LOW ENERGY GALACTIC CENTER GAMMA RAYS FROM LOW MASS X-RAY BINARIES

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ABSTRACT. The hard X-ray and low energy γ-ray emission from the galactic center region (GCR) has four components[1,2]: a power-law continuum between 20/50 keV and 200/300 keV with a power-law photon index β in the range $\sim$ 2.5 to $\sim$ 3.1; a harder spectrum with $\beta \sim$ 1.–1.5 between 200/300 keV and $\sim$ 511 keV; a narrow electron-positron annihilation line at 511 keV, reported to disappear[3,4] in less than $<$ 1/2 yr, although the temporal variation is controversial[5]; and an equally variable continuum emission between 511 keV and several MeV ("MeV bump"). All four have luminosities 10^{37}–10^{38} erg s^{-1}, if they are located 10 kpc away. We propose non-thermal processes in low mass X-ray binaries (LMXB's) concentrated in the galactic bulge as the direct source of the three continuum components of the emission, as well as of an escaping electron-positron $e^{\pm}$ wind whose positron annihilation relatively far from the star could be the source of the 511 keV line. We consider a model for energetic emission from LMXB's that reproduces the softer power-law component of the GCR continuum through synchrotron emission of relativistic electrons in the strongly non-uniform (dipolar) magnetic field of the neutron star. We also explain, with less confidence, the variable MeV bump as the result of interaction of harder γ-rays with the power-law photons. The harder power law might be due to Compton scattering of relativistic electrons or photons.

1. Overview

Massive black hole (b.h.) models of GCR hard radiation are ruled out by recent coded aperture observations[6,7]. The total X-ray (0.5–30 keV) luminosity of the Sgr A complex is clearly $< 10^{36}$ erg/s. The only bright hard X-ray ($>$ 30 keV) source in a 14° field of view observation (f.o.v.) is 50 arc minutes away from the galactic center direction and even this source, 1E1740.7-2942 with its luminosity of $2.4 \cdot 10^{37}$ erg/s (at 10 kpc) contributes only a fraction of the HEAO-3 (35° f.o.v.) spectral flux. A $\sim 10^2 M_\odot$ b.h.[8] is not yet excluded as the source of GCR hard radiation but its total luminosity, evolutionary origin and uniqueness would lack a natural explanation. It seems likely that the reported GCR spectrum is a sum of contributions of a few discrete objects located within several degrees of the galactic center direction; here we explore the possibility that these objects may be LMXB's—a hypothesis suggested by the typical luminosity of accreting neutron stars $\sim 10^{37}$ erg/s.

Arguments and calculations sketched below indicate that a LMXB endowed with an

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accelerator placed somewhere above the plane of the accretion disk (close to the inner edge of the disk) will give rise to a hard X-ray/soft γ-ray spectrum quite similar to the one reported from the GCR. The magnetospheric accretion-powered accelerator serves as a dynamo powering a fireball which shines in hard X-rays on the side facing the neutron star and in ~MeV γ-rays on the side facing away from the neutron star (Fig. 1).

A rapidly rotating magnetized neutron star surrounded by a Keplerian accretion disk may be a powerful accelerator of very energetic particles: differences in rotational speed, $\Delta\Omega$, between the star and parts of the disk to which it is coupled by its magnetic field can generate potential drops exceeding 10^{15} Volts. The maximum power expected[9] from such a dynamo is

$$L_a \sim \frac{(B_* R^3)^2 |\Delta\Omega|}{r_\mathrm{A}^3} \sim L_X \frac{R}{r_A}, \qquad (1)$$

where B_* is the surface dipole field of the neutron star, R is the stellar radius, r_A the radius of the inner edge of the accretion disk, and the X-ray luminosity sustained by accretion is L_X. For the X-ray pulsar Her X-1 with $B_* \sim 4{\cdot}10^{12}$G and $\Delta\Omega \sim \Omega \sim 4\ \mathrm{s}^{-1}$, $L_a \sim 10^{35}$ erg/s. This dynamo has been suggested[10] as the accelerator energy source for the particles which produce the TeV γ-rays claimed to be seen in observations of this binary and others[11,12].

For a near Eddington luminosity LMXB the typical values are $B_* \sim 6 \cdot 10^8$ G, $r_A \sim R$, and $L_{a,38} = L_a/10^{38}$ erg/s $\simeq 1$. Thus, such systems may be even more powerful sources of high energy particles and nonthermal γ-ray emission than Her X-1. However, the magnetic field near the interface between the corotating magnetosphere of the neutron star and the accretion disk (i.e., the region in which particle acceleration, perhaps involving field line reconnection, is expected) is $\sim 10^8$ G in LMXB's, as opposed to $\sim 10^6$ G in Her X-1, while the local X-ray flux is more than 100 times larger in that region for the LMXB system. These two features greatly increase the probability for $e^\pm$ pair production by very energetic photons created in LMXB's, and also cause subsequent electron synchrotron emission to be much more powerful.

