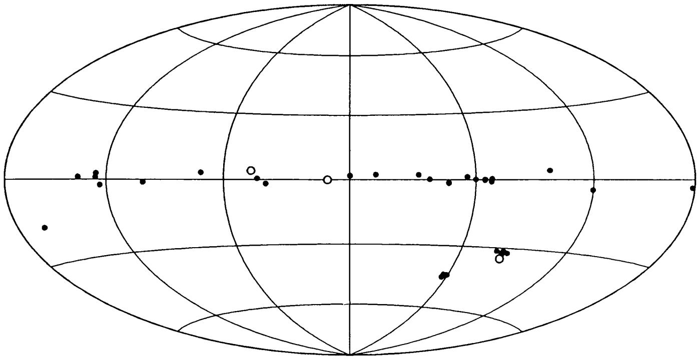

FIG. 3.—Bright X-ray pulsars (*filled circles*) and SGR sources (*open circles*) plotted in Galactic coordinates. There is a marked concentration toward the Galactic plane and Magellanic clouds for both classes. The distribution of radio pulsars, were they observable at distances greater than several kiloparsecs, would have a similar celestial distribution.

We consider what the inferred ratios of distances would be *if* peak fluxes reflect a "standard candle" mechanism. A measure of the average peak intensity of the brighter bursts from each source is given in Table 1. For 1900+14 and 1806−20, the brightest 30% of confirmed events are averaged. Because the KONUS sensitivity limit for 0526−66 is only a factor of 2 lower than the average peak intensity, we average all confirmed events detected by KONUS (intensities of observed events from this source group near 2.0×10^{-6} ergs cm^{-2} s^{-1}, comparable to the average value of 2.1×10^{-6} ergs cm^{-2} s^{-1}). Under these assumptions, the distance ratios are $d_{1900+14}/d_{1806-20} \simeq 1.5$ and $d_{0526-66}/d_{1806-20} \simeq 3.5$, roughly consistent with galactocentric distances for 1806−20 and 1900+14, and an LMC distance for 0526−66 (see Cline, Kouveliotou, and Norris 1987). At these distances, the peak luminosities for the most intense bursts from all three sources would be a few times 10^{41} ergs s^{-1}.

We do not include the March 5 superburst in the SGR peak intensity distribution of 0526−66 because it appears to be the sole example of a distinct phenomenon. The intense portion of the burst exhibited rapid hard-to-soft spectral evolution (Cline 1984). Figure 4 illustrates *Signe* energy-loss spectra of the initial 24 ms and succeeding 250 ms of the event. The spectra are believed to be negligibly affected by pulse pileup and dead-time effects which can distort spectral shape during high-intensity intervals (K. Hurley, private communication). Hardness ratios with 6 ms binning recorded by *PVO* (Fenimore *et al.* 1981) appear to corroborate this picture of spectral softening in March 5: a trend of decreasing hardness

TABLE 1

TEST OF HOMOGENEOUS SPATIAL DISTRIBUTION FOR SOFT GAMMA REPEATERS

Source	Peak Intensity (ergs cm^{-2} s^{-1})	V/V_{max}	A/A_{max}	Reference
1806 − 20...............	3.2×10^{-5}	0.068	0.16	Atteia *et al.* 1987
1900 + 14...............	1.5×10^{-5}	0.013	0.056	Mazets, Golenetskii, and Guryan 1979
0526 − 66...............	2.1×10^{-6}	0.15	0.33	Golenetskii *et al.* 1984, 1986

during the first 75 ms is accompanied by a significant excess above a blackbody fit in the energy range 250–1000 keV. The high-energy excess is absent during the rest of the pulse. These *Signe* and *PVO* high time resolution measurements may be interpreted as additional evidence for redshifted annihilation radiation, first claimed in the initial 4 s KONUS spectrum of the event (Mazets *et al.* 1979).

The salient point is that SGR specta (Fig. 4) have never been shown to attain characteristic energies comparable to those in the March 5 event, and SGR spectra have been shown to vary negligibly on a time scale as short as 128 ms (Kouveliotou *et al.* 1987). Although this is roughly 2 to 5 times longer than the evolutionary time scale revealed by *PVO* and *Signe* for March 5, the presence of emission in the range 300–500 keV still would have been discernible in the event-averaged spectra of many bright SGR bursts if such hard radiation had dominated during an interval as short as one-tenth of a burst's duration. (The first event observed from 1806 − 20, 1979 January 7, was recorded by the KONUS experiments on *Venera 11 and 12*, and reported by Mazets *et al.* (1982) to have a high-energy tail above 100 keV. However, other instruments [*ICE* and *Prognoz 7*] which detected this same event saw no emission above 100 keV with a limit in that energy regime approximately two orders of magnitude weaker than the hard emission observed in classical γ-ray bursts [Laros *et al.* 1986]. Since the instrumental background spectrum can be roughly as hard as a classical γ-ray burst, it is likely that the level of the KONUS background estimate—probably obtained over a 4 s integration period for a ∼200 ms burst—could have been somewhat inexact.)

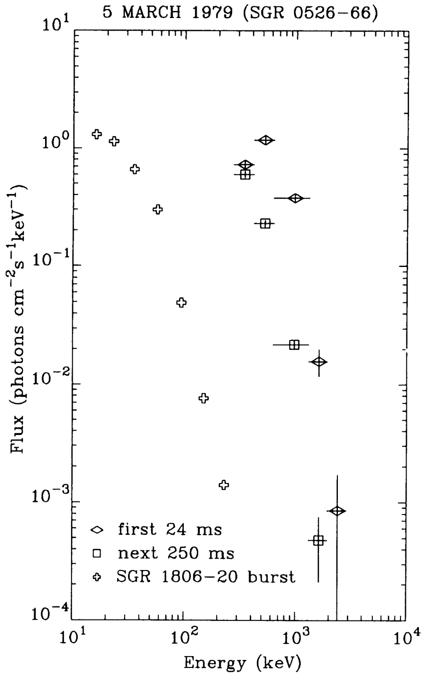

FIG. 4.—Energy-loss spectra from the *Signe* experiment of the hard onset and subsequent softening of the 1979 March 5 superburst (courtesy of K. Hurley). No information is available below about 250 keV on these short time scales which could further define the apparent turnover near 400 keV. For comparison, a canonical SGR burst spectrum is illustrated (Atteia *et al.* 1987); below about 18 keV, spectra from SGR 1806 − 20 decrease steeply (Fenimore 1987).

Furthermore, regardless of the ranges of SGR burst intensities from all three sources (each case limited by instrumental sensitivities), *a gap of a factor of 500 in peak intensity separates March 5 and the brightest SGR burst from 0526 − 66* (Golenetskii, Il'inskii, and Mazets 1984). By the standard of Harwit (1984), three orders of magnitude separation in an observable quantity constitutes sufficient grounds for entertaining two physically distinct causes.

c) Instrumental Selection Effects

We now address the question of comparative instrumental thresholds and possible selection effects. The KONUS instruments, which discovered the repeating nature of the first two SGRs, had quasi-omnidirectional response when integrated over the entire *Venera 11/12* and *13/14* missions (cf. Laros *et al.* 1982; Mazets and Golenetskii 1982). No other concurrent instruments (with requisite field of view) were sensitive enough to detect the SGR bursts from 0526 − 66 and 1900 + 14. This is partly attributable to the fact that most earlier γ-ray burst experiments were not sensitive to the hard X-ray spectrum of an SGR burst. Since the maximum peak intensities of the 0526 − 66 bursts are more than a factor of 10 below those of 1806 − 20, the KONUS instruments had the sensitivity to detect sources much fainter than 1806 − 20. *Venera 11/12* and *13/14* missed most of the 1806 − 20 bursts because these missions were active almost precisely during the gaps in 1806 − 20 burst activity. Of the more than 100 bursts observed by *ICE*, only the first burst reported by Laros *et al.* (1986) and a few in early 1983 were observable with the KONUS *11/12* and *13/14* instruments. Thus there is no inconsistency in SGR bursts reported by KONUS and *ICE*.

