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Gamma-Ray Emission from Cygnus X-1: Emission Mechanisms and Implications for the Standard Model

Recent observations of the black hole candidate, Cygnus X-1, have provided persuasive evidence for a sporadic hard spectral component extending into the MeV region of the electromagnetic spectrum. The measured fluxes above a few hundred keV represent excess luminosities of $\sim 10^{37}$ ergs $cm^{-2}s^{-1}$ over conventional Comptonization models and are comparable with the total X-ray luminosities. In this paper, we summarize the relevant γ-ray observations over the last two decades and review existing theoretical models in the light of MeV emission. When examined in detail, all models appear problematic in that they require *a priori* assumptions about the source or unreasonably high electron temperatures within the emission region. Taking into account recent high sensitivity measurements at other energies, the data indicate that the source behaves in a much more complicated fashion than that predicted by simple bi-modal models, closely resembling AGN at soft X- and γ-ray energies. We therefore suggest that a composite emission model may be more appropriate, in which the hard X-rays are produced by unsaturated Comptonization in the hot optically thin inner region of the accretion disk; the soft X-rays by a combination of local blackbody and Compton reflection of hard X-rays in the cool optically thick outer part of the accretion disk; and the MeV excesses by some pair related phenomena near the hole.

Key Words: *gamma-rays, X-rays, binaries, black holes, Cygnus X-1*

1. INTRODUCTION

Cygnus X-1 is one of the strongest X-ray sources in the celestial sky and perhaps, with the exception of A0620+00, is considered to be the best, and most convincing, black hole candidate. It is a

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binary system consisting of a blue supergiant (HDE226868) and a compact companion of stellar mass ($\sim 10\ M_\odot$). The X-ray emission is highly variable on timescales ranging from milliseconds to years and can be best understood in terms of disk accretion onto a black hole.[1] Within this context, a variety of models have been proposed.[2–5] Generally, the emission is attributed to the Comptonization of soft photons within either a hot ($T_e > 10^9$ K) optically thin region of the accretion disk,[3] or within a hot corona surrounding the disk.[4] Irregular longer-term luminosity variations have historically been classified into two principal states, characterized as either the "high state" (HS) or "low state" (LS) by the relative intensity of soft X-rays < 10 keV. Soft power law spectra, of photon index ~ 3, are generally observed during the high state, whereas during the low state the spectra are most consistent with an unsaturated Compton distribution. The soft X-ray luminosity in either of these states is anticorrelated with the corresponding hard (~ 100 keV) X-ray luminosity.[5]

From an analysis of data from the germanium spectrometer onboard HEAO-3, Ling *et al.*[6] reported an apparent extreme of LS behaviour, in which both the hard and soft X-ray fluxes were low simultaneously. They refer to this as the "super low state" (SLS). An extended analysis (Ling *et al.*[7]) of the same database revealed a continuous hard X-ray flux variation, which was apparently independent of the corresponding soft X-ray flux. Ling defined three levels, or periods, of hard x-ray emission within the LS (denoted by γ_1, γ_2, and γ_3), with transitions between levels taking weeks to months. From the fall of 1979 through spring 1980, HEAO-3 observed an evolution of the hard X-ray flux from γ_1 to γ_2 to γ_3, returning to the γ_2 level. In the convention of Ling *et al.*,[6] the γ_1 level corresponds to the SLS and the γ_2 level to what had previously been regarded as the canonical LS hard X-ray spectrum (e.g., Ref. 8). The γ_3 level had been seen on a few occasions previously. It is similar to the γ_2 level but $\sim 30\%$ more intense at 100 keV. Using data from two balloon flights of the Milan/Southampton (MISO) γ-ray telescope, Bassani *et al.*[9] confirmed a transition from the γ_1 to γ_2 level between 1979 and 1980. Both observations took place during the LS. Needless to say, this apparent hard X-ray flux variation within the LS poses problems for the classical bimodal model.

