Self-consistent computation of $\gamma$-ray spectra due to proton-proton interactions in black hole systems

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ABSTRACT

In the inner regions of an accretion disk around a black hole, relativistic protons can interact with ambient matter to produce electrons, positrons and $\gamma$-rays. The resultant steady state electron and positron particle distributions are self-consistently computed taking into account Coulomb and Compton cooling, $e^-e^+$ pair production (due to $\gamma-\gamma$ annihilation) and pair annihilation. While earlier works used the diffusion approximation to obtain the particle distributions, here we solve a more general integro-differential equation that correctly takes into account the large change in particle energy that occur when the leptons Compton scatter off hard X-rays. Thus this formalism can also be applied to the hard state of black hole systems, where the dominant ambient photons are hard X-rays. The corresponding photon energy spectrum is calculated and compared with broadband data of black hole binaries in different spectral states. The results indicate that the $\gamma$-ray spectra ($E > 0.8$ MeV) of both the soft and hard spectral states and the entire hard X-ray/$\gamma$-ray spectrum of the ultra-soft state, could be due to $p-p$ interactions. These results are consistent with the hypothesis that there always exists in these systems a $\gamma$-ray spectral component due to $p-p$ interactions which can contribute between 0.5 to 10% of the total bolometric luminosity. The model predicts that GLAST would be able to detect black hole binaries and provide evidence for the presence of non-thermal protons which in turn would give insight into the energy dissipation process and jet formation in these systems.

Key words: accretion, accretion disks—black hole physics

1 INTRODUCTION

Black hole X-ray binaries are generally observed to be in two distinct states. These states, which are named hard and soft, differ in their luminosity and spectral shapes. In the hard state, which is in general less luminous, the spectrum of the system can be described as a hard power-law with a spectral index $\Gamma \sim 1.7$ and a cutoff around 100 keV. This spectrum can be modeled as thermal Comptonization of soft photons by a plasma having temperature $T \sim 50$ keV (e.g. Gierliński et al. 1997). In contrast, the spectrum during the soft state consists of a blackbody-like component with $kT \sim 1$ keV, which typically dominates the luminosity and is generally considered to be thermal emission from an optically thick accretion disk. Apart from this soft (or disk) component, a hard X-ray power-law tail, with photon index $\Gamma \sim 2.5$ and no detectable cutoff up to $\sim 8$ MeV (McConnell et al. 2002), is also observed.

There have been several interpretations of the high energy ($E > 200$ keV) emission from black hole systems. It may arise from a photon starved innermost region of a disk which cools due to bremsstrahlung self-Comptonization (Melia & Misra 1993) or as emission due to $\pi^0$ decay, which are created by proton-proton interaction in a hot proton gas, $T > 10^{11}$ K (Kolykhalov & Sunyaev 1974; Jourdain & Roques 1994). While these possibilities maybe viable, they are based on assumptions of the geometry and physical properties of the system, which are not directly and independently verifiable, like the presence of a very hot proton gas or a photon starved region. Another interpretation is that the spectra arises due to Comptonization of photons by the bulk motion of matter falling into the black hole (Laurent & Titarchuk 1993). However, Niedźwiecki & Zdziarski (2000) have argued that the non-detection of spectral breaks at $E < 500$ keV is contrary to this model’s prediction. A detailed radiative model, which has been used to fit good quality broadband data of black hole systems, is the hybrid model which is inscribed in...
a spectral fitting code called EQPAIR (Poutanen & Coppi 1993; Gierliński et al. 1999). In the framework of this model, this high energy component arises from a plasma consisting of both thermal and non-thermal electrons that Comptonize external soft photons. Detailed spectral modeling of the observed soft state spectra demands the coexistence of thermal and non-thermal electrons in the emission region and hence the steady state non-thermal electron distribution is computed by assuming that there is an injection of non-thermal particles into the system where they cool by Comptonization and Coulomb interactions.