The *ICE* instrument which monitored 1806 − 20 has a field of view containing the entire ecliptic plane, ±5° in ecliptic latitude, and therefore the Galactic center and anticenter regions (Laros *et al.* 1987). It could have detected bursts from similar sources outside of the Galactic plane up to $|b| < 65°$. With a ratio of out-of-plane ($|b| > 5°$) to in-plane ($|b| < 5°$) coverage of roughly 17, *ICE* should have discovered sources out of the plane if the SGR parent population were approximately isotropically distributed, as is the classical γ-ray burster distribution. Furthermore, sources which produced SGR bursts as intense as the brightest 1806 − 20 bursts would have been detectable through the *ICE* collimators in X-rays; no such bursts have been found in a preliminary search (Laros 1987). A search for SGR bursts using the high time resolution memory records of *SMM*/HXRBS also has yielded no likely candidates (Kouveliotou *et al.* 1989).

These considerations of instrumental sensitivity can be quantified by the $V/V_{\max}$ test (Higdon and Schmidt 1990). Briefly, a $V/V_{\max}$ relation for SGRs may be generated by calculating $[C/C_{\max}]^{-1.5}$ for each source, where C is the observed peak intensity and $C_{\max}$ is the lowest intensity (maximum distance) for which the same event would still be detectable. $V/V_{\max}$ gives the ratio of observed volume to observable volume, and is less subject to systematic effects than are variations of the log $(N > S)$ − log (S) test. If a disk distribution were suspected, then an $A/A_{\max}$ test comparing observed area to observable area would also be appropriate. (This ratio must be adjusted per source if the Galactic latitude is appreciable; e.g., the $A/A_{\max}$ estimate for 0526−66 was increased by sec[33°]). Table 1 includes our estimates for $V/V_{\max}$ and $A/A_{\max}$, as a mere three sources do not merit a plot. We used for C the peak intensity of the brightest burst detected from each source, and estimated $C_{\max}$ from the least intense burst actually detected, per experiment. For 1900+14 and 0526−66, $C_{\max}$ is the same, that of the weakest 0526−66 burst seen by KONUS. Note that if the KONUS experiments had been active they would have observed some of the weakest bursts from 1806−20, and the entries for 1806−20 would then be even smaller than those we calculate from *Prognoz 9* data. The low values for $V/V_{\max}$ and $A/A_{\max}$ suggest that SGRs could be seen to much greater volumes or disk areas if the distribution of SGRs were homogeneous. Thus the edge of the distribution may already have been probed, or perhaps present instruments are sampling to a region where large holes exist in the distribution.

We conclude that since the observed SGR distribution does not appear to be due to instrumental selection effects, the sources are likely to be at galactocentric and LMC distances. The lack of detections of SGR counterparts, discussed in the next section, provide further evidence against a nearby source distribution.

III. SEARCHES FOR X-RAY COUNTERPARTS

Some models for SGRs (and other γ-ray bursters) predict that X-ray counterparts of the quiescent burst sources may be detectable; upper limits to X-ray emission from the γ-ray sources constrain these models. We have used both scanning and pointed observations made with *HEAO* A-1 (Wood *et al.* 1984) to set upper limits to quiescent X-ray emission. In the cases of 1806−20 and 1900+14 the *HEAO* observations were performed 6 to 12 months prior to the intervals during which burst activity was first monitored by *Venera 11/12*; thus there is no available evidence on burst activity during the epochs of X-ray observations. The *HEAO* pointed observation of the region containing 0526−66 occurred after the launch of *Venera 11/12*.

HEAO A-1 scanned the error box containing 1900+14 on 1977 October 10 and again on 1978 April 9. For maximum sensitivity, we summed the data obtained from all of the 1° × 4° scanning modules while the collimator response to the source exceeded 50%, thereby averaging scans over four days for each epoch. The 2 σ upper limits for the X-ray flux in the *HEAO* A-1 band (0.5–25 keV) are 1.3×10^{-11} and 1.9×10^{-11} ergs s^{-1} cm^{-2} for the 1977 and 1978 observations, respectively. The upper limits differ due to changing background rates and exposures. Similarly, 1806−20 was scanned on 1977 September 24 and 1978 March 22. Due to the proximity of the bright Galactic bulge X-ray source GX9+1, we used data from the smaller $1° \times \frac{1}{2}°$ fine scanning modules. The 2 σ upper limits for 1806−20 are 4.9×10^{-11} and 2.2×10^{-11} ergs s^{-1} cm^{-2}.

SGR 0526−66 is too close to the bright X-ray source LMC X-4 to obtain useful upper limits to its X-ray emission from the *HEAO* A-1 scanning data. A pointed observation of LMC X-4 by the *HEAO* A-1 2° × 8° pointing module was performed on 1978 September 25. During two satellite orbits, 1720 s of usable data was obtained. The background rate during this observation was 0.2 count cm^{-2} s^{-1}, almost wholly attributable to LMC X-4. We searched these data for pulsed emission at the reported periods for 0526−66, 8.0 s (Mazets *et al.* 1979; Cline *et al.* 1980) and 8.6 s (Loznikov *et al.* 1980). The latter period was reported for a *Kosmos 856* scanning observation of the source prior to the March 5 superburst, and the difference in periods has been interpreted as evidence of core collapse (Kazanas 1988). The 2 σ upper limit to pulsed emission from 0526−66, at either of the reported periods or their first harmonics, is 6.9×10^{-12} ergs s^{-1} cm^{-2}, assuming an arbitrary pulsed fraction of 10%.

The *HEAO* A-1 limits are particularly relevant to thermonuclear and accretion-driven burst models. In Table 2 we summarize the upper limits to X-ray emission discussed above. We follow the argument of Pizzichini *et al.* (1986) in deriving a

TABLE 2

QUIESCENT X-RAY UPPER LIMITS FOR SOFT REPEATERS

Source	Epoch	X-Ray Flux Upper Limit[a] (ergs cm^{-2} s^{-1})	SGR Burst Fluence[b] (ergs cm^{-2})	Accretion Rate/Area[c] ($M_{\odot}$ yr^{-1} km^{-2})	$\tau_{\rm rec}$[c] (days)	Accretion Rate[d] ($M_{\odot}$ yr^{-1})
0526−66	1978 Sep 25	$<6.9 \times 10^{-12}$	2.0×10^{-7}	$<2.3 \times 10^{-10}$	>0.4	$<4.4 \times 10^{-9}$
1806−20	1977 Sep 24	$<4.9 \times 10^{-11}$	1.5×10^{-6}	$<2.1 \times 10^{-12}$	>4	$<1.0 \times 10^{-10}$
	1978 Mar 22	$<2.2 \times 10^{-11}$	1.5×10^{-6}	$<1.6 \times 10^{-12}$	>10	$<4.5 \times 10^{-11}$
1900+14	1977 Oct 10	$<1.3 \times 10^{-11}$	1.0×10^{-6}	$<8.6 \times 10^{-12}$	>10	$<2.7 \times 10^{-11}$
	1978 Apr 9	$<1.9 \times 10^{-11}$	1.0×10^{-6}	$<1.3 \times 10^{-11}$	>7	$<3.9 \times 10^{-11}$

[a] Constant flux 2 σ upper limit for 1806−20 and 1900+14. Pulsed flux (at 8.0 s and 8.6 s) 2 σ upper limit for 0526−66; accretion values calculated for (arbitrary) pulsed fraction of 10%.