2. GAMMA-RAY EMISSION

In addition to the puzzling X-ray measurements, there have also been sporadic reports of a hard spectral component extending into the MeV region. For example, at energies above 1 MeV, Baker *et al.*[10] detected positive emission up to 6 MeV during a balloon flight of a NaI "anticollimation" telescope in September 1972. Later, Mandrou *et al.*[11] observed significant fluxes up to 3 MeV using a balloon-borne actively shielded CsI detector in June 1976. Ling *et al.*[7] reported a 5σ excess in HEAO-3 data which is qualitatively similar to that measured by Baker *et al.*[10] McConnell *et al.*[12] detected positive fluxes up to 9.3 MeV during a balloon flight of the University of New Hampshire's coded aperture imaging telescope in 1984; the significance of this measurement was 2.9σ in the (2–6.3) MeV region. Based on a re-analysis of the 1979 MISO flight data, Bassani *et al.*[9] found evidence for a hard spectral component in the 0.4–6.8 MeV range with an integral flux consistent with that reported by Ling *et al.*[7] over the same energy band (these measurements were contemporaneous). The excess was significant at the 3.5σ level and was not present during their 1980 flight. In an analysis of the available spectral data, Bassani *et al.*[9] find a weak negative correlation (2.7σ) between the hard X-ray fluxes (50–400 keV) and corresponding γ-ray fluxes (400–1500 keV). Such a causal link, if real, further suggests that the emission environment is considerably more complicated than a simple HS/LS bimodal system.

In Table I, we list all reported observations at MeV energies, including null results. Characteristically, the "measured" spectra in this region resemble broadened Gaussian distributions of width $\Delta E/E \sim 1$. Therefore, in order to compare different results, we have quantified the high energy excesses as equivalent line fluxes. These were derived by approximating each spectrum by a single temperature Compton distribution plus a broad Gaussian feature (see Fig. 1). Upper limits were calculated by assuming a 1 MeV bandwidth centered on 1.5 MeV, this being close to the median center energy of the positive results. For completeness, we also note the corresponding hard X-ray strengths in terms of their γ level. (All measurements took place during the LS.) The data suggest that MeV emission may be a common occurrence with a

TABLE I

A summary of observations of Cygnus X-1 at MeV energies. The upper limits (denoted by *) are at the 2σ level and were calculated by assuming a 1 MeV bandwidth centered on 1.5 MeV. Also listed for each measurement (where available) are the γ-state, the 5.6 day orbital phase and the 294 day precessional phase.

Experiment/ Institution [Ref.]	Date yr/m/d	γ State	Center Energy MeV	Equivalent Line Flux, γ's $cm^{-2}s^{-1}$	$\Delta E/E$	Phase 5.6 day	Phase 294 day
SOTON[10]	1972/9/23	–	1.95	$(3.8 \pm 1.2) \times 10^{-2}$	1.1	0.1	0.4
MPI[47]	1973/2/27	–	–	$< 3 \times 10^{-3*}$	–	0.1	0.9
UNH[48]	1976/5/16	γ_3	–	$< 3 \times 10^{-2*}$	–	0.8	0.9
CESR[11]	1976/6/6	γ_1	>1	$> 2 \times 10^{-3}$	≥1	0.4	1.0
RICE[49]	1977/10/4	γ_2	–	$< 4 \times 10^{-2*}$	–	0.1	0.6
HEAO-1[50]†	1977/10/25–11/18	γ_2/γ_3	–	$< 4 \times 10^{-3*}$	–	–	0.8
	1978/4/21–5/15	γ_2	–	$< 3 \times 10^{-3*}$	–	–	0.4
	1978/10/14–11/1	γ_2	–	$< 9 \times 10^{-3*}$	–	–	0.9
UCR[51]	1978/10/1	–	–	$< 3 \times 10^{-4*}$	–	0.7	0.9
HEAO-3[7]	1979/9/27–10/10	γ_1‡	0.97	$(1.4 \pm 0.3) \times 10^{-2}$	1.0	–	0.1
	1979/10/27–12/8	γ_2	–	$< 3 \times 10^{-3*}$	–	–	0.3
	1980/3/4–5/16	γ_2	–	$< 3 \times 10^{-3*}$	–	–	0.8
	1979/12/9–12/31	γ_3	–	$< 6 \times 10^{-3*}$	–	–	0.4
MPI[52]	1979/5/14	–	–	$< 2 \times 10^{-3*}$	–	1.0	0.6
MISO[9]	1979/10/1	γ_1	~0.7	$(1.9 \pm 0.7) \times 10^{-2}$	~1	0.9	0.1
	1980/5/18	γ_2	–	$< 5 \times 10^{-3*}$	–	0.0	0.9
UNH[12]	1984/10/1–10/2	γ_2††	4.32	$(6.4 \pm 1.9) \times 10^{-3}$	1.0	0.3	0.3

