ON THE ORIGIN OF MEV EMISSION FROM CYGNUS X-1

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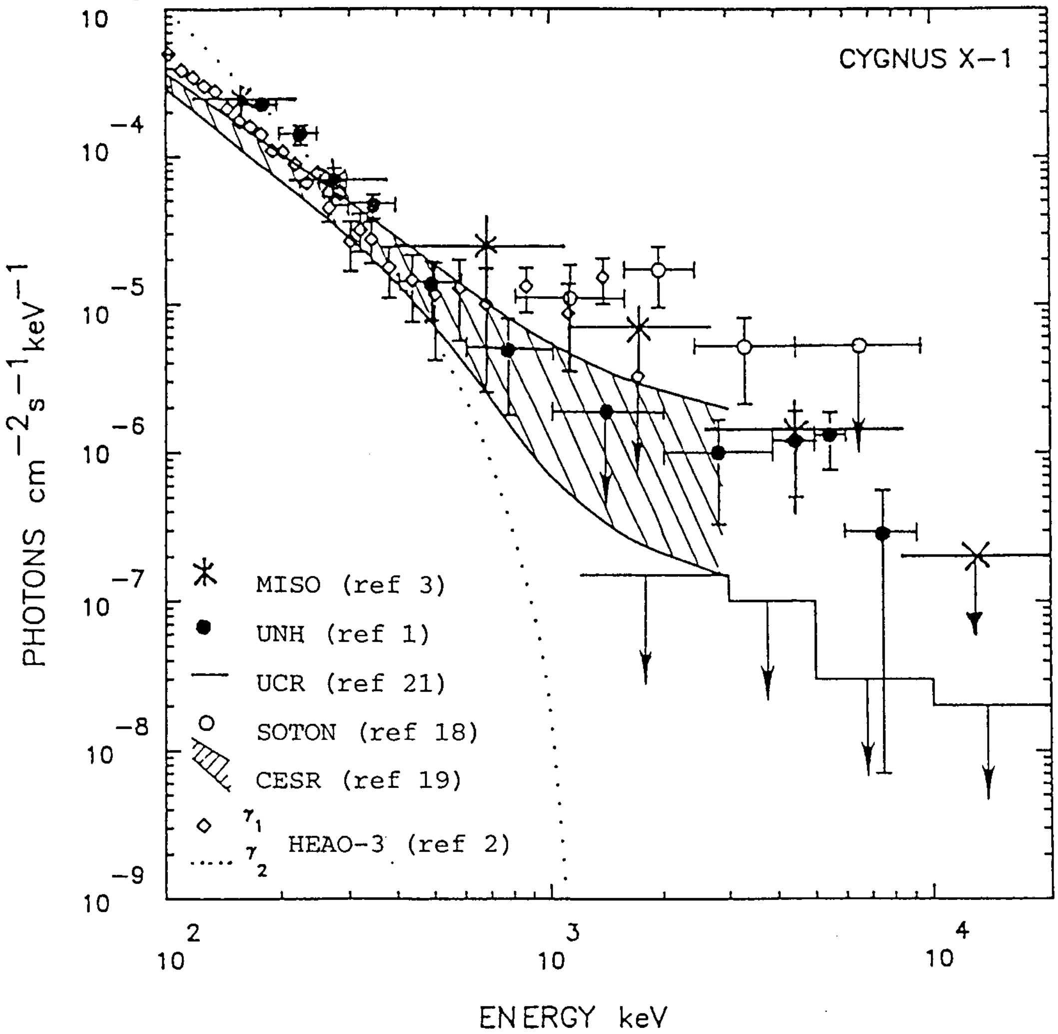
1. Introduction: Recent observations[1-3] of the black hole candidate, Cygnus X-1, have provided supporting evidence for a hard spectral component extending into the MeV region of the spectrum. The measured fluxes above a few hundred keV represent an excess luminosity of $\sim 10^{37}$ ergs $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ above that predicted by conventional Comptonization models and are comparable with the total X-ray luminosity. The existence of such a component is predicted by a number of models, although all appear to be problematic; either in that they require *a priori* assumptions about the source or unreasonably high electron temperatures within the emission region. However, the available experimental data suggests that MeV emission may be a common occurrence. In fact with few exceptions, the observational data (> 1 MeV) are most consistent with steady-state emission at the 10^{-6} to 10^{-5} photons $\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{keV}^{-1}$ flux level. In this paper, we will review and compare the various classes of emission model in the light of these measurements.