[b] References: Mazets, Golenetskii, and Guryan 1979; Atteia *et al.* 1987.

[c] For thermonuclear model of Hameury, Heyvaerts, and Bonazzola (1983): assumes $\alpha \equiv \epsilon_x/\epsilon_{\rm TN} = 100$, $\sum_{\rm crit} = 2.5 \times 10^{-13}\ M_{\odot}$ km^{-2}.

[d] Distances assumed: 55 kpc for 0526−66, 10 kpc for 1806−20 and 1900+14.

relation for the mass accretion rate per unit area:

$$\frac{\dot{M}}{A_0} < \left[\frac{F_x}{S_g}\right]\left[\frac{\epsilon_{\rm TN}}{\epsilon_x}\right]\left[\sum\nolimits_{\rm crit} \frac{c^2 R_{\rm ns}}{G M_{\rm ns}}\right], \qquad (1)$$

where F_x is the 2 σ upper limit on the X-ray flux in the A-1 bandpass (0.25–25 keV); S_g is the observed SGR fluence; ϵ_x and $\epsilon_{\rm TN}$ are the efficiencies for conversion of the gravitational potential energy of accreted material into X-rays during quiescence and into hard X-rays by thermonuclear detonation; and $\sum_{\rm crit}$ is the critical accreted mass per area required for ignition on a neutron star with radius $R_{\rm ns}$ and mass $M_{\rm ns}$. For canonical values of these parameters ($\epsilon_x = 0.1$, $\epsilon_{\rm TN} = 10^{-3}$, $\sum_{\rm crit} = 2.5 \times 10^{-13}\ M_\odot\ {\rm km}^{-2}$, $R_{\rm ns} = 16$ km, $M_{\rm ns} = 1.3\ M_\odot$) we have

$$\dot{M}/A_0 = 6.6 \times 10^{-7} [F_x/S_g]\ M_\odot\ {\rm km}^{-2}\ {\rm yr}^{-1} . \qquad (2)$$

The value used for $\sum_{\rm crit}$ is taken from Hameury and Lasota (1986), and we note that our value for ϵ_x (0.1) more conservatively reflects the uncertainty in estimates of gravitational to X-ray energy conversion than the ϵ_x (1.0) used by Pizzichini *et al.* (1986). In Table 2 we give our distance-independent limits on the accretion rate per unit area, $\dot{M}/A_0$, and the recurrence time, $\tau = \sum_{\rm crit}/(\dot{M}/A_0)$. The selected values for S_g are the average fluences for the three bursts from 1900+14, for the non-"flat-topped" bursts (with durations of roughly 0.1 s) from 0526−66, and for 12 bursts detected by *Prognoz 9* from 1806−20 (see references in Table 2). Seven of these 1806−20 bursts occurred during a 10 day interval, and many more bursts were detected by *ICE* during the same interval (Laros *et al.* 1987). Our calculations reflect the assumptions of the thermonuclear model of Hameury, Heyvaerts, and Bonazzola (1983). With suitable adjustments the limits are relevant for similar models with lower $\sum_{\rm crit}$, and therefore shorter τ (e.g., Woosley and Wallace 1982). The inconsistency of the predicted τ (several days) with the observed recurrence patterns (sometimes several events per day: Mazets, Golenetskii, and Guryan 1979; Laros *et al.* 1987) argues against thermonuclear models (see § V). Clearly, in the case of 1806−20 where several intervals between bursts are only a few hundred seconds or less, the predicted thermonuclear recurrence time scale widely misses the mark, by factors of 10^3 to 10^5.

We have also calculated the usual distance-dependent limits on the mass accretion rate from the observed limits on X-ray flux,

$$\dot{M} = 4\pi d^2 F_x / \epsilon_x c^2 . \qquad (3)$$

These limits are also given in Table 2, where we have used distances of 10 kpc for 1806−20 and 1900+14 and a distance of 55 kpc for 0526−66. If blackbody emission is assumed to result from heating of the neutron star surface by accretion, then $\sigma T^4 = 4\pi d^2 F/A$. For canonical parameters ($d = 10$ kpc, $F = 10^{-11}$ ergs cm^{-2} s^{-1}, $A_0 = 1$ km^2) the blackbody temperature is $T \simeq 1.8$ keV. A change of 10^4 in flux (down) or surface area (up), or 10^2 (down) in distance will move the blackbody peak only a factor of 10 (down) in temperature. Thus, for galactocentric and LMC distances, measurements in the soft X-ray band provide interesting constraints for thermonuclear models. At closer distances (100 pc) a significant fraction of the (lower temperature) blackbody flux would still be detected in the *HEAO* bandpass. The implications of the *HEAO* A-1 limits are discussed further in § V.

The argument that a significant portion of the persistent flux can appear in soft γ-rays for low accretion rates, as discussed by Langer and Rappaport (1982), may be mitigated by several effects, some of which those authors already note. Lower accretion rates result in the collisionless shock forming at higher altitudes and therefore lower field regions. The emission, which we assume is peaked at the cyclotron resonance, appears at lower energies than the surface field would indicate. Therefore, for a surface field of 10^{12} G ($= B_{12}$) a significant portion of the cyclotron emission will be emitted below about 12 keV. If instead the shock forms at low altitudes, some portion of the γ-ray emission produced by the hot electrons and by the cyclotron process will intercept the stellar surface and heat it, giving rise to a quasi-blackbody X-ray flux. For a shock at height h, the fraction of photons intercepted by the surface is

$$f \sim \sqrt{1 - \left(\frac{R_{\rm ns}}{R_{\rm ns} + h}\right)^2} \Big/ 2 . \qquad (4)$$

For an accretion rate of $5 \times 10^{-12}\ M_\odot$ yr^{-1}, somewhat below our upper limits, and a field as high as 2.5×10^{12} G, Figure 5 of Langer and Rappaport yields $h \simeq R$, or $f \simeq 0.4$. A detailed treatment of the effects of radiative transfer, which are neglected by Langer and Rappaport, would probably serve to scatter radiation toward lower frequencies.

Additional upper limits on counterparts for 0526−66 have been obtained by other observers. Pizzichini *et al.* (1986) obtained 3 σ upper limits for blackbody flux in the *Einstein* HRI bandpass (0.1–4.0 keV) of 10^{-11} ergs cm^{-2} s^{-1} (for an assumed distance of 55 kpc) or 4×10^{-13} ergs cm^{-2} s^{-1} (at 100 pc). The limits were obtained from the instrumental response by deconvolving a blackbody temperature assuming $\epsilon_x = 1.0$; for comparison with our method, their flux upper limits should be multiplied by a factor of approximately 10. The limits of Pizzichini *et al.* apply to epochs 1 and 23 months after the 1979 March 5 superburst, i.e., during the first period when SGR bursts were detected from 0526−66, and in between the KONUS *11/12* and *13/14* intervals of monitoring, respectively. Murakami *et al.* (1990) observed 1806−20 in 1988 September with the *Ginga* LAC instrument, also summing scan passes, as we did with *HEAO* A-1. They obtain an upper limit to persistent flux resulting from accretion of 10^{-11} ergs cm^{-2} s^{-1}, which would translate into a distance limit of 200 pc if the source had been burst active during that epoch. Schaefer *et al.* (1987) have determined an upper limit in the infrared K band of about magnitude 13. In the optical, two 18th magnitude stars lie near the edges of the March 5 error box; no other objects are visible down to about magnitude 23 (B. Schaefer, private communication).