The origin of these non-thermal particles is uncertain. A possible site may be a corona on top of a cold disk which is heated by magnetic field reconnections (Haardt & Maraschi 1991), but the details of the process are largely unknown. The acceleration process has to be highly efficient to produce non-thermal electrons in an environment where electrons cool rapidly by inverse Comptonization. If this acceleration process is mass-independent then protons are also expected to be accelerated to relativistic energies, for example by scattering off magnetic “kinks” in a Keplerian accretion disk (Eilek 1980; Eilek & Kafatos 1983; Mahadevan et al. 1997; Subramanian, Becker & Kafatos 1996). Some of these non-thermal protons may escape from the system and contribute to the jet formation (Subramanian et al. 1999). This is particularly interesting since there are some evidence that the X-ray producing region may be same as the base of the extended jet (Markoff et al. 2003). Hence the detection of these non-thermal protons will provide valuable clues to the nature of black hole systems.

Non-thermal protons would interact with the ambient thermal protons and produce electron-positron pairs, which would Comptonize photons to high energies. These high energy photons would produce further pairs by $\gamma - \gamma$ interaction and a pair cascade would ensue. Pair cascades initiated by the injection of pairs (or equivalently high energy non-thermal electrons) have been extensively examined (e.g. Lichtman & Zdziarski 1987; Svensson 1987). The effect of $p-p$ interactions and the resultant spectra have also been computed and studied (e.g. Stern et al. 1992; Eilek 1993; Eilek & Kafatos 1983; Mahadevan et al. 1997; Markoff et al. 1999; Zdziarski 1984). These works, in general, did not consider the presence of copious photons or have assumed that the ambient photons are in the UV range, a scenario relevant to AGN and under-luminous black hole systems. However, for black hole binaries, the system is dominated by either soft or hard X-rays depending on the spectral state. One of the important radiative interaction that would occur in such an environment is the inverse Compton scattering of X-rays by pairs with Lorentz factor $\gamma \approx 200$ that are produced by the $p-p$ interaction.

The standard methods to compute the inverse Compton spectra, assume that the interaction in the rest frame of the electron takes place in the non-relativistic Thompson limit, which is true only if electron Lorentz factor times the photon energy $\gamma \epsilon \ll m_e c^2$. This assumption is violated if the ambient photon energy is $\lesssim m_e c^2 / \gamma \approx 2$ keV. Thus, when Bhattacharyya et al. (2003) considered $p-p$ interaction in the presence of blackbody photons having temperature $T \approx 1$ keV, they used a general formalism to describe the inverse Compton process given by Blumenthal & Gould (1970). They found that for such a situation, which is relevant to the soft state of black hole binaries, the effect of non-thermal protons is to produce a broad feature around 1 – 50 MeV. Using the observed OSSE data for GRS 1915+105, they could constrain the fraction of non-thermal protons in the system to be $< 5\%$. Although Bhattacharyya et al. (2003), computed the change in energy of the photon (and hence the change in energy of the lepton) appropriately in the Klein-Nishina regime, they used, for simplicity, a diffusion equation to describe the kinetic evolution of the pairs, which intrinsically assumes that the change in energy of the particle per scattering is small. This assumption breaks down when the ambient photon energy is in X-rays, especially when there are a copious amount of ambient hard X-rays.

In this work, we extend the formalism developed by Bhattacharyya et al. (2003), by solving an integro-differential equation for the pair kinetic evolution which correctly takes into account the large energy changes that a lepton undergoes upon scattering with an X-ray photon. This not only allows for a more accurate estimation of the emergent spectra for systems in the soft state, but enables the scheme to be applied to the hard state also.

In §2 we describe the model and the assumptions made to compute the steady state non-thermal electron/positron distributions and the resultant photon spectra. In §3 some general results of the computation are presented along with comparison with observations of black hole systems Cyg X-1 and GRS 1915+105 in different spectral states. The main results of the work are summarized and discussed in §4.

