HIGH-ENERGY EMISSION FROM CYGNUS X-1

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1. Introduction. The University of New Hampshire Directional Gamma-Ray Telescope (DGT) observed the Cygnus region of the sky during a balloon flight on 1–2 October 1984. This instrument operates in the energy range of 160 keV to 9.3 MeV and employs the coded aperture technique to obtain images of the sky with an intrinsic angular resolution of 3.8°. The images obtained from the Cygnus observation clearly show evidence for Cyg X-1. The measured spectrum for Cyg X-1 extends up to ~ 9 MeV, with a marginally significant excess ($\sim 2.9\ \sigma$) in the (2–9.3) MeV energy range. Here, we shall review the observational results and discuss the implications of these observations in the context of current models for the source.

2. Observations. A detailed description of the DGT experiment has been presented elsewhere [1]. Observations with this instrument were obtained during a 30 hour balloon flight over Palestine, TX on 1–2 October 1984. A review of the major results from this balloon flight may be found in reference [2]. The Cygnus region, encompassing both Cyg X-1 and Cyg X-3, was observed from 2130 UT to 0030 UT and again from 0330 UT to 0630 UT with a total effective source exposure of 3.5×10^6 cm^2 s at 511 keV. The energy-loss spectrum of Cyg X-1, derived from the imaging data, is shown in Figure 1. The significance of the positive measurement in the (2–9.3) MeV range is 2.9 σ. There is no known mechanism which would produce such an artifact in the instrument itself. In fact, our observations of the Crab during the same flight show no evidence for such a feature [2,3].

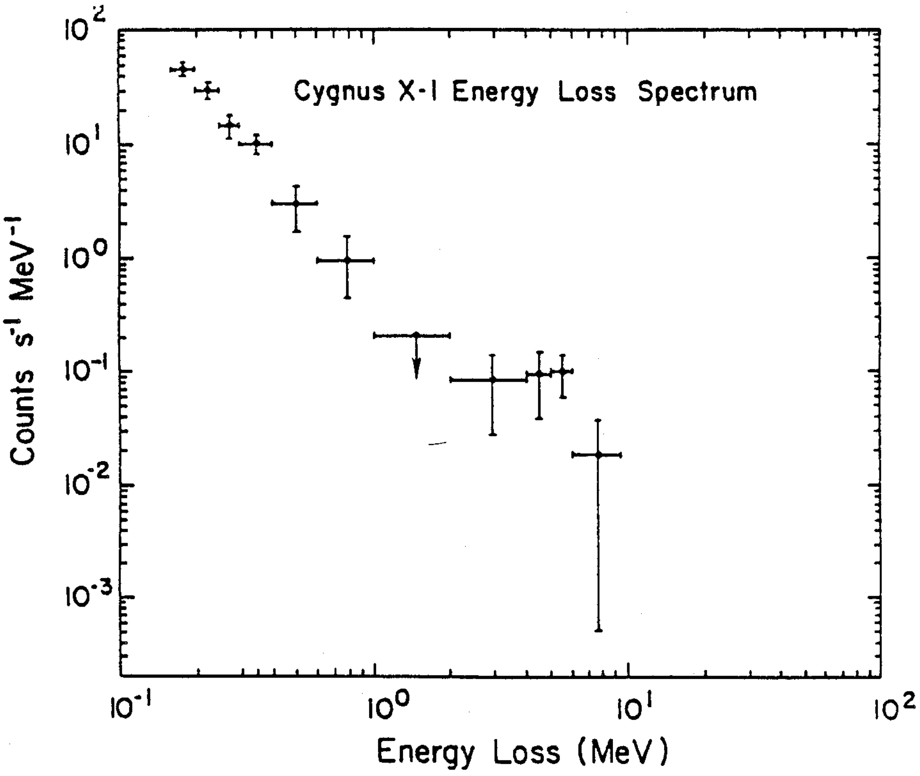

Figure 1.