Although 0526−66 has the smallest source error region in γ-ray astronomy (Cline *et al.* 1982), the limits noted above are relatively high because of the diffuse background presented by the N49 supernova remnant. However, since some models require that 0526−66 is much nearer than the other SGRs (e.g., Mazets *et al.* 1982), these observations are still relevant in the context of an SGR class. In § V we combine the additional information on 0526−66 with our observations to reinforce arguments against models involving a nearby origin for SGRs.

IV. SPECTRA OF GRB 1979 MARCH 5 AND SGR BURSTS

Several issues must be addressed if SGR sources are taken to be at distances of tens of kiloparsecs since then enormous luminosities and energy densities are required. First, Liang (1986) has presented an argument, based on the lack of a synchrotron self-absorption turnover in the initial pulse of the March 5 event, which appears to constrain the distance to the source to be much less than 55 kpc. Second, on the range of time scales which has been investigated, SGR spectra do not evolve throughout a burst (Golenetskii, Il'inskii, and Mazets 1984; Kouveliotou *et al.* 1987), whereas the initial pulse of the March 5 event does (Cline 1984). In fact, the shape of SGR spectra from burst to burst is nearly constant, even for 1806−20 where a range of peak intensities of 6 has been observed (Atteia *et al.* 1987). Third, regardless of the distance question, the narrowness of the burst spectra from 1806−20, which extend from about 10 keV to 150 keV, remains to be explained. These issues may be self-consistently resolved if the details and chronology of spectral evolution of March 5 are examined, and if the effects of strong magnetic fields on radiation transfer are taken into account for SGR burst spectra. Other aspects of the March 5 superburst have been addressed previously, i.e., radiation transfer accounting for features of the average continuum shape and annihilation line, a plausible energy source, the pulsating phase, etc. (Ramaty *et al.* 1980, 1981; Liang 1981; Ellison and Kazanas 1983).

There is some observational evidence which is consistent with the hypothesis that SGRs have a magnetic field $B_{12} \sim 1$. The spectrum of the first, relatively weak SGR event from 1806−20 detected by *ICE* (Laros *et al.* 1986) exhibited the hint of a low-energy turnover near 15 keV, but the evidence was not clear. Stronger bursts subsequently observed by *ICE* from this source, and weaker bursts that are co-added, exhibit definitive spectral turnovers or cutoffs with very steep slope. Preliminary analysis (Fenimore 1987) indicated that these spectra could not be fitted by employing any optically thick or thermal mechanism (including synchrotron self-absorption), except possibly photoelectric absorption by neutral species. However, the required column density would be so high (3×10^{24} atoms cm^{-2}) as to preclude interstellar absorption. Because two bursts separated by approximately 1 s were observed to have such spectra, it appears difficult to avoid ionization at the source. Gaussian lines at the cyclotron fundamental ($\nu_B \sim 18$ keV) and first harmonic, or emission from a cooling power-law distribution (with a similar value for ν_B) did provide acceptable fits. Further analysis has indicated that a combination of blackbody (at low energy) and thermal bremsstrahlung (at high energy) spectral forms may provide an acceptable fit. Yet the usual difficulties with thermal bremsstrahlung (e.g., very large aspect ratios for the burst emission) make this interpretation problematic (E. Fenimore, private communications).

For the seven KONUS spectra (measured above $\simeq 27$ keV) of the oscillating decay phase of March 5, deficiencies from an exponential fit are evident below 50 keV (Mazets *et al.* 1982); other functional forms might have fitted the data more closely. Spectra from 1900+14 do not show any indication of a turnover down to $\simeq$27 keV (Mazets *et al.* 1982); the field strength for this source would therefore have to be lower than $B_{12} \sim 2$.

The 8.0 s oscillating decay phase of the March 5 event may also be indicative of a strong magnetic field. It has previously been suggested that the pulsations could be the result of a burst afterglow, i.e., hot spots at the surface of the neutron star (Fenimore *et al.* 1981). However, the modulation depth of the pulsations was about 50% (Mazets *et al.* 1979). For compact, nonmagnetic neutron stars the fraction of pulsed flux emitted at the surface is significantly reduced at infinity by gravitational lensing (Wood, Ftaclas, and Kearney 1988, and references therein). Modeling of burst expansion (van Paradijs and Lewin 1988) suggests that at least some neutron stars are compact, with $\lambda = (R_{\rm ns}/R_{\rm S})/(M_{\rm ns}/M_0) \sim 2.5$, where $R_{\rm S}$ is the Schwarzschild radius and $M_\odot$ is 1 solar mass. For $\lambda \simeq 2.5$ the maximum modulation depth at infinity from two 20° radius antipodal caps of uniform intensity on the neutron star surface is about 10%; variations on geometry, intensity distribution, or viewing angle result in lower modulation. This problem is avoided (1) if the emission is beamed at the surface by a strong magnetic field, and/or (2) if pulsed emission arises at heights significantly above the surface.

These considerations lead us to consider the hypothesis that narrow SGR spectra are somehow related to the fundamental cyclotron frequency. We now examine this question more closely in connection with the high luminosity required by large source distances.

The distance constraint derived by Liang (1986) is based on the lack of a synchrotron self-absorption turnover down to 30 keV in the initial 4 s KONUS spectrum of the March 5 event (Mazets *et al.* 1982). However, spectral evolution of the initial pulse may imply an altered distance constraint. Using Liang's equation (11) and

$$\dot{n}h/\alpha_0 = 7.1 \times 10^{18} \nu_{\rm abs}^{(\delta+5)/2} \nu_B^{-(\delta+3)/2} \tag{5}$$

(J. Brainerd, private communication; cf. eq. [6.53] of Rybicki and Lightman 1979, for a noncooling power-law distribution), we may recast the distance constraint in the form

$$d \lesssim 3.9 \times 10^{-5} \nu_B^{(1-\delta/4)} \nu_{\rm abs}^{(\delta+5)/4} (A_{12}/F_{\rm obs})^{1/2} \text{ kpc} , \tag{6}$$

where ν_B is the cyclotron frequency, $\nu_{\rm abs}$ the self-absorption turnover frequency, A_{12} the projected emission area in units of 10^{12} cm^2, and $F_{\rm obs}$ the observed flux. Explicit dependence on δ, the power-law exponent for a distribution of cooling electrons, is retained. Spectra from the *Signe* experiment on *Venera 11* (Fig. 4) indicate that March 5 initially manifested a relatively hard spectrum which softened rapidly. Also, the spectrum of first 24 ms appears turned over below 400 keV (no spectral information is available below about 250 keV on this short time scale). An explanation for this peak, instead of (or in addition to) a redshifted annihilation line (Ramaty *et al.* 1980, 1981), is synchrotron self-absorption. In this case, appropriate values for constraining the distance via equation (6) would be $\delta \sim 3$ (estimated by comparing the initial 24 ms spectrum of Fig. 4, and Fig. 15 of Brainerd and Lamb 1987), and $F_{\rm obs} \sim 10^{-3}$ ergs cm^{-2} s^{-1}. Assuming a ν_B of $\sim$20 keV, the source is constrained to be at less than about 350 kpc. This must be considered a rough limit since rapid evolution most likely occurred during the initial 24 ms interval, and since we have coarsely estimated the spectral slope.