2 PAIR DISTRIBUTION AND RADIATION SPECTRA COMPUTATION

We consider a uniform sphere of non-relativistic thermal plasma with number density $n_T$ and radius $R$, in the presence of an external copious photon source. It is convenient to parameterize the luminosity of the external photons $L_{ph}$, in terms of the compactness parameter $l_{ph} \equiv L_{ph} \sigma_T / (R m_e c^3)$, where $\sigma_T$ is the Thomson cross-section. The spectral shape of the ambient photons is taken either to be a Wien peak or an exponentially cutoff power-law depending on the spectral state being considered. In this system, we assume that there is a power-law distribution of non-thermal protons with index $\alpha$, which would lead to proton-proton collisions i.e. the density of non-thermal protons is given by

$$n_{NT}(\gamma)\gamma d\gamma = n_o (\gamma - 1)^{-\alpha} d\gamma \quad (1)$$

The normalization $n_o$ of this distribution is characterized by the compactness parameter $l_{pp-p} \equiv L_{pp-p} \sigma_T / (R m_e c^3)$, where $L_{pp-p}$ is the total power in electron, positrons and $\gamma$-rays which would be produced in the proton-proton interactions.

The steady state positron density $N_+(\gamma)$ is determined by solving the integro-differential equation

$$\frac{\partial}{\partial \gamma} (\epsilon_{\gamma} N_+(\gamma)) + N_+(\gamma) \int_{1}^{\infty} d\gamma' P(\gamma, \gamma') =$$

$$\int_{1}^{\infty} d\gamma' P(\gamma', \gamma) N_+(\gamma') + N_+(\gamma) = Q_{+pp}(\gamma) + Q_{+\gamma\gamma}(\gamma) \quad (2)$$
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while the corresponding electron density $N_-(\gamma)$ is obtained from

$$\frac{\partial}{\partial \gamma}(\gamma c N_-(\gamma)) + N_-(\gamma) \int_1^{\gamma} d\gamma' P(\gamma, \gamma') - \int_{\gamma}^\infty d\gamma' P(\gamma', \gamma) N_-(\gamma') = Q_{-pp}(\gamma) + Q_{-\gamma\gamma}(\gamma)$$

(3)

Here, $P(\gamma, \gamma - e)de$ is the probability that a positron/electron with Lorentz factor $\gamma$ will suffer a collision and its Lorentz factor changes by an amount between $e$ and $e + de$ in time $dt$, where $e \equiv \hbar v/m_c c^2$ is the normalized photon energy. $Q_{\pm,\gamma\gamma}$ and $Q_{\pm,pp}$ are the creation rates of pairs due to $p - p$ interactions and photon-photon production respectively. $N_+(\gamma)$ is the annihilation rates of positrons with the thermal background electrons and $\gamma_C$ is the Coulomb cooling rate. This formalism to obtain the particle distribution follows from the results described in Blumenthal & Gould (1970) (and references therein), where the exact expression for $P(\gamma, \gamma - e)de$ has been derived. For small changes in particle energy, eqs. 2 and 3 can be reduced to diffusion equations [Blumenthal & Gould (1970)] i.e. the integral terms can be reduced to $\gamma_1 [\gamma_C N_+(\gamma)]$ where $\gamma_1$ is the inverse Compton cooling rate. It was these diffusion equations that were used by Bhattacharyya et al. (2003) as a simplifying assumption.

Following Eilek & Kafatos (1983), $e^+e^-$ production rate due to $p - p$ process is given by

$$Q_{\pm,pp}(\gamma) = \frac{n_e}{n_p} \int_{\gamma_p(l,c)}^{\gamma_p(h,c)} \sigma_{p\gamma}(\gamma_p) \beta_p \pi N_T(\gamma_p) d\gamma_p$$

(4)

where $\beta_p \equiv (1 - 1/\gamma_p^2)^{1/2}$ and $\gamma_p(k) \equiv 1 - \gamma_p$. The denominator of the integrand represents the appropriate energy distribution of the leptons produced, while the limits impose the allowed energy range and are given by

$$\gamma_p(l,c) = 1 + [\gamma_e + (\gamma_e^2 - 1)^{1/2} (\gamma_e^2 - 1)^{1/2} - 1]^{1/3}$$