†Line feature detected at 0.5 MeV in composite spectrum.
‡Weak (1.9σ) line feature later reported at 0.511 MeV.
††Obtained from quasi-contemporaneous EXOSAT observations. Iron line emission was also detected in the EXOSAT spectrum.

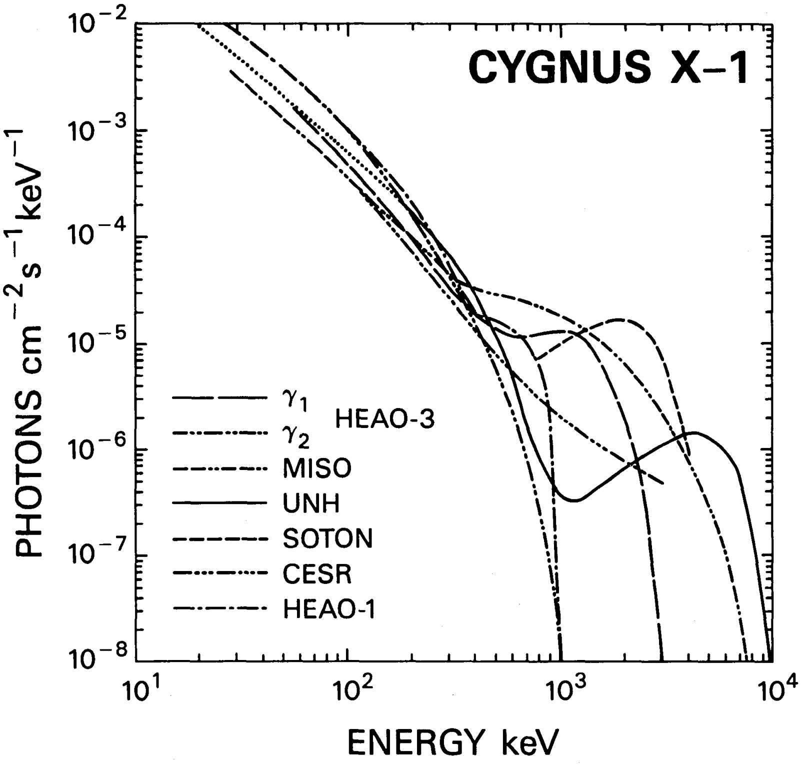

FIGURE 1 A compilation of all measurements of a γ-ray excess from Cygnus X-1. For the sake of clarity, we represent each spectrum by a single temperature Compton + Gaussian distribution, since the measurements are at a relatively low significance level (i.e., 3–5σ) above an MeV. For comparison, we also show the normal low-state or γ_2 spectrum. The references are as follows: HEAO-3 (Ref. 7); MISO (Ref. 9); UNH (Ref. 12); SOTON (Ref. 10); CESR (Ref. 11) and HEAO-1 (Ref. 50).

duty cycle as high as 30%. From Table I, we also note that MeV emission would seem to favor the γ_1 level and small phases in the 294 day precessional period reported by Priedhorsky, Terrell and Holt[13] for the UVB and soft X-ray bands.

3. THE EMISSION MECHANISM

The production of MeV γ-rays cannot be explained by standard Compton models since they predict vanishingly small fluxes at these energies. Thus, the high-energy excesses must be generated by another mechanism, some of which are discussed below.