The spectrum of the next 250 ms of March 5 exhibits no peak and has substantially softened, but is still much harder than an SGR spectrum (Fig. 4). From temporal profiles with different energy thresholds it can be shown (Mazets *et al.* 1982) that roughly half of the power in the initial pulse was emitted at energies below 100 keV. As this soft component must appear at some time during the initial pulse (the hardness ratios of Fenimore *et al.* [1981] indicate that the pulse softens until about 75 ms after onset, hardens slightly, and then softens substantially after 100 ms), a constraint similar to the one derived by Liang is still an issue. For the 250 ms spectrum of Figure 4 we estimate $\delta \sim 4$, and since no turnover is observed in the KONUS spectrum, assign $\nu_{\rm abs} \sim 30$ keV, the limit of spectral coverage. Consistency with an LMC distance then requires approximately a factor of 15 expansion of the emitting region to produce an emission area sufficiently large to avoid self-absorption.

From the spectrum of the initial pulse we see that the radiating plasma is mildly relativistic ($kT \sim m_e c^2$) in the burst frame of reference. Therefore, even a 10^{12} G magnetic field does not provide confinement against the super-Eddington luminosity if the plasma is radiation-dominated: for $T \gtrsim 170$ B_{12} keV the plasma will expand (Lamb 1982, p. 251). This explosion during the onset of the burst may be sufficient to lift the radiating region to a height of more than ~ 100 km, creating a large enough emission area to accommodate the high luminosity without synchrotron self-absorption. We note that analogous explosions are inferred to occur in X-ray bursts (e.g., Tawara, Kii, and Hayakawa 1984), with expansion of the emission region to more than 100 km at event onset in the absence of a strong magnetic field and at much lower temperatures ($kT \sim 1$ keV). By comparison, in the case of the spectrally harder March 5 burst, once the emitting plasma has overwhelmed the surface field, rapid expansion appears plausible. Detailed modeling would be necessary to confirm this scenario.

Emission from an expanded region at early times in the 5 March burst is suggested by the fact that the first, most intense interpulse (1 s after event onset) of the oscillating decay is retarded in phase by roughly $\pi/3$ relative to the succeeding interpulses (cf. Figs. 1 and 4, Mazets *et al.* 1982). One explanation of this apparent phase retardation is that during the expanded, radiation-dominated interval, the emission region lagged the quiescent field pattern. A necessary condition for the plasma to overwhelm the field is that the expansion radius exceed the Alfvén radius (Lamb 1982, p. 258),

$$r_{\text{Alfvén}} \simeq 10[(B_{12})^2(v_p/v_{\text{ff}})^{-2}(n/10^{26}\ \text{cm}^{-3})^{-1}]^{1/5}\ \text{km}\,, \quad (7)$$

where B_s and n are the surface field strength and number density, respectively, v_{ff} the free-fall velocity, and we have assumed that the flow is supersonic. Again, a detailed simulation would be required to determine if the maximum radius of expansion exceeded $r_{\text{Alfvén}}$.

Liang (1988) also applies constraints similar to equation (6) to the SGR bursts from $1806-20$, and finds upper limits to the source distance of 5–8.5 kpc. As mentioned above, however, the shape of the low-energy turnovers near 18 keV in $1806-20$ spectra do not suggest self-absorption. Also, equation (6) is derived assuming a classical treatment of synchrotron emission and it does not take into account general relativistic effects. Furthermore, the replacement made in equation (12) of Liang (1986) for the cooling power-law case, producing the self-absorption constraint, is inappropriate if the putative self-absorption frequency is near ν_B (J. Brainerd, private communication). Thus for magnetic field strengths suggested by the steep turnovers observed in $1806-20$ spectra, synchrotron self-absorption does not appear to be dictated, and a roughly galactocentric distance is not precluded for $1806-20$. Similar conclusions hold for $0526-66$ at 55 kpc and $1900+14$ at 10 kpc. It is likely, however, that radiation transfer in highly luminous bursts is influenced by additional effects, as we now discuss.

We assume $B_{12} \sim 1$ and address the spectral shape and lack of spectral evolution in SGR bursts. With characteristic energies of 30 keV and a pronounced dearth of soft X-ray photons below roughly 10 keV when observations are available (Fenimore 1987), SGR spectra are relatively narrow compared to the spectra of other high-energy transients. Even classical γ-ray bursts, whose power output peaks at energies in the hundreds of keV or higher, still exhibit average photon spectra which increase with decreasing energy to as low as 2 keV (e.g., Gilman *et al.* 1980; Katoh *et al.* 1984). Therefore, the soft X-ray paucity problem, which arises if a significant fraction of the γ-ray burst flux thermalizes upon intercepting the surface (Imamura and Epstein 1987), is more acute for SGR bursts. Recently it has been argued that the flux extending up to tens of MeV in γ-ray bursts can be produced in strong magnetic fields by a cascade of curvature and synchrotron radiation (Sturrock, Harding, and Daugherty 1989) or by cyclotron upscattering of low-energy photons by relativistic electrons (Fenimore, Epstein, and Ho 1989), and that sizable portions of this flux can escape if beamed (Ho, Epstein, and Fenimore 1990). Therefore, problems are introduced at each end of the observed spectrum if we assume that the SGR burst emission region is confined near the surface of neutron stars with 10^{12} G fields.

We suggest that the conditions of a 10^{12} G field and the high luminosity required if SGR sources are at distances of tens of kiloparsecs, together solve both the hard γ-ray and soft X-ray problems in a self-consistent way. In the context of γ-ray bursts and Cygnus X-1, Kazanas and Ellison (1986) and Kazanas (1986) discuss how soft quasi-thermal spectra result at sufficiently high luminosity and small source size. In their mechanism, the soft spectrum is produced as protons accelerated by shocks undergo nuclear interactions, thereby producing pions, and ultimately a high pair density. The model operates in a region of relatively low magnetic field so that the shock mechanism can accelerate protons efficiently; if instead $B_{12} \sim 1$, a high number density is required ($n > 3 \times 10^{25}\ \text{cm}^{-3}$). An alternative mechanism for producing the pairs and high-energy gammas in a strong magnetic field is by acceleration of ions to relativistic energies along an electric field (Mitrofanov 1984), with a resulting curvature radiation cascade (cf. Sturrock, Harding, and Daugherty 1989).

For either pair creation mechanism, the salient feature (Kazanas 1986) is that pairs injected via pion decay are not in equilibrium with the emitting plasma; the injected pairs cascade ($\gamma\gamma \rightarrow e\text{-}e+$) through several generations, giving rise to a high pair density. Hard γ-rays propagating through this cool pair plasma are degraded, and the emergent, observed radiation field is much cooler than $kT \sim m_e c^2$, for a sufficiently high pair density. Kazanas shows that for a high source compactness, L/R, the optical depth is large and the observed burst spectra can be arbitrarily soft, exhibiting a quasi-thermal shape. The pair optical depth (Kazanas and Ellison 1986) is related to the compactness,

$$\tau_{\text{pair}} \simeq 2.8[(L/R)/(10^{29}\ \text{ergs cm}^{-1}\ \text{s}^{-1})]^{1/2}\,. \quad (8)$$

For $L \sim 10^{40}$ ergs cm^{-2} s^{-1} and $R \sim 10^6$ cm, we obtain $\tau_{\text{pair}} \sim 10^3$. Thomson scattering would dominate the SGR spectrum at all frequencies *except* that the presence of the magnetic field significantly modifies the radiation transfer near the cyclotron frequency. Cyclotron opacity dominates electron scattering at the fundamental cyclotron energy, $\nu_B \sim 11.6$ keV ($B_{12} \sim 1$),

$$\tau_{\text{cyc}}/\tau_{\text{es}} \simeq 1.6 \times 10^4(B_{12})^{-1}(T/10^9\ \text{K})^{-1/2}\,, \quad (9)$$

while at energies greater than about 200 keV, electron scattering dominates (Lamb 1982, p. 266). SGR spectra are rapidly decreasing above 100 keV (Atteia *et al.* 1987); thus the observed spectra above ν_B are roughly consistent with cyclotron emission and scattering, modified at higher energies by scattering in an optically thick pair plasma.

