Fall 9-15-1988

Thermal Cyclotron Reprocessing of Gammy-Ray Bursts - Theory and Model Spectra

Dieter H. Hartmann
Department of Physics and Astronomy, Clemson University, hdieter@clemson.edu

S. E. Woosley
Board of Studies in Astronomy and Astrophysics, University of California at Santa Cruz & Insitute of Geophysics and Planetary Physics, University of California

Jonathan Arons
Department of Astronmy and Department of Physics, Unviersity of California at Berkeley & Insititute of Geophysics and Planetary Physics, University of California

THE ASTROPHYSICAL JOURNAL, 332:777–803, 1988 September 15

THERMAL CYCLOTRON REPROCESSING OF GAMMA-RAY BURSTS: THEORY AND MODEL SPECTRA[1]

DIETER HARTMANN AND S. E. WOOSLEY
Board of Studies in Astronomy and Astrophysics, University of California at Santa Cruz; and Institute of Geophysics and Planetary Physics, University of California, Lawrence Livermore Laboratory

AND

JONATHAN ARONS
Department of Astronomy and Department of Physics, University of California at Berkeley; and Institute of Geophysics and Planetary Physics, University of California, Lawrence Livermore Laboratory
Received 1987 December 21; accepted 1988 March 15

ABSTRACT

We examine the generation of infrared, optical, and ultraviolet flashes from single, magnetized neutron stars that are experiencing a γ-ray burst. Cyclotron reprocessing of energetic γ-ray burst photons in the neutron star magnetosphere is assumed to be the underlying mechanism responsible for the display at longer wavelengths, and thermal equilibrium is assumed in order to calculate the electron distribution function. It is shown that these are good approximations for a wide range of conditions expected in neutron star magnetospheres. The thermal cyclotron model proves capable of generating optical outbursts similar to bright historical events, although optical transients most likely would be much fainter. For a wide range of conditions the model predicts bright, nondelayed flashes, extending in some cases even beyond the ultraviolet. Since the emission at long wavelengths is correlated with the γ-rays down to time scales small compared with the burst duration, time-averaged spectra are calculated corresponding to the time-averaged γ-ray burst spectrum. For flashes that do not exhibit a spectral turnover in the optical region, $L_{\rm opt} \propto B_s^{\alpha}$ with $\alpha \sim \frac{3}{4}$, so that optical transients could be used to constrain the magnetic field strength and distance of γ-ray burst sources. The long-wavelength fluxes for the recently discovered soft repeating source SGR 1806−20 are also estimated.

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

I. INTRODUCTION

Since the discovery of cosmic γ-ray bursts in 1967 (Klebesadel, Strong, and Olson 1973), the nature of these events has remained an unsolved riddle. However, it is now widely believed that they originate on or near the surface of accreting neutron stars in the general vicinity of our own Galaxy (e.g., Lamb 1984; Woosley 1984). Beyond this paradigm there is still much uncertainty; typical source distances are not known to a reasonable degree of accuracy, the question of the neutron star membership in a binary system or the possible presence of an accretion disk has not been answered satisfactorily, and the presence of strong magnetic fields of order 10^{12} G as inferred from low-energy spectral features in some burst spectra has been the subject of much debate.

Typical observations of γ-ray bursters cover the photon energy range between a few tens of keV and a few tens of MeV. Ever since the discovery of these sources, it was realized that identifying them with objects emitting at other wavelengths would result in significant progress toward our understanding of these mysterious events. Unfortunately, to this date no object detected at any other wavelength has been unambiguously identified with a γ-ray burster.

Low-energy γ-ray burst counterparts might be identified during their quiescent phases. However, in this work we examine the *transient* emission at "optical" wavelengths that might accompany γ-ray bursts, the so-called optical flashes (or optical transients [OTs]). Here "optical" is defined in a general sense to include infrared and ultraviolet radiation. We further consider only the emission originating at the source, i.e., we exclude optical flashes produced in the Earth's atmosphere by fluorescence (Bhat *et al.* 1981) or Cerenkov emission from relativistic electrons that are created in the air by the primary γ-ray burst photons (Zhemerev, Medvedev, and Stepanov 1974; Fegan *et al.* 1975; Gopalakrishnan *et al.* 1981; Vzorov *et al.* 1985), and we seek an explanation that does not necessarily require companion objects.

We first summarize the observational and theoretical status of the research on transient optical flashes associated with γ-ray burst sources. For complementary reviews see Liang and Petrosian (1986) and Hartmann and Woosley (1988).

a) Optical Flashes: Present Observational Status

Early attempts to detect optical flashes from γ-ray burst locations (Grindlay, Wright, and McCrosky 1974), utilizing meteor patrol pictures of the prairie network, gave only lower limits for the ratio of energy emitted in the γ-range to the energy emitted in the optical band ($R_{\gamma o} = E_\gamma/E_o \sim 100$), consistent with more recent studies of similar nature (Halliday, Blackwell, and Griffin 1978; Hudec 1985; Hudec *et al.* 1984, 1986, 1987*a*). The intriguing discovery of three historical optical flashes within modern γ-ray burst error boxes on a subset of the archival photographs at Harvard (Schaefer 1981; Schaefer *et al.* 1984*b*) was the first indication that optical emission does indeed accompany γ-ray bursts. $R_{\gamma o}$ was found to be of order 10^3. Other archival searches stimulated by Schaefer's discovery continue to turn up further OT candidates (e.g.,

[1] *Lick Observatory Bulletin*, No. 1105.

Moskalenko *et al.* 1987), but the findings are not yet compelling. However, it should be kept in mind that the identification of historical optical transients with more recently observed γ-ray bursts (GRBs) is by no means guaranteed. Subsequent deep CCD surveys of the 1928 OT/1978 GRB field (Schaefer, Seitzer, and Bradt 1983; Pedersen *et al.* 1983) revealed no quiescent counterpart brighter than about 23d magnitude, and a recent search of about 1500 hr of archival plates covering 10 γ-ray burst error boxes (Atteia *et al.* 1985) did not reveal optical flashes of similar type to the ones reported by Schaefer and his coworkers. Perhaps the most convincing candidate for a truly cosmic optical flash source was recently discovered by Hudec *et al.* (1987*b*) on three archival plates of the Sonneberg Observatory collection (see also Bignami 1987). However, the association of this optical source with the nearby γ-ray burst GB 790325b appears to be unlikely (Hartmann *et al.* 1988; Laros 1988).

Several optical flashes were reported from the site of the famous 1979 March 5 event (Pedersen *et al.* 1984). The absence of simultaneous γ-ray bursts on these occasions places an upper limit of about 10^4 on R_{γ_o}. However, of all the transient events observed, only the optical flash of 1984 February 8 remains a strong candidate for a true optical flash from a γ-ray burst source (Schaefer *et al.* 1987*a*). This conclusion is consistent with a recent study by Maley (1987), who did not find coincidences between the optical flashes and known satellite positions. A possible periodicity of 164 days suggested for this source (Rothschild and Lingenfelter 1984) led to the worldwide "Multifrequency March 5, 1979, Burst Watch" program. So far, this program has resulted in the detection of two radio and two optical transients, but none has been confirmed by simultaneous observations with two or more instruments (see Hurley 1987 for a summary of the watch campaign).

Following Schaefer's original work, an increasing number of optical flash candidates have been suggested. In particular, the recently discovered "Perseus Flasher" (MacRobert 1985*a*, *b*; Katz *et al.* 1986) drew the attention of many workers in the field. However, despite considerable effort, no confirmation of the reality of this source was obtained. A near-Earth origin of these flashes, e.g., reflection of sunlight off tumbling satellites, was made plausible in several recent publications (Maley 1987; Schaefer *et al.* 1987*c*; Vanderspek, Zachary, and Ricker 1986). In fact, ground-based searches for optical flashes, archival as well as direct wide field of view (FOV) monitoring (ETC/RMT [Ricker *et al.* 1984; Teegarden *et al.* 1984] and GMS [Pedersen 1987]), are heavily contaminated by high background rates of satellite glints and meteors (Schaefer 1985; Schaefer *et al.* 1987*a*). A promising new approach to perform simultaneous multi-wavelengths wide-FOV monitoring from space is the High Energy Transient Experiment (HETE) that has been proposed to NASA by G. Ricker and collaborators. This experiment is designed to provide for the first time simultaneous burst observations in the UV, X-ray, and γ-ray bands.

As of this writing, we have to consider bright optical flashes accompanying all γ-ray bursts as a possibility but not an established fact. Simultaneous observations of γ-ray bursts and accompanying optical emission are needed to provide evidence for or against this paradigm. For additional details of major searches for optical flashes we refer the reader to the proceedings of the 1984 Stanford University Workshop on Gamma-Ray Bursts (Liang and Petrosian 1986) and the 1987 Los Alamos Laboratory Workshop on Multiwavelength Astrophysics (Hartmann and Woosley 1988).

b) Optical Flashes: Current Theory

Lucretius (*De rerum natura* bk. 4 [55 BC]) said: "There are some phenomena to which it is not enough to assign one cause: we must enumerate several, though in fact there is only one." Even with a marginal data base at hand, a variety of theoretical models have been suggested for the optical flash phenomenon. London and Cominsky (1983) modeled the 1928 OT/1978 GRB event as the reprocessing of a small fraction of the hard radiation by a companion main-sequence star, a degenerate dwarf, or an accretion disk (see also Epstein 1985). Reprocessing of X-rays into optical light is a well-known phenomenon in X-ray burst sources (London and Cominsky 1983; London 1984; Cominsky, London, and Klein 1987). London and Cominsky (1983) concluded that the particular event 1928 OT/1978 GRB could not be explained within the *binary reprocessing scenario.* The problem stems from the fact that one has to explain both the bright optical display during outburst ($R_{\gamma o}$ is *only* of order 10^3) and the extremely low emission during quiescent times, as inferred from the deep CCD surveys.

Rappaport and Joss (1985) reconsidered the work of London and Cominsky and concluded that this model might be viable after all. The new twist in their work was the consideration of nearby binary systems with H-rich secondaries of mass less than about 0.06 $M_\odot$ (dark dwarfs). A detailed investigation of the reprocessing of hard photons in the atmospheres of such low-mass stars was subsequently carried out by Melia, Rappaport, and Joss (1986), who found marginal agreement between the observed and calculated ratios of γ-ray fluence to optical fluence at the Earth for source distances near 25 pc. This result was also found in independent calculations of Cominsky, London, and Klein (1987). However, if the systems are that close, the nondetection of quiescent counterparts becomes a severe problem. More recently, Melia (1988) modeled the reprocessing of γ-ray burst photons in an accretion disk surrounding a neutron star. For the "standard" accretion disk the same dilemma emerges. As a possible solution Melia considered nearby "cold" disks in which the viscosity stems mainly from degenerate electrons (see also Epstein 1985; Michel 1985). That way one can generate sufficient optical fluence at Earth without generating a large quiescent flux of the disk. Melia found that optical/UV events similar to those discovered by Schaefer could be produced for burst distances between ~ 15 pc and ~ 250 pc. At these distances, a detection of the cold disk in the infrared should be possible for K-band sensitivities below ~ 2 μJy (see also Epstein 1985). Existing K-magnitude limits on a few γ-ray burst error boxes (Schaefer *et al.* 1987*b*), though already posing severe limits on this model, are not yet sufficient to test this prediction. However, improved IR observations with a limiting magnitude of $K \sim 22$ that can do so are in progress (B. E. Schaefer 1987, private comunication).

A different scenario involving a binary system has been suggested by Tremaine and Żytkow (1986). Reconsidering the model of Harwitt and Salpeter (1973) and Colgate and Petschek (1981), in which a comet impact on a neutron star causes the γ-ray burst, the authors propose that optical flashes might be generated *uncorrelated* with the γ-burst, by a comet impact on a white dwarf companion. However, the observational constraints from the ratio of transient to quiescent brightness appear to rule this out (Katz 1986; Schaefer *et al.* 1987*b*).

Interpreting the observation that no γ-ray burst source is associated with a luminous quiescent counterpart as an indication that they are in fact isolated objects, Katz (1985) proposed nonthermal processes in the neutron star magnetosphere as origin of the optical emission. Ruderman (1987) suggested that curvature radiation from electron-positron pairs that rapidly fill plasma-starved regions in the magnetosphere could produce transient optical emission. Collective processes for burst emission at wavelengths other than γ-rays were invoked recently by Liang (1985), who considered emission in the EUV region resulting from enhanced plasma line radiation at ω_p and $2\omega_p$, and Sturrock (1986), who discussed IR, optical, and UV emission resulting from plasma oscillations driven by a two-stream instability as in some models of radio pulsar emission. Unfortunately, no detailed calculations of the expected spectrum have been performed for the proposals of this paragraph.

Alternatively, Woosley and Arons considered the formation of optical flashes far above the surface of strongly magnetized neutron stars undergoing either a thermonuclear explosion of plasma accreted over long periods of time (*nuclear model*) or equivalently, a sudden impact of a large amount of plasma (*gravity model*), be it a solid body or plasma from an accretion disk (Woosley 1984). Strong surface fields are indicated in γ-ray burst sources by the observed low-energy features in the spectra of a small fraction of γ-ray bursts (e.g., Mazets *et al.* 1981) if these features can in fact be interpreted as cyclotron resonances (see Mészáros, Bussard, and Hartmann 1986 for a discussion of this interpretation). In Woosley and Aron's model the mechanism for the optical emission is cyclotron radiation from thermal electrons far above ($r \sim 10^8$ cm) the surface of the neutron star. The radiation is self-absorbed for about the first 100 harmonics, and the electrons are radiatively excited by Compton collisions with photons of the γ-ray burst. A schematic view of this thermal cyclotron reprocessing (TCR) model is shown in Figure 1. It is to the elucidating, expanding, and development of this model that the present paper is dedicated. We present the basic theory of the TCR model and give model spectra. The remainder of the paper is organized as follows: in § II we discuss the physical conditions that might be expected in the magnetosphere of a strongly magnetized neutron star that undergoes a γ-ray burst and present the basic physics of the TCR model. Specific predictions of the TCR model and a number of theoretical spectra obtained for different parameters are presented in § III. Finally, in § IV, we compare our spectra with observations and discuss the implications of our results for the development of new instrumentation.

II. THE THERMAL CYCLOTRON REPROCESSING MODEL

Following the earlier work of Woosley and Arons (Woosley 1984), we conjecture that the observed optical flashes are generated by reprocessing of γ-ray burst photons in the magnetospheres of strongly magnetic neutron stars. The magnetospheric plasma is heated by Compton interactions with the γ-ray burst to temperatures of the order of several hundred keV and emits photons at energies small compared with typical γ-ray energies (~ 1 MeV) as a result of cyclotron transitions in a strong magnetic field. With the additional assumption that the particle distribution functions are thermal, we shall call this scenario *thermal cyclotron reprocessing.* Although hot, magnetized plasma is a copious source of cyclotron photons, the emission at low frequencies is heavily suppressed if the plasma is optically thick to its own radiation. This self-absorption up to a limiting frequency $\omega_* = m_* \omega_c$ leads to the formation of a spectrum that is approximately that of a blackbody up to the frequency of the "last" optically thick cyclotron harmonic number m_* and drops rapidly to zero for

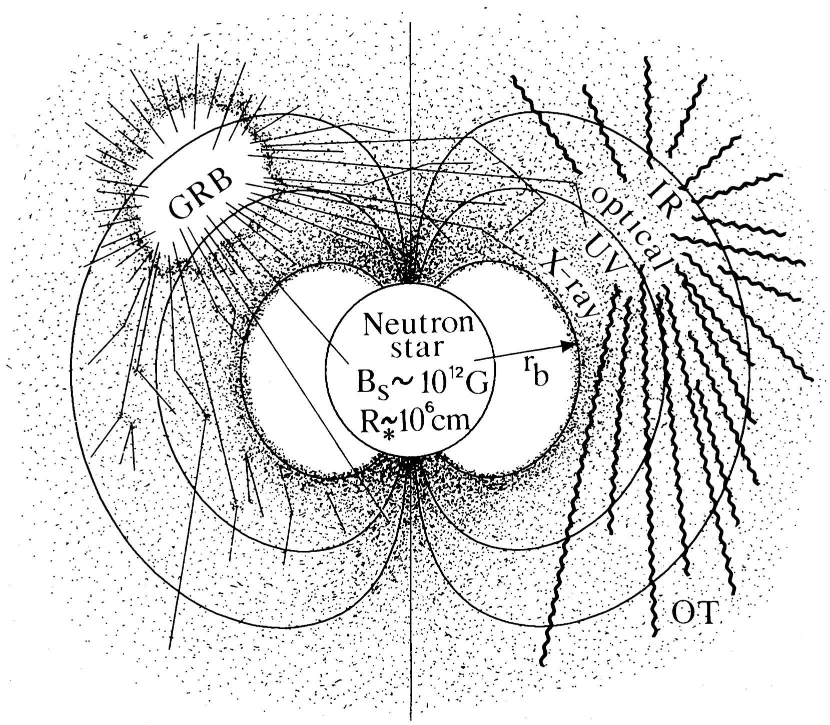

FIG. 1.—Schematic view of the thermal cyclotron reprocessing model. The γ-ray burst source region is assumed to be inside a plasma-filled magnetosphere around a strongly magnetized neutron star. The burst of hard photons energizes the plasma electrons through Compton scattering, and low-energy photons are then generated by cyclotron emission in the strong magnetic field. The bulk of the reprocessed "optical" radiation originates at a distance from the neutron star surface where the cyclotron fundamental frequency falls near the optical wavelength band. A plasma-deficient inner cavity with radius r_b is indicated.

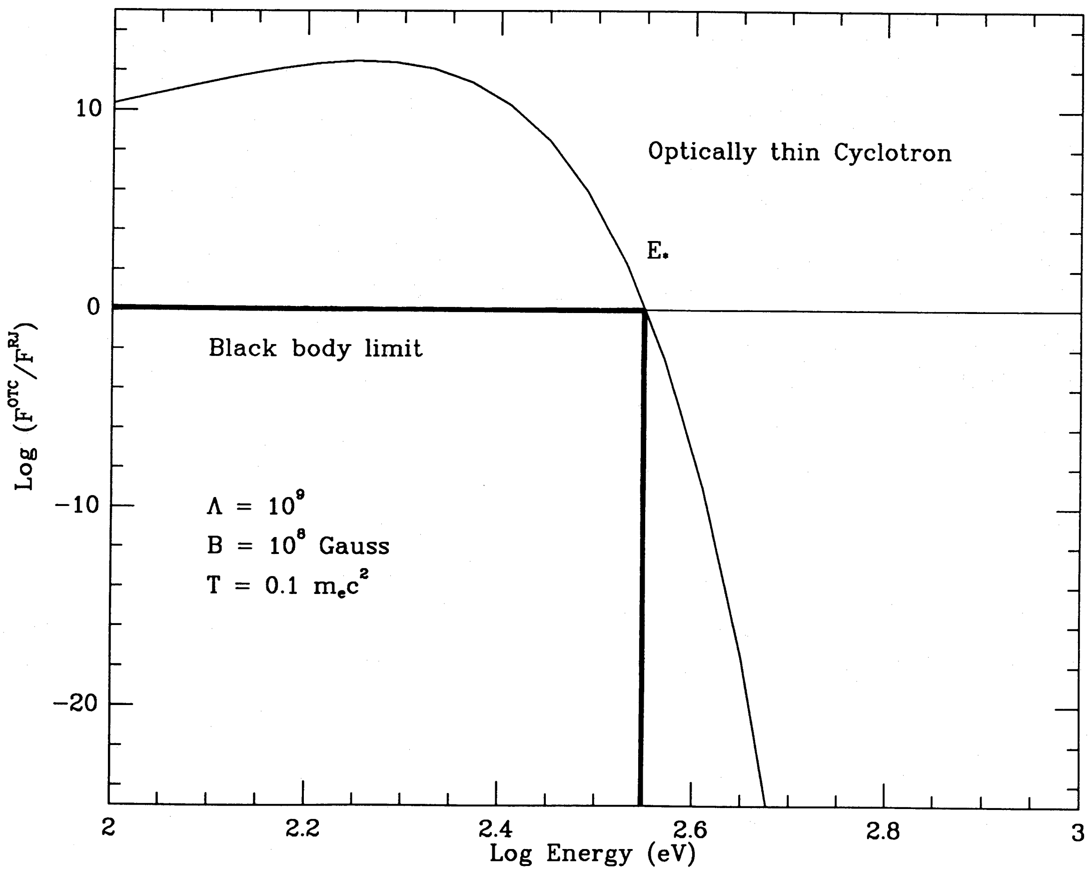

FIG. 2.—Thermal cyclotron spectrum (normalized to the blackbody flux) as a function of photon energy. Assumed temperature, magnetic field strength, and the dimensionless plasma parameter are given in the figure. Self-absorption results in an actually emitted flux that is blackbody-limited up to a "critical" energy E_* above which the plasma becomes optically thin. In the TCR model emission above E_* is neglected. The resulting spectrum is indicated by the bold solid line.

frequencies above this value (Fig. 2). If the emission site is at a distance $r_{\rm opt}$ from the neutron star surface such that $m_* \omega_c [B(r_{\rm opt})]$ falls near optical frequencies, the possibility for the generation of optical flashes arises.

