CONF-871245--5

UCRL- 98226
PREPRINT

MAR 17 1988

SPECTRAL MODELLING OF THE SOFT GAMMA
RAY REPEATER

Edison P. Liang
LAWRENCE LIVERMORE NATIONAL LABORATORY
Livermore, CA 94550

This Paper was Prepared for Submittal to
The Workshop on Nuclear Spectroscopy of
Astrophysical Sources
Washington, D. C.
13-16 December, 1987

February, 1988

Lawrence
Livermore
National
Laboratory

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily imply endorsement or recommendation by the United States Government. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

SPECTRAL MODELLING OF THE SOFT GAMMA RAY REPEATER *

E. P. Liang

Lawrence Livermore National Laboratory, Livermore, Ca. 94550

ABSTRACT

This paper summarizes the results of numerical modelling of the spectra of the soft gamma ray repeater (SGR 1806-20). Parameters of the emission region can be extracted from the spectral fits under the simplistic assumption of isothermal and homogeneous emission layers. Limits on the luminosity distance of the source can also be derived if we make specific interpretations of the low frequency turnover in the observed spectrum.

INTRODUCTION

The recently discovered soft gamma ray repeater SGR 1806-20¹⁻³, together with the March 5, 1979⁴ and March 24, 1979 soft gamma bursters, probably represent a distinct new class of high energy transient. They are distinguished by their chaotic repetition patterns and a soft exponential spectrum with an almost universal color temperature of $\sim 45 \pm 10$ keV (cf. Refs. 1, 4). While the repetition pattern is already the subject of much speculation⁵, here we concentrate on extracting the maximum amount of physical information out of the spectral data of SGR 1806-20, by making the anzatz that to first order we can approximate the emission region as a homogeneous and isothermal layer. Despite the simplistic nature of such models, these results should provide a useful framework for constructing more refined astrophysical models and confronting future observational data.

Since a summary of our results is already being published elsewhere⁶, here we will concentrate on the discussion of ideas and issues which supplement and complement those in Ref. 6.

SPECTRAL MODELS

We consider four specific thermal (single-temperature) emission models which, to our judgement, provide the best fit to the published spectral data of SGR 1806-20^{1,3}. These are: a. optically thin thermal bremsstrahlung (TB), b. self-Comptonized bremsstrahlung (CB), c. thermal synchrotron^{7,8} (TS) and d. cooling synchrotron with thermal injection⁹ (CS). We have also modelled the spectra with blackbody or Wien (saturated Comptonization), but the fits are much worse than the above models so we did not pursue them further. We compute the bremsstrahlung spectra including Comptonization and self-absorption effects using a Monte Carlo code developed by Canfield⁹ and the synchrotron spectra with a code generalized from that of Brainerd^{8,10}. Synchrotron self-absorption is included approximately via semi-analytic techniques. In the bremsstrahlung cases we estimate the emission measure and intrinsic flux by interpreting the low frequency turnover as self-absorption. In the synchrotron cases the turnover is interpreted as either due to self-absorption or first harmonic cutoff, leading to different distance limits. Given the large error bars of the sub-10keV data, the reality and interpretation of the turnover are obviously debatable. Hence our distance estimates can be taken as conservative upper limits.

*This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

BREMSSTRAHLUNG MODEL PARAMETERS

Figure 1 illustrates the comparison of sample model bremsstrahlung spectra of different Thomson depths τ and temperatures T with the published data of SGR 1806-20 (we have combined the data of GB790107 and GB831119 to maximize the energy coverage since the two spectra coincide in the overlapping range and there is no significant spectral variation among the recurrent events). The emission measure n^2h (n =electron density, h =emission layer thickness) required for the low frequency turnover comes to $\sim 10^{51} \text{cm}^{-5}$ and is relatively insensitive to the Thomson depth and temperature in the range that gives the best fit. Even though we have not yet performed a detailed chi-square analysis, just from eyeballing we conclude that in the τ - T plane a narrow ellipse covering the temperature range ~ 30 -40 keV and Thomson depth range ~ 0 -1 would correspond to the best fit parameters (Fig. 1 inset). For example, for $\tau = 0$ the best fit temperature is ~ 40 keV and for $\tau = 1$ the best fit temperature is ~ 30 keV. For temperatures < 30 keV or > 40 keV the fit gets progressively worse independent of τ . Similarly, for $\tau > 1$ the fit gets progressively worse for all temperatures.