The detailed operation and output of the accelerator is irrelevant in the following as long as the initial energy of the outflowing γ-rays or $e^\pm$ it produces greatly exceeds 10^2 MeV and the total power from the accelerator approaches that of Eq. (1). A stream of very high energy $e^\pm$ and/or γ-rays is emitted from the region of the accelerator in the neutron star direction along the local magnetic field lines. A similar stream moving in the opposite direction (towards the disk) is emitted from the other end of the accelerator (see Fig. 1, inset). Each stream will be the source of an $e^\pm$ – γ-ray cascade, in which pair creation by γ-rays on the strong flux of ~keV accretion powered X-rays of the LMXB plays a crucial role. Some of these accretion X-rays are, in turn, converted into γ-rays by inverse Compton scattering on energetic shower $e^\pm$ pairs. These processes continue to distribute the total power among the rapidly multiplying $e^\pm$'s and γ-rays until the energy of the γ-rays drops below the threshold of pair creation—this may occur at different energies for the two streams. For the stream flowing towards the star, the threshold occurs at $\sim$ 100 MeV and photons of this energy can travel a considerable distance before creating a pair in the stellar magnetosphere. Synchrotron radiation will be the dominant $e^\pm$ energy loss mechanism of pairs thus created and a large fraction of energy will then be emitted in hard X-rays, giving a power-law spectrum ($\beta \sim 3$).

The shower which propagates away from the star does not move into magnetic fields large enough for synchrotron radiation to dominate. Inverse Compton scattering and subsequent pair production by the resulting γ-ray can continue as long as there is a sufficient local flux of hard enough X-rays; under certain conditions an optically thick cloud of $\sim$MeV photons and $e^{\pm}$ pairs may form. This cloud would be responsible for the MeV bump reportedly seen in the GCR spectrum.

2. The Spectrum

For LMXB's, the magnetic field strength in the region of the gap is $B = B_8 \cdot 10^8$ gauss with $B_8 \sim 1$. The presumed accelerator is at a distance $r = r_6 \cdot 10^6$ cm away from the neutron star, with $1 \lesssim r_6 \lesssim 10$. The accelerator power satisfies $L_a \sim L_X$, and $L_X = L_{X,38} \cdot 10^{38}$ erg/s (with $L_{X,38} \approx 0.1$–1) where L_X is the luminosity of soft X-ray photons of energy $E_X \approx 3\,\mathrm{keV}(L_{X,38})^{1/4}$, typical of the assumed isotropic black body release of accretion energy. TeV γ-rays will pair create in the 10^8 G field, and initiate an electromagnetic cascade when the angle between the the magnetic field and the photon momentum exceeds $\sim 3 \cdot 10^{-3}$ radians. Photons of energy $E_\gamma \gtrsim 40\,\mathrm{GeV}$ create pairs on the magnetic field ($\gamma \rightarrow e^{\pm}$) or, for lower values of E_γ, create pairs in collision with the soft X-ray photons of energy E_X; the optical depth for the latter process is $\tau_1 \sim 4 \cdot 10^3 r_6^{-1} \, (E_\gamma/\mathrm{GeV})^{-1} \, L_{X,38}^{1/2}$. The electrons quickly lose their energy to a few photons either through synchrotron radiation or through inverse Compton scattering, and the process is repeated for the energetic photons thus created until their energy is smaller than the threshold value for pair creation, E_t.

On the side of the neutron star, $E_t = (m_e c^2)^2/E_X \sim 100\mathrm{MeV} \cdot L_{38}^{-1/4}$ and fireball photons of energy slightly exceeding E_t can either leave the system (as will all photons of energy $E < E_t$, unless they are intercepted by the disk or the star) or travel a considerable distance before they are absorbed in a collision with an X-ray/γ-ray photon, thus creating "last generation" electron pairs of energy, in units of electron rest mass, $\gamma_f \approx E_t/(2 m_e c^2) \sim 10^2$. Note that as E approaches E_t from above, the pitch angle ψ of the created pairs increases. These electrons will gyrate about the magnetic field lines and each of them will give rise to a (time integrated) synchrotron spectrum of power-law index $-3/2$. The high energy cut-off of such an individual spectrum depends on the local magnetic field. The envelope of these spectra (summed over electrons, i.e., effectively over the strength of the spatially varying magnetic field) yields a broken power-law photon number spectrum:

$$N(E) \propto \begin{cases} E^{-1.5} & \text{if } E_{min} < E < E_1 \\ E^{-\beta} & \text{if } E_1 < E < E_2 \end{cases}$$

where $E_{min} \simeq 1eV \cdot B_8$ (1eV is the cyclotron energy in a magnetic field of 10^8 gauss), $E_1 = 10\,\mathrm{keV}(\gamma_f/100)^2(B_8^{\perp})_{min}$, $E_2 = 10\mathrm{keV}(\gamma_f/100)^2(B_8^{\perp})_{max}$, and $(B_8^{\perp})_{min}$ and $(B_8^{\perp})_{max}$ are the minimum and maximum values of the transverse magnetic field (i.e., $B^{\perp} = B \sin \psi$) encountered by the last generation pairs. The shape of the spectrum is somewhat sensitive to the spatial distribution of the pair creation rate $R_+(\vec{r})$. A dipole field yields $\beta = 2.7$, 3.0, 3.3, respectively, for $R_+(\vec{r}) \propto r^{-1}$, $R_+(\vec{r})$ =const, and R_+ constant along magnetic flux tubes. Up to a quarter of the dynamo power, i.e., $\frac{1}{4}L_a$, is converted to last generation (~ 50MeV) $e^{\pm}$ pairs (produced at a rate of $R_i \sim 10^{42}\,\mathrm{s}^{-1} r_6^{-2} L_{a,38}$ erg s^{-1}) and hence to the synchrotron emission described.

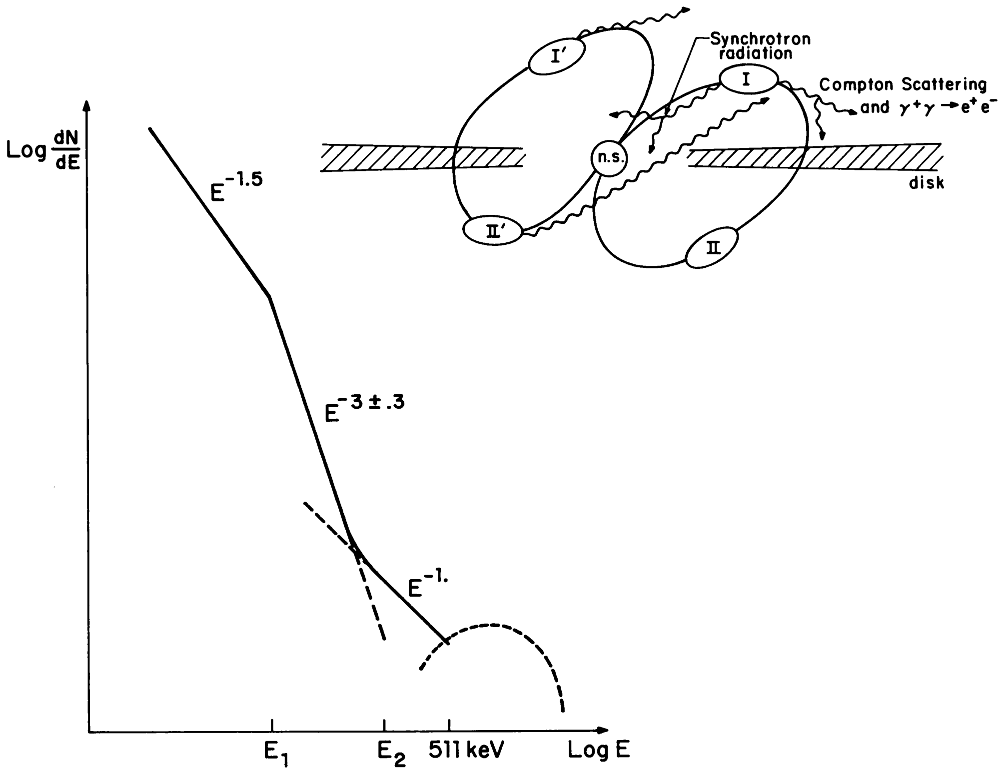

Figure 1. The theoretical X-ray/γ-ray spectrum of some accreting neutron stars. Note the similarity with the HEAO-3 galactic center region spectrum. The MeV bump (dotted line) may occur in only a subset of systems exhibiting the broken power-law (solid line) spectrum, the detailed shape of the bump has not been computed. The spectrum below $E_2 \sim 10^2$ keV is due to synchrotron radiation, the part between E_2 and $\sim$ 511 keV is due to Compton scattering of $\sim$ 100 MeV photons (whose emission is also predicted, but which are not shown in the figure). The break at E_1 may occur anywhere between $\sim$ 10 keV and $\sim$ 100 keV.
Inset: The geometry of the emitting region. The placement of the presumed accelerator(s) (ovals I, II,...) is shown, as well as representative magnetic field lines (solid curves) and photon trajectories (wiggly lines).