In order to explain the observations of archival events, Schaefer (1981) and Schaefer *et al.* (1984*b*) infer that a total optical luminosity of

$$L_{\rm opt} \sim 5 \times 10^{36} R_{\gamma o}^{-1} D_{100}^2 \left(\frac{F_\gamma}{F_0}\right)\left(\frac{t_\gamma}{t_{\rm opt}}\right) \text{ ergs s}^{-1} \quad (1)$$

needs to be extracted from a γ-ray burst at a distance $100D_{100}$ pc that has a total observed flux in units of $F_0 = 4 \times 10^{-6}$ ergs cm^{-2} s^{-1} above 30 keV, and a duration of t_γ and $t_{\rm opt}$ in the γ-ray and optical regimes respectively. In the thermal cyclotron reprocessing model this occurs first by pumping energy into magnetospheric electrons by Compton scattering of hard γ-ray burst photons generated above the stellar surface and then by consequent reprocessing of this energy into lower energy channels by the process of thermal cyclotron emission. Because of substantial uncertainties in the values of $R_{\gamma o}$, D_{100}, and the ratio of burst durations at optical and γ-ray energies, optical luminosities at least an order of magnitude different from the "canonical" value 10^{36} ergs s^{-1} are possible.

Electron cyclotron radiation has been extensively studied in connection with laboratory fusion plasmas (Trubnikov 1958; Drummond and Rosenbluth 1960, 1963; Lam, Scharer, and Audenaerde 1985) and has been invoked for the X-ray emission from accreting neutron stars (Trümper *et al.* 1978; Voges *et al.* 1982) and active galactic nuclei (e.g., Takahara and Tsuruta 1982). It is the standard model for optical emission of AM Herculis cataclysmic variables, where it is assumed that an accreting magnetic white dwarf generates the observed strongly polarized light by this process (Chanmugam and Wagner 1979; Lamb and Masters 1979; Wada *et al.* 1980; Wickramasinghe and Meggit 1982; Langer, Chanmugam, and Shaviv 1982; Thompson and Cawthorne 1987). We note, in fact, that the physical conditions inferred for the AM Her systems are similar to the conditions in the neutron star magnetosphere at the distances we shall be considering, although the temperatures are of course much higher here.

a) *Magnetospheric Conditions*

It is generally believed that most, if not all, neutron stars are born with surface dipole magnetic field strengths of order of 10^{12} G. On the other hand, the consequent temporal evolution of the field is not very well understood. Radio pulsar observations indicate that the torques on rotating neutron stars decay (implying dipole moment decay *or* field alignment; cf. Michel 1986, 1987; Kundt, Özel, and Ercan 1987) on *e*-folding time scales as short as 10^7 yr (Lyne, Manchester, and Taylor 1985). However, recent work on neutron stars in binary systems indicates that such a rapid decay does not continue indefinitely, but rather that torque decay slows down after some 10 *e*-folding times, perhaps leaving the neutron star with a residual torque corresponding to a dipole moment with a surface field of order of 10^9 G (Taam and van den Heuvel 1986; van den Heuvel, van Paradijs, and Taam 1986; Kulkarni 1986). Also, the observation of cyclotron line features in γ-ray burst spectra itself indicates that field decay may not occur for many neutron stars.

Our ignorance regarding the multipole geometry is even greater. Flowers and Ruderman (1977) have argued that old neutron stars can have strong core-supported fields, but that the field geometry becomes highly disordered on time scales of $\sim 10^7$ yr due to ohmic dissipation in the crust (see also Wang and Eichler 1987). Here we assume for simplicity an axisymmetric dipole field

$$\boldsymbol{B}(r, \theta) = B(r)[(\cos\theta)\hat{e}_r + \tfrac{1}{2}(\sin\theta)\hat{e}_\theta] , \tag{2}$$

where θ is the angle between the radial vector $\boldsymbol{r}$ and the axis of symmetry $\hat{z}$. We parameterize the magnitude of the field by

$$B(r) = B_s\left(\frac{r}{R_*}\right)^{-m} , \tag{3}$$

where the surface field strength B_s and the power m are free parameters. This prescription, though apparently inconsistent for m different from 3, is useful to study the sensitivity of the thermal cyclotron reprocessing model to assumptions on the magnetic field configuration. We have also studied radial fields. In the following we will adopt a *standard* neutron star radius R_* of 10^6 cm. For the magnetospheric plasma electron density a similar scaling law,

$$n_e(r) = n_e(r_b)\left(\frac{r}{r_b}\right)^{-n} , \tag{4}$$

is adopted, where $r \geq r_b \geq R_*$ allows for a plasma-free sphere of radius r_b around the neutron star. There is no reason to expect the inner magnetospheric boundary to be spherically symmetric; this assumption was made merely for numerical convenience. Furthermore, since it is not *a priori* clear where this boundary should be located, we treat r_b as a free parameter. To estimate the expected range of the introduced parameters, we consider in the following a number of scenarios for loading the magnetosphere with plasma. Optical depth considerations are used below to determine roughly the "surface" value of the electron density, $n_e(r_b)$. If the magnetic field is sufficiently strong, a substantial amount of plasma might pile up at the magnetospheric radius (Arons *et al.* 1984 and references therein)

$$r_m \sim 3.5 \times 10^{10} \mu_{30}^{4/7} M^{-2/7} \dot{M}_{11}^{-2/7} \text{ cm} \gg R_* , \tag{5}$$

where $\mu_{30} = B_s R_*^3$ in units of 10^{30} G cm^3, M is the neutron star mass in solar units, and $\dot{M}_{11}$ is the mass accretion rate in units of 10^{11} g s^{-1}. In that case r_b would be of order r_m. In the limit of large mass accretion rates the matter eventually descends to the surface of the neutron star at the polar caps, being confined to an area of order 1 km^2. However, for extremely small accretion rates (as invoked for γ-ray burst sources) the polar "cap" may extend over the entire surface of the neutron star (Arons and Lea 1976, 1980; Arons *et al.* 1984; Arons, Klein, and Lea 1987; Arons 1986, 1987), corresponding to the case $r_b = R_*$. The density profile in that case is expected to have approximately $n = 2$. The same situation would occur if the field geometry is highly disordered ($m \gg 3$). On the other hand, in a thermonuclear explosion at or near the polar cap(s), proposed to be the cause of a substantial fraction of all γ-ray bursts (Woosley and Taam 1976), it is likely that a strong radiatively driven wind will be generated by the explosion. This impulsively loads the magnetosphere. Plasma streaming along magnetic field lines will fill magnetic shells beyond a radius that depends on the extent of the original polar cap and is of order 10^8 cm for a 1 km^2 cap. The flow geometry in that case may be approximated by $n = m$, and simple mass conservation arguments lead to an estimated surface density (at R_*) of about 10^{21} cm^{-3} (Woosley 1984). The plasma flow, however, would not be stationary beyond the radius r_s given by $B^2(r_s)/8\pi \sim \rho v^2(r_s)$. Considering outflow at the escape velocity ($v \sim 10^{10}$ cm s^{-1}), inflow in free fall, and rotation with a period $P \sim 1$ s, we estimate $r_s \sim 10^8$, 10^9, and 10^{10} cm, respectively. In this paper we consider several different model magnetospheres. We assume that the magnetospheric plasma is optically thin to the photons from the γ-ray burst, so that local Compton equilibrium will lead to a temperature distribution in the magnetosphere that depends on the γ-ray burst photon spectrum. The determination of the equilibrium temperature is described below. A typical value is 10^9 K or, equivalently, 100 keV (we use energy units throughout this paper), and we find that a constant temperature is established on short time scales. With a prescription of the magnetospheric conditions in hand, we now consider the question of the suitable "site" for the generation of the "optical" radiation.

b) The "Optical"-Flash Site

Schaefer and Ricker (1983) showed that the optical flashes must originate from a region orders of magnitude larger than a neutron star if thermal processes are to be responsible for the optical emission. Furthermore, for our model to work we need to consider locations at a distance above the neutron star surface such that the product of the local cyclotron frequency and the critical harmonic number m_* is of the order of optical frequencies. For the assumed neutron star radius of 10^6 cm, a surface field strength of 10^{12} G, and dipole geometry this leads to typical distances of $r \sim 10^8$ cm, consistent with the constraint of Schaefer and Ricker. In addition, in order to get photons with energies of a few electron volts out of the flash site, we require that the plasma frequency be less than about $\nu_{\rm opt} \sim 10^{15}$ Hz. This constrains the electron density to $n_e \leq 10^{22}$ cm^{-3}. Consider now the interaction of photons from the γ-ray burst site somewhere in the magnetosphere (Fig. 1) but not too close to the neutron star surface (otherwise too high an X-ray flux would be produced by γ-ray reprocessing in the neutron star surface; Epstein 1986; Imamura and Epstein 1987) with the magnetospheric electron gas. Making use of the scaling laws discussed earlier (eqs. [3] and [4]), the time between Compton encounters per photon can be estimated in the Thomson limit for an isotropic electron gas:

$$t_{\rm enc} = (n_e \sigma_{\rm T} c)^{-1} \sim 5 \times 10^{-9} n_{22}^{-1} r_6^n \text{ s} , \tag{6}$$

where $n_{22} = n_e(R_*) \times 10^{-22}$ cm^{-3}. However, this encounter time is not identical with the Compton time scale for the coupling of photon and electron energy, which is roughly given by equation (6) with the electron density replaced by the photon number density. For a large fraction of the magnetosphere this Compton time is much longer than the particle equilibration time (Fig. 3*a*), so that the non–LTE character of the γ-ray burst photon spectrum does not cause a non–LTE particle distribu-

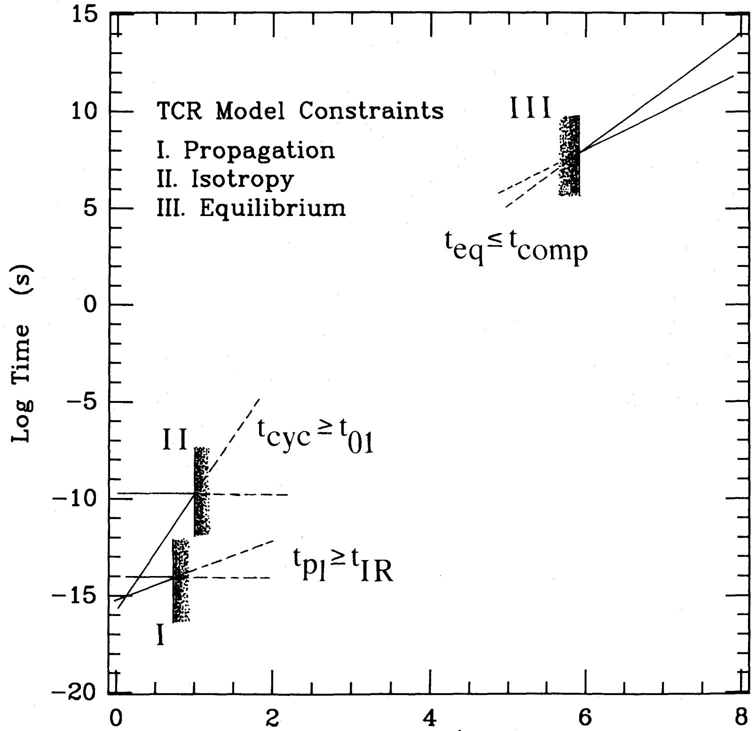

FIG. 3*a*

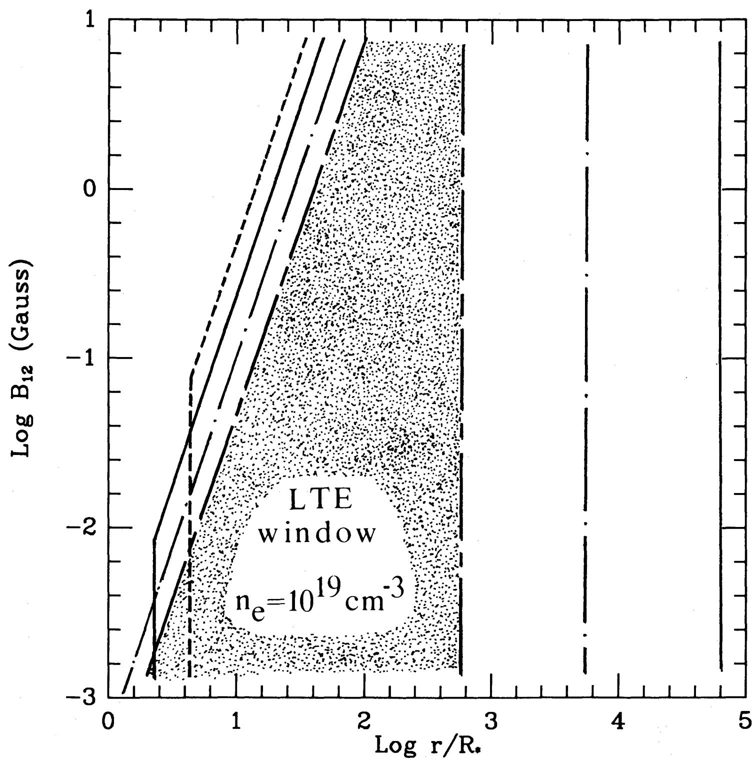

FIG. 3*b*

FIG. 3.—(*a*) Comparison of various time scales as a function of radius (normalized to the neutron star radius). Conditions I–III (Appendix A) have to be met for the TCR model to be applicable. For the set of parameters given in Appendix A this leads to the three constraints shown. At radii to the right of condition I ($t_{pl} \geq t_{IR}$) and condition II ($t_{cyc} \geq t_{01}$), and to the left of condition III ($t_{eq} \leq t_{Comp}$), the TCR model assumption of LTE is justified. For the particular case shown the TCR model assumptions are justified between about 10 and 10^6 neutron star radii. (*b*) On the basis of conditions I–III (Appendix A), we estimate the radius window where the TCR model assumptions are justified as a function of the surface magnetic field and particle density. The window is located between the lines. Different lines correspond to the densities of 10^{21} (*solid line*), 10^{20} (*dash-dot line*), 10^{19} (*long-short–dashed line*), and 10^{22} cm^{-3} (*dashed line*), respectively. For felds below 10^{12} G the model assumptions are justified in a sufficiently large radial window around the "optical" site as long as the surface density is in excess of about 10^{19} cm^{-3} (note that this value corresponds to the assumption $r_b = R_*$ and $n = 3$).

tion function. Employing the above scaling laws, we obtain for the ratio of encounter time to cyclotron time at the fundamental

$$\frac{t_{\rm enc}}{t_{\rm cyc}} \sim 2 \times 10^7 B_{12}^2 n_{22}^{-1} r_6^{n-2m} , \quad (7)$$

where $B_{12} = B_s/10^{12}$ G. When this ratio approaches unity, Compton scattering will cause a substantial population of high Landau states. Depending on the angle θ between the incident photon wavevector and the local magnetic field direction, each collision transfers some fraction (Arons, Klein, and Lea 1987),

$$\frac{\Delta\omega}{\omega} = \frac{1 + (\mu + \delta)(\epsilon\delta - \beta)}{\epsilon(\mu + \delta)^2} \times \left[1 - \left\{1 - \frac{2\epsilon\delta(\mu + \delta)^2(\epsilon\mu - \beta)}{[1 + (\mu + \delta)(\epsilon\delta - \beta)]^2}\right\}^{1/2}\right], \quad (8)$$

of the photon energy ω to the electrons, some of which goes into parallel kinetic energy ($T_{\parallel}$) and some of which leads to the excitation of higher Landau levels ($T_{\perp}$). Here $\mu = \cos\theta$, $\epsilon = \hbar\omega/m_e c^2$, $\beta = pc/m_e c^2$ are determined by the electron initial state; however, $\delta = \mu' - \mu$ is not uniquely determined because, in contrast to field free Compton scattering, the absorption of transverse momentum by the magnetic field leads to the conservation of energy and parallel momentum only. For average angles $\mu \sim \delta \sim 0.5$ and typical photon energies of order 1 MeV, this implies a single scattering energy transfer efficiency of about 20%. Near the surface the "perpendicular temperature" $T_{\perp}$ will be very small because of the rapid cyclotron cooling. At $r \sim 10^8$ cm, however, a nonnegligible population of the Landau levels is established by the joint action of Compton scattering and Coulomb collisions. A basic assumption of our present model is that at the "optical" flash site (at $r \sim 10^8$ cm), the energy perpendicular to the field is characterized by a temperature $T_{\perp}$ approximately equal to the temperature $T_{\parallel}$ parallel to the magnetic field, i.e., we assume an isotropic electron distribution function. Provided that the cyclotron decay time is sufficiently long, the distribution function will rapidly become isotropic owing to particle collisions. In Appendix A we further justify our assumption of a thermalized and isotropic distribution function. For a range of magnetic field strengths and plasma densities we show in Figure 3*b* the radial extent of the zone in the envelope where our approximations are valid.

The equilibrium temperature attained is given approx-

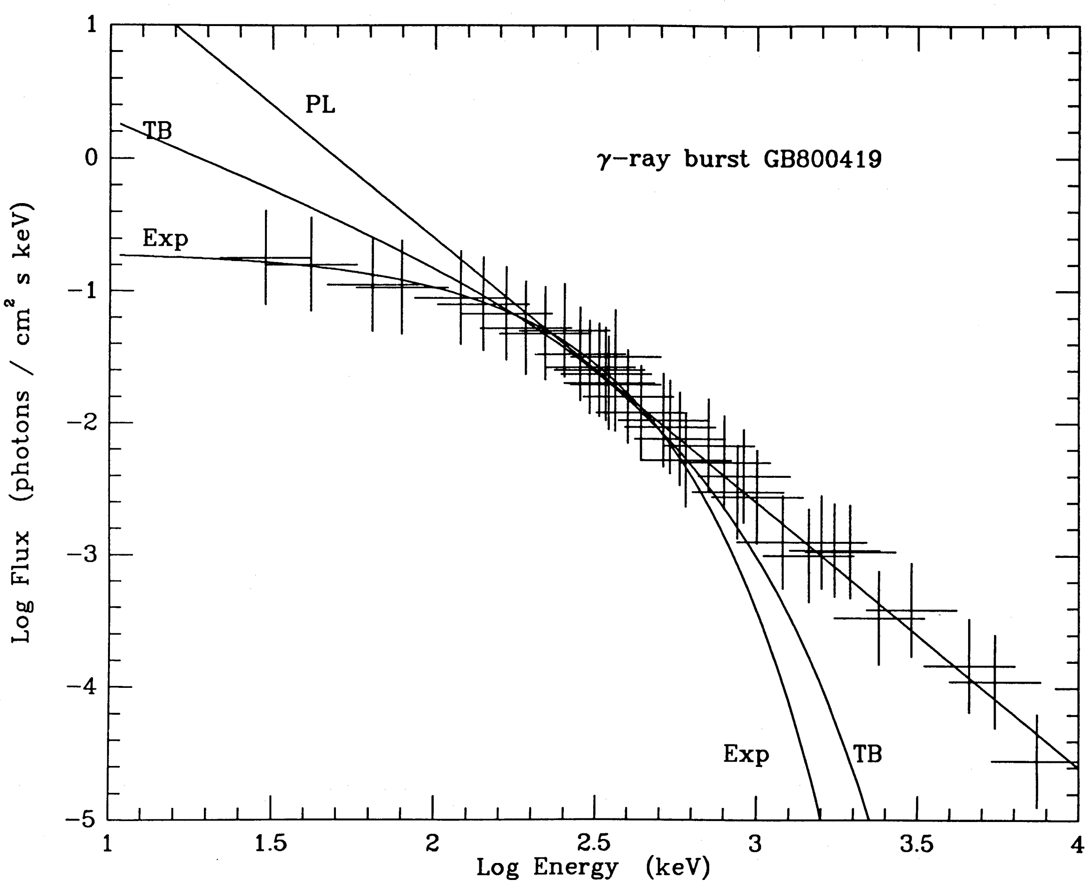

FIG. 4*a*

FIG. 4.—(*a*) Adopted input spectrum of γ-ray burst GB 800419. The data (*crosses*) are adopted from Dennis *et al.* (1981) and Nolan *et al.* (1984). The crosses shown approximately represent the measured error bars. Different functional forms can be used to fit the spectrum in different energy regimes. We employ a combination of a simple exponential, thermal bremsstrahlung, and a power law. These forms are convenient but should not be considered as representing the GB 800419 underlying radiation mechanisms. It is the spectral shape that determines the Compton equilibrium temperature of the plasma surrounding the neutron star that undergoes the γ-ray burst. (*b*) Same spectrum as in (*a*) but showing the power per logarithmic energy bandwidth, $P = d(\text{power})/d[\log(\text{photon energy})] \propto E^2(dN/dE)$, where dN/dE is the photon number flux per energy interval. The figure illustrates that GB 800419, like the majority of γ-ray bursters, emits predominantly in the MeV range and exhibits a salient decline at X-ray energies, a phenomenon termed "X-ray paucity" (Epstein 1986; Imamura and Epstein 1987).

