THE ASTROPHYSICAL JOURNAL, 297:L21–L24, 1985 October 15

SOFT X-RAY PRODUCTION BY PHOTON SCATTERING IN PULSATING BINARY NEUTRON STAR SOURCES

R. W. BUSSARD AND P. MÉSZÁROS
Department of Astronomy, The Pennsylvania State University

AND

S. ALEXANDER
Department of Physics, The Pennsylvania State University
Received 1985 April 8; accepted 1985 June 21

ABSTRACT

A new mechanism is proposed as a source of soft ($E_s < 1$ keV) radiation in binary pulsating X-ray sources, in the form of photon scattering which leaves the electron in an excited Landau level. In a plasma with parameters typical of such sources, the low-energy X-ray emissivity of this mechanism far exceeds that of bremsstrahlung. This copious source of soft photons is quite adequate to provide the seed photons needed to explain the power-law hard X-ray spectrum by inverse Comptonization on the hot electrons at the base of the accretion column.

Subject headings: radiation mechanisms — X-rays: sources

I. INTRODUCTION

The radiation of the pulsing X-ray binaries is widely believed to result from the impact of accreting plasma on the atmosphere of a strongly magnetized neutron star. Near the stellar surface, photon densities can arise that are greater than the atmospheric particle densities. In a nonmagnetized plasma, such a situation is conducive to emission by double Compton scattering, which becomes competitive with bremsstrahlung as a source of soft radiation (e.g., Lightman 1981). The presence of a strong magnetic field, however, introduces resonances in the bremsstrahlung rate at harmonics of the cyclotron frequency. Specifically, the Coulomb excitation, mainly via electron-ion collisions, of the quantized transverse energy levels of the electrons followed by radiative de-excitation leads to strongly enhanced emission at or near multiples of $\hbar\omega_c = 11.6\ B_{12}$ keV (Ventura 1973; Bussard 1980; Langer 1981). The purpose of this *Letter* is to point out that there also exists a resonance in the double Compton scattering process that leads to the production of copious amounts of soft X-radiation.

In its simplest terms, the process we wish to consider can be described as a Compton-like scattering in which the electron is left in an excited magnetic state. Later, the electron will radiatively de-excite, and the net effect is thus the production of a photon. In diagrammatic terms, it is analogous to double Compton scattering, which consists of three vertices and two propagators, but in the presence of the strong magnetic field, the second propagator can become a real (on the mass shell) excited state electron, effectively decoupling the third vertex from the diagram. The result is that the rate for our process is more nearly the Compton-like rate than the double Compton. That is, the rate is calculated in the same manner as simple scattering, with the initial electron in the ground magnetic state, the final electron in an excited state (only the first is considered here), and the final photon frequency on average is less than that of the initial photon by the cyclotron frequency. For the case that the electron's initial and final states are both magnetic ground states, the scattering cross section has been given by Herold (1979). The conditions for the initial state to be taken as the ground state are well satisfied in the parameter regimes typical of the binary X-ray pulsars (e.g., Bussard 1980).

Because of the resonant nature of the Coulomb interaction, it appears likely that most bremsstrahlung-like photons are created near the cyclotron frequency, being subsequently redistributed in frequency by Comptonization. In this *Letter*, we point out that these photons will spawn a great deal of soft radiation, whose density is limited only by the Rayleigh-Jeans bound, via the process described above. This mechanism provides a new source of soft photons which can be redistributed to higher frequencies by inverse Comptonization. A natural explanation is thereby provided for the power-law spectrum above a few keV seen in most pulsing X-ray binaries (White, Holt, and Swank 1983). Calculations by Mészáros and Nagel (1985*a*, *b*) have shown that the continuum and line spectra of typical X-ray binaries are satisfactorily reproduced if an unspecified source of soft X-rays ($E_s \lesssim 1$ keV) is assumed. We shall show here that the resonant double Compton analog provides the required copious source of soft radiation.