These same requirements—a high-luminosity, radiation-dominated burst and an optically thick pair plasma—serve to convert soft X-rays to cyclotron photons by the resonant Compton scattering process. Brainerd (1989*b*; cf. Dermer 1989) shows that the first excited Landau level (= 1) is significantly populated compared to the ground level (= 0) if the radiation density is sufficiently high, and the ratio of cross sections for resonant Compton scattering, $1 \rightarrow 0 : 0 \rightarrow 0$, is larger than unity for photons with energies below about 5 keV. For a luminosity of a few times 10^{39} ergs s^{-1} the transition probabilities are approximately equal (Brainerd, eq. [2]), assuming an emission area the size of the whole neutron star surface, and that all the pair energy is converted to radiant luminosity. For SGR burst luminosities greater than $\sim 10^{40}$ ergs s^{-1}, the $1 \rightarrow 0$ transition will dominate completely. Therefore, soft X-rays will preferentially scatter off particles occupying the first excited level, rather than the ground level, and be converted to cyclotron energy photons; the high photon flux near the cyclotron frequency ensures prompt radiative reexcitation of the emitting particle. The high-energy γ-rays scattered by the optically thick pairs will emerge near the cyclotron frequency, thus the cyclotron flux necessary to upscatter soft X-rays will be continuously pumped.

In effect, a sufficiently high density of pion-produced pairs in a strong magnetic field can narrow the spectrum on both the low and high ends, by degrading hard γ-rays, thereby enhancing the cyclotron flux necessary for resonant Compton upscattering of soft X-rays. Even at number densities high enough (3×10^{25} cm^{-3}) for the shock mechanism to accelerate protons in a 10^{12} G field, the 30 keV plasma would still be radiation-dominated and magnetically confined near the stellar surface since $B^2/8\pi \gg aT^4 \gg nkT$ (see Lamb 1982, Fig. 5). No appreciable spectral evolution is therefore expected since the characteristic observed frequency of the burst is defined by the magnetic field of the last scattering zone, which is near the surface field value. That evolution *is* observed in classical gamma-ray bursts, where strong magnetic fields are inferred to exist from the presence of spectral features attributable to cyclotron absorption or scattering (e.g., Murakami *et al.* 1988), is not inconsistent with the requirements for SGRs: classical bursts routinely attain characteristic energies sufficient ($kT \gtrsim 200$ keV) to overwhelm the energy density of the magnetic field during portions of an event (as we suppose happened in the March 5 burst). An observable annihilation line is not expected in SGR bursts since only annihilating pairs within the last scattering zone will contribute, and therefore the relative strength, line to continuum, is inversely proportional to the optical depth, $\tau_{\rm pair}^{-1} \sim 10^{-3}$ (Brainerd 1989*a*).

Thus, the narrow SGR spectra observed from 1806−20 are consistent with burst luminosities as high as 3×10^{41} ergs s^{-1}. Predicting the precise spectrum of an SGR burst will of course require extensive modeling (e.g., angular dependences, importance of higher cyclotron harmonics in resonant Compton scattering, constraints from lack of observable annihilation line), a program which we plan to undertake.

V. DISCUSSION

We have argued for the viewpoint that the three known SGR bursters are explained most economically and consistently as belonging to a single class, with source distances of tens of kiloparsecs. The SGR celestial distribution, probable progenitors, burst maximum flux ratios, $V/V_{\rm max}$ and $A/A_{\rm max}$ tests, lack of counterparts in other wavebands, and burst spectral characteristics—all are consistent with this picture.

If a hypothesis for nearby SGRs is nevertheless entertained, one is confronted with the question: Over a monitoring period of 10 yr, why is the number of sources detected so few and so well correlated with distant Population I objects, while the observed range in the sources' maximum peak intensities is greater than 10? The claim may be made that the March 5 superburst represents the upper end of the intensity distribution for 0526−66, and that its high Galactic latitude is consistent with it being the nearest SGR source of a disk population. However, as discussed in § II, counting March 5 as an SGR burst then requires explaining a *gap* of a factor of 500 in this source's burst luminosity distribution. Considering the contrast in spectral hardness of the March superburst and SGR bursts, it seems more plausible that the unique intensity of March 5 reflects a burst mechanism that is qualitatively distinct from, but obviously intimately related to, the SGR burst mechanism.

We now discuss the viability of several proposed models for SGR energy release mechanisms. The inadequacies of some energy release mechanisms have been stressed previously for the specific case of 1806−20 (Laros *et al.* 1987; Atteia *et al.* 1987; Kouveliotou *et al.* 1987). In attempts to explain the March 5 superburst, some models have been proposed outside the framework of an SGR class, necessarily requiring the SGR bursts from 0526−66 to be of a qualitatively different nature than those from the other two SGRs. Although this viewpoint ignores the apparent unity of an SGR class, the existence of two inherently different mechanisms for SGR bursts is not *a priori* precluded. Each of these models, however, appears to be deficient in one or more respects in explaining the characteristics of SGR bursts themselves and/or the statistics of their recurrence. We then discuss SGR active lifetimes, an issue which is related to the likely progenitor population.

a) Improbable Energy Release Mechanisms

Models involving accretion of objects have been advanced to explain the SGR energy release mechanism and spectra. Livio and Taam (1987) proposed comets accreting onto nearby neutron stars ($d \sim 100$ pc). This model has been criticized by Paczyński (1989) on the basis of the probable dearth of comets near neutron stars and by Boer, Hameury, and Lasota (1989) because of the inadequate population of nearby neutron stars. Boer *et al.* avoid the statistical problems by assuming nearby (15 pc) white dwarfs to be the objects undergoing cometary accretion. They predict an optically thin thermal bremsstrahlung spectrum, which is inconsistent with the spectra below about 20 keV for the strong events observed by *ICE* (Fenimore 1987). In addition, Boer *et al.* contend that 0526−66 must be of a different nature, even though the burst attributes of this source are very similar to those of 1806−20 and 1900+14. Spectral variability might be expected in some accreting object scenarios, when an expanded radiating surface collapses, as predicted by Colgate and Petschek (1981). In any case, nearby white dwarfs should be found in the SGR error boxes if the model is somehow correct (Paczyński 1989).

A model involving episodic accretion from a disk driven by a radiation instability has been proposed by Epstein (1985) for 0526−66. The model predicts a relationship between burst strength and recurrence time, which is not observed in 1806−20 (Laros *et al.* 1987), the SGR which provides the most statistically sensitive test. Recurrence times predicted by the model (0.2 yr) for 0526−66 are too long to explain some intervals for that burster, and would be longer still for 1806−20 if its distance is roughly 10 kpc. Also for large distances, direct powering by episodic accretion events encounters the problem of super-Eddington luminosities (10^{41} ergs s^{-1}). This appears particularly relevant for the longer, flat-topped bursts from 0526−66.