(5)

and

$$\gamma_p(h,c) = 1 + [\gamma_e + (\gamma_e^2 - 1)^{1/2} (\gamma_e^2 - 1)^{1/2} - 1]^{1/3}$$

(6)

where $\gamma_e \equiv 70$. The approximate but analytical cross-section ($\sigma_{p\gamma}$) is tabulated for different energy ranges by Eilek & Kafatos (1983).

Pair production rate from photon-photon interactions is approximated to be

$$Q_{\pm,\gamma\gamma}(\gamma) = c \int n_e(2\gamma_e - \gamma) n_\gamma(e, \gamma - e) d\gamma$$

(7)

where it has been assumed that for two photons annihilating with energies $e$ and $e'$, the resultant Lorentz factor is $\sim (e + e')/2$. The approximate form for the cross section $\sigma_{\gamma\gamma}(e, e')$ is given by Coppi & Blandford (1994). The positrons primarily annihilate with the background thermal electrons at a rate given by

$$N_+(\gamma) = N_+(\gamma) n_T \sigma_{e^+e^-} (1, \gamma)c$$

(8)

where the approximate form of the cross section is given by Coppi & Blandford (1994).

It is worthwhile to note that, while the numerical computation of the integro-differential equations (eqs. 2 and 3) are relatively straightforward, there are a few minor but tricky points that have to be taken into consideration. In particular, the number conservation of photons for the inverse Compton process has to be strictly satisfied in the numerical computation, in order to obtain the correct and stable particle density solution.

The equilibrium photon density inside the sphere is a solution of

$$Q_{\gamma, IC} + Q_{\gamma, pp} + Q_{\gamma, e^+e^-} = n_\gamma(e) \left[ \frac{R_{\gamma\gamma} + c}{R(1 + \tau_{\gamma\gamma}(e))} \right]$$

(9)

where $R_{\gamma\gamma}(e)$ is the rate of photon annihilation and $\tau_{\gamma\gamma}$ is the Klein-Nishina optical depth. $Q_{\gamma, IC}$, $Q_{\gamma, pp}$ and $Q_{\gamma, e^+e^-}$ are the photon production rates due to inverse Compton, $p - p$ interaction and pair annihilation respectively. The photon production due to $p - p$ reaction is given by

$$Q_{\gamma, pp}(e) = \frac{m_e}{m_p} \pi n_p c \int_{\gamma_p(l,c)}^{\gamma_p(h,c)} \frac{\sigma_{p\gamma}(\gamma_p) \beta_p \pi N_T(\gamma_p) d\gamma_p}{(\gamma_p^2 + 1)^{1/2} (\gamma_p^2 + 1)^{1/4} (\gamma_p^2 + 1)^{1/4} (\gamma_p^2 + 1)^{1/4}}$$

(10)

For simplicity, the scattering of high energy photons with the thermal particles are neglected here and the implications of this assumption are discussed in the last section. The interactions of photons with high energy protons, which requires a much larger threshold photon energy ($\gamma_p > 300$), have also been neglected. As noted by Bhattacharyya et al. (2003), such interactions are not important when $\alpha > 2$ and depend on the unknown high energy cutoff of the proton acceleration process.