3. Analysis. In order to derive a photon spectrum which corresponds to the energy-loss spectrum of Figure 1, we incorporate the known response function of the DGT instrument. For a particular source spectrum model, a library of response spectra are produced, each of which corresponds to the predicted energy-loss spectrum for some fixed set of model parameters. By comparing the observed energy-loss spectrum with those contained in the response library, the best-fit model parameters can be derived, along with the statistically allowable ranges of those parameters.

We have tested various source spectral models using the observed energy-loss spectrum. The simplest such model is that of a pure power-law spectrum. The DGT data is consistent with a featureless power-law of the form $3.73 \times 10^{-3}\ E_{\mathrm{MeV}}^{-2.35}$ photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{MeV}^{-1}$. This provides a marginally-acceptable fit with a reduced χ^2 of 1.71 for 9 degrees of freedom. However, this power-law spectrum, when extended beyond the DGT energy range, is not consistent with either the X-ray measurements (e.g., [4]) or with the upper limits obtained by the SAS-2 satellite [5].

X-ray observations of Cyg X-1 are generally described in terms of a single-temperature inverse Compton model [6] with electron temperatures in the range of (20–80) keV and with optical depths of 2–5 [4,7,8]. The inverse Compton model explains many of the observed X-ray features of Cyg X-1, including not only the observed spectrum, but also the spectral changes which result from changes in the overall luminosity. Attempts to fit the DGT data with this model proved unsuccessful. (The best fit resulted in a reduced χ^2 of 1.96 for 8 degrees of freedom.) Although the emission below 1 MeV can be adequately described by such a model, the model falls far short of the data points above 2 MeV.

The success of the Compton model in explaining not only the X-ray measurements, but also the DGT data below 1 MeV, suggest that the emission above 2 MeV may arise due to some other production mechanism. We have briefly investigated three possible MeV mechanisms: 1. a high-temperature annihilation line [9], 2. electron bremsstrahlung resulting from the decay of charged pions in the accretion flow [10], and 3. nuclear line emission [11].

We have modeled a high-temperature annihilation feature as a Gaussian with a mean photon energy of $1.2\ kT_e$ and a FWHM of $2.6\ kT_e$. The results of this analysis indicate a mean electron plasma temperature for the annihilation region of 3.5 MeV. This is considerably higher than the electron plasma temperature (20 keV to 80 keV) required to explain the X-ray data. In order to reconcile this difference in temperature, one would have to invoke a model with two distinct emission regions.

In order derive reasonable estimates of the photon flux above 1 MeV, a photon spectrum has been derived using a model which consists of power-law and inverse Compton components. The power-law was chosen so as to fit the data above 1 MeV and is given by the form $1.8 \times 10^{-3}\ E_{\mathrm{MeV}}^{-0.6}$ photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{MeV}^{-1}$ The Compton component is consistent with an electron temperature of $kT_e = 80$ keV and an optical depth of $\tau = 2.0$. The resulting fit, shown in Figure 2, yields a reduced χ^2 of 1.60 for 6 degrees of freedom.

The flux values derived from this model can now be used to evaluate the feasibilty of other production mechanisms which might explain the observed MeV emission. The standard models of Cyg X-1 [12] predict the existence of a very hot ion plasma ($\sim 10^{12}$K). This plasma may be capable of supporting pion production via p–p interactions. In this case, the (2–9.3) MeV emission would be interpreted as electron bremsstrahlung resulting (via muon decay) from the decay of charged pions. If the emission results from this process, then we would also expect there to be emission (at energies > 50 MeV) from the decay of neutral pions. We have considered the particular model of Eilek and Kafatos [10] in order to estimate the high-energy emission. Based on the DGT flux level, we would expect a flux of $\sim 3.5 \times 10^{-3}$ photons cm^{-2} s^{-1} between 100 and 150 MeV from neutral pions. This is three orders of magnitude higher than the upper limit on emission >100 MeV of 2.7×10^{-6} photons cm^{-2} s^{-1} based on observations from the SAS-2 satellite [5]. Unless the high-energy emission is time-variable, this would appear to be an unlikely explanation for the DGT observations.