A "bump" in the MeV region of the spectrum can be produced by a blueshifted positron annihilation feature produced in a relativistic pair plasma as proposed by Zdziarsky[14] and Ramaty and Mezaros.[15] Assuming an optically thin source region, the available data suggests electron plasma temperatures ranging from ~ 1 to 5 MeV, which is clearly different from those needed to explain the hard X-ray emission (i.e., $kT_e \sim 80$ keV). In order to reconcile these results, it would be necessary to invoke a model with two distinct emission regions. However, the apparent anticorrelation of fluxes above and below 400 keV requires that these regions are physically connected to some extent.

Liang and Dermer[16] developed an elegant two-component model in which the high energy emission is produced in a hot ($kT_e \sim 400$ keV) pair-dominated plasma (i.e., $z = n_+/n_p >> 1$, where n_+ and n_p are the positron and proton densities, respectively). The X-rays are assumed to emanate from a physically distinct region with little or no exchange of photons. This model appears quite successful in explaining both the HEAO-3 results[17] and the earlier HEAO-1 observation of a similar feature near 500 keV.[18] Yet it cannot produce γ-rays above a few MeV (as required by the UNH data, for example) due to the onset of thermal instabilities in the pair plasma. As with most two-component models, it also suffers from the basic problem of sustaining two distinct particle populations.

The observation of an annihilation feature correlated with the MeV emission would provide strong support for the existence of pairs at the source, as discussed, for example, by Dermer and Liang.[19] Ling and Wheaton[20] searched the HEAO-3 γ_1 spectrum for such a feature and reported tentative evidence for a weak (1.9σ) line centered at (510.7 ± 1.1) keV. The feature was found to be intrinsically narrow (of width a few keV) with a flux of $(4.4 \pm 2.4) \times 10^{-4}$ photons cm^{-2}s^{-1}. Obviously, if this result is correct, the positrons must be annihilating at some distance from the hole in order to avoid a substantial redshift (i.e., $d > 100$ Schwarzchild radii). This is possible. Kovner[21] has shown that positrons can escape from the vicinity of a black hole under the influence of radiation pressure alone, since the Eddington limit for pairs is reduced by a factor of $m_p/m_e = 1836$, compared to ordinary matter.

Some models (e.g., Ref. 3) postulate the existence of a two-temperature plasma in which the ion population reaches a much higher temperature ($T_i \sim 10^{12}$ K) than the electrons ($T_e \sim 10^8$ K).

If there exists an efficient mechanism for randomizing the kinetic energy of the inflowing ions before they reach the event horizon, say, by spiraling rather than radially accreting through the disk, pion production may take place.[22,23] The resulting γ-ray flux above 100 MeV may be estimated by assuming that the ions thermalize and the observed MeV emission is primarily due to electron bremsstrahlung from charged pion decay. Based on the calculations of Eilek and Kafatos,[23] this is found to be $\sim 10^{-3}$ photons $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, which is three orders of magnitude greater than the reported SAS-2 upper limit.[24] Therefore, unless the emission is time variable or degraded by high opacity, this model is incapable of explaining the observed MeV excesses. (This is consistent with the conclusion of Aharonian and Vardanian[25] that the proton thermalization timescale above the π creation threshold is longer than the radial plasma free-fall time.)

High ion temperatures within the accretion disk also lead to the possibility of nuclear line emission.[26] While the observed spectra are qualitatively similar to that expected from broadened line features, Aharonian and Sunyaev[27] argued that spallation will suppress line emission by inhibiting the repeated thermal excitation of nuclei in the source region. Specifically, they estimate the nuclear line luminosity to be $< 10^{-3}$ of the X-ray luminosity, which is inconsistent with the measurements. The UNH result,[12] for example, indicates that the luminosities above and below 1 MeV are comparable ($L \sim 3 \times 10^{37}$ ergs s^{-1}). Furthermore, while it is tempting to ascribe the UNH MeV excess to a broad ^{12}C feature, it would be difficult to reconcile this assertion with the other measurements for which there are no obvious counterparts. Even invoking an ad hoc explanation, such as a strong redshift, cannot explain all the results.