imately by the Compton temperature at which electron heating by photons of typical energy $\langle E_\gamma \rangle$ is balanced by inverse Compton cooling. Considering all relevant time scales, we are led to the conclusion that $T_{\|} \sim \langle E_\gamma \rangle \sim T_{\perp}$ roughly represents the conditions in the magnetosphere. Therefore, we are able to invoke the theory of cyclotron emission from a plasma in thermal equilibrium, self-absorbed for many harmonic numbers, to obtain an estimate of the emergent spectrum (Bekefi 1966). For $r_b \geq R_*$ we neglect the possible contribution of plasma near the magnetic poles to the reprocessed spectrum. This is justified because the known X-ray paucity of γ-ray burst spectra (Imamura and Epstein 1987) and substantial γ-ray emission extending up to ~ 100 MeV (from *SMM* observations; e.g., Matz 1986) strongly suggest that the γ-rays originate high above the neutron star surface (see Fig. 1). As seen from that site, plasma confined to the vicinity of the magnetic poles subtends an extremely small solid angle and therefore cannot contribute substantially to the reprocessing of the γ-rays. The next step is to estimate consistently the magnitude of the magnetospheric equilibrium temperature established by Comptonization.

c) *Energy Deposition and Equilibrium Temperature*

Higdon and Lingenfelter (1986) showed that careful consideration of selection biases leads to the conclusion that the effective spectral "temperatures" of most γ-ray bursters are of order 1 MeV. This contrasts with earlier "canonical" values of about 100 keV frequently stated in the literature. In fact, the flux per logarithmic interval in energy of a typical γ-ray burst peaks around 1 MeV, i.e., most of the burst energy is carried by those high-energy photons (Epstein 1986). Spectral shapes can be represented by a variety of functions that correspond to various radiation mechanisms. Between photon energies of 100 keV and 1 MeV one often finds that a simple optically thin bremsstrahlung spectrum works well. Above 1 MeV a power law appears favorable to fit the data taken by the *SMM* satellite (Nolan *et al.* 1984; Matz *et al.* 1985; Matz 1986), and at energies below 100 keV a simple exponential can be used to describe a flattening of the spectra. Here we use the functional form

$$f_\gamma(\omega_m) = f_0(\omega_m)\omega_m e^{-\beta_0\omega_m} + f_1(\omega_m)\omega_m^{-\alpha} + f_2(\omega_m)e^{-\beta_2\omega_m}\ \mathrm{cm^{-2}\ s^{-1}\ keV^{-1}}\,, \quad (9)$$

where $\omega_m = \hbar\omega/m_e c^2$ and the step functions $f_i(\omega_m)$ select the appropriate functional form in a particular energy range. The inverse temperature parameters β_i are of order 1, and α is typically around 2.5 (Matz 1986). Note that the above functional is chosen for mere numerical convenience and does not necessarily represent the radiation processes operating in the burst source. The burst spectrum employed as input in this calculation is shown in Figures 4*a* and 4*b* and is chosen specifically to mimic the spectrum of GB 800419 (Dennis *et al.* 1981; Nolan *et al.* 1984). The flux-averaged photon energy of this spectrum is ~ 175 keV. If future observations provide simultaneous long-wavelength and γ-ray spectra, a consistent treat-

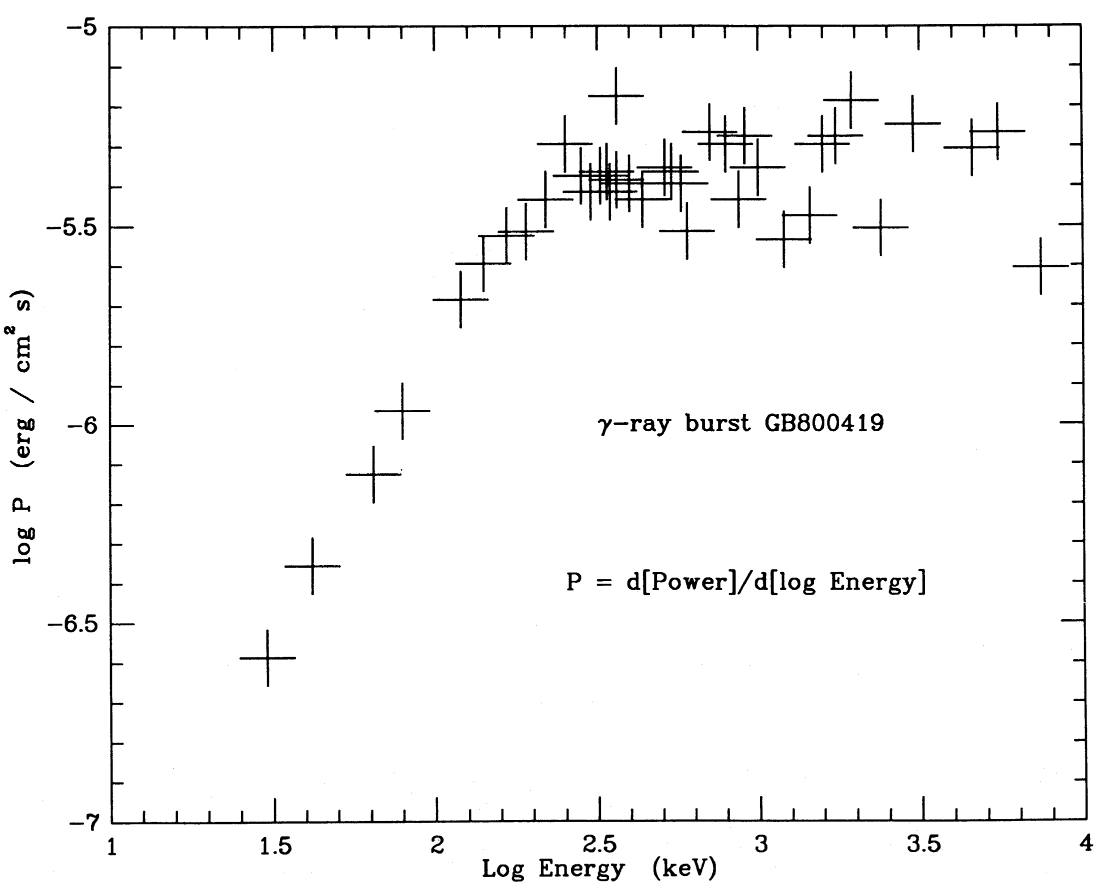

FIG. 4*b*

ment can be performed, but at the present time it suffices to use the above spectrum as an example.

Because of the large abundance of photons with energies above the electron rest mass, an exact calculation of the energy deposition requires a fully relativistic treatment of the Compton scattering cross section. In case of large Compton optical depth Monte Carlo techniques are used to calculate the photon-plasma interaction (e.g., Pozdnyakov, Sobol', and Syunyaev 1985). In this work we consider the opposite limit where the magnetospheric plasma is optically thin to Compton scattering. In that case the radiation field does not need to be calculated self-consistently; the γ-ray burst spectrum passes through the envelope essentially unmodified. Under these circumstances the calculation of the equilibrium temperature simplifies enormously. Except for high temperatures, the situation considered here is similar to the one of the intercloud medium of active galactic nuclei for which exact thermal Compton energy exchange rates have been derived by Guilbert (1986). To estimate the equilibrium temperature $T_{\rm eq}$ of the magnetospheric electron gas, we neglect cyclotron cooling and calculate $T_{\rm eq}$ implicitly from the condition that the thermal Compton energy exchange rate vanishes:

$$\int_0^\infty f_\gamma(\omega_m)\hat{\sigma}(\omega_m, \beta_m)\delta\omega_m(\omega_m, \beta_m)d\omega_m = 0 , \qquad (10)$$

where f_γ is the observed differential photon number spectrum described above, $\hat{\sigma}$ is the total Klein-Nishina scattering cross section averaged over a relativistic Maxwell-Boltzmann distribution with $\beta_m = mc^2/T$, and $\delta\omega_m$ is the average energy transfer per scattering (Guilbert 1986). The temperature obtained from the solution of equation (10) gives only an upper limit, but the true equilibrium should be close to this temperature because cooling by self-absorbed cyclotron photons is not very effective throughout most of the magnetosphere. For the selected input spectrum we obtain from equation (10) a temperature of 116 keV, which is close to our previous (§ II*b*) rough estimate, i.e., T is of the same order as the average photon energy. It is important to realize that one of the most important parameters of the cyclotron reprocessing model, the temperature of the plasma, is not a free parameter—as was assumed for convenience in a preliminary study (Hartmann, Woosley, and Arons 1987)—but has to be determined consistently from the observed γ-ray burst spectrum.

The time scale for reaching the optically thin Compton equilibrium temperature can be estimated from

$$t_{\rm eq}{}^{-1} = \frac{\dot{\beta}_m}{\beta_m} \sim 1.1 \times 10^7 \left(\frac{D_{100}}{R_6}\right)^2 \left(\frac{r_b}{R}\right)^{-2} y^{-2} \frac{\beta_m(y)}{K_2(\beta_m)} \times \int f_\gamma(\omega_m)\Phi(\omega_m, \beta_m)d\omega_m \ {\rm s}^{-1} \qquad (11a)$$

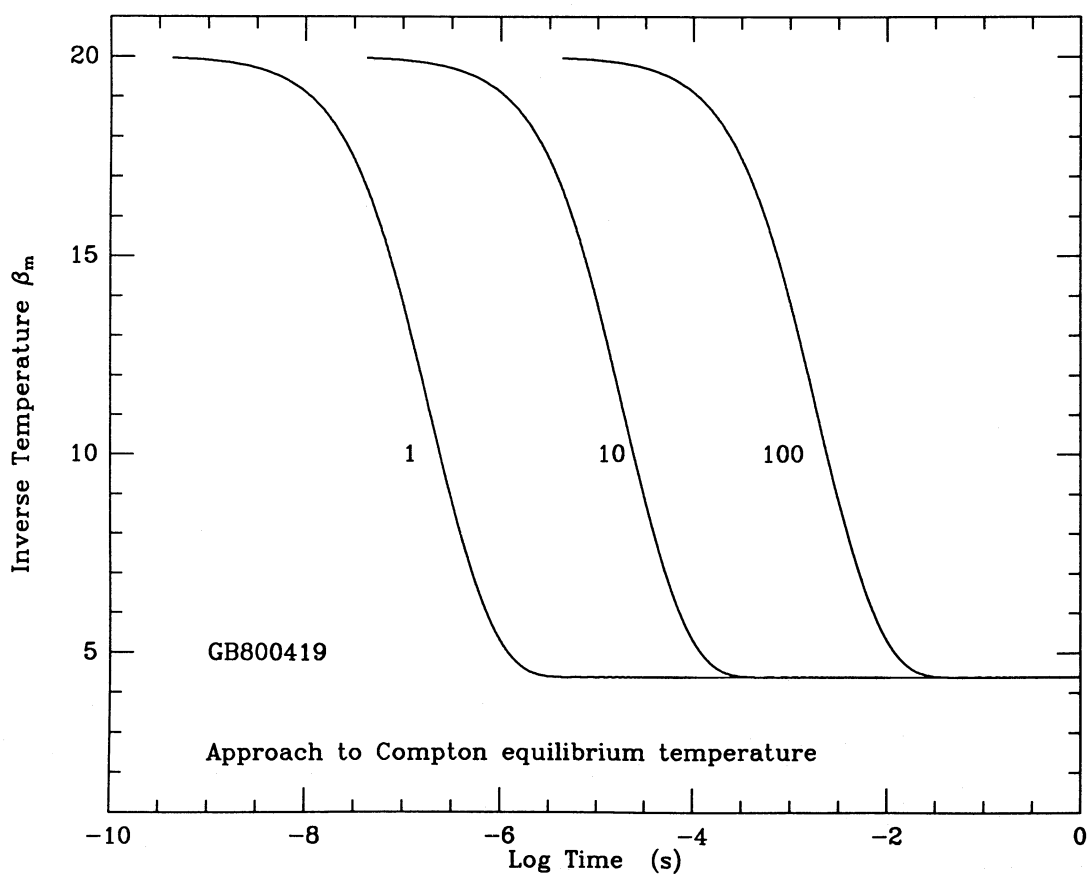

FIG. 5.—Approach of the magnetospheric plasma temperature (or its inverse β_m) at three distances in the envelope (the parameter of the curves is $x = r/r_b$) to the equilibrium value as given by the solution of the rate equations (11a) and (11b). On time scales generally short compared with typical burst durations (~1 s), the plasma reaches $T_{\rm eq}$ throughout the magnetosphere, so that the constant temperature is a good approximation unless the burst is of extremely short duration, as in the case for bursts from the soft repeating source SGR 1806 − 20 (Atteia *et al.* 1987).

where $y = r/r_b$ and

$$\Phi(\omega_m, \beta_m) = \int_{-\infty}^{+\infty} G(\omega_m e^{\phi})\left(\frac{1}{\beta_m} + \sinh\phi - \omega_m\right) \times e^{2\phi - \beta_m \cosh\phi} d\phi\,, \quad (11b)$$

where G is defined in Guilbert (1986). For typical parameters we find that this time scale is much shorter than the duration of the γ-ray burst, $t_\gamma \sim 1$ s. The approach to the equilibrium temperature for different positions in the magnetosphere calculated from equation (11) is shown in Figure 5. It is clear that for all but the shortest bursts a uniform temperature is established on time scales short compared with the burst duration. This justifies our assumption of an isothermal magnetosphere. Because of the short response time of the plasma in establishing the temperature, it is clear that the optical emission should track temporal changes of the γ-ray burst spectrum. An observed time correlation between long-wavelength emission and γ-ray flux would strongly support the TCR model. Here, since a time averaged γ-ray burst spectrum is used as input, the calculated optical spectrum is time-averaged correspondingly.

Our assumption that the optical depth τ_ω be small for all photon energies ω above $\omega_0 \sim 30$ keV,

$$\tau_\omega = \int_{r_b}^{r_{max}} n_e(r)\sigma_\omega(T) dr \ll 1\,, \quad (12)$$

can be used to estimate an upper bound on the "surface" electron number density by

$$n_s^{-1} = \frac{10^{22}\ \mathrm{cm}^{-3}}{n_e(r_b)} \sim 6.65 \times 10^{-1} r_b \zeta_{max} \tau_{0.01}^{-1} \int_1^{y_{max}} y^{-n} dy\,, \quad (13)$$

where $\tau_{0.01} = \tau/0.01$ and ζ_{max} is the maximum normalized scattering cross section in the range of frequencies for which the plasma is assumed to be optically thin. Above this density our model is internally inconsistent. As is apparent from Figure 6, high plasma temperatures result in a substantial reduction of the scattering cross section (Svensson 1982; Guilbert 1986). It is now straightforward to calculate the thermal energy stored in the magnetosphere:

$$E_{th} = 6\pi T_{eq} \int_{r_b}^{R_{max}} r^2 n_e(r) dr \sim 3 \times 10^{17} r_b^3 T_{eq} n_s \int_1^{y_{max}} y^{2-n} dy \text{ ergs.} \quad (14)$$

During the γ-ray burst this energy level is maintained by the Compton scattering events; however, after the burst is turned

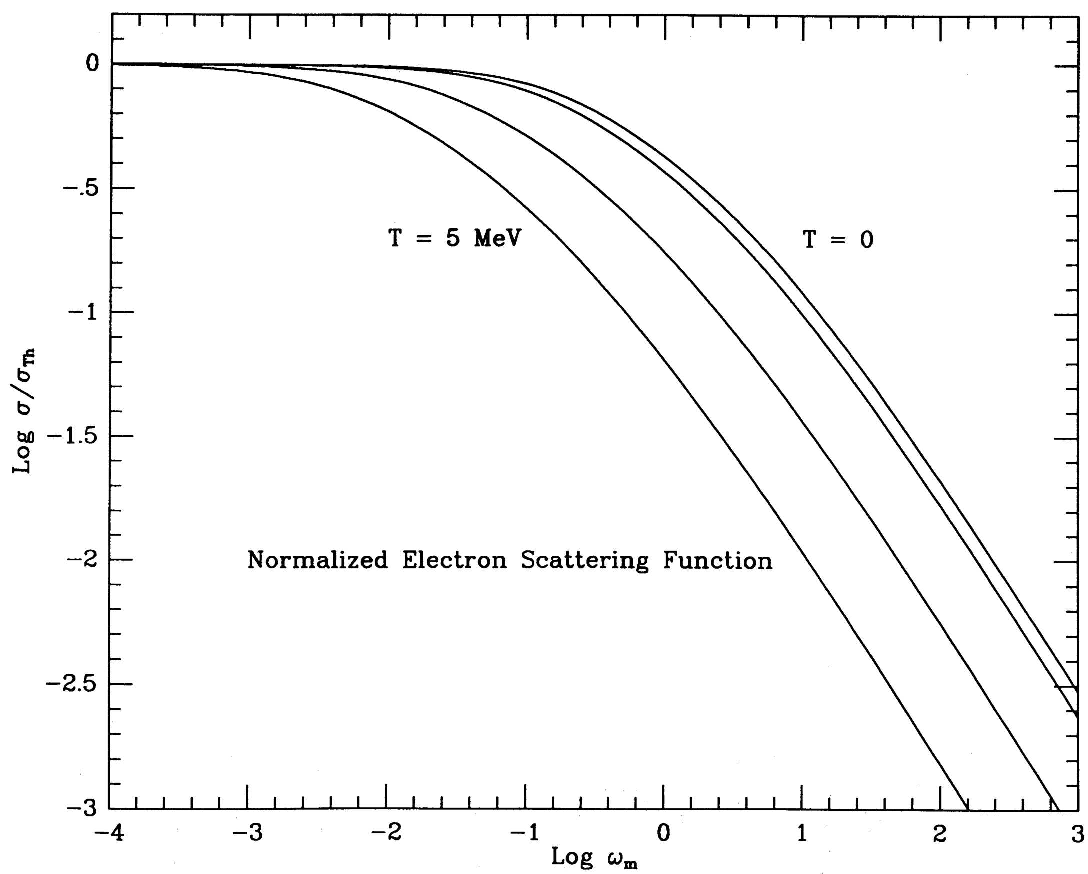

FIG. 6.—Electron scattering cross-section (normalized to the Thomson value) at finite plasma temperature as a function of photon energy (in units of the electron rest mass). To obtain the cross section, an average over the relativistic Maxwell-Boltzmann distribution has been carried out. The plotted function is identical with $8\pi/3$ times the dimensionless scattering function of Svensson (1982). At zero temperature the well-known Klein-Nishina dropoff due to relativistic effects becomes important for photon energies above mc^2. With increasing temperature an additional strong decrease occurs as a result of electron motion. Shown are cross sections for $T = 0, 0.5, 2.5$, and 5 MeV.

off, this energy is released on a decay time scale,

$$t_{\rm dec} = \frac{E_{\rm th}}{L_{\rm cyc}} \sim 0.57\, \frac{n_s r_b r_8^7}{B_{12}^3} \int_1^{y_{\rm max}} \frac{y^{2-n}}{m_*^3(y)}\, dy \ {\rm s}\ . \quad (15)$$

For typical parameters we find that $t_{\rm dec} \ll t_\gamma$ and therefore that the optical flash essentially coincides with the γ-ray burst.

d) The Emitted Spectrum

Hot, magnetized plasma generates copious amounts of cyclotron photons, but the escape of these photons from their source region is suppressed by self-absorption. Between the local fundamental cyclotron frequency $\omega_c(r)$ and a critical frequency $\omega_* = m_*(r)\omega_c(r)$, above which the plasma becomes optically thin to its own cyclotron photons, the resultant spectrum is well approximated by the Rayleigh-Jeans tail of a blackbody spectrum characterized by the temperature $T_{\rm eq}$. The individual harmonics are broadened into a continuum by Doppler shift and by magnetic field gradients, so that the neglect of discrete quantum mechanical structure can be justified if (e.g., Mészáros, Bussard, and Hartmann 1986)

$$\left(\frac{\Delta\omega}{\omega_c}\right)_{\rm FWHM} \sim \left(\frac{8kT_\parallel}{m_e c^2}\right)^{1/2} \cos\theta \sim 1\ ,$$
$$\left(\frac{\Delta\omega}{\omega_c}\right)_{\rm FWHM} \sim \frac{B - \langle B\rangle}{\langle B\rangle} \sim 1\ , \quad (16)$$

where θ is the photon propagation angle with respect to the magnetic field direction. For given electron number density and magnetic field strength it is straightforward to calculate the critical harmonic number m_* above which there is no self-absorption. The relevant quantity that determines m_* is the dimensionless size parameter (Bekefi 1966)

$$\Lambda = \frac{\omega_p^2}{\omega_c}\frac{R}{c} = 4\pi e\, \frac{n_e R}{B} = 6.036 \times 10^6 n_{e_{15}} R_6 B_6^{-1}\ , \quad (17)$$

which is related to the column density or optical depth at the cyclotron fundamental of a homogenous slab of thickness R viewed perpendicular to the field which is assumed to be parallel to the slab surface. For the conditions estimated above we obtain typical values of order of 10^9 for A. The number m_* can be expressed as a function of Λ and the temperature T (Bekefi 1966). Many workers have provided approximation formulae to their calculations of $m_*(\Lambda, T)$. For values of Λ between $\sim 10^3$ and $\sim 10^6$, relevant in plasma fusion devices, m_* has been found to vary as $\Lambda^{1/6}$ (Trubnikov 1958, 1973; Bekefi 1966). This result has been employed by Woosley (1984) in an earlier version of this work. However, for the large values of Λ, found in the present study, these fits overestimate m_*. Chanmugam and Wagner (1979) give some values of m_* in the range $\Lambda = 10^2$–10^{10}, and Wada *et al.* (1980) have provided a simple fit to their results,

$$m_* = 47.4\Lambda^{1/20} T^{1/2}\ , \quad (18)$$

which indicates an extremely weak dependence of m_* on the magnetic field strength. For Λ values even higher, encountered in accretion disks around supermassive black holes, the results of Takahara and Tsuruta (1982) may be used (Apparao 1984). We have used the fit of Wada *et al.* (1980) in our preliminary study (Hartmann, Woosley, and Arons 1987). However, a detailed comparison between the maximum trapped harmonic according to this equation and the one obtained when we estimate m_* directly from the cyclotron opacity given by Robinson and Melrose (1984)—which we use for the radiation transport calculation described below—reveals large discrepancies (see Fig. 7). Because the cyclotron reprocessing model is naturally very sensitive to this parameter, we have recalculated m_* for an extended grid in Λ and temperature T and have obtained new fits (Fig. 8) for the Λ-T parameter space considered here (see Appendix B for numerical details).