Finally, we consider nuclear line emission. The very high ion temperatures which are predicted would provide enough energy to excite the nuclear levels of the plasma constituents. This may, in fact, provide an explanation for the DGT observations. It has been pointed out, however, that spallation effects may be important in such a plasma [13]. Spallation would tend to remove nuclei from the population and hence reduce the emissivity of nuclear lines. The resulting nuclear line luminosity is expected to be no more than $\sim 10^{-3}$ of the total X-ray luminosity. The present observations indicate equal luminosities in the region from 1 keV to 1 MeV and in the region above 1 MeV. If spallation is an important process, then it may not be possible to interpret the observed emission as nuclear line emission from a thermal plasma.

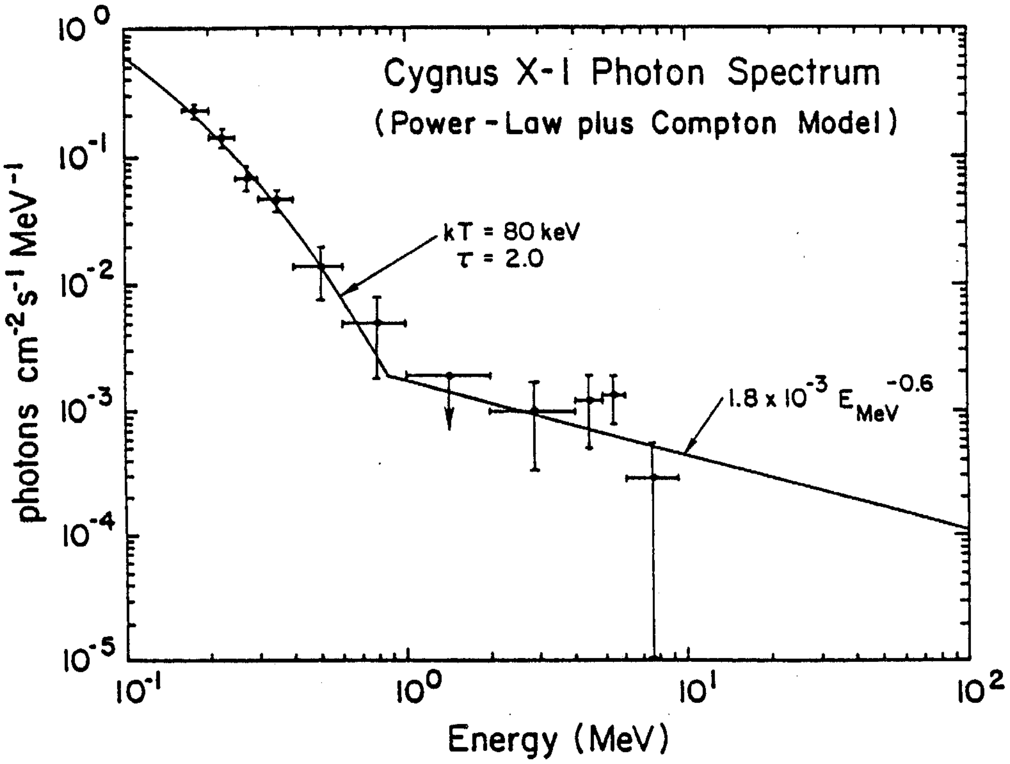

Figure 2.

The above discussion has concentrated on thermal mechanisms which might operate within the context of present models for Cyg X-1. Another possibility is that this radiation might be produced by some nonthermal process. This would imply some acceleration mechanism operating within (or near) the accretion region. More research (both experimental and theoretical) is clearly needed in order to determine the origin of the (2–9.3) MeV emission.

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