The efficient acceleration of relativistic particles near an accreting black hole is predicted by a number of non-thermal models (for a review see Kafatos, Shapiro and Silberberg[28]). For example, relativistic electrons can be generated by a variety of electromagnetic as well as purely gravitational processes such as Penrose pair production. Protons and heavier nuclei may be accelerated to ultrahigh energies by shock-wave or stochastic Fermi acceleration. Gamma-rays may then be generated by a variety of processes, including those described above. However, while non-thermal models usually reproduce measured spectra well, they lack predictive power since the acceleration mechanism is often chosen to produce a particular population of particles, rather than for any physical reason.

Finally, with respect to non-thermal models, it is interesting to note that Fomin *et al.*[29] reported the detection of PeV γ-rays from Cygnus X-1, based on EAS observations carried out from November 1984 to September 1986. For the period October 1985 to September 1986, the measured excess is marginally significant with an integral flux of $(5.4 \pm 1.8) \times 10^{-13}$ photons $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ above 0.7 PeV. A low energy extrapolation of this flux is in remarkable agreement with the measured MeV fluxes for an assumed spectral slope of ~ -2.1.

4. THE BIGGER PICTURE

The available experimental data suggest that MeV emission may be a common occurrence. However, when the various emission models are examined in detail, it is apparent that, while much effort has been spent constructing the micro- and macro-physics behind the hard X-ray emission, a self-consistent model incorporating these “excesses” has yet to be developed. The apparent anticorrelation of the hard X- and γ-rays, the continuous hard X-ray flux variation within the LS, and the possibility of annihilation radiation all conspire against a simple bi-modal model. Even disregarding the behaviour at these energies, recent soft X-ray measurements are also at variance with the standard model and provide important clues into the nature of the source. For example, the soft X-ray results of Barr and van der Woerd[30] are particularly interesting. In a detailed analysis of EXOSAT data (0.4–12 keV) obtained during the LS, they find that the spectrum is inconsistent with a superposition of featureless blackbody spectra expected from standard viscous accretion disk models (α disks). In fact, it cannot be fit by any simple function, requiring at least four distinct spectral components: a hard power law distribution of photon spectral index 1.4 (which dominates above a few keV), a soft power law spectral component of index 3.2 which dominates in the region 0.8–2 keV (perhaps residual high state emission?), an iron line at

6.3 keV, and a broad emission feature centered at 700 eV, probably complex iron L shell emission. The presence of structure in the soft X-ray spectrum is significant because it is exactly what one would expect from the reprocessing of X-rays by cold matter in the vicinity of a black hole (see Refs. 31 and 32)—for example in the optically thick regions of the outer part of the accretion disk. (The reprocessing is unlikely to take place in the photosphere of the companion because the equivalent width of the iron line would be ~ 5 times smaller than measured and also the line flux would be modulated at the binary period, which is not observed.[33] That some reprocessing is taking place has been suspected, as evidenced by the deep iron K-edge near 7 keV, presumably from X-ray reflection off cold matter. The soft X-ray excess measured by EXOSAT is then naturally explained as thermal re-radiation of the absorbed luminosity from the disk itself. For Cygnus X-1, the calculations of Done *et al.*[34] have shown that the observed spectrum over the energy range 4 to 40 keV is better fit by a power law input spectrum and its reflection from an ionised accretion disk than a traditional Compton distribution (χ^2 of 88/110 dof as opposed to 103/108 dof). Preliminary results indicate that the fit is sensitive to the input spectral shape being reprocessed and promise to provide a good diagnostic of the system when higher quality data become available. Needless to say, such a result can have profound implications at γ-ray energies since (a) it is these photons which fuel Compton models and (b) if reprocessing is taking place, there may be observable consequences in the γ-ray region of the spectrum, such as annihilation and Compton features.