The merits of a thermonuclear energy release for the March 5 superburst are discussed in Woosley and Wallace (1982). Their models I and II predict recurrence times of 0.38 and 240 yr, respectively, and soft X-ray tails persisting for minutes to an hour after the γ-ray event. The thermonuclear model of Hameury *et al.* (1982) also predicts X-ray emission before and after the γ-ray burst. The details of how soft γ-ray emission is produced are not elucidated in these models, and they are not proposed specifically to explain SGR bursts. Nevertheless, we consider their applicability to SGR bursts.

Irrespective of source distances, there are several difficulties with the SGR bursts having a thermonuclear origin. No correlations are evident between burst fluence and the following burst interval for 1806−20 (Laros *et al.* 1987), as is observed in thermonuclear X-ray bursts (Lewin and Joss 1983). No extended soft X-ray tails are evident, even when several burst time profiles are summed together (Laros 1987). HXRBS identified a low-intensity component in two strong bursts (Fig. 1), but its persistence in each case is less than 1 s before and after the main event (Kouveliotou *et al.* 1987). Also, the very short recurrence times between some SGR bursts are incompatible with the predictions of thermonuclear models, as can be seen from the lower limits for recurrence times, listed in Table 2, derived from our *HEAO* A-1 upper limits for X-ray flux. A thermonuclear origin for 1806−20 has been discussed previously by Laros *et al.* (1987) and appears highly improbable. During November 1983 when 1806−20 was highly active, the required accretion to feed nuclear burning would translate into a bright source by X-ray standards. From the reported fluences of Atteia *et al.* (1987), and the *ICE* burst intensity distribution of Laros *et al.* (1987), assuming $\alpha \equiv \epsilon_x/\epsilon_{\rm TN} \sim 100$, we estimate that the X-ray flux, independent of distance, would have been about 2×10^{-9} ergs cm^{-2} s^{-1}, as bright as some of the luminous low-mass X-ray binaries.

Some models require multiply gravitationally lensed objects such as superconducting cosmic strings (Babul, Paczyński, and Spergel 1987) or supernovae (Paczyński 1986), and place some, but not all, SGRs at cosmological distances. Given the apparent neutron star nature of 0526−66 (e.g., 8 s periodicity) and the uniformity of SGR burst characteristics, these models do not economically explain the SGRs.

b) SGR Active Lifetimes and Likely Progenitor Population

As elaborated by Kouveliotou *et al.* (1989), if we indeed see to the edge of the galactic SGR distribution (as implied by the $V/V_{\rm max}$ test), we may assume that SGRs are neutron stars and estimate the SGR active lifetime in terms of the fraction of Galactic neutron stars which become SGRs. For a neutron star birth rate, $R_{\rm ns}$, the SGR-active lifetime can be expressed

$$\tau_{\rm active} \sim N_{\rm active}/(R_{\rm ns} f_{\rm SGR}) , \qquad (10)$$

where $f_{\rm SGR}$ is the fraction of neutron stars which become SGR sources. (Neutron stars which may be created by accretion-induced collapse of white dwarfs would be irrelevant to this discussion if they were born with weak magnetic fields, as believed; see Grindlay and Bailyn 1988.) Assuming that as many as 10 sources may be "active" (since the length of active episodes is not well constrained and since some SGR bursts possibly were missed by KONUS instruments; see estimate by Atteia *et al.* 1987), and using the observed supernova rate of about 1 in 50 years for $R_{\rm ns}$, we have

$$\tau_{\rm active} \sim 500 \text{ yr}/f_{\rm SGR} . \qquad (11)$$

The (apparently) anomalously low luminosity of SN 1987A would imply a significantly higher $R_{\rm ns}$ than previous extragalactic searches have estimated (Gaskell and Schmitz 1989), and therefore $\tau_{\rm active}$ would be lower.

An "active episode" is not a well-defined interval, but the meaning of $\tau_{\rm active}$ is clear: $\tau_{\rm active}$ comprises the sum of all SGR-active episodes in a source's lifetime. SGR 1900+14 was observed to produce bursts for only one and a half days out of 3 yr of monitoring by KONUS *11/12* and *13/14* (Mazets, Golenetskii, and Guryan 1979). *ICE* observations show that 1806−20 was intermittently active from 1979 to 1984, while *ICE* and HXRBS monitoring suggest that the source has been quiescent since then (Laros *et al.* 1987; J. Laros, private communication; Kouveliotou *et al.* 1989). SGR activity from 0526−66 was first observed 14 hr after the March 5 superburst, but continued throughout the *Venera 11/12* and *13/14* missions (Golenetskii, Il'inskii, and Mazets 1984). Thus, the duration of SGR–active episodes may well be source-dependent, e.g., a function of evolutionary state. Observations by the *Gamma Ray Observatory*'s Burst and Transient Source Experiment (GRO/BATSE) will extend the monitoring of these sources to more than 15 yr. If such future observations better determine $\tau_{\rm active}$, then $f_{\rm SGR}$ can be better constrained.

From equation (10) we see that SGRs are either rare objects, or objects which pass through (many?) active episodes whose total duration is relatively short. Note that if only one neutron star per hundred manifested SGR activity, then $\tau_{\rm active}$ would be about 5×10^5 yr. Total active SGR lifetimes would still be much shorter than, for instance, those of typical low-mass X-ray binaries, for which the accretion phase lasts 10^8–10^9 yr (van den Heuvel 1983), or of X-ray pulsars, whose 10^{12} G magnetic fields decay on a time scale of a few × 10^6 yr (White 1987).

Even though only the product $\tau_{\rm active} f_{\rm SGR}$ is constrained in equation (11), we can make an independent argument that $\tau_{\rm active}$ is short if the progenitors of SGRs are the Galactic radio pulsars, which number ($N_{\rm pulsar}$) ~ 1.5×10^5 (Narayan 1987). In this case all Galactic pulsars would be potentially detectable SGR sources if the arguments of § II are true. Pulsar characteristic ages, $\tau_{\rm char}$, are a few times 10^6 yr, and their magnetic fields are about 10^{12} G (Manchester and Taylor 1977). In § IV we argued that SGRs also have magnetic fields of order 10^{12} G. Assuming that SGRs evolve from radio pulsars and that the populations are in equilibrium, the SGR-active lifetime can be expressed in terms of the fraction, $f_{\text{pulsar-SGR}}$, of radio pulsars that become SGR sources while their magnetic fields are still relatively strong:

$$N_{\rm SGR}/\tau_{\rm active} = f_{\text{pulsar-SGR}} N_{\rm pulsar}/\tau_{\rm char} ,$$

or,

$$\tau_{\rm active} \sim \tau_{\rm char} N_{\rm SGR}/(f_{\text{pulsar-SGR}} N_{\rm pulsar})$$
$$\sim \text{few times } 100 \text{ yr}/f_{\text{pulsar-SGR}} \qquad (12)$$

The fraction $f_{\text{pulsar-SGR}}$ depends upon the distribution of such initial parameters as magnetic field strength and configuration, and rotation period, as well as the evolutionary path of the neutron star; a significant fraction of pulsars could end their lives with strong enough fields to become SGRs. We note that since only about 450 pulsars (Manchester 1987) out of 10^5 in the Galaxy are close enough to have been detected, we should not expect to have found pulsars in SGR error boxes. It is therefore possible that live pulsars could be SGR–active, if pulsing does not mask or preclude SGR activity, in which case $f_{\rm SGR}$ could be close to unity.