II. PRODUCTION RATE

For the purposes of this *Letter*, we shall adopt the nonrelativistic approximation, and we take the electron parallel momentum distribution to be Maxwellian. For an electron initially in the ground magnetic state but left in the jth excited state after the scattering, the parallel velocity that is required to produce a photon at ω' from a photon at ω is $v = (\omega - \omega_c - \omega')/(k_\parallel - k'_\parallel)$, where $k_\parallel$ is the component of the wave vector parallel to the field. Here, we consider only the ground and first excited states, $j = 0$ or 1. For the case that $j = 1$, it can be seen that the final frequency should satisfy $\omega' = \{\omega[1 - (v\mu/c)] - \omega_c\}/[1 - (v\mu'/c)]$, where μ and μ' are the cosines of the propagation angles with respect to the magnetic field direction. If the incident frequency is less than the cyclotron frequency, the incident photon should lie in the core of the resonance, defined roughly by $|(\omega - \omega_c)/(2^{1/2}k_\parallel v_T)| < 3$, where $v_T = (T/m)^{1/2}$. In this case, only rather soft final photons are allowed. However, if the incident frequency is greater than the cyclotron frequency, one would expect a local maximum in the rate, due to the influence of the electron distribution function, near $\omega' = \omega - \omega_c$, corresponding to $v = 0$.

We have calculated the photon scattering rates fully relativistically, and the results will be presented elsewhere. In the nonrelativistic approximation, the following simple expression serves to describe the process whereby the electron remains in the first excited state,

$$\frac{w(\omega', \mu')}{w_{\rm Th}} = \frac{3}{8} f(v) \frac{\hbar\omega_c}{mc^2} \frac{\omega}{\omega'} |k_\parallel - k'_\parallel|^{-1} \times \mu^2(1 + \mu^2)(1 - \mu'^2), \qquad (1)$$

where v is the electron velocity given above, and the rest of the symbols have their usual meanings. In obtaining equation (1), we have averaged the initial photon polarization and summed over the final polarization. In Figure 1, we show the results of equation (1) plotted with the results of the full calculation. Figure 1a shows the case for an initial frequency less than the cyclotron frequency, and Figure 1b shows one case when the initial frequency is greater than the cyclotron frequency, showing the local maximum discussed above. To obtain the total soft photon production rate, equation (1) can be averaged over initial angles and integrated over final angles (analytically by ignoring $k'_\parallel$ compared to $k_\parallel$) to give

$$\frac{w(\omega')}{w_{\rm Th}} = \frac{3}{8} \frac{\hbar\omega_c}{mc^2} \frac{c}{(2\pi)^{1/2} v_T} \frac{1}{\omega'} \times \left[\left(1 - \frac{1}{3}x^2\right) e^{-x^2} - \frac{1}{3}x^2(1 - x^2) E_1(x^2)\right], \qquad (2)$$

where $E_1(x)$ represents the exponential integral, and x is given by

$$x = \frac{c}{2^{1/2} v_T} \frac{\omega - \omega' - \omega_c}{\omega}. \qquad (3)$$

By comparing this production rate to the amount of time spent by a resonant photon in the core, we estimate that, for typical parameters, as many as several soft photons may be produced in each excursion in the core.

Finally, we shall derive an expression for soft photon production in the case of a Wien distribution at temperature T, equal to the electron parallel temperature, in terms of the total