The standard Compton model still gives the best qualitative description of the hard X-ray spectrum and the longer term variability; however, the behavior in the soft X- and γ-ray regions closely resembles that observed in other black hole candidates. For example, many workers have long commented on the similarities of the X-ray spectra of Cygnus X-1 and AGN (Seyferts and quasars). Both show rapid variability and a hard power law of photon spectral index, $\alpha \sim 1.6$. The report of a soft X-ray excess from Cygnus X-1 at energies < 2 keV can be considered significant, since such emission is also seen in about 50% of unobscured Seyferts in the EXOSAT spectral survey.[35] Lastly, regarding recent reports of iron line emission from Cygnus X-1 (e.g., Barr and van der Woerd[30] and references therein), GINGA has detected similar features in the spectra of nearly all the AGN it's been able to clearly resolve at low energies.[36]

At gamma-ray energies, the few AGNs which have been positively detected show evidence of a strong spectral component at MeV energies (e.g., the Seyfert galaxies NGC 4151 and MCG 8-11-11.[37]) In the case of NGC 4151, the MeV component may be correlated with flaring activity at other wavelengths. Recently, Lingenfelter and Ramaty[38] have also pointed out the striking similarities between the continuum spectrum of the compact source at the Galactic center measured in 1979 and the Cygnus X-1 γ_1 spectrum reported by Ling *et al.*[7] This source is also a strong black hole candidate and sporadic emitter of narrow 511 keV line emission as well as a hard MeV spectral component. In a detailed analysis of the available data, Lingenfelter and Ramaty[38] conclude that the variations in the continuum fluxes above 511 keV are highly correlated with the 511 keV annihilation line strength.

Apart from the Galactic Center, the evidence for annihilation radiation from black hole candidates is suggestive, but not compelling. For example, Owens[39] presented evidence for a weak (3.3σ) feature at a center energy of 502.2 ± 0.4 keV from the peculiar radio galaxy NGC 1275. Wheaton *et al.*[40] reported a 2.2σ feature centered at 509.1 keV in the spectrum of the type II Seyfert, NGC 1068. Both features are intrinsically narrow (of width a few keV) and are tentatively interpreted as redshifted annihilation radiation. In the case of Cygnus X-1, Nolan and Matteson[18] reported the HEAO-1 observation of a 3σ broadened feature centered at 500 ± 75 keV and most recently (as mentioned previously), Ling and Wheaton reported a narrow, weak (1.9σ) 511 keV line in the HEAO-3 γ_1 spectrum. Interestingly, the fractional line width of the HEAO-1 result is similar to that found for the MeV emissions (i.e., $\Delta E/E = 0.8$) in contrast to the value of ~ 0.005 reported by Ling and Wheaton[20] for the HEAO-3 measurement. (This suggests that the HEAO-1 observation may be more closely related to the MeV measurements of Cygnus X-1 discussed earlier.) The definitive observation of annihilation radiation would be a powerful diagnostic, since models which involve the reprocessing of pairs in cold matter invariably give rise to narrow 511 keV radiation, as well as soft X-ray excesses, a break in the spectrum above 1 MeV and the canonical $E^{-1.7}$ power law above a few keV (e.g., see Ref. 41). If such a process were occurring in the Cygnus system, then we might also expect to see a backscattered annihilation feature near 170 keV as predicted for the Galactic center.[42] Indeed such a peak may have already be seen. Agrawal *et al.*,[43] Watanabe[44] and Ma *et al.*[45] all reported the detection of weak features in the 100–200 keV energy region.

From the preceding discussions, we conclude that sporadic MeV, annihilation, steady state iron line and excess soft X-ray emissions appear to be common properties of black holes. In the case of Cygnus X-1, all four may have been observed, the first two simultaneously, providing strong evidence for the presence of pairs if confirmed. The data suggest that all these emissions are related, and therefore we feel that the key to understanding MeV emission lies in high sensitivity measurements at other energies. Existing theoretical models can explain one or more of these components; however, the real challenge is to develop a self-consistent model incorporating all of these phenomena within the framework of conventional Comptonization models. Perhaps the solution will lie in combining the standard model with a pair plasma model[16] and the recently developed X-ray reflection models for AGN.[41] We have discussed this and explored a preliminary geometry elsewhere.[46] Clearly, long term observations with high spectral and temporal sensitivity are fundamental to this work. Finally, from the above discussion, it is also apparent that much can be learned about Cygnus X-1 from detailed multi-frequency observations of other black hole candidates and *vice versa*.

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