2. X-ray emission: The X-ray emission from Cygnus X-1 can be understood in terms of disk accretion onto a black hole.[4] Various accretion models have been proposed.[5-9] Generally, the emission is attributed to the Comptonization of soft photons within a hot ($T_e > 10^9$K) optically thin region of the accretion disk[7], or alternately, a hot corona surrounding the disk[4]. Irregular long-term luminosity variations may be classified into two principal states, characterized as either the "high state" (HS) or "low state" (LS) by the relative intensity of the soft X-ray emission at energies less than 10 keV. The soft X-ray luminosity in either of these states is generally anticorrelated with the corresponding hard (~ 100 keV) X-ray luminosity.[11-14] From an analysis of HEAO-3 data, Ling *et al.*[15] presented evidence for the existence of a third, or "super low state" (SLS), in which the hard and soft X-rays fluxes were low simultaneously. Based on an extended analysis of the HEAO database, Ling *et al.*[2] suggest that there may exist as many as three distinct γ-ray states above a few hundred keV within the LS (denoted by γ_1, γ_2, and γ_3). The X-ray spectra for these 'states' intersect at around 400 keV and display a new type of anticorrelation with the corresponding flux above 400 keV. This apparent decoupling of the X- and γ-ray fluxes suggests that the emission environment is much more complex than that explained by a simple bimodal model. However, at least two of these states may be reconciled within the framework of conventional models. For example, in the convention of Ling *et al.*[15], the γ_1 state corresponds to the SLS and the γ_2 state to the normal or LS. Confirmation for the SLS was provided by Perotti *et al.*[16] based on flight data from the MISO telescope in 1979. In a later paper, Bassani *et al.*[3] confirm a spectral variation from the γ_1 to γ_2 states between 1979 and 1980 with an apparent anticorrelation between the hard X and γ-rays pivoting around ~ 400 keV. Furthermore, in an analysis of the available world data they find a weak negative correlation ($< 3\sigma$) between the X-ray fluxes (50–400 keV) and corresponding γ-ray fluxes (400–1500 keV).

3. Gamma-ray emission: In addition to the "canonical" LS spectra usually observed[17], there have been sporadic reports of a hard spectral component extending into the MeV region of the spectrum. These are shown graphically in Fig. 1 and listed in Table 1, along with reported lower limits. For example, at energies above 1 MeV, Baker *et al.*[18] (SOTON) detected positive emission between 1 and 6 MeV and later Mandrou *et al.*[19] (CESR) observed measurable fluxes up to ~ 3 MeV. McConnell et al.[1] (UNH) found evidence for positive fluxes up to 9.3 MeV. The total significance of this measurement was 3σ in the 2–6.3 MeV region. Ling *et al.*[2] have reported a 5σ excess which is qualitatively similar to that measured by Baker et al.[18] Based on a re-analysis of the 1979 MISO flight data, Bassani *et al.*[3] have also presented evidence for a hard spectral component in the 0.4–6.8 MeV range with an integral flux which is consistent with that reported by Ling *et al.*[2] over the same energy band (these measurements were contemporaneous).

The excess is marginally significant at the 3.5σ level and was not present in the data from their 1980 flight. Characteristically, all of the above spectra can be approximated by a power law of spectral index < 1 in the MeV region.