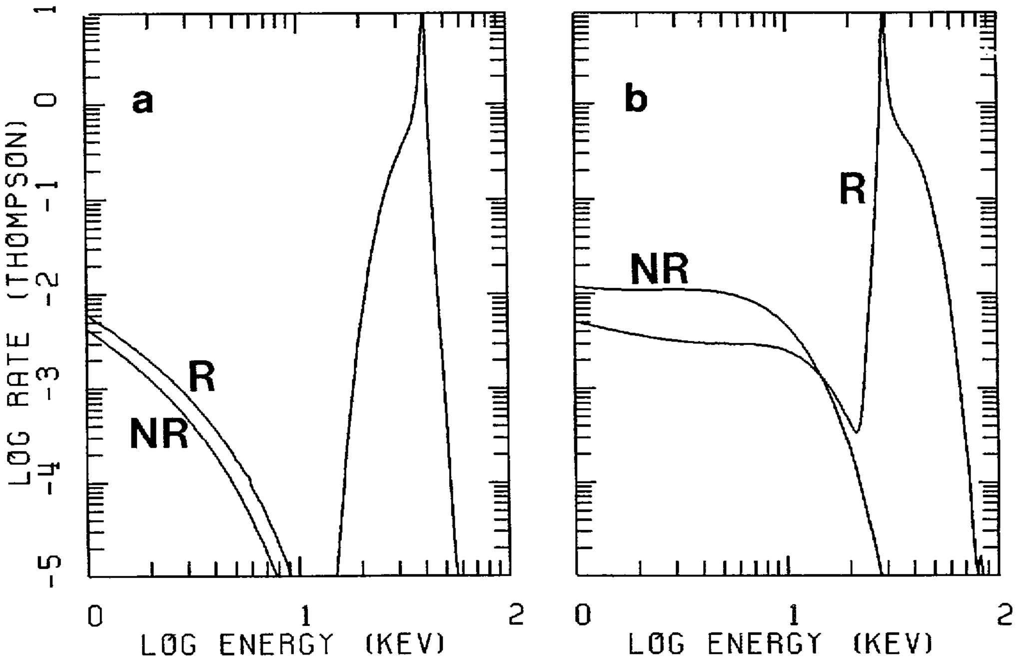

FIG. 1.—Differential scattering rate normalized to the Thomson cross section, averaged over initial and summed over final polarizations. We took $kT_e = 10$ keV, $\hbar\omega_c = 38$ keV, $\theta_{\rm in} = 45°$, $\theta_{\rm out} = 120°$, for the initial photon energy being (a) 30 keV (*left panel*) and (b) 45 keV (*right panel*). Upper curves (R) with the resonance: fully realistic calculation. Lower curves (NR) for soft frequencies only: the nonrelativistic soft photon production rate from eq. (1).

photon density n_γ, or $u_\gamma/(3T)$ with u_γ the energy density,

$$q(\omega') = \frac{8}{3}\pi\frac{r_e^2 c}{\omega'} n_e n_\gamma \frac{(\hbar\omega_c)^4}{mc^2 T^3} \times \exp\left[-\frac{\hbar\omega_c}{T}\left(1-\frac{\hbar\omega_c}{mc^2}\right)\right] G_W(u), \quad (4)$$

where n_e is the electron density, r_e is the classical electron radius, and the units of q are photons per cubic centimeter per second per unit angular frequency (ω). Here, the u and G_W are defined as

$$u = \frac{c}{2^{1/2}v_T}\frac{\hbar\omega_c}{mc^2};$$

$$G_W(u) = \frac{3}{16\pi^{1/2}}\int_{-\infty}^{\infty} dx\, e^{-(x+u)^2} \times\left[\left(1-\frac{1}{3}x^2\right) - \frac{1}{3}x^2(1-x^2)e^{x^2}E_1(x^2)\right]. \quad (5)$$

The value of the G function is 2/15 at low u, remains reasonably constant up to $u \approx 1$, and falls off as $1/(4u^2)$ at large u.

III. APPLICATIONS AND CONCLUSIONS

To estimate the importance of the effect under discussion, we compare it to the production of radiation by free-free emission as given by Nagel and Ventura (1983), taking the low-frequency limit of their Gaunt factor. The ratio of soft photon production given by equation (4) to that by free-free emission is

$$\frac{q(\omega')}{q_{ff}(\omega')} = \frac{\pi^{3/2}}{\alpha}\frac{n_\gamma}{Z^2 n_i}\frac{(\hbar\omega_c)^3}{mT^2} \times \exp\left[-\frac{\hbar\omega_c}{T}\left(1-\frac{\hbar\omega_c}{mc^2}\right)\right]\frac{uG_W(u)}{\ln(T/\hbar\omega)}. \quad (6)$$

The ion density at the source can be estimated in the usual way from the luminosity and some assumptions about the surface area and efficiency for conversion of infall energy to X-radiation. This gives $n_i \approx 3 \times 10^{21}$ cm^{-3} L_{37}, while the Thompson depth is $\tau_{\rm Th} \approx 66.5(n_e/10^{22}$ cm$^{-3})(r/0.1$ km), where r is a length through the source along the line of sight. One can obtain a lower limit on the photon density by making the simplest assumption, that of free streaming, which gives $n_\gamma \geq 2 \times 10^{24}$ $(\langle\hbar\omega\rangle/10$ keV$)^{-1}$ $L_{37}A_{10}^{-1}$ cm^{-3}. In a diffusive case, the density will clearly be greater than this. Thus, equation (6) shows that photon production by scattering will always be dominant; for a different view of two-photon scattering, see also Woosley (1984) and Kirk, Melrose, and Peters (1984).