Equations 2, 4, and 6 are solved self-consistently to obtain electron and positron distributions as well as the radiative flux. The output spectrum depends on the spectral shape of the external photons and three other parameters: the Thomson optical depth $\tau$, photon compactness $l_p$, and the ratio of proton-proton compactness $l_p/\alpha$, to that of the external photon, $\beta \equiv l_p/\alpha$. The results are insensitive to the non-thermof optical index $\alpha$ and apart for an overall normalization factor, to the size $R$ of the system. From the definition of compactness ($L \propto R^4$), it follows that for a fixed value of $l$, the normalization of the photon spectrum will be proportional to $R$. The spectral shape primarily depends on the inverse Compton and pair production processes, which are characterized by $\tau_{IC} \sim n_{\gamma, e} \sigma_{\gamma\gamma} R$ and $\tau_{e^+e^-} \sim n_{\gamma} \sigma_{\gamma\gamma} R$. Since the soft photon density $n_{\gamma, e} \propto l_p/R^2 \propto l_p/R$ and similarly, the high energy photon density, $n_{\gamma} \propto l_p/\alpha \propto l_p/R$, and $\tau_{IC}$ and $\tau_{\gamma\gamma}$ are independent of $R$ for specified compactness. Thus, parameterizing the luminosities in terms of compactness renders the shape of the spectrum to be nearly independent of the size of the system.

3 RESULTS

3.1 Soft State

The computed radiated spectra due to $p - p$ interactions, corresponding to parameters typical of the soft state of black hole binaries, are shown in Figure 1. Since the motivation of this work is to investigate the possibility that the $\gamma$-ray part of the spectrum is due to $p - p$ interactions, a detailed fit to the broad band data, especially the low energy part of the spectrum, is not being attempted. Instead, the dominant soft component is being represented by a a Wien peak like spectrum at $kT_{ph} = 1$ keV and high compactness, $l_p/\alpha = 250$. The corresponding luminosity is
$L \approx 10^{38} \text{ ergs s}^{-1} \left( \frac{l_{\text{ph}}}{250} \right) \left( \frac{R}{10^{2} \text{ cm}} \right)$

where $R \approx 10^{7} \text{ cm}$ is the size of the system. The optical depth of the thermal electrons is of order unity and is taken to be $\tau = 2.5$ in Figure 1. The spectra plotted in the figure, correspond to three different values of the compactness ratio $\beta \equiv l_{p-p}/l_{\text{ph}} = 0.001, 0.01$ and 0.1 respectively, which represent increasing efficiency of the acceleration process to produce non-thermal protons. At low $\beta$ values the spectra are hard with a break around $\sim 80 \text{ MeV}$. This cutoff is due to the interaction of higher energy photons with the ambient soft photons of energy $\sim 3 \text{ keV}$ to generate pairs. The hard spectra are due to inverse Comptonization of photons by a steady state pair distribution $N_{\pm}(\gamma) \propto \gamma^{-2}$ (Figure 2). Such a distribution is expected when pairs are injected at a large energy ($\gamma \approx 200$) and are cooled by inverse Comptonization. Essentially in the diffusion approximation, the cooling rate $\gamma_{\text{IC}} \propto \gamma^{2}$, which leads to $N(\gamma) \propto \gamma^{-2}$ when pair creation due to photon-photon interaction can be neglected. For higher compactness ratio, $\beta = 0.01$, pair creation due to photon-photons affects the particle distribution at low $\gamma$ (Figure 2), which leads to a softer output spectra (Figure 1). For still larger values of $\beta = 0.1$, apart from the change in particle distribution due to photon-photons pair production, another break at around 511 keV appears in the radiated spectrum, since the density of high energy photons is large enough for pairs to be produced by self interaction.

Figure 1 also shows for comparison, the computed spectra obtained using the diffusion approximation to solve for the particle distribution as described in Bhattacharyya et al. (2002). While, quantitative differences can be seen when the compactness ratio is large (spectra marked 2 and 3), the qualitative features of the spectra are similar.