Figure 1



In order to directly compare the positive results, we have approximated each spectra by a single temperature Compton (STC) distribution plus a broad Gaussian feature. These results are tabulated in Table 1, along with all other observational data at these energies. The experimental data suggest that MeV emission may be a common occurrence. In fact, with only a few exceptions, all the observational data are consistent with steady state emission at the 10^{-6} to 10^{-5} photons $cm^{-2}s^{-1}keV^{-1}$ flux level. Furthermore, there is also a suggestion that this emission may be correlated with the 294 day precessional phase[20] (see the last column of Table 1). From Fig. 1, it can be seen that the CESR data[19] agree well with the UNH data points[1] above 1 MeV, but are consistently lower below this energy. Also, the SOTON data[18] are in conflict with most of the positive measurements at these energies, as are the UCR upper limits[21] which lie $\sim 2\sigma$ below the UNH data points and $\sim 4\sigma$ below the SOTON results. However, it should be pointed out that, with the exception of the null UCR results and the positive SOTON results, all measurements above $\sim$ 500 keV are arguably in agreement, within statistics.

Compton models predict vanishingly small fluxes at MeV energies and therefore cannot be invoked to explain any of the measured excesses. This would suggest that the high energy emission is generated by another mechanism. We discuss possible mechanisms below.

Table 1: Observations of Cyg-X1 at MeV energies

Experiment	Date yr/m/d	γ state	Center energy MeV	Equivalent line flux, γ's $cm^{-2}s^{-1}$	ΔE/E	Phase 294 day
SOTON[18]	1971/9/23	–	1.95	$(3.8 \pm 1.2) \times 10^{-2}$	1.1	0.1
MPI[22]	1973/2/27	–	–	$< 3 \times 10^{-3*}$	–	0.9
CESR[19]	1976/6/5 - 6/6	γ_1	–	$> 2 \times 10^{-3}$	–	0.0
RICE[23]	1977/10/4	γ_2	–	$< 4 \times 10^{-2*}$	–	0.6
HEAO-1[24]	1977/10/23 - 11/20	γ_3	†	$< 1 \times 10^{-2*}$	–	0.7
	1978/4/15 - 5/23	γ_2	–	–	–	0.3
	1978/10/13 - 11/27	γ_2/γ_3	–	$< 1 \times 10^{-3*}$	–	0.9
UCR[21]	1978/9/30	–	–	$< 3 \times 10^{-4*}$	–	0.8
HEAO-3[2]	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	–	$< 1 \times 10^{-3*}$	–	0.2
	1980/3/4 - 5/16	γ_2				0.7
	1979/12/9 - 12/31	γ_3	–	$< 6 \times 10^{-3*}$	–	0.4
MPI[25]	1979/5/14	–	–	$< 1 \times 10^{-3*}$	–	0.6
MISO[3]	1979/10/1	γ_1	~ 1	$(1.9 \pm 0.7) \times 10^{-2}$	~ 1	0.1
	1980/5/18	γ_2	–	$< 5 \times 10^{-3*}$	–	0.9
UNH[1]	1984/10/1 - 10/2	γ_2	4.32	$(6.4 \pm 1.9) \times 10^{-3}$	1.0	0.3

*2σ UL; assumed bandwidth = 1 MeV centered on 1.5 MeV. †Line feature detected at 0.5 MeV.

4. Origin of the MeV excess: A high-temperature annihilation feature, as proposed by Ramaty and Meszaros[26] and Zdziarski[27] may be modeled as a Gaussian distribution with a mean photon energy $\sim 1.2\ kT_e$ and FWHM of $2.6\ kT_e$. Assuming an optically thin source region, the available experimental data suggests electron plasma temperatures ranging from, $\sim$ 1 to 5 MeV. This temperature is clearly different from the electron temperatures needed to explain the low energy emission (*i.e.*, $kT_e \sim 80$ keV). Therefore, in order to reconcile these results, it would be necessary to invoke a model with two distinct emission regions. This may present some difficulty in that, based on the apparent anticorrelation of fluxes above and below 400 keV, it is clear that these two regions must be physically connected to some extent.

