A Thermal-Nonthermal Inverse Compton Model for Cyg X-1

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Abstract. Using Monte Carlo methods to simulate the inverse Compton scattering of soft photons, we model the spectrum of the Galactic black hole candidate Cyg X-1, which shows evidence of a nonthermal tail extending beyond a few hundred keV. We assume an ad hoc sphere of leptons, whose energy distribution consists of a Maxwellian plus a high energy power-law tail, and inject 0.5 keV blackbody photons. The spectral data is used to constrain the nonthermal plasma fraction and the power-law index assuming a reasonable Maxwellian temperature and Thomson depth. A small but non-negligible fraction of nonthermal leptons is needed to explain the power-law tail.

INTRODUCTION

Cygnus X-1 is the brightest and most studied Galactic black hole candidate. Its high-energy spectrum has been extensively modeled in attempts to determine what processes produce the continuum emission. While several models debate the detailed geometry of the system [1-4], many agree that the 10-200 keV portion of the spectrum is a result of inverse Compton scattering of soft X-ray photons. Early modeling attempts assumed a single temperature Maxwellian plasma [5]. However such simple models do not adequately fit the observations [6,7]. More complex models, such as one with two plasma regions of different temperature, increase the goodness-of-fit substantially [3].

When Cyg X-1 is in the normal (γ2) state, a high-energy power-law is observed in the γ-ray continuum [8]. This is typically attributed to some nonthermal process. It is possible that the power-law is due to inverse Compton scattering off of a high-energy power-law tail in the plasma energy distribution. If so, both the emission above and below 300 keV could originate from the same plasma.
Fitting the Cyg X-1 Spectrum

We wish to see if the high-energy spectrum of Cyg X-1 can be explained simply by Comptonization from a single plasma region with a Maxwellian+power-law energy distribution. We simulated Comptonized spectra with a Monte Carlo code based on the algorithm of Pozdnyakov, Sobol, and Syunyaev [9]. We compared the results to combined BATSE and COMPTEL data from 1991 [8,10]. Though this data has already been unfolded through the detector response using an assumed model, it serves to give us an approximate solution.

The parameters that define the shapes of our simulated spectra are the temperature of the thermal leptons (electrons and pairs) $T_e$, the Thomson depth $\tau_T$, the fraction of nonthermal leptons $\xi$, and the energy index of the nonthermal leptons $p$. Generating and interpolating over a 4-dimensional parameter space is computationally intensive and for this study we fixed both $T_e = 65\text{ keV}$ and $\tau_T = 2.45$. A value of $T_e$ very close to this was determined for this data assuming single temperature analytic Comptonization [8]. The parameter $\tau_T$ was determined from the spectral index $\alpha$ of the 30 to 70 keV spectra, as suggested by Pozdnyakov, Sobol and Syunyaev [9], where the equations

$$\gamma = \frac{\pi^2}{3} \frac{mc^2}{(\tau_T + \frac{3}{2})^2 T_e}$$

(1)

and

$$\alpha = -\frac{3}{2} + \sqrt{\frac{9}{4} + \gamma}$$

(2)

are solved for $\tau_T$. This left two free spectral shape parameters, $\xi$ and $p$. We calculated a $6 \times 6$ grid of simulated spectra, with $\xi$ ranging logarithmically from 0.25% to 8.0% and $p$ ranging from 3.25 to 4.5. These grid points were chosen based on our experience with this code applied to other astrophysical phenomena [11,12]. We iterated our code until the statistical signal-to-noise within the range of 30 keV to 2020 keV was less than 10 in each of the 22 bins. Bins above 500 keV were smoothed in a manner similar to that in Pozdnyakov, Sobol and Syunyaev [9]. A simple spline algorithm allowed us make our model continuous so we could evaluate a $\chi^2$ between our simulation and the discrete data.

Figure 1 shows a reasonable fit of our code to the BATSE and COMPTEL data, where $\xi = 0.5\%$ and $p = 3.5$. To see what range of the parameter space is acceptable, we next examined $\chi^2$ over the entire grid. In Figure 2, we plot the confidence levels of fits on this grid. Contours are drawn here assuming a polynomial interpolation between grid points. This shows that for a fixed $T_e = 65\text{ keV}$ and $\tau_T = 2.45$, there is a 68.3% (1\sigma) confidence that $\xi$ lies between 0.25% and 1.0% and $p$ is between 3.25 and 4.25.
FIGURE 1. Fit of Maxwellian+nonthermal Comptonization model to unfolded spectrum of Cygnus X-1 where $T_e = 65$ keV, $\tau_T = 2.45$, $\xi = 0.5\%$, and $p = 3.5$. Also plotted for comparison is a fit of the same model with no nonthermal electrons or pairs.

We remind the reader that this is a crude way to test a model since we are comparing to already unfolded data. However, by showing a reasonable match between our simulated spectra and the unfolded spectra, we can be confident that more a rigorous procedure would also work.

SUMMARY AND CAVEATS

We find that the X-ray/$\gamma$-ray spectra of the normal state of Cygnus X-1 can roughly be reproduced by Comptonization of 0.5 keV blackbody photons through a combination thermal-nonthermal plasma. For $T_e=65$ keV and the Thomson depth $\tau_T=2.45$, we determine that the fraction of nonthermal leptons $\xi = 0.5\%+0.5\%$ and the energy index of the nonthermal leptons $p = 3.5^{+0.75}_{-0.25}$.

While these results place first-order limits on the nonthermal lepton distribution, several modifications to these procedures would be necessary in order to reliably determine the allowed parameter space. The current Monte Carlo code does not require self-consistency between the lepton distribution and the radiative cooling. This obviously must be corrected to produce physically meaningful results. It is also necessary to generate a four-dimensional grid of simulated spectra to allow all four shape parameters to vary. This grid should also extend to lower values of $\xi$ and $p$ since our current grid does nec-
FIGURE 2. Confidence level contours in $\xi - p$ parameter space for fits of model to Cyg X-1 spectrum. Confidence levels are calculated from goodness-of-fit statistic $\chi^2$ assuming 11 degrees of freedom (14 data points - 3 fit parameters). See Press et al. 1993 for details.

essarily exclude solutions in this portion of the parameter space. Finally, any future work would require folding our simulated spectra through the detector responses to allow direct comparison with the $\gamma$-ray count data.

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