The high energy (5–50) soft state spectra are characterized by a steep power-law of photon index $\Gamma \approx 2.5$, and hence cannot be explained as emission from $p - p$ interactions, since in this energy range the expected spectral index is $\Gamma < 2$ (Figure 1). Indeed, the soft state spectra can be described by the hybrid model, where non-thermal electrons are injected into a plasma. In Figure 3 we reproduce the unfolded data points based on such a model (the "EQPAIR" model) as fitted by McConnell et al. (2002). These data obtained from instruments on board the BeppoSAX and CGRO satellites cover a wide energy range from $\approx 0.5 \text{ keV}$ to $\approx 8 \text{ MeV}$. As shown by McConnell et al. (2002), the spectrum at energies $< 1 \text{ MeV}$ can be represented as an extension of the non-thermal spectra at hard X-rays. On the other hand, the $\gamma$-ray (i.e. the 1–8 MeV) spectrum, maybe due to an additional component, especially since there are uncertainties about the relative normalization of the different instruments used to make the composite spectrum. A second component interpretation is supported by the non-detection by COMPTEL of any flux in the energy range from 750 keV to 1 MeV, indicating a possible spectral break in that region, although the low statistics of the data does not allow for a definite conclusion. Thus, we attempt to fit the $\gamma$-ray part of the spectrum, as emission from $p - p$ interactions, using parameters that are consistent with those obtained by McConnell et al. (2002). The required compactness ratio $\beta \equiv l_{p-p}/l_{\text{ph}} \approx 0.046$, can be compared with $l_{\text{pair}}/l_{\text{ph}} = 0.11$ obtained by the EQPAIR fit. This indicates that if the $\gamma$-ray spectrum is due to $p - p$ collisions, the energetics of the proton acceleration that produces non-thermal protons is comparable to the electron one. The factor of two difference, between the two ratios, could be either due to the neutrino emission, which has not been added to $l_{p-p}$ or to the uncertainties involved in the theoretical modeling and...
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Figure 3. Broad band soft state data of Cyg X-1 reproduced from McConnell et al. (2002). Solid line is the computed spectrum for \( \beta = 0.046, \ l_{ph} = 125, \ kT_{ph} = 0.4 \) keV, \( \tau = 2.5 \) and \( \alpha = 2.5 \). The thick broad line shows the estimated GLAST sensitivity [http://www-glast.slac.stanford.edu/software/IS/glast_lati_performance.html].

Fitting of the data. If the γ-ray spectrum is not due to this process, the above estimate serves as an upper limit on the energetics of the non-thermal acceleration of the protons. For the parameters used to compute the p-p component, the ratio of the non-thermal proton density to the thermal one turns out to be \( \approx 0.03 \), which is consistent with that estimated earlier by Bhattacharyya et al. (2003).

Zdziarski & Gierliński (2004) have estimated the sensitivity of a \( 4 \times 10^4 \) s GLAST observation to be \( \approx 10^{-3} \) keV cm\(^{-2}\) s\(^{-1}\) at 10 GeV. Figure 3 shows that the predicted spectrum at that energy is a couple of order of magnitude higher than this limit and would be easily detectable. The extension of the hybrid plasma model fit to the data (McConnell et al. 2002) to 10 GeV also predicts a similar flux. However, as pointed out by Zdziarski & Gierliński (2004), the hybrid plasma model assumes a low value of compactness \( l_{ph} \approx 4 \) and a high value of the maximum Lorentz factor of the electrons, \( \gamma_{max} = 10^4 \). For a more realistic value of compactness or if electrons are not accelerated to such high energies, there will be a sharp cutoff in the hybrid plasma spectrum at \( \approx 1 \) GeV. Thus, a GLAST observation of Cyg X-1 (or black hole binaries in general) during the soft state, should be able to discern between these models.

Black hole systems exhibit a variation of the soft state spectrum, which is sometimes denoted as a separate state and is called Very High or Intermediate state (VHS/IS). Here the hard X-ray power-law is nearly equally luminous as the soft component. The black hole system GRS 1915+105 displays a wide variety of spectral shape and its γ class behavior (as classified by Belloni et. al. 2000) is similar to the VHS state of other black hole systems. Zdziarski et al. (2001) have fitted the broad band data of this source obtained from instruments on board RXTE and CGRO, by the hybrid model and the unfolded data based on that model is reproduced in Figure 4. The absence of high energy COMPTEL data does not allow for detailed fits, but a comparison of the 600 keV flux with the computed spectrum provides an upper limit of the compactness ratio \( \beta = 0.075 \), which again can be compared to the ratio \( t_{n/1}/l_{ph} = 0.11 \) required by the hybrid model fit (Zdziarski et al. 2001).