Some models[7] 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 electron population ($T_e \sim 10^8$K). If there exists an efficient mechanism for randomizing the kinetic energy of the inflowing ions before they reach the event horizon, pion production may take place.[28–30] Such a process could result in the emission of γ-radiation above 1 MeV *via* the decay of neutral and charged pions. An estimate of the π° decay γ-ray flux at energies > 100 MeV may be obtained by assuming that the observed MeV emission is primarily due to electron bremsstrahlung resulting from the decay of charged pions. Based on the calculations of Eilek and Kafatos[30] we estimate this flux to be a few times 10^{-3} photons $cm^{-2}s^{-1}$ which is three orders of magnitude greater than the upper limit derived from SAS-2 observations.[31] Therefore, unless the high-energy emission is time variable or degraded by high opacity, this model appears to be incapable of explaining the observations of an MeV excess. This conclusion is also consistent with the calculations of Aharonian and Vardanian[32] which show that the time taken for the energy of the protons in the Maxwellian "tail" to exceed the pion creation threshold is longer than the radial plasma free-fall time, thus indicating that pion production at the level indicated by the present results is extremely unlikely.

High ion temperatures within the accretion disk lead to the possibility of nuclear line[33] emission. The thermal energy of the protons in such a plasma will be well above the nuclear excitation energy threshold (*i.e.*, $\sim$ 10 MeV). While the observed SOTON, UNH and HEAO-3 spectra are qualitatively similar to that which would be expected from broadened line emission, Aharonian and Sunyaev[34] have argued that spallation would tend to remove the nuclei from the emission region, effectively suppressing line emission. Specifically, the nuclear line luminosity is estimated to be at most, $\sim 10^{-3}$ of the total X-ray luminosity, whereas the UNH results, for example, indicate 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 broadened line emission from ^{12}C, it would be difficult to reconcile this assertion with the SOTON or HEAO-3 measurements for which there are no obvious counterparts. Even invoking an *ad hoc* explanation such as a strong redshift would appear to be at a variance with the present results. Thus, it may not be possible to interpret the observed emission as nuclear line emission from a thermal plasma.

Most of the present observations can be explained in terms of the two-component thermal model proposed by Liang and Dermer[35]. This model was motivated by the HEAO-3 data and leads to the conclusion that the X-ray and γ-ray emissions must emanate from two physically distinct regions with little or no exchange of photons. However, as with most two-component models, it requires unreasonably high electron temperatures in order to explain an excess at MeV energies. We may therefore be led to consider a nonthermal process in order to account for the observed excess emission.

The efficient acceleration of relativistic particles near an accreting black hole is predicted by a number of models.[36] For example, relativistic electrons can be generated by a variety of electromagnetic as well as by purely gravitational processes such as Penrose pair production. Protons and heavier nuclei may be accelerated to ultra-high energies by betatron, shock-wave, or stochastic Fermi acceleration. Once particles have been accelerated, MeV emission may then be generated by a variety of processes, including those described above.

Finally, with respect to a non-thermal model, it is interesting to note that Fomin *et al.*[37] have tentatively reported the detection of TeV γ-rays from Cygnus X-1, based on EAS observations carried out from 1984 November to 1986 September. For the period 1985 October to 1986 September, the measured excess represents a phase averaged integral flux above 7×10^{14} eV of $(5.4 \pm 1.8) \times 10^{-13}$ photons $cm^{-2}s^{-1}$. While a low energy extrapolation of this flux is in remarkable agreement with the measured MeV fluxes for an assumed spectral slope of ~ 2.1, it must be pointed out that the effect was apparently absent from 1984 November to 1985 June. However, a phase analysis of the data, from this time period, yields a positive detection at a phase of ~ 0.7 with respect to the optical 5.6 day orbital phase. The derived flux is marginally significant; $F = (1.9 \pm 0.8) \times 10^{-13}$ photons $cm^{-2}s^{-1}$.

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