For the $\tau = 0$, $T=40$ keV case, the emission measure of 10^{51}cm^{-5} corresponds to an intrinsic flux above 30 keV of $\sim 2.4 \times 10^{27} \text{ergs/cm}^2 \cdot \text{s}$. For a neutron star of 10 km radius, the luminosity distance would be ~ 3.4 kpc using the published value for the observed flux above 30 keV (cf. Ref. 1). In the opposite case of $\tau = 1$, $T=30$ keV the same emission measure gives rise to an intrinsic flux above 30 keV of $\sim 1.9 \times 10^{27} \text{ergs/cm}^2 \cdot \text{s}$ and a luminosity distance of ~ 3.0 kpc. Since the self-absorption turnover frequency is uncertain to a factor of ~ 2 (cf. Fig. 1), the emission measure and intrinsic flux are uncertain to a factor of ~ 4 (since the absorption frequency $\nu_a \ll$ temperature T so $\exp(\nu_a/T) \approx 1$). Hence the luminosity distance estimate is uncertain to within a factor ~ 2 . In any case the distance falls short of the galactic center (~ 8.5 kpc) unless the stellar radius (or effective emission surface size) is significantly larger than 10 km. Since in all cases the Thomson depth is ≤ 1 , the thickness of the emission layer is $\leq 2 \times 10^{-3} \text{cm}$ and the electron density $\geq 7 \times 10^{26} \text{cm}^{-3}$. Such a dense thin emission layer is hard to visualize in realistic astrophysical situations. This plus the lack of a confinement mechanism for the plasma against the superEddington flux makes the bremsstrahlung models rather implausible.

SYNCHROTRON MODEL PARAMETERS

Figure 2 illustrates the comparison of model synchrotron spectra with the spectral data. It shows that given the uncertainties of the sub-10 keV data, the turnover can be modelled either as self-absorption or first harmonic cutoff. Of course if future observations can pin down the spectrum below ~ 4 keV then the two interpretations can definitely be distinguished. As in all synchrotron spectral models, the spectral shape at high frequencies can only constrain the product $\nu_c = \nu_B T^2$ (where ν_B is the cyclotron frequency) but not the field strength B or the temperature T separately. If the low frequency turnover is due to first harmonic cutoff, then the field strength and temperature are indeed obtained separately. In this case an upper limit to the intrinsic flux can be estimated from the

lack of self-absorption down to the first harmonic. Note that in this case we expect to see the feature of the second harmonic as well due to the low temperature. On the other hand, if the low frequency turnover is due to self-absorption, we would need to invoke additional conditions to obtain the magnetic field strength. In the present context we propose to use the plasma confinement condition $B^2/8\pi > F/c$ (where F is total radiation flux at the source) for the field lower limit, and the condition that the first harmonic be located below 10 keV for the field upper limit. In this case a range of the intrinsic synchrotron flux can be estimated.

For the steady thermal case the formula for self-absorption can be found in Ref. 7. For the cooling case (with initial thermal injection) we derive the approximate self-absorption opacity using Tucker's formula¹¹ by substituting v_A/v_B for γ_1 (where γ_1 is the transverse Lorentz factor) into the time-averaged cooling particle distribution function derived by Brainerd⁸ and its derivatives. This is admittedly a crude procedure but we believe it should be adequate for the present purposes. The resultant emission parameters for both cases are listed in Ref. 6 so they will not be repeated here. We note that the resultant luminosity distance upper limit for a 10 km radius neutron star is ~ 5.5 kpc for both first harmonic cutoff models. The distance range for the steady thermal self-absorption model is $\sim 3.5 - 12$ kpc and the corresponding range for the cooling thermal self-absorption model is $\sim 6 - 14$ kpc. As expected, the cooling case gives the largest distance since the cooling particles tend to self-absorb at lower frequencies. Both self-absorption models allow a galactic center distance (~ 8.5 kpc).