To estimate the emitted cyclotron radiation flux, we approximate the local source function by a Rayleigh-Jeans spectrum ($\hbar\omega_* \ll T_{\rm eq}$) truncated below the fundamental frequency ω_c and above the "critical" frequency $m_*\omega_c$ (Trubnikov 1958; Hirshfield, Baldwin, and Brown 1961; Drummond and Rosenbluth 1963; Bekefi 1966; see Fig. 2), which leads to a flux of

$$F_{\rm cyc} \sim \frac{T_{\rm eq}}{12\pi^2 c^2}(m_*\omega_c)^3 = 5.28 \times 10^{25} T_{\rm eq} E_*^3 \ {\rm ergs\ cm^{-2}\ s^{-1}}\ , \quad (19)$$

where $E_* = m_*\hbar\omega_c$ is measured in keV. Because the optically thin cyclotron spectrum at high harmonic numbers drops very rapidly with increasing photon energy (Trubnikov 1973), only a very small fraction of the energy is radiated above $m_*\omega_c$. Furthermore, the neglect of this portion of the spectrum is a conservative assumption, because the inclusion of it would result in optical flashes that are slightly brighter and extend to somewhat higher energies than those calculated here. For the total luminosity from a small homogeneous emitting sphere of radius R situated at a distance r from the neutron star ($R \ll r$), one obtains

$$L_{\rm cyc} = \frac{T_{\rm eq}\omega_*^3 R^2}{3\pi c^2} \sim 1.03 \times 10^{30} T_{\rm eq} m_{100}^3 B_{12}^3 R_6^2 r_8^{-9} \ {\rm ergs\ s^{-1}}\ , \quad (20)$$

where $m_{100} = m_*/100$ and $T_{\rm eq}$ is measured in MeV. Equation (20) demonstrates the sensitivity of the thermal cyclotron emission to the source location above the neutron star surface, as well as the capability of the thermal cyclotron reprocessing model to accommodate extremely luminous events.

In order to determine the reprocessed spectrum received by a distant observer, we now consider the radiation transport in the envelope. The complete knowledge of the source function,

$$S_\omega(r) = \{B_\omega^{\rm RJ}(T_{\rm eq})\,|\,\omega_c(r) \le \omega \le m_*(r)\omega_c(r)\}\ , \quad (21)$$

simplifies the radiation transport problem to calculating the *formal solution.* We use the tangent-ray discretization scheme (e.g., Mihalas 1978) to calculate this solution along a ray of given impact parameter (see Fig. 9 for details of the geometry and the notation). The emergent intensity for a given impact parameter is obtained from

$$I_\omega^{\rm em}(p) = \int S_\omega(p, z) e^{-\tau_\omega(p,z)} \kappa_\omega(p, z) dz\ , \quad (22)$$

where τ_ω is the total optical depth along the ray (measured from the observer's position inward) at frequency ω, and the absorption coefficient κ_ω is given in Appendix B. Finally, the total flux received by an observer at distance D is then obtained from an integration over the impact parameter,

$$f_\omega = 2\pi D^{-2} \int_0^{p_{\rm max}} I_\omega^{\rm em}(p) p\, dp\ . \quad (23)$$

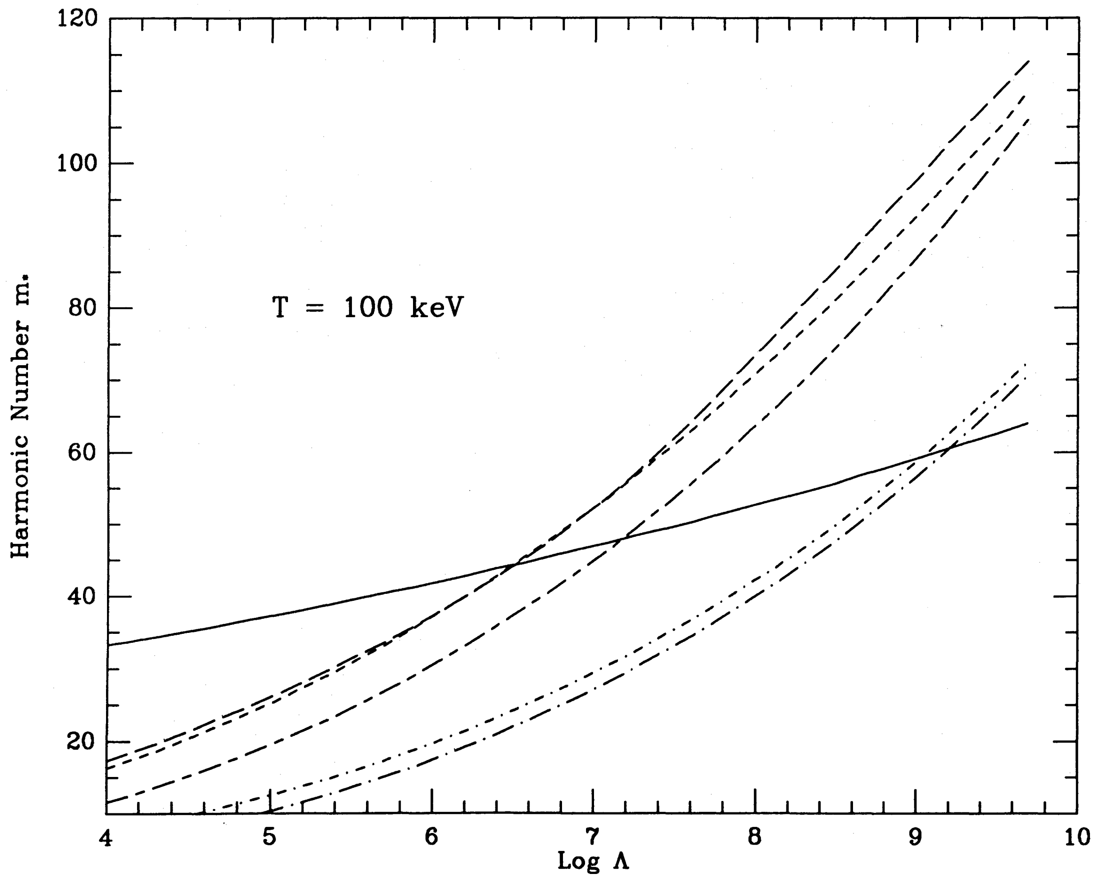

FIG. 7.—Maximum harmonic number m_* for which hot plasma is optically thick to its own cyclotron radiation as a function of the dimensionless plasma parameter Λ for a temperature of 100 keV. Shown separately are the ordinary model (*long dash-dot line*) and the extraordinary mode (*long dash–short dash line*). In comparison we plot the results of Petrosian and Harding (1986) (*dash-dot line*), Masters (1978) (*short-dashed line*), Pacholczyk (1970) (*long-dashed line*), and the fit of Wada *et al.* (1980) (*solid line*). Note that our earlier calculations (Hartmann, Woosley, and Arons 1987) were based on the fit of Wada *et al.* (1980), which in the context of the TCR model does not reproduce the correct values of m_* accurately enough.

In the following section we discuss theoretical spectra calculated in this way for a number of different parameter combinations.

III. MODEL SPECTRA AND PREDICTIONS

a) Classical Bursts

The model spectra presented in this section extend in photon energy from the IR to the UV. Although it is possible in the case of extreme choices of parameters, the thermal cyclotron reprocessing model does not generally produce radio bursts or soft X-ray bursts. A rapid drop in photon flux at energies below the IR and above the UV is essentially a consequence of the finite size of the magnetosphere. The hardest photons are generated near the inner boundary r_b, and most of the low-energy photons originate near the outer radius $R_{max} \gg R_*$. A model spectrum is completely determined by the temperature T_{eq} of the plasma, the neutron star's surface magnetic field B_s, the plasma density n_s, and the power indices n and m in the scaling laws assumed for the run of the magnetic field and the density. For simplicity we assume a γ-ray burst distance of 100 pc.

As discussed in § II, the temperature of the magnetosphere should be determined consistently from the observed γ-ray burst spectrum. However, because of the lack of simultaneous observations at optical and γ-ray energies at the present time, we had to make an arbitrary choice. Because spectral information over a large energy range is available for GB 800419 (Dennis *et al.* 1981; Nolan *et al.* 1984) and the possible presence of cyclotron features suggests that a strongly magnetized neutron star (as required for our model to work well) might be involved (but see Fenimore, Klebesadel, and Laros 1983), we chose this particular burst. The duration of this burst was approximately 3 s, and the total flux above 30 keV was $F_\gamma \sim 1.8 \times 10^{-5}$ ergs cm^{-2} s^{-1}. Like most γ-ray bursts, GB 800419 radiates predominantly in the MeV range (Figs. 4*a* and 4*b*) and shows a deficiency of X-rays (Epstein 1986; Imamura and Epstein 1987). Following the procedure described in § II*c*, we estimate that this particular spectrum corresponds to an equilibrium temperature of 116 keV (model 1). Parameters of all models presented in this work are summarized in Table 1.

Figure 10*a* shows the emitted spectral flux of models with temperatures of 100 keV (model 3), 200 keV (model 2), and ~25 keV (SGR 1806−20 = model 17). Apparently strong emission extending from the IR to the UV is generated by cyclotron reprocessing of hard γ-ray burst photons. In particular, high-T models yield brilliant UV flashes. The numerical noise visible in the figures is due to the zoning of the magnetosphere. Cases in which the γ-ray burst causes temperatures much in excess of several hundred keV lead to a relative

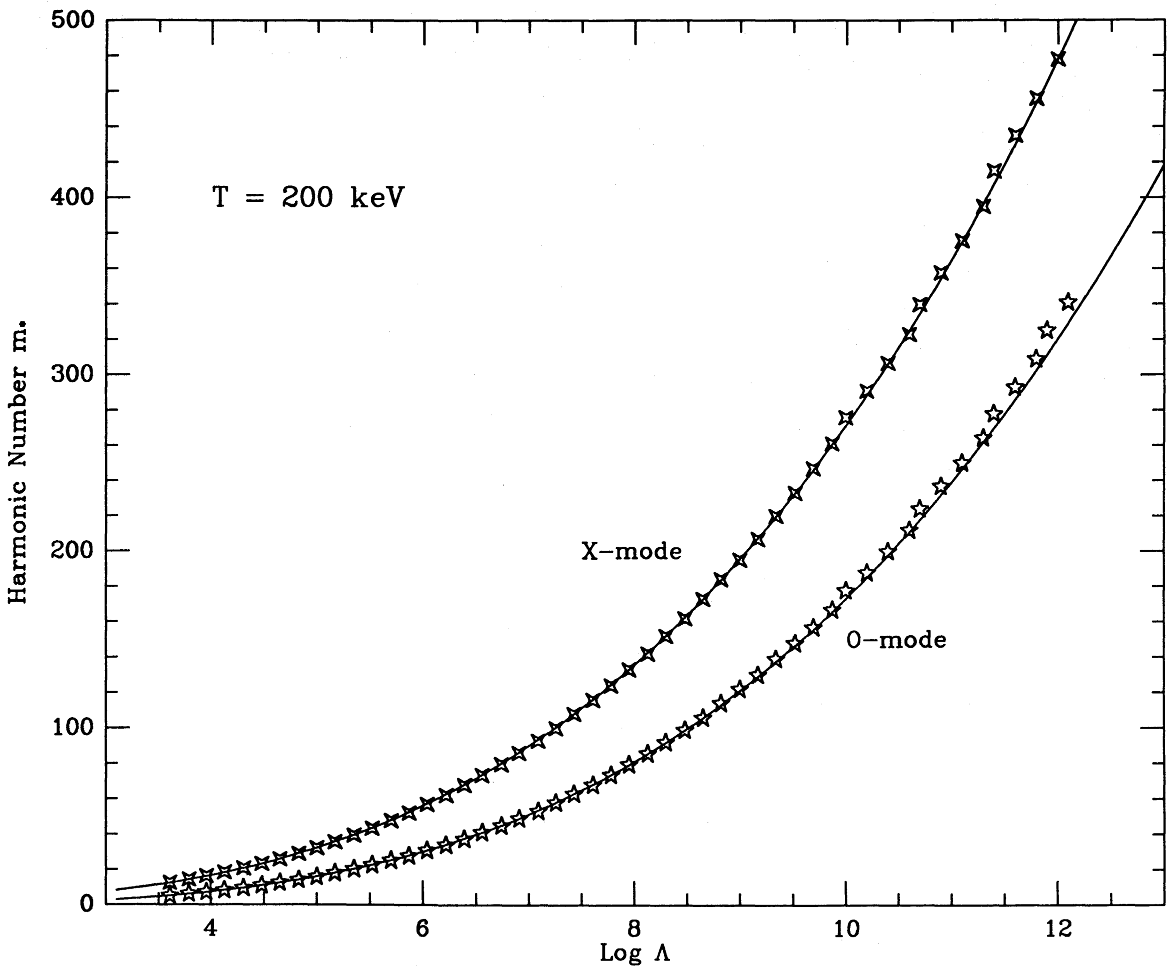

FIG. 8.—Maximum harmonic number for self-absorbed cyclotron radiation at a temperature of 200 keV. Shown separately are the ordinary (*o*) and extraordinary (*x*) photon polarization modes. The solid lines are our numerical fits described in Appendix B.

TABLE 1

SUMMARY OF MODEL PARAMETERS

Model	T (keV)	B (10^{12} G)	m	n_s (10^{22} cm^{-3})	n	r_b (10^8 cm)	$R_{\gamma o}$
1.........	116	1.0	3	1 (−7)	0.5	0.6	1.5 (5)
2.........	200	1.0	3	1 (−7)	0.5	0.6	4.5 (3)
3.........	100	1.0	3	1 (−7)	0.5	0.6	5.8 (5)
4.........	116	0.1	3	1 (−7)	0.5	0.6	...
5.........	116	0.5	3	1 (−7)	0.5	0.6	1.0 (7)
6.........	116	2.0	3	1 (−7)	0.5	0.6	1.1 (4)
7.........	116	1.0	4	1 (−7)	0.5	0.6	...
8.........	116	1.0	3	1 (−8)	0.5	0.6	1.5 (6)
9.........	116	1.0	3	1 (−6)	0.5	0.6	2.4 (4)
10.........	116	1.0	3	1 (−7)	3.0	0.6	1.8 (5)
11.........	116	1.0	3	1 (−7)	0.5	1.0	...
12.........	116	1.0	3	1 (−7)	0.5	0.1	8.1 (3)
13.........	116	1.0	3	1 (−3)	3.0	0.6	4.3 (3)
14.........	116	1.0	3	1 (0)	3.0	0.6	2.6 (3)
15.........	116	0.1	3	1 (0)	3.0	0.6	3.0 (6)
16.........	116	0.01	3	1 (0)	3.0	0.6	...
17.........	24.3	1.0	3	1 (−7)	0.5	0.6	...

NOTE.—Parameters for the 17 calculated TCR spectra. Model 1 is referred to in the text as the "standard" model. Model 17 corresponds to our calculation for the recently discovered *soft γ repeater* SGR 1806−20 (Atteia *et al.* 1987; Laros *et al.* 1987; Kouvelioutou *et al.* 1987). The last column is not a model parameter but the inverse reprocessing efficiency $R_{\gamma o}$ (ratio of energy emitted in the blue band to the γ-ray burst energy) obtained from the TCR model. Numbers in parentheses are powers of 10.

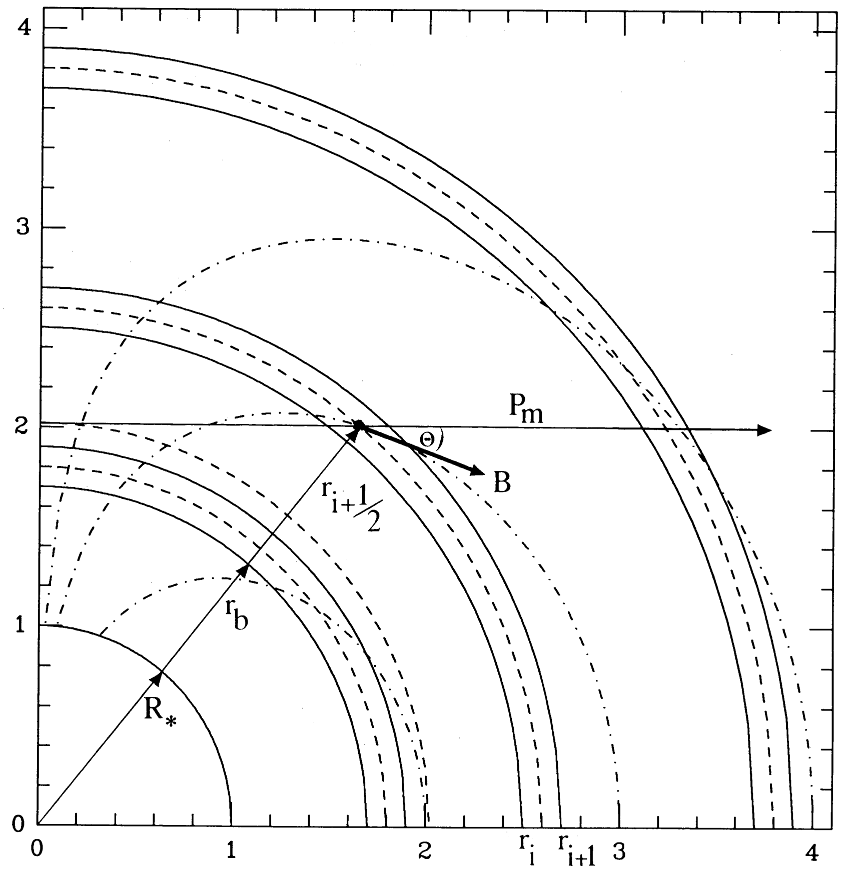

FIG. 9.—Ray geometry and notation for radiation transport calculation in the magnetosphere of a strongly magnetized neutron star. The magnetosphere is divided in radial zones (about 100) with boundaries r_i, r_{i+1} and center $r_{i+1/2}$. A ray with impact parameter p_m intersects a zone at a distance z along the line of sight. The contribution of that zone to the optical depth depends on the magnetic field strengths at $r_{i+1/2}$ and the angle of propagation, θ, between the magnetic field and the ray.

"overproduction" of soft X-rays that could conflict with the observed X-ray paucity of γ-ray bursts (Epstein 1986; Imamura and Epstein 1987).

With the temperature fixed at the Compton equilibrium value of 116 keV, we investigate now the sensitivity to the remaining parameters. In Figure 10*b* we compare spectra with surface magnetic field strengths between 10^{11} and 2×10^{12} G. From these models we conclude that in general a "sufficiently" strong magnetic field is needed to generate brilliant optical or even UV flashes. The actual value of the "critical" field, however, depends in a complex way on all the other model parameters. For example, a low field neutron star heated to high temperature by the γ-ray burst would appear similar to a strongly magnetized neutron star with only a moderate temperature of the magnetosphere. Particularly interesting are bursts that have emission extending far into the UV, i.e., that do not turn over before $E \sim 4$ eV. In the optical wavelength band we then find that the flux scales with the surface field strength as

$$F_{\rm opt} \propto B_s^{\alpha} , \qquad (24a)$$

where α is about $\frac{3}{4}$. For given surface field strength but decreasing faster than a dipole field (model 7: $m = 4$), we find that the total flux decreases rapidly and that the high-energy turnover is shifted to lower energies (Fig. 10*b*). However, in that case the plasma perhaps reaches the neutron star surface, i.e., $r_b = R_*$.