Next, we consider the implications of our results for radiative transfer calculations. Lyubarskij and Sunyaev (1982) pointed out that Comptonization of soft photons in a shock at the surface of neutron stars would give a power-law spectrum. For the magnetized X-ray binaries, the most recent calculations are those of Mészáros and Nagel (1985*a*, *b*). These authors considered two classes of models, one with self-emission only, and one with an additional external source of soft photons. For the self-emitting models, the astrophysically interesting case corresponds to the depth of 100 cm, or 50 g cm^{-2}, since this is an upper limit to the value expected for Coulomb or nuclear proton stopping (Harding *et al.* 1984). We can estimate the soft emission directly from the photon density at the cyclotron resonance given as a function of the depth in Mészáros and Nagel (1985b). For this we use equation (2) by replacing ω with ω_c everywhere except in the x, which is proportional to $\omega - \omega_c$. This gives

$$q(\omega') = \frac{32}{45}\pi\frac{r_e^2 c}{\omega'} n_e \omega_c n_\gamma(\omega_c)\frac{\hbar\omega_c}{mc^2}, \quad (7)$$

for the production rate. By integrating over the final frequency from 0.1 keV to 3.8 keV and over Thompson depths greater than 10, we obtain the number of soft photons that would be produced by their density of cyclotron photons. Then by arbitrarily assuming that these photons were Comptonized to an average energy of 10 keV, we obtain a power comparable to theirs. The problem that arises in the self-emitting model, without soft sources, is the presence of a thermal turnover below several keV, contrary to the observed spectra which show a monotonic decrease of photon flux with energy. We suggest that incomplete Comptonization of the soft photons produced in scattering could provide the missing flux below a few keV for this model.

In the externally illuminated model of Mészáros and Nagel (1985*b*), a reasonably good spectrum was obtained by assuming an input of soft seed photons, the source of which was not discussed. By taking the results of their model and performing the same analysis as for the previous model, we obtain a production rate about a factor of 5 less than that assumed for the seed source. Furthermore, the process of the two-photon decay of the first Landau excitation will contribute roughly an equal amount to the production of soft radiation (J. Kirk, private communication). Given the uncertainties in all the numerical estimates, we feel that the postulated source and our calculated production rate are fully consistent.

We are grateful to J. Kirk for pointing out an error in our original version of this work. R. W. B. would like to express appreciation to F. K. Lamb at the University of Illinois, where this effect was initially noticed in scattering rate calculations. Discussions with S. Langer there were also interesting and useful. The research at Penn State was supported by NSF grant AST 83-13886 and at Illinois by NASA grant NSG 7653.

REFERENCES

Bussard, R. W. 1980, *Ap. J.*, **237**, 870.
Harding, A. K., Mészáros, P., Kirk, J. G., and Galloway, D. J. 1984, *Ap. J.*, **278**, 369.
Herold, H. 1979, *Phys. Rev. D*, **19**, 2868.
Kirk, J. G., Melrose, D. B., and Peters, J. G. 1984, *Proc. Astr. Soc. Australia*, **5**, 478.

Langer, S. H. 1981, *Phys. Rev. D*, **23**, 325.
Lightman, A. P. 1981, *Ap. J.*, **244**, 392.
Lyubarskij, Y. E., and Sunyaev, R. A. 1982, *Soviet Astr. Letters*, **8**, 330.
Mészáros, P., and Nagel, W. 1985*a*, *Ap. J.*, in press.
______. 1985*b*, *Ap. J.*, submitted.
Nagel, W., and Ventura, J. 1983, *Astr. Ap.*, **118**, 66.
Ventura, J. 1973, *Phys. Rev. A*, **8**, 3021.
White, N. E., Holt, S. S., and Swank, J. 1983, *Ap. J.*, **270**, 711.
Woosley, S. E. 1984, in *High Energy Transients in Astrophysics*, ed. S. E. Woosley (AIP Conf. Proc. 115) (New York: AIP), p. 485.

S. Alexander: Department of Physics, The Pennsylvania State University, University Park, PA 16802

R. W. Bussard and P. Mészáros: Department of Astronomy, The Pennsylvania State University, 525 Davey Laboratory, University Park, PA 16802