Another variation of the soft state spectra is the so called ultra-soft state, where the spectrum is dominated by the soft blackbody like emission, with a weak hard X-ray tail. This state has been observed in many black hole systems like GRS 1915+105, GX 339-4 and XTE J1550-564. An example of this state is shown in Figure 5. Here the data is reproduced from Zdziarski et al. (2001), and is unfolded based on the EQPAIR model fit to observation of GRS 1915+105 in the α class using RXTE and CGRO satellites. A remarkable observational feature is that for all these sources, the weak high energy tail is hard with a photon spectral index \( \Gamma \approx 2 \), for which currently there is no theoretical explanation (Zdziarski & Gierliński 2004). For high compactness the spectra due to \( p-p \) interaction, is expected to have such a hard spectral slope (Figure 6). Indeed as shown in Figure 5, the hard X-ray spectra can be explained solely as emission from such a process with a compactness ratio \( \beta \approx 0.008 \). Again, the absence of data greater than 1 MeV does not allow for a clear identification. However, the data is consistent with the hypothesis, that in the Ultra-soft state, the emission from accelerated non-thermal electrons is absent and hence, only the hard spectra arising from \( p-p \) interactions is observed.

3.2 Hard State

Figures 6 and 7 show the computed spectra and particle densities for different values of compactness ratio \( \beta \), when the ambient photon density is similar to that found in the
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Figure 5. Broad band Ultra-soft state ($\gamma$ class) data of GRS 1915+105 reproduced from Zdziarski et al. (2001). Solid line is computed spectrum for $\beta = 0.008$, $l_{ph} = 555$, $kT_{ph} = 1.35$ keV, $\tau = 5.0$ and $\alpha = 2.5$.

Figure 6. The radiated spectra for parameters typical of the hard state of black hole binaries, which are $l_{ph} = 250$, $E_c = 100$ keV, $\tau = 1.0$ and $\alpha = 2.5$. The three curves labeled as 1, 2 and 3 are for compactness ratio $\beta \equiv l_{p-p}/l_{ph} = 0.001$, 0.01 and 0.1 respectively. The solid lines represent the total spectra, the dotted lines represent the spectral component due to $p-p$ interactions and the dot dashed line represents the thermal component. The dashed line represent the spectral components obtained using the diffusion approximation as described in Bhattacharyya et al. (2003).

Figure 7. The particle distributions corresponding to the spectra shown in Figure 6. The dotted (solid) lines represent the positron (electron) distributions.

hard state of black hole binaries. In this state, the spectrum is dominated by a thermal Comptonized component, which is approximated here as an exponentially cut off power law with photon index $\Gamma = 1.7$ and cut off energy $E_c = 100$ keV. As the average photon energy in the plasma is higher than that of the soft state, the cut-off in the photon spectrum due to pair production appears at $\approx 3$ MeV instead of $\approx 80$ MeV. In the soft state, the shape of the computed spectra and particle density depended on the compactness ratio $\beta$. This was due to increasing self-interaction of the non-thermal photons to produce pairs as compactness increased. However, in the hard state, since the number density of ambient photons with energy $> 500$ keV is large, pair production is dominated by interaction of non-thermal photons with the background ambient ones even for large compactness. Thus, the shape of the computed spectra is relatively invariant to $\beta$ as shown in Figure 6 and in particular the slope of the expected spectrum at energies $> \text{MeV}$ is insensitive to the parameters of the model.

Figure 6 also shows for comparison, the computed spectral components due to $p-p$ interaction, obtained using the diffusion approximation to solve for the particle distribution as described in Bhattacharyya et al. (2003). Similar to what was found for the soft state (Figure 5), only quantitative differences can be seen while the qualitative features of the spectra are similar. This suggests that even when the ambient photons have energy $\sim 100$ keV, the diffusion approximation can reveal the salient features of the high energy spectrum.