The dependence on the inner radius r_b of the plasma-free zone around the neutron star is shown in Figure 10*c*. It is important to notice that the spectrum "saturates" with decreasing bubble radius. Again concentrating on the optical window, this implies essentially *no dependence on* r_b for spectra that do not exhibit an early turnover.

The dependence on the plasma density in the magnetosphere is shown in Figure 10*d*. For bursts that do not turn over in the optical window, we find a weak dependence on the density,

$$F_{\rm opt} \propto n_s^{\beta} , \qquad (24b)$$

where $\beta \sim 0.1$.

The very strong dependence of the cyclotron opacity on the polarization state of the photons (Appendix B) might lead to a significant degree of polarization of the "optical" flash. In Figure 11 we decompose the "standard" spectrum (model 1) into the two transverse polarization modes. Apparently the strongest polarization occurs at the spectral turnover. Because of the various simplifying assumptions made in our model, we did not attempt to calculate the degree of polarization, but based on the similarity of the physical conditions inferred for the AM Her systems to those at the "optical flash" site, we expect strong ($\sim 10\%$) linear and circular polarization similar to that observed in AM Her systems (Tapia 1977; Michalsky, Stokes, and Stokes 1977; Krzeminski and Serkowski 1977;

Wickramasinghe and Meggit 1982; Liebert *et al.* 1982). A detailed, model-dependent calculation of the polarization properties of "optical" flashes should be considered when polarimetry of transient sources in this spectral range becomes feasible.

Figure 12 shows a few additional spectra of models to further explore the sensitivity of the spectrum to the parameters. Summarizing the results presented in Figures 10–12, we conclude that, depending on parameter combinations, a variety of different transients should accompany γ-ray bursts, if the source is associated with a strongly magnetized neutron star. If thermal cyclotron reprocessing is in fact responsible for these long-wavelength transients, then the "zoo" of events should include IR-only flashes as well as IR-optical flashes and IR-optical-UV flashes simultaneous with the γ-ray bursts. However, dromedary-like flashes, i.e., those with peak fluxes in the IR and UV but minima in the optical, should not be observed. Only when multiwavelength data with sufficient time and energy resolution become available can we attempt to consistently determine important model parameters such as the magnetic field strength. The almost linear dependence on B_s found in this study (eq. [24a]) combined with a weak dependence on the other model parameters will be helpful in this regard.

It remains to be calculated what fraction of the reprocessed energy is actually sampled by the energy window (E_l, E_h) employed for the observations. The historical plates analyzed by Schaefer (1981) are sensitive from about $E_l = 2.5$ eV to $E_h = 3.2$ eV. A somewhat larger window is available in broadband CCD detectors such as the Explosive Transient Camera

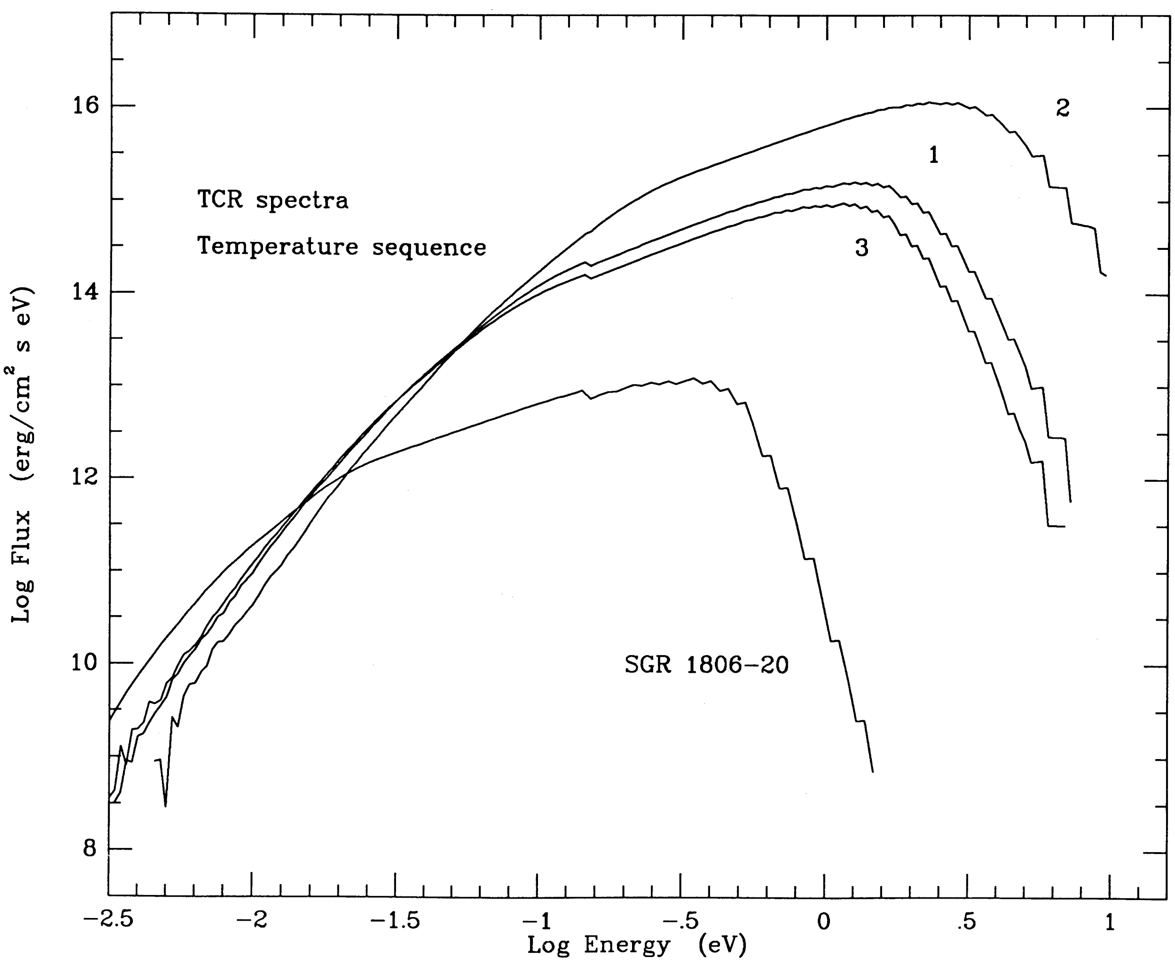

FIG. 10*a*

FIG. 10.—(*a*) Emergent energy spectra for model parameters given in Table 1. Four models demonstrate the temperature dependence of the TCR model. The "standard" model (1) has $T = 116$ keV. With increasing temperature the flux increases and the spectral turnover shifts to higher energies. One model (17) spectrum was calculated for parameters of the soft repeating γ-ray burst source in the vicinity of the Galactic center (SGR 1806−20). No detectable optical (or UV) flashes are expected from this source. (*b*) Same as (*a*). Several model spectra were calculated to study the dependence of the TCR model to the assumption about the magnetic field. Models 1, 4, 5, and 6 correspond to field strengths between 10^{11} and 2×10^{12} G. With increasing magnetic field the flux increases and shifts to higher energies. Model 7 shows what happens if the field drops more rapidly than a dipole field. For $n = 4$ and $B_s = 10^{12}$ G the resulting spectrum is much below that of a dipole field of about 5×10^{10} G. (*c*) Same as (*a*) The TCR model's dependence on the inner radius of the plasma-filled magnetosphere r_b is shown for three models. If the matter extends closer to the neutron star surface, plasma at higher field strengths contributes to the emission and thus the spectra shift to higher energies. (*d*) Same as (*a*). The dependence on the plasma density is demonstrated by four models. Increasing density implies more electrons contributing cyclotron photons and therefore a larger flux. Larger densities also imply larger maximum harmonic numbers m_*, which results in a shift of the spectral turnover to higher energies. The dependence on the radial scaling of the density (model 1 vs. model 10) is not very dramatic.

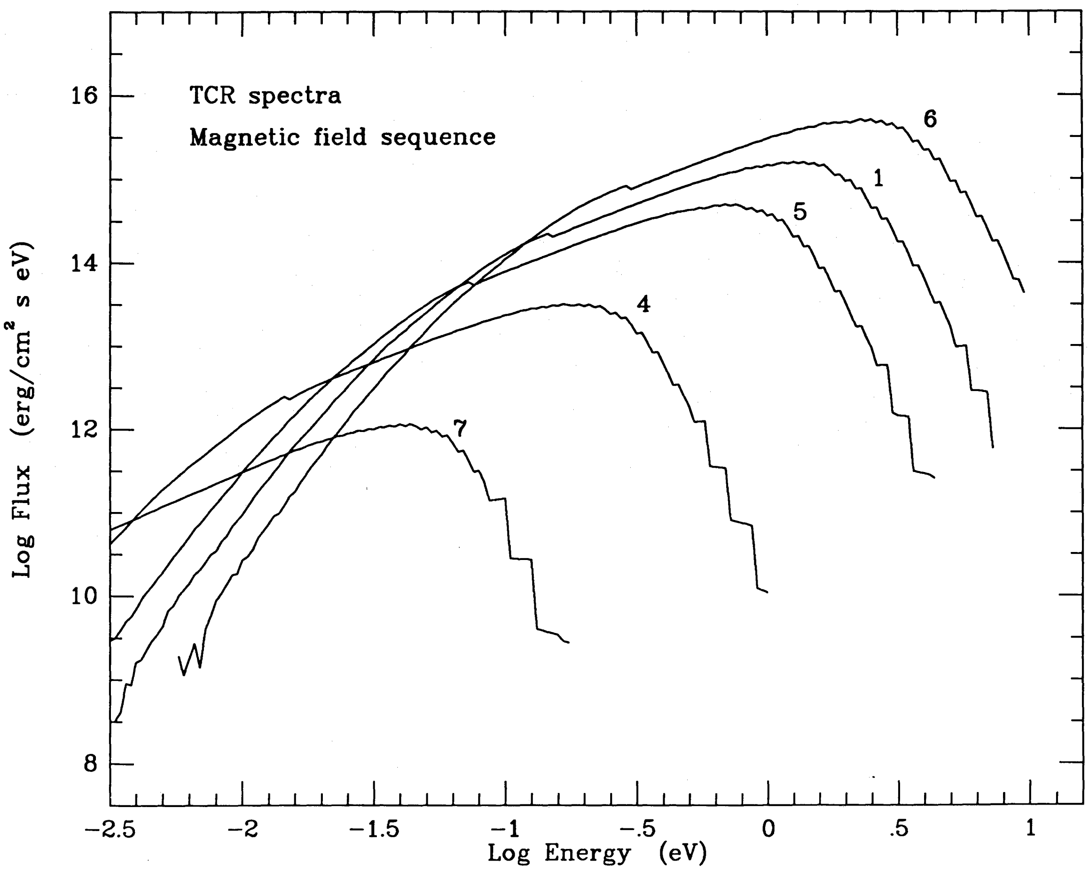

FIG. 10*b*

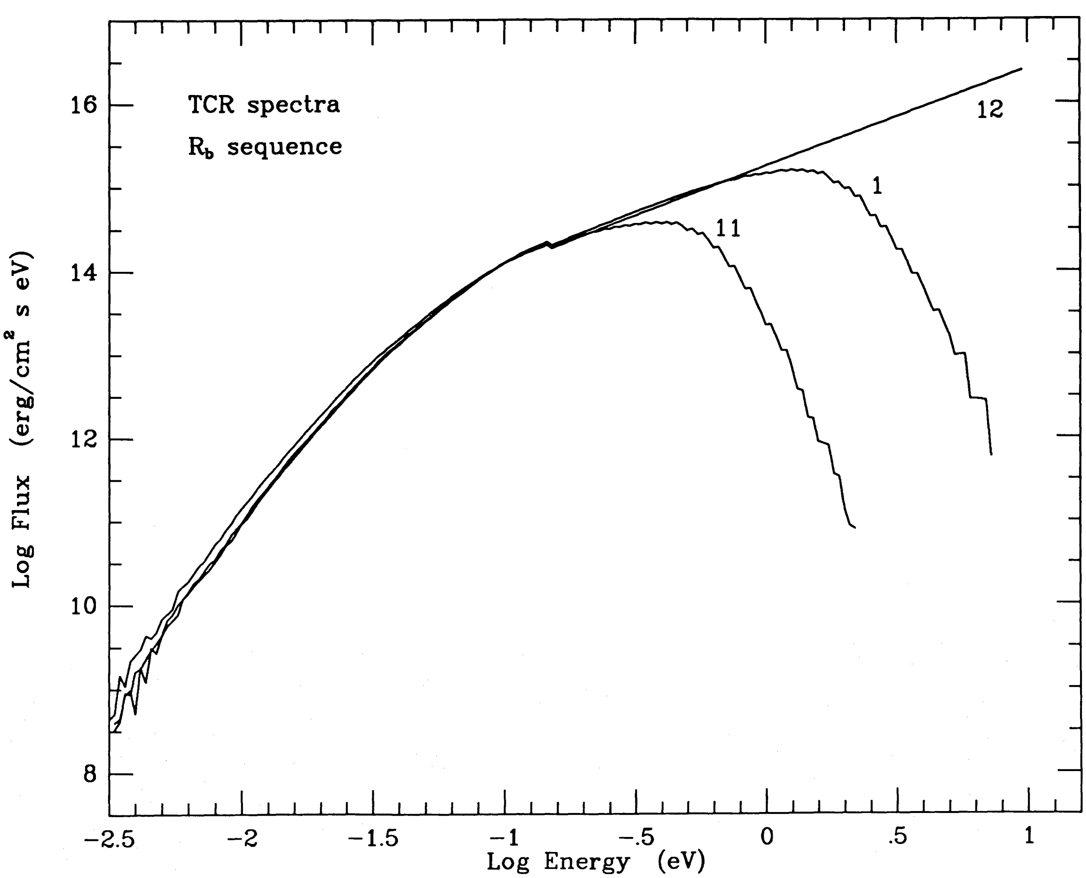

FIG. 10*c*

(ETC) (Ricker *et al.* 1984). We calculate the ratio $R_{\gamma o}$ of burst energy at γ-ray frequencies to that in the optical window by

$$R_{\gamma o}^{-1} = \left(\frac{t_\gamma}{t_{\rm opt}}\right) F_\gamma^{-1} \int_{E_l}^{E_h} F(E) dE \,, \quad (25)$$

where F_γ is the total flux of GB 800419 and the ratio of time scales is assumed to be unity. The values of $R_{\gamma o}$ for all our spectra are given in the last column of Table 1. Typically we find $R_{\gamma o} \sim$ a few times 10^3–10^5 which is somewhat larger than the observed values discussed in § I. However, variations of 1 order of magnitude or even more are easily accommodated in both model and observations. In particular, we have assumed that reprocessing occurs throughout the magnetosphere, which results in an optimistic estimate of $R_{\gamma o}$. Taking into account that probably only a fraction of the magnetosphere is available for reprocessing, $R_{\gamma o}$ becomes significantly larger than the "observed" value. What is really needed are simultaneous multiwavelength observations!

b) The Soft Repeating Source SGR 1806 − 20

Recently, a recurrent γ-ray burst source has been discovered in the direction of the Galactic center (Atteia *et al.* 1987; Laros *et al.* 1987; Kouveliotou *et al.* 1987). First observed on 1979 January 7 (Laros *et al.* 1986), the source has had more than 100 outbursts since! Bursts from this repeater are distinct from the "classical" bursts in the sense that their spectra are *soft* ($kT \sim 30$ keV), their durations are *short* (10–100 ms), and they repeat with temporal separations between 10 s and 1 yr with a strong tendency to bunch in time (Laros *et al.* 1987). This burster, now termed Soft Gamma Repeater (SGR) 1806 − 20, may be the third member of a novel class of γ-ray bursts (together with SGR 0526 − 66 and SGR 1900 + 14) (Mazets *et al.* 1982; Golenetskii, Ilyinskii, and Mazets 1984; Laros *et al.* 1986).

The distance to the source is not known. If the repetition is caused by gravitational microlensing, the distance may be cosmological (Paczyński 1987; Babul, Paczyński, and Spergel 1987; but see Babul, Piran, and Spergel 1987). The resemblance of some source characteristics of SGR 1806 − 20 to those of X-ray burst sources (repetition, location, and soft spectra) suggests perhaps a distance between 5 and 10 kpc (Cline 1986; Kouveliotou *et al.* 1986, 1987). If so, their peak luminosities appear to be in excess of 10^3 Eddington luminosities! On the other hand, if burst peak fluxes are Eddington-limited, source distances are of order 200 pc (Atteia *et al.* 1987). In our analysis we assume a distance of 100 pc, as for all the other calculations.

The observed properties of SGR 1806 − 20 place severe constraints on the viability of models proposed for the typical γ-ray burst events as applied to this soft γ-ray repeater. Livio and Taam (1987) demonstrated that a model involving a comet cloud around a neutron star is consistent with the observational data. In order to generate γ-ray burst–like events (instead of X-ray bursts), the neutron star is expected to be strongly magnetized (Woosley 1984; Howard, Wilson, and Barton 1981; Katz 1985). We assume that SGR 1806 − 20

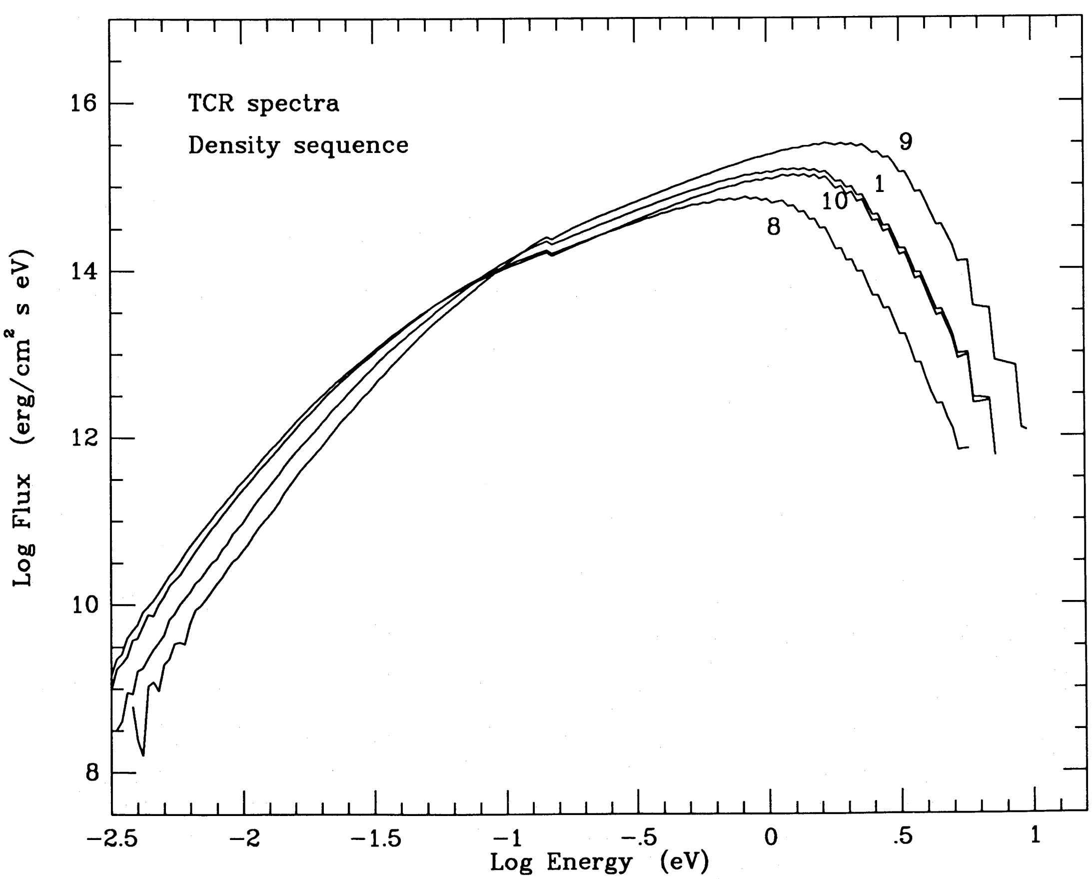

FIG. 10*d*

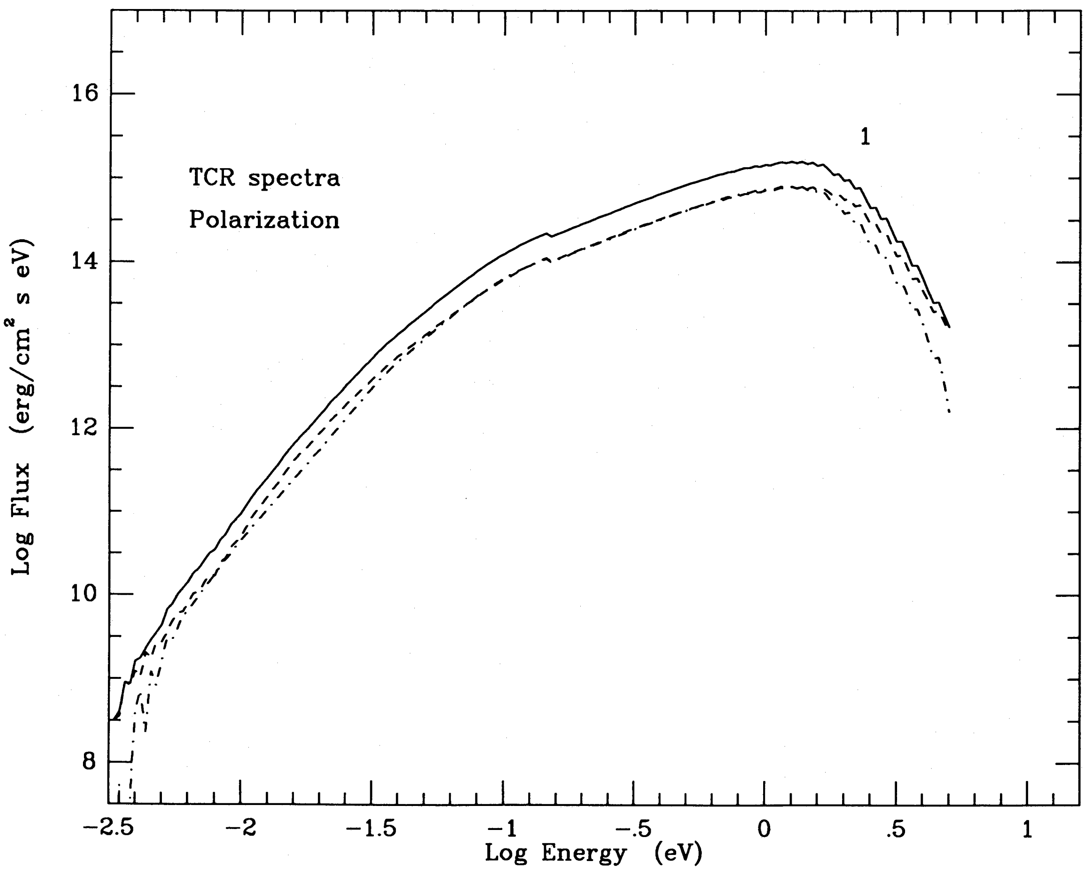

FIG. 11.—The presence of strong magnetic fields suggests that the emergent spectrum could have substantial polarization. A decomposition of the "standard" spectrum into the ordinary (*dash-dot line*) and extraordinary (*dashed line*) photon polarization modes indicates that this should be observed preferentially near the spectral turnover.

involves a neutron star with a surface field of 10^{12} G, our "canonical" value.