For the outward propagating shower (on "the far side" of the accelerator) at least in some LMXB systems the dominant emission mechanism for the electrons is inverse Compton scattering. Each electron, then, would give rise to a photon spectrum of index $\beta = 1.5$, i.e., $N(E) \propto E^{-3/2}$, just as in the synchroton case, except that now $E_X < E < \gamma_f^2 E_X$. Since $L_X \sim L_a$, the number of photons at the high energy end of this nearly flat spectrum is sufficient to be optically thick to pair creation by photons of energy exceeding $E_b \approx 2(m_e c^2)^2/(\gamma_f^2 E_X) \sim 1$ MeV. The optical depth for this process is $\tau_2 \sim (L_{a,38})\gamma_f^{-1}\tau_1 \sim 40(L_{a,38})\,r_6^{-1}$. If $\tau_2 > 1$, no photons of energy exceeding E_b will break out on the far side of the accelerator produced fireball as long as most of the Compton boosted "target" X-ray photons are not moving in the same direction as the $E > E_b$ γ-rays. The extent to which they may not, depends on the field line geometry and the extent to which target photons from the other showers, including those on the other side of the disk, can be encountered by the γ-rays. If inverse Compton emission dominates on the far side, and $\tau_2 > 1$, the remaining half of the dynamo power is distributed evenly among $\sim 1\,\mathrm{MeV}$ photons—which, if observed, would give rise to a 1 MeV bump in the spectrum—and $\sim 1\,\mathrm{MeV}$ electrons and positrons. The latter are created at a rate $\frac{1}{4}L_a/1\,\mathrm{MeV} \sim 10^{43}\ \mathrm{s}^{-1}\ L_{a,38}$. Not knowing the detailed geometry of the accelerator and hence the fireball or the disk thickness we are unable to predict in what fraction of LMXB's emitting hard X-rays the optically thick cloud of 1 MeV electrons/positrons and photons will be formed or the likelihood of MeV bump observation. We are uncertain as to the ultimate fate of the positrons created in this cloud, but if they were channeled along magnetic field lines to the companion star or if they managed to escape the binary system altogether they could contribute to the narrow 511 keV spectrum observed in the GCR spectrum. This line has been observed at a flux corresponding to a pair creaton rate of $\sim 5 \cdot 10^{42}\mathrm{s}^{-1} \cdot (d/10\,\mathrm{kpc})^2$ for an isotropic point source a distance d away from us, the exact value of the rate depending on the mode of annihilation (the positronium fraction). Perhaps it is significant that copious production of positrons is associated in our model with the MeV bump; such a correlation has in fact been reported by the HEAO-3 group[2], but is controversial[5,13].

3. Conclusions

We find that equipping a canonical LMXB with a magnetospheric electron accelerating mechanism of plausible characteristics leads to the emission of hard X-rays with an inverse power-law spectrum of photon index $\beta \approx 3$. The power in the hard X-rays is comparable to the total luminosity of the source. This could explain the observed hard X-ray emission of such objects as Cyg X–2,[14] Cyg X–3,[15] and GX5–1.[16]This mechanism provides the justification for identifying the power-law component of the galactic center spectrum with the sum of X-ray emission of a few discrete sources[17]. Our model may be applicable to low-luminosity bursting X-ray sources[18,19] which show power-law spectra in the range 1-20 keV.

The theoretical spectrum of our model is shown in Fig. 1. The broken power-law is due to synchrotron emission of electrons ($e^{\pm}$) created in a region of spatially varying dipolar magnetic field. The pairs are created by γ-rays interacting with accretion X-rays. Compton scattering of some of these 100 MeV γ- rays from the surface of the accretion disk may explain the hard component of the GCR spectrum and its cut-off at about the electron rest energy $m_e c^2$; the relative strength of this component depends on the detailed geometry of the system. Some of the hard γ-rays may escape from the system and hence we predict that accreting neutron stars which emit hard X-rays may be sources of $\sim 10^2$ MeV γ-rays of comparable luminosity.

Some of the sources may also be copious producers of positrons and ~MeV γ-rays, but this conclusion depends sensitively on the specific parameters of the system, in particular on the unknown geometrical placement of the accelerator. The variable MeV bump could then be explained by the emission of one or two LMXB's and in principle enough positrons would be produced at the same time to account for the 511 keV annihilation line. It is not clear whether the positrons can diffuse to a suitable annihilation site. We predict that the MeV bump is not a phenomenon unique to the galactic center direction and urge that the soft gamma-ray spectra of relevant accreting neutron stars be carefully observed, particularly for evidence of broad and narrow emission features.

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