Rotation is slowed by electromagnetic braking during the pulsar lifetime. Subsequent to the active pulsar phase, braking mechanisms which may operate (e.g., gravitational radiation) are much less efficient and the rotation period no longer decreases significantly. Therefore, the period during which large structural stresses accumulate as a consequence of rotational deceleration is effectively bounded. During this interval the conditions necessary to produce starquakes exist. If these stresses are relieved on time scales comparable to or shorter than $\tau_{\rm char}$, then the hypothesis that starquakes in (half-) dead pulsars provide the energy for SGR bursts is consistent, in terms of apparent celestial distribution and population numbers, with radio pulsars being the progenitors of SGRs.

c) Circumstantial Evidence for Starquakes

The characteristics of the 1979 March 5 superburst by themselves do not necessarily favor the viewpoint that SGR 0526−66 is in the LMC. Association with the LMC is suggested by the coincidence of the source error box with the supernova remnant N49 (Cline *et al.* 1982). Cline (1981) has summarized the unusual properties of this burst, which include a rise time of $\gtrsim 0.2$ μs and width of the initial spike of 150 ms, a uniquely intense peak flux, and an oscillating decay with a periodicity of 8.0 s. Scenarios invoking neutron star corequakes to explain the March 5 superburst have been proposed (Ramaty *et al.* 1980, 1981; Kazanas 1988). At the LMC the peak flux of March 5 translates into an omnidirectional peak luminosity of more than 5×10^{44} ergs $\rm s^{-1}$, requiring a catastrophic event, as these previous treatments have hypothesized.

Since other energy release mechanisms involving thermonuclear events or accretion scenarios do not appear favorable, we consider the observational evidence that the SGR burst mechanism is generically related to that of the March 5 superburst, i.e., that both kinds of events involve release of internal gravitational potential energy. As Blaes *et al.* (1990) have noted, it is not clear that neutron starquakes occur, but the analogy to deep focus earthquakes—whose initiating mechanism is not well understood either—provides one motivation for their consideration. Other authors have investigated possible mechanisms of energy release in starquakes. Theories advanced to explain classical γ-ray bursts may contain elements relevant to SGR bursts (Pacini and Ruderman 1974; Tsygan 1975; Fabian, Icke, and Pringle 1976). In particular, Mitrofanov (1984) discusses dynamical conditions which may produce sufficient energy to power SGR bursts. We estimate that the total energy release of all 1806−20 events observed by *ICE* was roughly 10^{42} ergs (Laros *et al.* 1987), assuming a source distance of 10 kpc. Mitrofanov estimates the total mechanical energy available in (single) crustal starquakes to be 10^{46} ergs of which 10^{43} ergs may converted to γ-ray luminosity, whereas Blaes *et al.* estimate the maximum mechanical energy which can be stored in the crust to be much less, 10^{44} ergs for a 10^{-2} strain. Although there are discrepancies in theoretical treatments of these complex physical problems, we nevertheless examine the observations to see what evidence exists that starquakes power SGR bursts.

A few circumstantial clues in the chronology of SGR events suggest neutron star quake activity. The rarity of active SGRs suggests that these sources may be passing through relatively short periods of structural readjustment, during which the SGR mode is enabled and the available energy expended. This view is consistent with the idea that the March 5 superburst triggered an SGR–active mode in 0526−66. The KONUS *11/12* experiments were active for about 6 months prior to March 5, but did not detect any SGR bursts. The average interval between subsequent SGR bursts detected by KONUS *11/12* from 0526−66 was about 1 month. The fact that no superburst was observed to be associated with the other two SGRs suggests that active periods persist or recur on a time scale longer than a few years.

In addition, Kazanas (1988) explains the *Kosmos* 856 (Loznikov *et al.* 1980) observation of an 8.6 s period, observed in 1976 from a 3° × 3° field which included 0526−66, as a change in the neutron star's moment of inertia at the instant of the March 5 event. Kazanas' explanation is consistent with the phase transition model of Ramaty *et al.* (1980). Mechanisms which might bring about a phase transition include cooling of the neutron star, loss of angular momentum, or accretion. Such a catastrophic event could leave the star in an metastable configuration with the potential for generating smaller releases of gravitational potential energy as the stellar material seeks equilibrium.

The stochastic pattern of SGR events and burst fluences might argue for a chaotic temporal process like earthquakes, for which recurrences are somewhat unpredictable (Julian 1990). Unfortunately, the meager evidence we have on glitches in pulsars is not sufficient to compare with the event pattern of 1806−20, at least for glitches in pulsar rotation with energetics large enough to meet the requirements for SGR bursts.

d) Future Observations of SGRs

Possibly fruitful approaches to searching for SGR burst counterparts are inspecting archival plates and monitoring source error regions in real-time for optical flashes. These approaches have been applied to two of the SGR sources, 0526−66 and 1900+14. The quest is more encouraging and potentially more efficient for SGRs than for classical bursters since SGRs are known to repeat on short time scales. Pedersen *et al.* (1984) discovered three flashes during real-time monitoring from the 0.1 $\rm arcmin^2$ source error region for 0526−66. Greiner *et al.* (1987) found three images on archival plates of 1900+14. Although one of these images lies very near but outside the border of the 3° × 0.04° source error region, the authors do not credit the image as necessarily being associated with 1900+14 since the frequency of plate defects and other unidentified photographic images can account for the majority of finds. Unfortunately, the concurring opinion of Hudec *et al.* (1987) emphasizes that all such investigations to date, including the experiment of Pedersen *et al.*, are plagued with the same difficulty: no candidate optical flashes have been observed by two independent telescopes or recorded simultaneously on two plates, or observed simultaneously with an SGR burst. This criterion of confirmation is usually applied to the γ-ray bursts themselves, and is especially appropriate in the case of SGRs since the bursts are usually so brief as to resemble in some respects the much more numerous noise spikes. Future search programs which may incorporate simultaneous γ-ray and optical monitoring would afford the potential of providing additional valuable constraints on SGRs. However, because of the high amount of reddening, optical detection is problematic if the sources are indeed located at galactocentric distances near the plane.

Even though the number of active SGRs appears to be very small, repeated outbursts provide multiple opportunities for observing the same source. Thus, it may turn out that the nature of SGRs and their burst mechanism(s) may be more easily unraveled than the mystery of classical hard spectrum γ-ray bursts. If SGR bursts result from neutron star quakes, strong vibrational modes may be excited which would drive oscillations in the magnetic field and in the emerging photon flux (Mitrofanov 1984). Such a signature would provide a probe of the neutron star interior. The BATSE experiment on *GRO* will have microsecond timing with spectral coverage down to about 15 keV (Fishman *et al.* 1989), affording the capability to search for neutron star oscillations in the millisecond regime. Oscillations at a level of 10% of the mean intensity should be discernible in intense SGR bursts. If only weaker oscillations are present, or if the oscillations are quasi-periodic, incoherent summation of Fourier transforms of several bursts from the same source could be performed to increase sensitivity. The fast, low-intensity component discovered in two bursts by HXRBS could be studied by summing several events. The spectrum of this component, if related to burst onset and/or cessation (which the HXRBS temporal profiles suggest), might be expected to differ significantly from the spectrum of the main event. In addition, it is important to monitor active SGRs with instruments sensitive to energies appreciably below the spectral turnover near 20 keV for possible fast evolution. This would aid resolution of the question of the radiation mechanism and yield information regarding reprocessed radiation if the sources are in binary systems.

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