We approximate the average γ-ray spectrum of SGR 1806−20 by a simple exponential function with fitting temperature $T = 30$ keV (Fig. 13). The Compton equilibrium temperature of the magnetospheric plasma for this input spectrum, obtained from the solution of equation (10), is 24.35 keV. We estimate from equations (11) that deviations from isothermality by more than 10% occur for bursts with durations less than ~ 100 ms. Because of the observed brevity (FWHM ≤ 16 μs to ~ 0.13 s) of all events (Atteia *et al.* 1987), the equilibrium temperature cannot be achieved in the outer parts of the magnetosphere. The temperature gradient at large radii, however, would only lead to small changes at the long-wavelength end of the spectrum. Inclusion of the time development of the temperature gradient makes the model calculations much more cumbersome and will therefore be carried out only if high-precision data for simultaneous optical/γ-ray bursts from this source become available.

With distance and magnetic field strength chosen according to the discussion above, we have calculated one additional spectrum for SGR 1806−20, with the other parameters chosen to be the same as our "standard" model. The result is shown in Figures 10*a*, 12, and 14. The lower temperature causes optical flashes from this source to be relatively weak. For parameters near those selected here, *no* "optical" flashes should be observed from this source. Ground-based monitoring of SGR 1806−20 has not yet turned up any optical flashes consistent with our expectations (G. R. Ricker 1987, private communication). It is worthwhile mentioning that R. Hudec and coworkers (1988 private communication) have recently found evidence for two archival optical flashes close to, but not inside, the error box of SGR 1806−20.

IV. DISCUSSION

To put the thermal cyclotron model in perspective, we point out some distinctive differences between flashes generated by this process and those produced by other scenarios for which testable predictions are available. The binary reprocessing scenario in its various forms described in § I*b* predicts a delay of 1–10 s between the γ-ray burst and the arrival of the reprocessed radiation. In contrast, the TCR model predicts that there should be no substantial delay. Furthermore, a possible hydrodynamic response of the illuminated companion object together with geometrical effects produce a smearing of the optical flash on about the same time scale, so that the temporal correlation between the γ-ray and optical flux expected in the TCR model should not exist if reprocessing occurs far away from the neutron star. Furthermore, the calculations of Melia, Rappaport, and Joss (1986) revealed pulsations in the reprocessed optical light that provide an unmistakable signature of this model.

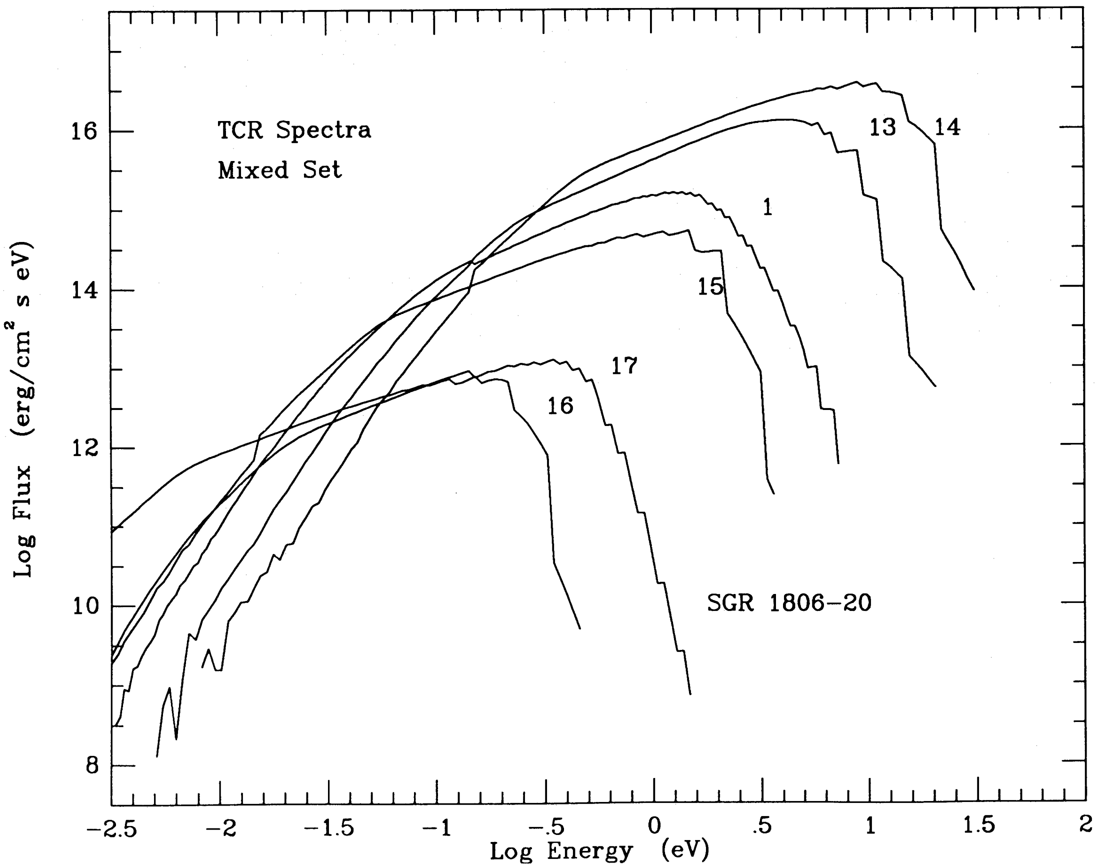

FIG. 12.—The range of possible long-wavelengths transients accompanying γ-ray bursts that can be accommodated by the TCR model is quite large, even without pushing the parameters. This is demonstrated by a comparison of the "standard" model (1) and the spectrum of SGR 1806−20 with several spectra not already shown in Figs. 10*a*–10*d*. Bright UV flashes as well as ultradim transients result from different natural choices of parameters.

The fact that no optical counterpart has been identified poses severe constraints on models that invoke reprocessing in a binary system (Schaefer *et al.* 1987*b*; Liang 1987; Katz 1986). Those constraints are much less stringent for the cyclotron reprocessing model, because a companion star or a disk is not essential for the model to work (although a companion star is a convenient donor of plasma).

Because of these very different fingerprints of the proposed models, we are confident that forthcoming multiwavelength data from space-based detectors (HETE, GRO, Ginga, and others) as well as ground-based instrumentation (ETC/RMT, GMS) will ultimately provide us with a clear interpretation of the origin of "optical" flashes associated with γ-ray burst events. We note that for most of the alternative models discussed in § I*b* testable predictions still need to be made. An easy distinction between the model of Tremaine and Żytkow (1986) and the TCR as well as the binary reprocessing model can be obtained, because in Tremaine and Żytkow's model the optical flashes and the γ-ray bursts should be uncorrelated. Even a nondetection of the assumed optical–γ-ray connection would be a valuable constraint.

Thus far no detailed spectral information at long wavelengths exists, but information on brightness and time scales is available owing to the enduring efforts of Schaefer, Pedersen, and their coworkers. In Figure 14 we compare our theoretical spectra with the γ-ray burst GB 800419 spectrum, predictions of the disk reprocessing model (Melia 1988), archival data (Schaefer 1981), optical flashes seen from the March 5 source region (Pedersen *et al.* 1984), and the expected sensitivity of the proposed HETE instrument (Ricker *et al.* 1987).

Apparently, transient events exceeding 9th magnitude in the optical bands can be generated by cyclotron reprocessing even for a relatively weak γ-burst such as GB 800419 (note, that Schaefer's 4th magnitude events are associated with a γ-ray burst of much larger fluence). However, many events will be too dim to be detected easily by present instrumentation and thus will escape our attention. We estimate that typical fluxes should be less than about 1 flux unit (fu) in the near-IR and about 0.01 fu in the far-IR. Extrapolation to radio wavelengths (though our model does not strictly apply in that regime) leads to the conclusion that no detectable radio outbursts are generated in the TCR model. However, it takes only a fraction of about 10^{-8} of the γ-ray burst energy to generate a detectable radio flux, and our model breaks down at the large radii where radio emission might originate.

The best prospect for simultaneous multiwavelength observations of γ-ray bursts is the High Energy Transient Experiment (HETE) under development by Ricker *et al.* (1987). This experiment covers the UV, X-ray, and γ-ray spectral bands. As now envisioned, the experiment will be a free-flying platform released from NASA's space shuttle. Figure 14 demonstrates that the anticipated sensitivity of the UV Transient Camera Array on board is sufficient to detect a large fraction of transients predicted within the framework of the TCR model.

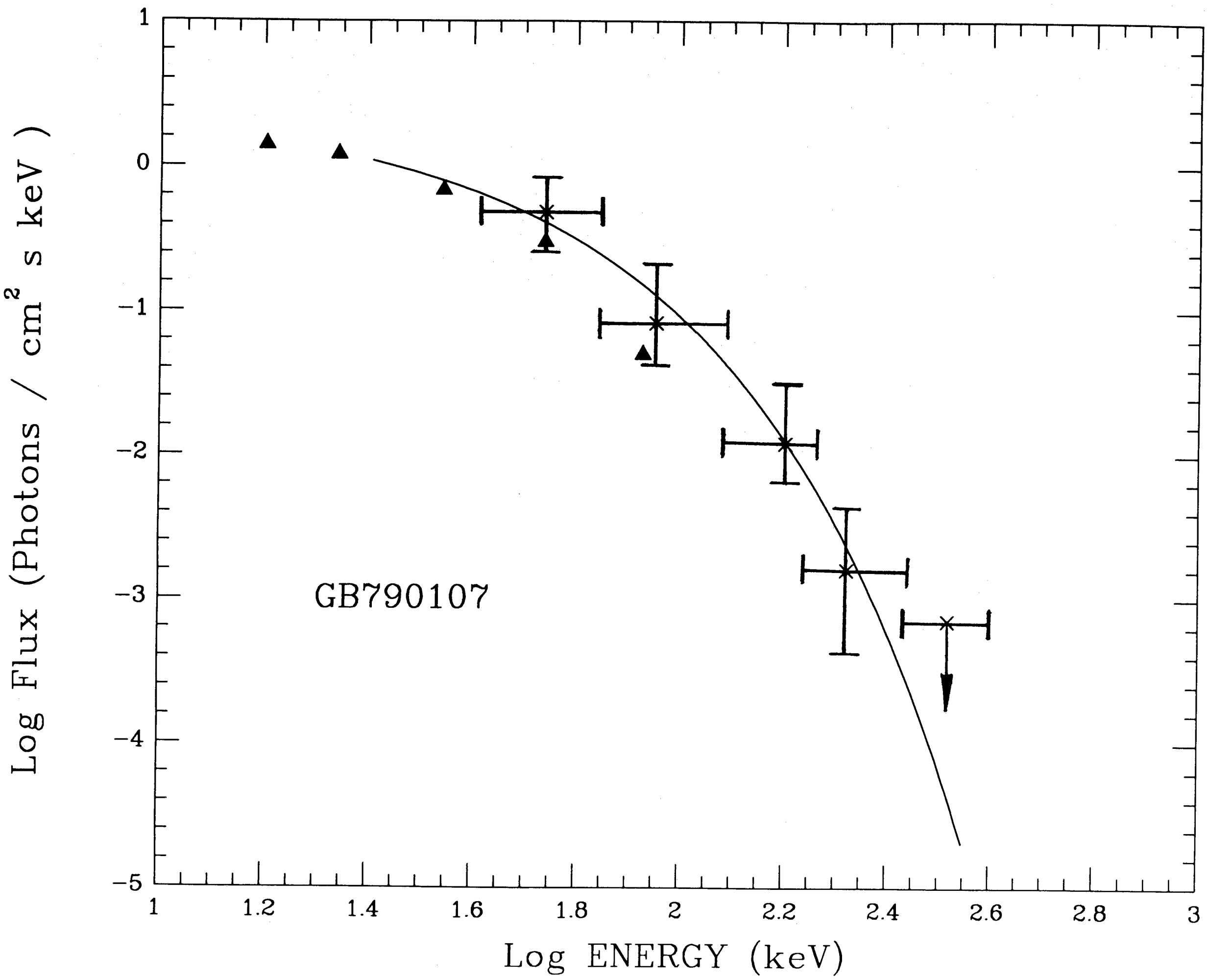

FIG. 13.—Average spectrum of γ-ray bursts from the soft repeating source SGR 1806−20. Points with error bars are average values of spectra presented in Atteia *et al.* (1987). The triangles represent the spectrum of the first detection of this source on 1979 January 7 (Laros *et al.* 1986). We fit the spectrum with a single exponential function exp (E/kT) with a temperature of 30 keV (*solid line*). The spectrum of SGR 1806−20 resembles closely that of an X-ray pulsar and is intermediate between the classes of "classical" (hard) γ-ray bursts and X-ray bursts (Hartmann and Woosley 1988). The Compton equilibrium temperature resulting from this input spectrum was determined from eq. (10) to be $\sim$25 keV.

Although our calculations indicate that HETE would in fact miss many long-wavelength transients accompanying γ-ray bursts, a few truly simultaneous detections in several wavelength bands are probably enough to create a scientific breakthrough. On the other hand, even a nondetection would be useful to constrain the theoretical models discussed here.

The main results and predictions of the thermal cyclotron reprocessing model can be summarized as follows:

1. Luminous bursts in the IR to UV spectral range are inevitably generated if a γ-ray burst occurs inside or near a plasma-filled magnetosphere around a strongly magnetized neutron star. The ratio of energies carried by optical photons to that carried by γ-rays is of the order of a few times 10^{-3} to a few times 10^{-5}, reasonably consistent at the upper end with the observations. Note that, although it is not the intent of this work to explain the particularly bright optical flashes observed by Schaefer *et al.*, the parameter space of the TCR model is sufficiently large to accommodate these transients.

2. The optical spectra can be used in a consistent way to confirm the conjectured presence of strong magnetic fields in γ-ray burst sources. A γ-ray spectrum that suggests a strong magnetic field by the presence of a low-energy absorption feature (interpreted as cyclotron resonance) should give a strong optical burst if the spectrum does not result in two low a temperature. In those cases only few free parameters remain (both B and T are approximately determined by the γ-ray burst spectrum!) to fit the observed spectrum.

3. A wide variety of long-wavelength transients is anticipated. Doubly peaked spectra ("dromedary-like" transients) would argue against the present model. Fluxes extending over large spectral ranges (varying from burst to burst) should be detectable in the form of IR-UV, IR-optical, or IR flashes. Narrow wavelength band ("line-type") transients are not expected within the framework of the TCR model.

4. The duration of the optical transient is to good approximation identical with the duration of the γ-ray burst itself. In addition, the temporal structure of the reprocessed flux should be correlated with the γ-ray flux down to time scales short compared with the burst duration (although this correlation does not necessarily extend to the shortest fluctuations of order

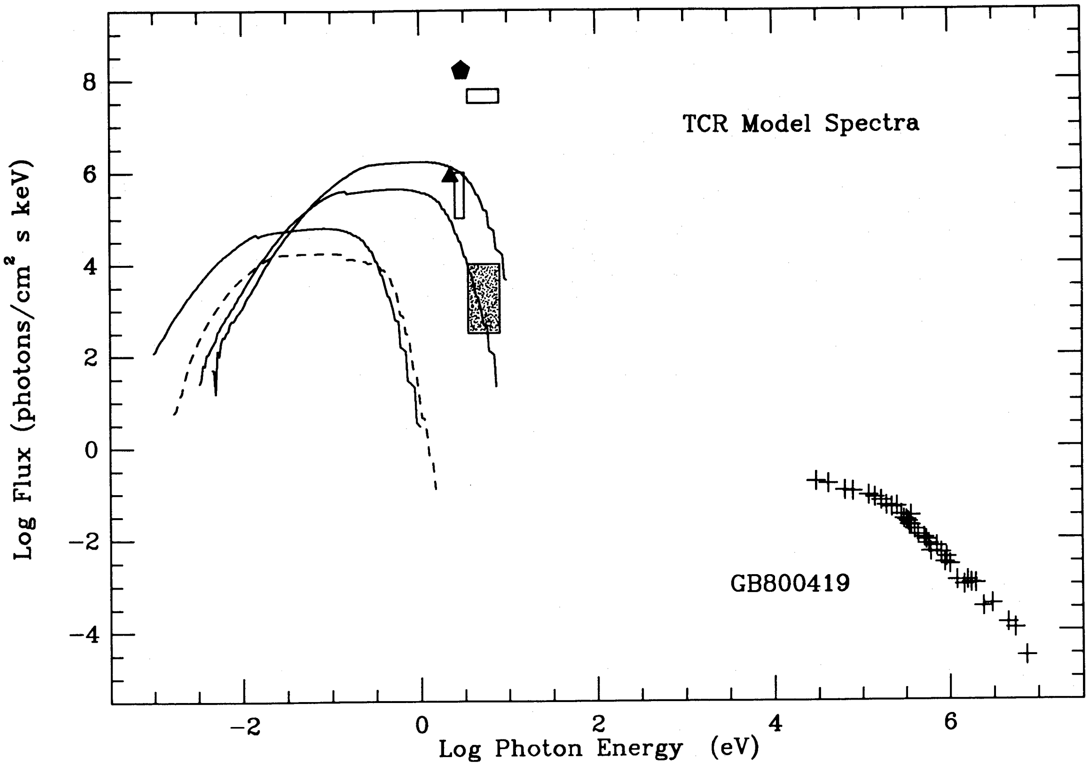

FIG. 14.—A few TCR spectra in comparison with observations of historical optical transients (Schaefer 1981) (*filled hexagon*): optical flashes from the 1979 March 5 source (Pedersen *et al.* 1984) (*filled triangle*), predictions for the recent disk reprocessing model (Melia 1987) (*open rectangles*), and the expected sensitivities for the proposed High Energy Transient Experiment (HETE) space mission (Ricker *et al.* 1987) (*shaded rectangle*). Shown are spectra of our "standard" model (1) (*central solid curve*), a high-temperature model (2) (*upper solid curve*), a low magnetic field model (4) (*lower solid curve*), and a model for SGR 1806−20 (17) (*dashed line*). These spectra roughly represent the typical range of long-wavelength emission in the TCR model. Also shown is the γ-ray burst input spectrum. We assume a burst distance of 100 pc. The ratio of γ-ray burst energy to energy emitted in the blue band, $R_{\gamma o}$, is between a few times 10^3 and 10^7. Note, that Schaefer's observations of a very bright ($m_v \sim 4$) transient (*filled hexagon*) are thought to be associated with γ-ray bursts much stronger than GB 800419, leading to $R_{\gamma o} \sim 10^3$. The fact that no simultaneous γ-ray bursts have been seen for the optical events of Pedersen *et al.* placed an upper limit of $\sim 10^4$ on $R_{\gamma o}$, which is within the range of the calculated TCR models.