The broadband hard state data of Cyg X-1, using RXTE and BeppoSAX satellites, were analyzed and fitted using the EQPAIR model by McConnell et al. (2002). The unfolded data is reproduced in Figure 8. Most of the spectra can be represented by thermal Comptonization, but there is evidence for a different high energy spectral component in the $0.7-8$ MeV range, which was explained as emission from
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The non-thermal protons interact via $p-p$ collisions to produce electron/positron pairs and $\gamma$-rays. These high energy pairs cool by inverse Comptonization of ambient photons. The effect of subsequent pair production due to photon-photon interactions and annihilation of positrons with ambient electrons, is taken into account. Unlike previous works, the scheme does not assume that the energy change of the leptons during inverse Compton scattering is small. Hence it can be applied to black hole binary systems, where the dominant ambient photons are X-rays.

Comparison of the computed spectra with the broadband X-ray/$\gamma$-ray spectra of black hole binaries in different spectral states reveal:

- The hard X-ray spectra (3–800 keV) of the soft and Very High state (VHS), are too steep to be explained as emission due to $p-p$ interactions. However, the observed $\gamma$-ray spectra (0.8–8 MeV), especially for the soft state, could be due to such interactions. In this interpretation, an unknown acceleration process energises both electron and protons, producing their non-thermal distributions. While the electron non-thermal distribution gives rise to the hard X-ray emission, the protons are the origin of the $\gamma$-rays. The powers going into accelerating protons and electrons are within a factor of two.

- For the ultra-soft state, the observed hard X-ray spectra ($E >$ 5 keV) could be entirely due to $p-p$ interactions. This interpretation gives a natural explanation for the similar hard X-ray spectral slope ($\Gamma \approx 2$) observed whenever a black hole is in the ultra-soft state.

- For the hard state, the observed $\gamma$-ray spectrum (0.5–8 MeV) can be explained as emission due to $p-p$ interactions alone. The predicted steep spectral shape in this energy range, is not sensitive to the model parameters, and matches well with the observations.

- For both the soft and hard states, the model predicts that for reasonable parameters, GLAST should be able to detect black hole binaries. This in contrast to the situation when only non-thermal electrons are present in the system, where very low compactness and large maximum Lorentz factor of the electrons have to be postulated, in order for GLAST to make a similar detection.

These results are consistent with the hypothesis that there always exists a spectral component due to a non-thermal proton distribution in black hole binaries. This component peaks at $\gamma$-rays and can contribute between 0.5 to 10% of the bolometric luminosity. In the ultra-soft state, this component is visible for $E >$ 5 keV. During the soft and hard states, the emission is detectable only when $E >$ 0.8 MeV, since other spectral components dominate at lower energies. This hypothesis can be verified using future observations by GLAST.

The scheme does not include scattering of high energy photons with thermal electrons. Although the Klein-Nishina cross section decreases with photon energy, such scatterings can be important especially when the Thompson optical depth is significantly greater than unity, a case more pertaining to the soft state. In fact, the inability of the present model to explain the hard X-ray emission during the soft state, may be an artifact of this assumption. If that is true, then it may be possible that only protons are accelerated in black hole binaries and not electrons. This is theoretically appealing given the complexities of accelerating electrons to

4 SUMMARY AND CONCLUSION

A self-consistent scheme, which computes the electron/positron and radiation energy distribution inside a thermal plasma having non-thermal protons, is developed.
high energies in a region where inverse Compton cooling is
efficient. However, several sophisticated modification of the
present scheme have to be undertaken before this speculation
can be tested.

Evidence of non-thermal protons in black hole binaries,
would shed light on the energy dissipation process that occur
in the inner regions of the accretion disk. These energetic
protons could also be the origin of the outflows/jets that are
observed in many of these systems. Such insights may finally
lead to a comprehensive physical picture of these enigmatic
sources.

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