From the microphysical point of view, a cooling particle distribution is also most plausible. Even at the low field strength of $\approx 10^{10}$ G required for confinement (cf. Table I of Ref. 6), the synchrotron cooling time is $\approx 10^{-12}$ sec and is much shorter than the coulomb coupling time to hot protons to maintain a steady thermal distribution for densities $< 10^{24}/\text{cm}^3$. In this case however, the initial injection temperature of the electrons must exceed ~ 100 keV to account for the observed spectrum (cf. Ref. 6). In most x-ray pulsar models¹², the hard x-ray spectrum is produced by Comptonization with τ_T , 1 and $T \sim \text{few} - 30$ keV in a super-teragauss field. Any turnover would be due to Compton saturation or bremsstrahlung self-absorption. However, for SRG 1806-20, the location of the turnover, hardness of the spectrum and lack of any harmonic feature from 8-200 keV distinguish it from most x-ray pulsars and are hard to reconcile with the strong field Compton models. Hence we opt for a weak field ($< 10^{12}$ G), optically thin, high temperature scenario, such as may be produced in a collisionless accretion shock above the stellar surface. Note that to maintain a synchrotron radiation flux of $\sim 10^{28} \text{ erg/cm}^2 \cdot \text{s}$ (cf. Ref. 6) by proton accretions the proton density in the accretion flow must be $\sim 5 \cdot 10^{21}/\text{cm}^3$ assuming $\sim 0.1 mc^2$ energy conversion. In a $> 10^{10}$ G field the proton gyroradius and hence the minimum shock thickness < 0.002 cm. This is small compared with the cooling distance of the heated electrons (~ 0.03 cm). If the shock is not pair-dominated (which seems likely) so that lepton density $\sim$ proton density, the total Thomson depth of the shock plus post-shock cooling layer is $\sim 10^{-4}$. Interestingly this is consistent with the Thomson depth needed for the synchrotron self-absorption turnover (cf. Ref. 6). A conception of this picture is depicted in Fig. 3.

Fig. 1. Comparison of self-Comptonized bremsstrahlung spectra with data of SGR 1806-20. Data are taken from published results of Prognos 7, Prognos 9 and ICE (Refs.1,3). a. $T=40$ keV, $\tau = 1$; b. $T=40$ keV, $\tau = 0.1$; c. $T=30$ keV, $\tau = 1$; d. $T=30$ keV, $\tau = 0.01$. In all cases $n^2 h = 10^{51} \text{ cm}^{-3}$. Inset: Schematic ellipse illustrating the best fit parameters in the τ - T plane. No confidence level can be given until chi-square analysis is performed.

Fig. 2. Comparison of model synchrotron spectra with data: a. cooling synchrotron with $B=1.2 \times 10^{12}$ G, injection temperature=102 keV, no self-absorption; b. steady thermal synchrotron with $B=6 \times 10^{10}$ G, $T=330$ keV, $\tau = 0.02$. Inset: Schematic ellipse illustrating the best fit parameters in the B - T plane.

CONCLUSIONS

We show that rough emission parameters and luminosity distance limits for SGR 1806-20 can be obtained by modelling the spectrum with simple single temperature models. The results favor the synchrotron model over the bremsstrahlung-Compton models. However, only self-absorbed synchrotron emissions from a cooling distribution of injected hot e^+ electrons (as opposed to a true thermal distribution) appears likely if the particle density is $< 10^{24}/\text{cm}^3$ and collective plasma processes do not operate. A prediction of this model would be that the x-ray spectrum below ~ 4 keV should be very close to a quasi-Rayleigh-Jeans spectrum. Future x-ray observation of this source should be able to verify or dismiss this model.

REFERENCES

1. J. L. Atteia et al., *Astrophys. J. Lett.* **320**, L105 (1987).
2. J. G. Laros et al., *Astrophys. J. Lett.* **320**, L111 (1987).
3. J. G. Laros et al., *Nature* **322**, 152 (1986).
4. E. P. Mazets et al., *Astrophys. Sp. Sci.* **84**, 173 (1982).
5. A. Babul et al., *Astrophys. J. Lett.* **316**, L49 (1987).
6. E. P. Liang, *Nature*, to appear (1988).
7. E. P. Liang et al., *Astrophys. J.* **271**, 766 (1983).
8. J. Brainerd and D. Q. Lamb, *Astrophys. J.* **313**, 231 (1987).
9. E. Canfield et al., *Astrophys. J.* **323**, 000 (1987).
10. J. Brainerd, Harvard University Ph.D. Thesis (1985).
11. W. Tucker, *Radiative Processes in Astrophysics* (MIT, Cambridge, 1975).
12. See, e.g. P. Meszaros, *AIP Conf. Proc.* No. 115, p.165, S. Woosley ed (AIP, N.Y., 1984); Aron, J. et al. *Ap. J.* **312**, 666 (1987).

Figure 3

Fig. 3. Artist conception of an optically thin synchrotron cooling collisionless shock model for accretion onto a magnetized neutron star that may be relevant to the soft gamma repeater.