10 ms observed in γ-ray burst sources). Furthermore, there should be no substantial delay between the γ-ray burst and the optical transient.

5. Strong ($\sim 10\%$) linear and circular polarization due to the presence of the magnetic field should be observable predominantly in the spectral turnover at high energies. (In the case of reprocessing in a companion star or an accretion disk, similarly strong linear polarization can arise if electron scattering is important, e.g., Chandrasekhar 1950.) For the disk geometry, however, the degree of polarization depends strongly on the inclination angle.

6. The possibility of generating "optical" flashes from *isolated* neutron stars could solve the puzzle that arises from the nondetection of quiescent optical counterparts down to extremely faint magnitudes. Unless extremely nearby, an isolated neutron star would be undetectable to present instrumentation. To be clear, the TCR model does not require a companion star, but a companion certainly would be a convenient donor of magnetospheric plasma.

It is our pleasure to thank R. Epstein, K. Hurley, S. Langer, R. London, and G. Ricker for many helpful discussions. We are grateful to the referee for comments that were very useful in clarifying the TCR model assumptions. This research was supported in part by grants 87-11 and 88-11 from the Institute of Geophysics and Planetary Physics at the Lawrence Livermore National Laboratory, in part by the Institute of Geophysics and Planetary Physics at the Los Alamos National Laboratory under project No. 142, in part by the California Space Institute under grant CS-69-85, in part by grants AST 83-17462, AST 86-15816, and AST 84-18185 from the National Science Foundation, and in part by the taxpayers of California. Portions of this work were performed under the auspices of the US Department of Energy at the Lawrence Livermore National Laboratory, under contract W-7405-Eng-48.

APPENDIX A

JUSTIFICATION OF THE LTE ASSUMPTION

We have based the present cyclotron reprocessing model on the assumption that the electron distribution function is thermal and isotropic. In this appendix we consider various relevant time scales to explore the parameter space in which this assumption is valid. For simplicity we assume the γ-ray burst emission region to be centered on the neutron star. Further, we assume that the magnetosphere is optically thin to the hard γ-ray burst photons, so that the energy deposition by Compton scattering quickly leads to a constant temperature throughout the magnetosphere (see § II*c*). However, plasma density and magnetic field strength depend on the distance from the neutron star surface. For simplicity we employ the scaling laws

$$n_e(r) = 10^{22} n_{22} \left(\frac{r}{r_b}\right)^{-n} \text{cm}^{-3}, \qquad B(r) = 10^{12} B_{12} \left(\frac{r}{R_*}\right)^{-m} \text{G}, \tag{A1}$$

where n and m, the "surface" density n_{22}, and the surface field strength B_{12} are free parameters. The neutron star surface is assumed to be located at $R_* = 10^6$ cm, and $r_b \geq R_*$ is the inner radius of the plasma-free sphere (assumed here to equal the stellar radius). We define $x = r/R_*$ and first compare the time scale of electron plasma oscillations,

$$t_{\text{pl}} = 2\pi \left(\frac{4\pi n_e e^2}{m_e}\right)^{-1/2} = 1.11 \times 10^{-15} n_{22}^{-1/2} x^{n/2} \text{ s}, \tag{A2}$$

with the inverse cyclotron frequency,

$$t_{\omega_c} = 2\pi \frac{m_e c}{eB} = 3.56 \times 10^{-19} B_{12}^{-1} x^m \text{ s}, \tag{A3}$$

and the approximate inverse frequencies of IR, optical, and UV photons,

$$t_{\text{IR}} \sim 10^{-14} \text{ s}, \qquad t_{\text{OPT}} \sim 10^{-15} \text{ s}, \qquad t_{\text{UV}} \sim 10^{-16} \text{ s}. \tag{A4}$$

The propagation of cyclotron radiation will be suppressed if its inverse frequency becomes longer than t_{pl}. Thus, in order to produce observable IR, optical, or UV flashes by cyclotron emission, the plasma density needs to be sufficiently low. For $x \gg 1$ this condition is generally satisfied.

For strong magnetic fields the quantum nature of electron motion is important. The cyclotron transition time from the first excited Landau state to the ground state is given by the inverse Einstein A coefficient,

$$t_{\text{cyc}} = \frac{3m_e c^3}{4e^2 \omega_c^2} = \; = 2.56 \times 10^{-16} B_{12}^{-2} x^{2m} \text{s}. \tag{A5}$$

Obviously, close to the surface of a strongly magnetized neutron star, cyclotron cooling will rapidly establish a one-dimensional electron distribution function, with the vast majority of electrons residing in the ground state. Excitation of higher states by collisions occurs on a much longer time scale. The collisional rates at the cyclotron fundamental as calculated by Bussard (1980) give a time scale for collisional excitation of the first Landau state (Arons, Klein, and Lea 1987)

$$t_{01} = (n_e \langle \sigma v \rangle)^{-1} = 10^{-10} n_{22}^{-1} \gamma_{01}^{-1} x^n \text{ s}, \tag{A6a}$$

with

$$\gamma_{01} = 8.23 B_{12}^{-3/2} H(x_c) e^{-x_c} x^{3m/2},$$
$$H(x_c) = \begin{cases} 0.15 x_c^{1/2} & \text{if } x_c \leq 7.5, \\ 0.41 & \text{if } x_c \geq 7.5, \end{cases} \tag{A6b}$$
$$x_c = \frac{\hbar\omega_c}{T_e} = 1.16 \times 10^{-2} T_e^{-1} B_{12} x^{-m},$$

where T_e is the one-dimensional electron temperature in MeV. For the above estimate, only electron-proton collisions have been considered, which is well justified considering the smallness of the dipole moment in electron-electron collisions (Bussard 1980). Electron spin-flip transitions are neglected because of their small cross sections. In the derivation of equation (A6) excitations to higher harmonics are neglected, so that equation (A6a) gives an upper limit for the excitation time.

In addition to collisional excitation, higher Landau states are populated by Compton scattering events. A γ-ray burst photon encounters magnetospheric electrons on a time scale

$$t_{\text{enc}} = (n_e \sigma_T c)^{-1} = 5 \times 10^{-9} n_{22}^{-1} x^n \text{ s}. \tag{A7}$$

This, however, is not the time scale on which the electron distribution function is energetically coupled to the photon heat bath. Because we are interested in possible deviations from a thermal electron distribution function (e.g., caused by Compton contact with the non–LTE γ-ray burst photons), we need to consider the net rate of Compton energy exchange. In the case of a one-dimensional electron distribution we use (Arons, Klein, and Lea 1987)

$$\partial_t u_e = \Gamma_c - \Lambda_c = \frac{4n_e \sigma_T}{3m_e c} u_\gamma (T_\gamma - T_e) H_c(x_\gamma, \eta_c), \tag{A8}$$

where η_c is proportional to the photon chemical potential (zero for a Planckian radiation field); u_γ and u_e are the energy densities of photons and electrons, respectively; H_c is a magnetic correction of order unity if $x_\gamma = \hbar\omega_c/T_\gamma$ is much smaller than unity (as applies here because γ-ray burst spectral "temperatures" $T_\gamma = \langle E_\gamma \rangle \sim$ several 100 keV; e.g., Higdon and Lingenfelter 1986). Because

Klein-Nishina corrections are neglected in equation (A8), the estimate of the energy exchange rate could change by a factor of about 2 at temperatures of order 100 keV. For strong magnetic fields (i.e., $x_\gamma \to \infty$) equation (A8) coincides with Iwamoto's (1983) result. For an isotropic distribution function the factor 4/3 has to be replaced by 4. In either case, the Comptonization time, i.e., the time scale to bring electrons and photons in equilibrium via Compton scattering, is given by

$$t_{\rm Comp} \sim \frac{u_e}{\partial_t u_e} = \frac{3}{8} \frac{T_e}{T_\gamma - T_e} \frac{n_e}{u_\gamma} t_{\rm enc} . \tag{A9}$$

At the onset of the γ-ray burst Compton scattering heats the electrons on time scales $t_{\rm Comp} \ll t_{\rm enc}$. With the approach to the equilibrium temperature $T_{\rm eq}$, $t_{\rm Comp}$ increases to

$$t_{\rm Comp} \sim \frac{3}{8} \frac{\tau}{1-\tau} \frac{m_e c^2}{T_\gamma} \frac{n_e}{n_\gamma} t_{\rm enc} , \tag{A10}$$

where $\tau = T_{\rm eq}/T_\gamma$ depends upon the spectral form of the γ-ray burst (see the discussion in § IIc), and $u_\gamma = n_\gamma T_\gamma$ has been used. From our experience with the spectrum of GB 800419 (for which $\tau \sim 0.9$, and $mc^2/T_\gamma \sim 3$) it appears useful then to consider

$$t_{\rm Comp} \sim \zeta \frac{n_e}{n_\gamma} t_{\rm enc} , \tag{A11}$$

where $\zeta \sim 10$ for GB 800419. Evaluating the number density ratio in equation (A11), we obtain

$$t_{\rm Comp} \sim 1.5 \times 10^{-4} \left(\frac{R_{*6}}{D_{100}}\right)^2 n_0^{-1} x^2 \text{ s} , \tag{A12}$$

where n_0 is the integrated γ-ray burst spectrum ($n_0 \sim 1$ photon cm^{-2} s for GB 800419).

As long as the Comptonization time is long compared with the electron-proton and electron-electron energy exchange time scales, the energy input from Compton collisions will lead to thermalized electrons, i.e., their distribution function will *not* reflect the extreme non–LTE character of the γ-ray burst photon spectrum. However, to also isotropize the electrons, Coulomb collisions have to compete with cyclotron transitions. For protons the cyclotron decay time is longer by a factor of $(m_e/m_p)^3$, so that Coulomb interactions easily create and maintain an isotropic distribution function. Because the protons do not interact as strongly with the radiation field as the electrons do, their temperatures may be different, in which case energy will be exchanged on the time scale (Kirk and Galloway 1982)

$$t_{\rm ex} = (n_e \langle \sigma_{\rm ep} v \rangle)^{-1} \sim 10^{-5} n_{22}^{-1} T_e^{3/2} x^n (\ln \Lambda)^{-1} \text{ s} , \tag{A13a}$$

where the Coulomb logarithm is given by

$$\ln \Lambda = 19.84 + \ln T_e - 0.5 \ln (n_{22} x^{-n}) . \tag{A13b}$$

Although the electrons are in contact with a non–LTE radiation field, Coulomb collisions drive the electron distribution function to its thermal equilibrium. Any nonthermal features are erased by collisions on the time scale (Krall and Trivelpiece 1986)

$$t_{\rm eq} \sim \frac{m_e}{2m_p} \left[\Phi(1) - \frac{4}{e\sqrt{\pi}}\right]^{-1} t_{\rm ex} \sim 2.2 \times 10^{-2} t_{\rm ex} , \tag{A14}$$

where Φ is the Gaussian error function. The effect of electron-electron collisions in strong magnetic fields has been neglected because no detailed calculations exist to date, although the QED cross section has been calculated (Allen, Melrose, and Parle 1985).

With increasing temperature of the magnetosphere the electron distribution function relaxes to equilibrium also by Compton interactions with the self-absorbed cyclotron photons. Locally the plasma is optically thick up to a maximum harmonic number m_* (see Appendix B), which causes a blackbody spectrum up to that frequency. The equilibration time scale due to the soft photons is given by

$$t_{\rm BB} \sim 3 \times 10^{-19} \alpha^{-1}(B, m_*) T_{\rm eq}^4 \text{ s} , \tag{A15}$$

where $\alpha(B, m_*)$ ($\ll 1$) is the fraction of cyclotron photons up to $m_* \omega_c(B)$ relative to a blackbody spectrum at temperature $T_{\rm eq}$.

Finally, we add a few additional time scales that might be useful to guide the physical intuition. Under the physical conditions of interest, the rates of microscopic processes are usually fast compared with macroscopic time scales such as the free-fall time,

$$t_{\rm ff} = 5 \times 10^{-5} x^{3/2} \text{ s} , \tag{A16}$$

and the diffusion time of low-energy cyclotron photon for which the optical depth is huge. In our model Compton scattering feeds energy into the electron plasma, resulting in temperatures T_e of the same order as that of typical γ-ray burst photons. This energy is consequently thermalized and redistributed by Coulomb collisions. We are concerned with the validity of the Maxwellian electron distribution function for calculating the emission of cyclotron radiation at energies $m_* \hbar\omega_c \ll T_e$. It is therefore important to estimate the time needed to establish the part of the Maxwellian distribution function which excites these low-energy transitions:

$$t_{\rm dist} \sim 7 \times 10^{-10} T_e (m_* B_{12})^{1/2} (n_{22} \ln \Lambda)^{-1} G(\zeta)^{-1} x^{n-m/2} \text{ s} , \tag{A17}$$

where

$$G(\zeta) = 0.5[\Phi(\zeta) - \zeta\Phi'(\zeta)]\zeta^{-2} , \tag{A18}$$

with

$$\zeta = 0.108\left(\frac{m_* B_{12}}{T_e}\right)^{1/2} x^{-1/2} . \tag{A19}$$

In the limit $x \gg 1$ we obtain

$$t_{\rm dist} \sim 6 \times 10^{-9}(n_{22} \ln \Lambda)^{-1} T_e^{3/2} x^n \text{ s} . \tag{A20}$$

The efficiency for cyclotron radiation at high harmonics drops rapidly when $t_{\rm cyc} \ll t_{\rm dist}$, because the losses from the distribution function cannot be replenished by collisions. Thus, when the γ-ray burst is turned off, high harmonic cyclotron emission cannot be maintained over times longer than the cyclotron time scale, which is generally much shorter than the γ-ray burst duration even for low fields at large distances from the neutron star surface. As a consequence the optical flash ceases very rapidly after the γ-ray flux drops. This fact, together with the rapid establishment of the equilibrium temperature after the burst's onset, leads to an "optical" display that essentially coincides with and tracks the γ-ray burst.

The importance of bremsstrahlung compared with cyclotron emission for the energy balance of a slab of magnetized plasma can be estimated by comparing the bremsstrahlung cooling time scale (Lamb 1984),

$$t_{\rm br} \sim 1.6 \times 10^{-6} T_e^{1/2} n_{22}^{-1} x^n \text{ s} , \tag{A21}$$

with the thermal cyclotron cooling time. The presence of a strong magnetic field leads only to small changes in the estimate of $t_{\rm br}$ (Iwamoto 1983).

Some of the above time scales, estimated as a function of $x = r/R_*$, are shown in Figure 3*a* for the following set of parameters $\{n_{22}, B_{12}, T_e, n, m, D_{100}, n_0\} = \{1, 1, 0.116, 0.5, 3, 1, 1\}$. One sees that at about $10^{8.5 \pm 1}$ cm above the neutron star surface the plasma conditions are generally favorable for the TCR model. Note that most of our models were calculated with $x \geq 0.6$, whereas we assume here that $x \geq 1$. Close to the neutron star the electron distribution function is nonisotropic because of the strong magnetic field, and at larger distances the densities become too low to maintain LTE in the non–LTE photon bath. To explore the general range of validity of the TCR model, we vary the density and the magnetic field strength to determine the fraction of the parameter space in which our assumptions are justified. We use the following conditions: (I) propagation constraint, $t_{\rm pl} \geq t_{\rm IR}$; (II) isotropy constraint, $t_{\rm cyc} \geq t_{01}$; (III) LTE constraint, $t_{\rm eq} \leq t_{\rm Comp}$. Where these conditions are met, the TCR model assumptions are valid (Fig. 3*a*). The resulting phase diagram (Fig. 3*b*) demonstrates that there is sufficient space for the thermal cyclotron reprocessing model to operate.

APPENDIX B

GYROSYNCHROTRON OPACITY AND MAXIMUM HARMONIC NUMBER m_*

For magnetized plasmas at temperatures above $\sim$10 keV, cyclotron absorption (and emission) at high harmonic numbers becomes important. For the conditions encountered in the thermal cyclotron reprocessing scenario, the results of Robinson and Melrose (1984) were used to calculate the absorption coefficient. The analytic formulae these authors provide are accurate over a wide range of parameters, especially a large range of harmonic numbers, and at the same time are sufficiently simple to allow a numerical formulation of a detailed treatment of the radiation transport in the extended neutron star magnetosphere. Below we give the absorption coefficient, which is dependent upon the frequency, angle of propagation, and polarization mode. Deviations of the plasma refractive index from unity have been ignored, and some of the terms have been rearranged. The approximation to the electron distribution function that Robinson and Melrose used (their eq. [30]) has been replaced by the complete relativistic Maxwell-Boltzmann function, which accounts for the appearance of the modified Bessel function of second order, K_2, in our expression for the gyrosynchrotron absorption coefficient:

$$\begin{aligned}\kappa_\omega^\sigma = {} & \kappa_0 \beta_m^2 K_2^{-1}(\beta_m) \exp(-\beta_m \gamma_0)(\sin\theta)^{-4}\left(\frac{\omega}{\omega_c}\right)^{-1/2} s_0^{-3/2} Z^{2s_0} \\ & \times \gamma_0^{3/2}(\gamma_0^2 - 1)\zeta_0^2 - 1)\zeta_0^2(\zeta_0{}^2 - 1)(1 + T_\sigma^2)^{-1}(1 - \beta_0^2\cos^2\theta)\left(1 + 4.53\frac{s_c}{s_0}\right)^{1/6} \\ & \times \left\{\left[c_\sigma\left(1 + 0.85\frac{s_c}{s_0}\right)^{-1/3} + (1 - \beta_0^2)^{1/2}(1 - \beta_0^2\cos^2\theta)^{1/2}\right]^2 + \frac{\beta_0^2 T_\sigma^2 \zeta_0 \sin^4\theta}{2(s_c + s_0)}\right\} ,\end{aligned} \tag{B1}$$

where $\sigma = o, x$ stands for the ordinary and extraordinary photon polarization mode, and the following abbreviations have been used:

$$\beta_m = \frac{m_e c^2}{kT} ,$$

$$\kappa_0 = \frac{\pi e n_e}{(2\sqrt{2})B} = 5.335 \times 10^{-10} \frac{n_e}{B} \text{ cm}^{-1} ,$$

$$\gamma_0 = \left[1 + \left(\frac{2\omega}{\beta_m \omega_c}\right)(1 + 4.5x)^{-1/3}\right]^{1/2} ,$$

$$x = \frac{\omega \sin^2 \theta}{\omega_c \beta_m} ,$$

$$\beta_0 = (1 - \gamma_0^{-2})^{1/2} ,$$

$$\zeta_0 = \left(\frac{1 - \beta_0^2}{1 - \beta_0^2 \cos^2 \theta}\right)^{-1/2} ,$$

$$s_c = 1.5\zeta_0^3 ,$$

$$s_0 = \gamma_0\left(\frac{\omega}{\omega_c}\right)(1 - \beta_0^2 \cos^2 \theta) ,$$

$$T_x^{-1} = a + (1 + a^2)^{1/2} = -T_o ,$$

$$a = \frac{\omega_c \sin^2 \theta}{2\omega |\cos \theta|} ,$$

$$c_\sigma = T_\sigma \cos \theta(1 - \beta_0^2) ,$$

$$Z = (\zeta_0 + 1)^{-1}(\zeta_0^2 - 1)^{1/2} e^{1/\zeta_0} .$$

For high plasma densities, cyclotron self-absorption limits the radiation flux to the blackbody value for all frequencies that are optically thick. With the opacity given in equation (B1), we now calculate the maximum frequency, ω_*, for which this is the case. First define a "critical" harmonic number $m_* = \omega_*/\omega_c$ by

$$R\kappa_\omega^\sigma(\beta_m, \theta) = 1 , \tag{B2}$$

where R is a characteristic length scale over which the magnetic field is assumed to be constant. The maximum frequency of the extraordinary mode exceeds that of the ordinary mode. The critical harmonic number calculated from equation (B2) can be approximated by the following expansion:

$$m_*^\sigma(\Lambda, T) = \sum_{n,m=1}^{4} C_{nm}^\sigma T^{m-1}(\log_{10} \Lambda)^{n-1} , \tag{B3}$$

where the dimensionless plasma parameter Λ is given by equation (17) in the main text and the temperautre, T, is measured in MeV. The coefficients C_{nm}^σ in equation (B3) are given in Table 2. The fit obtained here is accurate to a few percent over the temperature range 2 keV to 2 MeV and the optical depth range $\Lambda = 10^3$–10^{12}. This is more than sufficient considering the many other approximations that must be made in the present study. Figure 7 shows our fit to the exact data of m_*^σ for a temperature of 200 keV, typical for the Compton equilibrium temperature of the neutron star magnetospheres considered in our optical flash model.

