LOW-ENERGY GAMMA RAYS FROM CYGNUS X-1

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ABSTRACT

Cyg X-1 was observed by the CESR balloon borne telescope *OPALE*, in June 1976. The high-energy spectrum of the source, which was in its "superlow state", was seen to extend well beyond 1 MeV. In this paper, the observed low-energy γ-ray component of Cyg X-1 is compared with the predictions of recent models involving accretion onto a stellar black hole, and including a possible contribution from the pair-annihilation 511 keV γ-ray line.

1. Introduction The hard X-ray/low-energy γ-ray emission from Cygnus X-1 was detected by the CESR scintillation-counter telescope *OPALE*, in the course of a balloon flight performed in 1976, June 5-6 (1). The photon spectrum of the source was derived from the electron spectrum obtained in the CsI(Tl) detection crystal, by means of a program which used a data library consisting of detector responses to a set of calibrated radioactives sources (2). It provides for the first time an estimate of the high-energy emission of Cyg X-1 in the 800 keV-3 MeV region, which is particularly interesting because of the recent report of spectral flattening in the adjacent (300-800 keV) energy range (3).

At present time, the hard X-ray emission of Cyg X-1 is well explained in terms of disk accretion onto a black hole, the hard X-ray production mechanism being generally believed to result from the Compton scattering of soft photons in the hot zone of the disk. The best fit to the hard X-ray spectrum, as measured by several groups (3,4,5), is obtained using the Sunyaev-Titarchuk (ST) analytical solution of the emergent Comptonized X-ray spectrum (6). It is then worthwile to extent this comparison in the low-energy γ-ray domain, only explored with the *OPALE* telescope.

2. Comparison with Comptonization spectra It is well established now that, in the X-ray domain, the spectrum of Cyg X-1 is variable and shows several modes (5). Therefore, it is appropriate to determine the state of the source

during the *OPALE* observation, before any attempts of comparison between current emission models and the observed results.

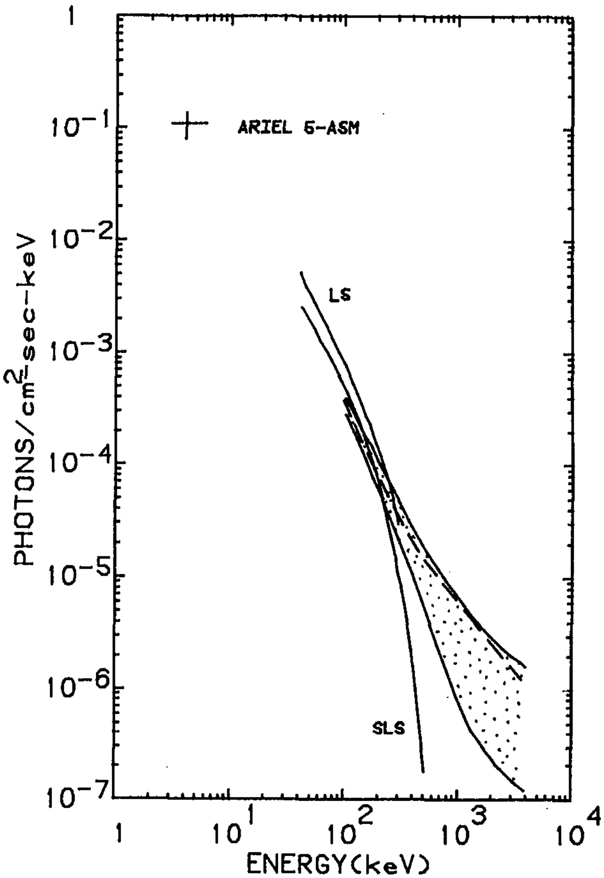

FIG. 1.-Differential photon spectrum of Cyg X-1 derived from the *OPALE* data (hatched area). The 3-6 keV flux measured in the contemporary *Ariel 5* ASM observation (7) is also indicated, as well as the best fit Comptonization model spectrum to the LS and SLS hard X-ray data (solid line), and the best composite fit (Comptonization plus power law) spectrum to the *OPALE* data (broken line).

The hatched area in Figure 1 is the most probable region for the source photon spectrum, derived from the statistical errors in the detected electron spectrum at the $\pm 1\sigma$ level. The two observed hard X-ray spectra typical of the "low state" (LS) and "superlow state" (SLS) are also displayed in Figure 1. Clearly, the *OPALE* low channels meet the SLS points. Moreover, contemporary data are available from the *Ariel 5* All Sky Monitor (ASM), yielding a 3-6 keV flux of ~0.09 photons cm^{-2} s^{-1} keV^{-1} (7), i.e. also close to the typical SLS value, as reported by Ling *et al.* (5). In conclusion, all the available observational material supports that in 1976, June 5-6, Cyg X-1 was in the "superlow state", characterized by low X-ray flux in both the soft and hard energy regions.