It is of interest to compare our result with those reported previously. Utilizing the Carlini approximation combined with the method of steepest descent to evaluate the integrals, Petrosian and Harding (1986) derived the semirelativistic approximation

$$m_* = \frac{\pi\sqrt{\pi}}{6} \beta_m^{3/2} \Lambda \exp\left[-1.65\beta_m^{2/3}\left(\frac{m_*}{\sin \theta}\right)^{1/3}\right] . \tag{B4}$$

In the extreme relativistic case we can use Pacholczyk's (1970) approximations to derive the following equation

$$m_* = \frac{\beta_m \Lambda}{(4\sqrt{3})K_2(\beta_m)} \int_0^\infty dz\, e^{-z} \int_{y0}^\infty dy\, K_{5/3}(y) , \tag{B5a}$$

where the lower integration limit is given by

$$y_0 = \frac{2\beta_m^2 m_*}{3(\sin \theta)z^2} . \tag{B5b}$$

TABLE 2

NUMERICAL FIT COEFFICIENTS C^{σ}_{nm}

n	m = 1	2	3	4
		o-Mode		
1.........	−3.21112975 (+0)	+6.68033586 (+1)	−4.55518550 (+2)	+2.30503746 (+2)
2.........	+1.79655354 (+0)	−4.92915397 (+1)	+3.54864845 (+2)	−1.77797897 (+2)
3.........	−1.77026427 (−1)	+1.08289891 (+1)	−9.50153873 (+1)	+4.84568355 (+1)
4.........	+6.06791362 (−3)	−1.23119536 (−2)	+7.59192046 (+0)	−4.06974659 (+0)
		x-Mode		
1.........	−2.08742916 (+0)	+6.56499664 (+1)	−3.50949585 (+2)	+8.67078489 (+1)
2.........	+2.34384382 (+0)	−5.77769598 (+1)	+3.10773185 (+2)	−8.41716345 (+1)
3.........	−2.86972246 (−1)	+1.67637581 (+1)	−1.01721893 (+2)	+3.40772931 (+1)
4.........	+9.49706419 (−3)	−1.92706324 (−1)	+9.50415455 (+0)	−3.74706628 (+0)

Note that all the equations above have to be inverted numerically. In contrast, Wada *et al.* (1980) give the simple fit

$$m_* = 33.9\Lambda^{1/20}\beta_m^{-1/2} , \tag{B6}$$

which has been used in an earlier version of this study (Hartmann, Woosley, and Arons 1987). Unfortunately, in the Λ-T range of interest here, it fails to reproduce the detailed fit of Masters (1978),

$$\begin{aligned} m_* = &+0.44 - (0.18 + 3.8\beta_m^{-2}) \log \beta_m \\ &+(0.159 + 0.87\beta_m^{-1} \log \beta_m + 0.72\beta_m^{-2}) \log \Lambda \\ &-(0.0109 + 0.023\beta_m^{-1})(\log \Lambda)^2 \\ &+0.00033(\log \Lambda)^3 , \end{aligned} \tag{B7}$$

or our results obtained from Robinson and Melrose's opacity (Fig. 6). Our fit and the one given by Masters are qualitatively similar, but to be consistent with our transfer calculation we employ equation (B3).

It is apparent that the differences between the various estimates of m_* are not negligible. On the other hand, some reasonable accuracy in the determination of m_* is essential for the thermal cyclotron reprocessing model. An overestimate of this parameter would lead to a spurious UV flash, whereas an underestimate could even result in a breakdown of our assumption of LTE. This is so, because one would have to go closer to the neutron star surface to get the emission into the optical wave band, but there deviations from LTE become more important. As a consequence of the above discussion we find the results of Hartmann, Woosley, and Arons (1987), who used the fit of Wada *et al.* (1980), inaccurate in detail, though the general conclusions of the authors remain valid as is demonstrated in the present study.

REFERENCES

Allen, M. C., Melrose, D. B., and Parle, A. J. 1985, *Proc. Astr. Soc. Australia*, **6**, 211.
Apparao, K. M. V. 1984, *Astr. Ap.*, **139**, 375.
Arons, J. 1986, in *Proc. Mediterranean School on Plasma Astrophysics, Plasma Penetration into Magnetospheres*, ed. N. Kylafis, J. Papamastorakis, and J. Ventura (Iraklion: Crete University Press), p. 141.
———. 1987, in *IAU Symposium 125, Origin and Evolution of Neutron Stars*, ed. D. J. Helfand (Dordrecht: Reidel), p. 207.
Arons, J., Burnard, D. J., Klein, R. I., McKee, C. F., Pudritz, R. E., and Lea, S. M. 1984, in *AIP Conf. Proc. 115, High Energy Transients in Astrophysics*, ed. S. E. Woosley (New York: AIP), p. 215.
Arons, J., Klein, R. I., and Lea, S. M. 1987, *Ap. J.*, **312**, 666.
Arons, J., and Lea, S. M. 1976, *Ap. J.*, **207**, 214.
———. 1980, *Ap. J.*, **235**, 1016.
Atteia, J.-L., *et al.* 1985, *Astr. Ap.*, **152**, 174.
Atteia, J.-L., *et al.* 1987, *Ap. J. (Letters)*, **320**, L105.
Babul, A., Paczyński, B., and Spergel, D. N. 1987, *Ap. J. (Letters)*, **316**, L49.
Babul, A., Piran, T., and Spergel, D. N. 1987, preprint.
Bekefi, G. 1966, *Radiation Processes in Plasmas* (New York: Wiley).
Bhat, C., Kaul, S., Kaal, C., and Sapru, M. 1981, *Proc. 17th Internat. Cosmic Ray Conf.* (Paris), paper XG2.1-9.
Bignami, G. F. 1987, *Nature*, **330**, 316.
Bussard, R. W. 1980, *Ap. J.*, **237**, 970.
Chandrasekhar, S. 1950, *Radiative Transfer* (Oxford: Oxford University Press).
Chanmugam, G., and Wagner, R. L. 1979, *Ap. J.*, **232**, 895.
Cline, T. L. 1986, *Adv. Space Res.*, **6**, (No. 4), 5.
Colgate, S. A., and Petschek, A. G. 1981, *Ap. J.*, **248**, 771.
Cominsky, L. R., London, R. A., and Klein, R. I. 1981, *Ap. J.*, **315**, 162.
Dennis, B. R., Frost, K. J., Kiplinger, A. L. Orwig, L. E., Desai, U., and Cline, T. L. 1981, in *AIP Conf. Proc. 77, Gamma Ray Transients and Related Astrophysical Phenomena*, ed. R. E. Lingenfelter, H. S. Hudson, and D. M. Worrall (New York: AIP), p. 153.
Drummond, W. E., and Rosenbluth, M. N. 1960, *Phys. Fluids*, **3**, 45.
———. 1963, *Phys. Fluids*, **6**, 276.
Epstein, R. I. 1985, *Ap. J.*, **291**, 822.
———. 1986, *IAU Colloquium 89, Radiation Hydrodynamics in Stars and Compact Objects*, ed. D. Mihalas and K.-H. A. Winkler (Lecture Notes in Physics, Vol. **255** [Berlin: Springer]), p. 305.
Fegan, D., McBreen, B., O'Sullivan, C., and Ruddy, V. 1975, *Nucl. Instr. Meth.*, **129**, 613.
Fenimore, E. E., Klebesadel, R. W., and Laros, J. G. 1983, *Adv. Space Res.*, **3**, 207.
Flowers, E., and Ruderman, M. A. 197, *Ap. J.*, **215**, 302.
Golenetskii, S. V., Ilyinskii, V. N., and Mazets, E. P. 1984, *Nature*, **307**, 41.
Gopalakrishnan, N., Gupta, S., Ramana Murthy, P. V., Sreekantan, B., Tonwar, S., and Viswanath, P. 1981, *Proc. 17th Internat. Cosmic Ray Conf.* (Paris), paper XG2.1-6.
Grindlay, J. E., Wright, E. L., and McCrosky, R. E. 1974, *Ap. J. (Letters)*, **192**, L113.
Guilbert, P. W. 1986, *M.N.R.A.S.*, **218**, 171.
Halliday, I., Blackwell, A., and Griffin, J. 1978, *Roy. Astr. Soc. Canada*, **73**, 15.
Hartmann, D., Pogge, R. W., Hurley, K., Vrba, F., and Jennings, M. 1988, in preparation.
Hartmann, D., and Woosley, S. E. 1988, in *Proc. 4th LANL Workshop on Space Physics and Astrophysics, Multiwavelength Astrophysics*, ed. F. Cór-

dova, W. Priedhorsky, and E. Rühe (Cambridge: Cambridge University Press) chap. 10, in press.
Hartmann, D., Woosley, S. E., and Arons, J. 1987, *Bull. AAS*, **18**, 928.
Harwitt, M., and Salpeter, E. E. 1973, *Ap. J. (Letters)*, **186**, L37.
Higdon, J. C., and Lingenfelter, R. E. 1986, *Ap. J.*, **307**, 197.
Hirshfield, J. L., Baldwin, D. G., and Brown, S. C. 1961, *Phys. Fluids*, **4**, 198.
Howard, W. M., Wilson, J. R., and Barton, R. T. 1981, *Ap. J.*, **249**, 302.
Hudec, R. 1985, *Space Sci. Rev.*, **40**, 715.
Hudec, R., *et al.* 1986, *Adv. Space Res.*, **6**, (No. 4), 51.
———. 1987*a*, *Astr. Ap.*, **175**, 71.
Hudec, R., Borovicka, J., Danis, S., Franc, V., Peresty, R., and Valnicek, B. 1987*b*, in *Proc. COSPAR/IAU Symposium on the Physics of Compact Objects: Theory versus Observations* (Sofia), ed. N. White, in press.
Hudec, R., *et al.* 1984, *Adv. Space Res.*, **3**, (Nos. 10–12), 115.
Hurley, K. 1987, *Astr. Letters Comm.*, **25**, 145.
Imamura, J. N., and Epstein, R. I. 1987, *Ap. J.*, **313**, 711.
Iwamoto, N. 1983, *Ap. J.*, **265**, 1021.
Katz, B., *et al.* 1986, *Ap. J. (Letters)*, **307**, L33.
Katz, J. I. 1985, *Ap. Letters*, **24**, 183.
———. 1986, *Ap. J.*, **309**, 253.
Kirk, J. G., and Galloway, D. J. 1982, *Plasma Phys.*, **24**, 339.
Klebesadel, R. W., Strong, I. B., and Olson, R. A. 1973, *Ap. J. (Letters)*, **182**, L85.
Kouveliotou, C., *et al.* 1986, *Adv. Space Res.*, **6** (No. 4), 191.
Kouveliotou, C., *et al.* 1987, *Ap. J. (Letters)*, **322**, L21.
Krall, N. A., and Trivelpiece, A. W. 1986, *Principles of Plasma Physics* (San Francisco: San Francisco Press).
Krzeminski, W., and Serkowski, K. 1977, *Ap. J. (Letters)*, **216**, L45.
Kulkarni, S. R. 1986, *Ap. J. (Letters)*, **306**, L85.
Kundt, W., Özel, M. E., and Ercan, E. N. 1987, *Astr. Ap.*, **177**, 163.
Lam, N. T., Scharer, J. E., and Audenaerde, K. R. 1985, *IEEE Trans. Plasma Sci.*, **PS-13**, 25.
Lamb, D. Q. 1984, *Ann. NY Acad. Sci.*, **422**, 237.
Lamb, D. Q., and Masters, A. R. 1979, *Ap. J. (Letters)*, **234**, L117.
Langer, S. H., Chanmugam, G., and Shaviv, G. 1982, *Ap. J.*, **258**, 289.
Laros, J. G. 1988, *Nature*, **333**, 124.
Laros, J. G., *et al.* 1986, *Nature*, **322**, 152.
Laros, J. G., *et al.* 1987, *Ap. J. (Letters)*, **320**, L111.
Liang, E. P. 1985, *Nature*, **313**, 202.
———. 1987, *Comm. Ap.*, **12**, 35.
Liang, E. P., and Petrosian, V. eds. 1986, *AIP Conf. Proc. 141, Gamma Ray Bursts* (New York: AIP).
Liebert, J., Stockman, H. S., Williams, R. E., Tapia, S., Green, R., Rautenkranz, F., and Ferguson, D. H. 1982, *Ap. J.*, **256**, 594.
Livio, M., and Taam, R. E. 1987, *Nature*, **327**, 398.
London, R. A. 1984, in *AIP Conf. Proc. 115, High Energy Transients in Astrophysics*, ed. S. E. Woosley (New York: AIP), p. 581.
London, R. A., and Cominsky, L. R. 1983, *Ap. J. (Letters)*, **275**, L59.
Lyne, A. G., Manchester, R. N., and Taylor, J. H. 1985, *M.N.R.A.S.*, **213**, 613.
MacRobert, A. 1985*a*, *Sky and Tel.*, **69**, 148.
———. 1985*b*, *Sky and Tel.*, **70**, 54.
Maley, P. D. 1987, *Ap. J. (Letters)*, **317**, L39.
Masters, A. R. 1978, Ph.D. thesis, University of Illinois at Urbana-Champaign.
Matz, S. M. 1986, Ph.D. thesis, University of New Hampshire, Durham.
Matz, S. M., Forrest, D. J., Vestrand, W. T., Chupp, E. L., Share, G. H., and Rieger, E. 1985, *Ap. J. (Letters)*, **288**, L37.
Mazets, E. P., Golenetskii, S. V., Aptekar, R. L., Guryan, Yu. A., and Ilyinskii, V. N. 1981, *Nature*, **290**, 378.
Mazets, E. P., *et al.* 1982, *Adv. Space Sci.*, **84**, 173.
Melia, F. 1988, *Ap. J. (Letters)*, **324**, L21.
Mészáros, P., Bussard, R. W., and Hartmann, D. 1986, in *AIP Conf. Proc. 141, Gamma-Ray Bursts* (New York: AIP), p. 121.
Michalsky, J. J., Stokes, G. M., and Stokes, R. A. 1977, *Ap. J. (Letters)*, **216**, L35.
Michel, F. C. 1985, *Ap. J.*, **290**, 721.
———. 1986, *Physics Today*, **39**, 9.
———. 1987, *Nature*, **329**, 310.
Mihalas, D. 1978, *Stellar Atmospheres* (San Francisco: Freeman).
Moskalenko, E. I., *et al.* 1987, in *Proc. COSPAR/IAU Symposium on the Physics of Compact Objects: Theory versus Observations* (Sofia), ed. N. White, in press.
Nolan, P. L., Share, G. H., Matz, S., Chupp, E. L., Forrest, D. J., and Rieger, E. 1984, in *AIP Conf. 115, High Energy Transients in Astrophysics*, ed. S. E. Woosley (New York: AIP), p. 399.
Pacholczyk, A. G. 1970, *Radio Astrophysics* (San Francisco: Freeman).
Paczyński, B. 1987, *Ap. J. (Letters)*, **317**, L51.
Pedersen, H. 1987, *Adv. Space Res.*, **6** (No. 4), 61.
Pedersen, H., *et al.* 1984, *Nature*, **312**, 46.
Pedersen, H., Motch, C., Tarenghi, M., Danziger, J., Pizzichini, G., and Lewin, W. H. G. 1983, *Ap. J. (Letters)*, **270**, L43.
Petrosian, V., and Harding, A. K. 1986, in *AIP Conf. Proc. 141, Gamma-Ray Bursts*, ed. E. P. Liang and V. Petrosian (New York: AIP), p. 198.
Pozdnyakov, L. A., Sobol', I. M., and Syunyaev, R. A. 1985, *Ap. Space Sci. Rev.*, **2**, 189.
Rappaport, S. A., and Joss, P. C. 1985, *Nature*, **314**, 242.
Ricker, G. R., Doty, J. P., Fenimore, E. E., Hurley, K., Lamb, D. Q., Rappaport, S. A., and Woosley, S. E. 1987, *Concept Study of the High Energy Transient Explorer (HETE)*, proposal submitted to NASA.
Ricker, G. R., Doty, J. P., Vallerga, J. V., and Vanderspek, R. K. 1984, in *AIP Conf. Proc. 115, High Energy Transients in Astrophysics*, ed. S. E. Woosley (New York: AIP),
Robinson, P. A., and Melrose, D. B. 1984, *Australian J. Phys.*, **37**, 675.
Rothschild, R. E., and Lingenfelter, R. E. 1984, *Nature*, **312**, 737.
Ruderman, M. 1987, in *Proc. 13th Texas Conf. on Relativistic Astrophysics*, ed. M. P. Ulmer (Singapore: World Scientific), p. 448.
Schaefer, B. E. 1981, *Nature*, **294**, 722.
———. 1985, *A.J.*, **90**, 1363.
Schaefer, B. E., *et al.* 1987*c*, *Ap. J.*, **320**, 398.
Schaefer, B. E., *et al.* 1984*b*, *Ap. J. (Letters)*, **286**, L1.
Schaefer, B. E., *et al.* 1987*b*, *Ap. J.*, **313**, 226.
Schaefer, B. E., Pedersen, H., Gouiffin, C., Poulsen, J. M., and Pizzichini, G. 1987*a*, *Astr. Ap.*, **174**, 338.
Schaefer, B. E., and Ricker, G. R. 1983, *Nature*, **302**, 43.
Schaefer, B. E., Seitzer, P., and Bradt, H. V. 1983, *Ap. J. (Letters)*, **270**, L49.
Sturrock, P. A. 1986, *Nature*, **321**, 47.
Svensson, R. 1982, *Ap. J.*, **258**, 335.
Taam, R. E., and van den Heuvel, E. P. J. 1986, *Ap. J.*, **305**, 235.
Takahara, F., and Tsuruta, S. 1982, *Progr. Theor. Phys.*, **67**, 485.
Tapia, S. 1977, *Ap. J. (Letters)*, **212**, L125.
Teegarden, B. J., von Rosenvinge, T. T., Cline, T. L. and Kaipa, R. 1984, in *AIP Conf. Proc. 115, High Energy Transients in Astrophysics*, ed. S. E. Woosley (New York: AIP), p. 687.
Thompson, A. M., and Cawthorne, T. V. 1987, *M.N.R.A.S.*, **224**, 425.
Tremaine, S., and Żytkow, A. N. 1986, *Ap. J.*, **301**, 155.
Trubnikov, B. A. 1958, *Soviet Phys. Doklady* **3**, 136.
———. 1973, *Soviet Phys.—JETP Letters.*, **16**, 25.
Trümper, J., Pietsch, W., Reppin, C., Voges, W., Staubert, R., and Kendziorra, E. 1978, *Ap. J. (Letters)*, **219**, L105.
van den Heuvel, E. P. J., van Paradijs, J. A., and Taam, R. E. 1986, *Nature*, **332**, 153.
Vanderspek, R. K., Zachary, D. S., and Ricker, G. R. 1986, *Adv. Space Res.*, **6** (No. 4), 69.
Voges, W., Pietsch, W., Reppin, C., Trümper, J., Kendziorra, E., and Staubert, R. 1982, *Ap. J.*, **263**, 803.
Vzorov, N. N., Gorbachëv, L. P., Matronchik, A. Yu., and Mozgov, K. S. 1985, *Soviet Astr. Letters*, **11**, 184.
Wada, T., Shimizu, A., Suzuki, M., Kato, M., and Hoshi, R. 1980, *Progr. Theor. Phys.*, **64**, 1986.
Wang, Z., and Eichler, D. 1987, preprint.
Wickramasinghe, D. T., and Meggit, S. M. A. 1982, *M.N.R.A.S.*, **198**, 975.
Woosley, S. E. 1984, in *AIP Conf. Proc. 115, High Energy Transients in Astrophysics*, ed. S. E. Woosley (New York: AIP), p. 485.
Woosley, S. E., and Taam, R. E. 1976, *Nature*, **263**, 101.
Zhemerev, A. V., Medvedev, Yu. A., and Stepanov, B. M. 1974, *Cosmic Res.*, **12**, 531.

D. Hartmann: Board of Studies in Astrophysics, University of California at Santa Cruz, Santa Cruz CA 95064 [Bitnet: hartmann@ucscloa]

S. E. Woosley: Board of Studies in Astronomy and Astrophysics, University of California at Santa Cruz, CA 95064 [Bitnet: vwoosley@ucscloa]

J. Arons: Department of Astronomy, University of California at Berkeley, Berkeley, CA 94720 [Bitnet: arons@astroplasma.berkeley.edu]