Figure 1 shows the best ST Comptonized model fit to the hard X-ray SLS spectrum, as derived by Ling *et al.* (5); with the exception of the low energy channels, the ST Comptonization spectrum differs significantly from the *OPALE* results. An analytical solution for the Comptonization spectrum has been also proposed by Colpi *et al.* (8), in the framework of a two temperature model of spherical accretion onto a black hole. One of their derived photon spectrum is well suited to the Cyg X-1 case: it corresponds to an accreting black hole of 10 $M_\odot$ with an accretion rate of 10^{16} g s^{-1}. When normalized to the *OPALE* low channels, this spectrum still contributes beyond 300 keV, but it falls well below the high-energy tail of the Cyg X-1 spectrum, as inferred from the *OPALE* data.

3. Is a positron annihilation line compatible with the γ-ray data? The Cyg X-1 spectrum, as derived from the *HEAO-1* A2 and A4 experiments, shows also a significant excess beyond 300 keV, with respect to the ST Comptonization model (3). Nolan and Matteson (NM) have suggested that this spectral feature may be a broad positron annihilation line, superimposed on a ST spectrum adjusted to the low-energy channels (9). In order to test if the *OPALE* results support such a possibility, and taking advantage of the detector response function library, a calculated electron spectrum has been derived from the composite NM photon spectrum, and compared with the data points as measured in the detector.

It should be noticed that the NM analysis relate to an average spectrum, derived from 3 extended observations, during which Cyg X-1 was in a more active state (LS), than during the *OPALE* observation. In order to favor the comparison, the NM spectrum has been normalized (by a factor of ~0.5) to match the low channels of the *OPALE* SLS spectrum. In spite of all, the result is an unacceptable fit ($\chi^2 \simeq 17$ for 5 degrees of freedom), most of the excess χ^2 coming from the higher energy range. This tends to rule out the possibility that the γ-ray excess may be due to positron annihilation alone, either as a broad 511 keV excess (9), or as a continuum resulting from the Comptonization softening of pair-annihilation induced photons (10).

4. Discussion At this point, it appears useful to question if the observed γ-ray excess is entirely related to Cyg X-1. Firstly, it should be stressed that the Crab Nebula spectrum, as measured by the same experiment (11), appears fully compatible with the power-law spectrum which extents from soft X-rays to high-energy γ-rays, without any excess in the MeV region. This rules out any interpretation of the observed excess in the Cyg X-1 case in terms of locally induced background.

Another source of background is related to the unresolved galactic emission. On the basis of the *COS-B* survey (12), it is visible that such a background could be certainly disregarded in the Crab Nebula observation, but may contribute in the Cygnus case. An estimate of this background could be derived in the following manner: first, one has to evaluate from the *COS-B* results (12), the flux of the galactic emission from the Cygnus region within the *OPALE* field of view, and in the energy range 70-5000 MeV. Then the assumption is made that the entire galactic spectrum, from 100 keV to few GeV, proposed by Mandrou *et al.* (13) for the central regions of the Galaxy ($-45° \leq \ell \leq +45°$), still holds in the Cygnus region. It is then straightforward to determine the unresolved galactic emission contribution in the *OPALE* range. It turns out that, particularly in the MeV region, this unresolved galactic background contributes to less than 10% of the reported flux, which can be then considered as entirely due to Cyg X-1.

It is well beyond the scope of this paper to propose an emission mechanism aiming to account for the low-energy γ-ray excess suggested by the *OPALE* data. However, to illustrate the exigence of an additonal spectral component, and since ST Comptonization spectrum produces an excellent fit below 200 keV, a calculated electron spectrum has been derived from a composite ST plus power-law photon spectrum, and compared with the data points as measured in the detector. The best fit ($\chi^2 \simeq 0.9$ for 3 degrees of freedom), has been found for a combination of a Comptonization spectrum, similar in shape to the SLS spectrum, but normalized by a factor of 0.65, plus an additional power-law spectrum $dN/dE = AxE^{-\gamma}$, where $A = 7.50 \times 10^{-2}$ photons cm^{-2} s^{-1} keV^{-1}, and $\gamma = 1.3$. Obviously, such an additional component, as shown in Figure 1, cannot extend too much in the high-energy domain, otherwise Cyg X-1 would have been detected as a point source by *COS-B*. It remains that the MeV region is particularly intriguing in the case of Cyg X-1, and an additional observational effort is required to disentangle the puzzling situation raised by the *OPALE* observation.

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