

Constraints on the Low-Energy Cutoff in the Electron Distribution of the PKS 0637–752 Jet

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ABSTRACT

We re-analyze the *Chandra* ACIS spectrum of the kpc-scale jet in PKS 0637–752 to investigate the possible low energy cutoff in the relativistic electron spectrum producing the non-thermal radiation in the scenario of inverse Compton emission off the cosmic microwave background. This was among the first objects targeted by the *Chandra* Observatory and gives a unique opportunity to study the low energy X-ray emission free of contamination. As previously reported in the literature, the spectrum can be fit by a power law, with the slope predicted by the radio spectrum, modified by low energy absorption through the Galaxy as determined from the spectrum of the quasar core and by HI 21 cm observations. We obtain a marginally better fit to the 0.3–7 keV spectrum with an model of inverse Compton emission produced by an electron population that exhibits a cutoff at $\gamma_{\min} (\Gamma_{10} \delta_{10})^{1/2}$ between about 50 and 80, depending on the model. If the bins between 0.3–0.55 keV are not included in the fit, the reduced bandpass of the spectrum lends itself to the placement of upper limits on γ_{\min} only. The observed optical flux can be used to constrain γ_{\min} from below; the constraint is not very strong, but does suggest that γ_{\min} must be higher than 1 to avoid overproducing the optical emission. We investigate the effect of uncertainties in the column density for galactic absorption as well as the calibration of *Chandra* for these early observations. Finally, we discuss the implication of these limits on the jet luminosity in this source.

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1. INTRODUCTION

The initial observations to focus *Chandra* using the presumed point source PKS 0637–752, a quasar at redshift 0.651 (Savage, Browne, & Bolton 1976), revealed a remarkable X-ray jet structure (Schwartz *et al.* 2000; Chartas *et al.* 2000), coincident with the radio jet reported by Tingay *et al.* (1998). Schwartz *et al.* (2000) pointed out that the X-ray emission could not be explained reasonably by thermal bremsstrahlung, by an extension of the radio synchrotron spectrum, by synchrotron self-Compton, or by inverse-Compton (IC) from any likely source of seed photons provided that the magnetic field was near its equipartition value. Nonetheless they concluded that IC from the same electrons producing the radio emission was the most likely source of the X-rays in view of the similarity of the X-ray and radio surface brightness profile.

Tavecchio *et al.* (2000) and Celotti, Ghisellini & Chiaberge (2001) solved the dilemma by invoking bulk relativistic motion of the 100 kpc scale jet. Relativistic motion with bulk Lorentz factor Γ has the effect of requiring a smaller magnetic field in the rest frame for minimum energy conditions, and of increasing the apparent energy density of the cosmic microwave background (CMB) by a factor of Γ^2 on average as seen by the radiating electrons. Such an IC/CMB explanation subsequently has been applied successfully to explain the X-ray emission from powerful quasar and FR II radio jets; e.g., by Sambruna *et al.* (2002); Harris & Krawczynski (2002); Siemiginowska *et al.* (2002, 2003); Sambruna *et al.* (2004); Marshall *et al.* (2005); Schwartz *et al.* (2006); Sambruna *et al.* (2006) and Schwartz (2007).

Tavecchio *et al.* (2000) pointed out that the scenario in which low energy electrons underwent Compton scattering on an external photon field gave an opportunity to infer parameters of the low energy portion of the relativistic electrons for the first time. They estimated $\gamma_{\min} \sim 10$ for the PKS 0637–752 jet, by constructing a fiducial spectral model which fit the broad band radio, optical and X-ray flux data. In the present work we perform a more rigorous assessment of γ_{\min} by performing a detailed spectral fitting of the ACIS X-ray spectrum and incorporating the optical flux measured by the *Hubble Space Telescope* (Schwartz *et al.* 2000). PKS 0637–752 is in the unique position among identified X-ray jet sources in that, because the exposures were done so early in the lifetime of *Chandra*, the low-energy X-ray spectrum is free of the contamination and associated loss of sensitivity that affect later observations. The main source of uncertainty remains the low-energy calibration of ACIS, and we contrast results obtained from a wider bandpass (0.3–7 keV) than is usually

used for imaging spectral analysis using *Chandra* with the equivalent results if the bandpass is restricted to the better-calibrated range of 0.55–7 keV.

Section 2 lists the observations and data reduction for this investigation. The development of the custom IC/CMB spectral models is detailed in Section 3, which are then applied to the data in Section 4 to derive limits on γ_{\min} . The interpretation of the model fits, including a comparison between two different prescriptions for the calculation of the IC/CMB spectrum and a discussion of the effect of the shape of the electron distribution at the γ_{\min} cut-off, is the topic of Section 5. Section 6 summarizes the paper.

2. OBSERVATIONS AND DATA REDUCTION

PKS 0637–752 was observed by *Chandra* using the ACIS-S instrument as part of the initial focusing period. This early in the mission, there was no loss of low-energy sensitivity due to the contamination layer. We thus have an opportunity with this object to push the X-ray spectrum to lower energies than is currently possible.

Table 1 lists the details of the *Chandra* observations that were used in this investigation, all of which were carried out in the FAINT TIMED mode of ACIS. We selected the observations based on whether the quasar and jet were positioned on the back-illuminated S3 chip, which excludes two observations (ObsID 1059 and 1061).

Other observations were discarded: ObsID 1057 and 62558 because the identification of the quasar and jet was unclear, and ObsID 1093, 1264, and 1265 since they do not appear to contain any useful data. Although most of the remaining observations were not at the best focus, the quasar and jet are clearly separated, and the jet spectrum can be extracted without contributions from the quasar core.

For each observation, the evt2 file was re-extracted from the evt1 file in order to apply the latest calibrations, as outlined in the ACIS data preparation thread on the CIAO web page (CALDB version 3.2.4). Since the observations were taken early in the mission, and the focal temperature was different from $-120\text{ }^{\circ}\text{C}$, no time-dependent gain or CTI correction was used.

Extraction regions for the jet and background were defined individually for each observation, since in some cases the departure from optimal focus necessitated a larger extraction region to include all events from the jet. The extraction regions were divided into an inner and outer jet, the first of which included the faint X-ray emission of the bridge between the quasar core and the bright radio/optical/X-ray knots, which comprised the second region.

The regions for one of the observations (ObsID 62554) are shown in Figure 1. No significant differences in the spectra between these two sub-regions were found, although the low number of counts in the bridge spectrum make a detailed comparison difficult. All subsequent fits used only the outer jet extraction region.

Using the CIAO tool `dmextract`, the counts in each observation’s source and background extraction regions were combined into pulse invariant (PI) channels to form the individual spectra. A grouping algorithm was applied to have a minimum of 2 counts per bin. Weighted ancillary response files (WARF) and redistribution matrices (WRMF) were created using the tools `mkwarf` and `mkrmf`, as appropriate for extended sources. (`mkacisrmf` does not apply for these observations due to their early observation dates.) To check for background flares, the light curve of the S3 chip excluding the region around the quasar and jet was analyzed visually and the few occurrences of spikes in the count rate filtered out in the extraction.

Because the results reported in this investigation depend heavily on the correct modeling of the low-energy response of `acis`, alternative calibration products were extracted to investigate the effect of uncertainties in the calibration (Grant, C. & Bautz, M., private communication). Sets of WARF and WRMF were constructed using -100°C and -120°C FEF files. In addition, for the -100°C FEF calibration products, the Quantum Efficiency Uniformity file was varied between the flat version N0001 and the version N0002 that includes information on how the quantum efficiency varies for the S3 chip. Results obtained from the different calibration products are included in the relevant section.

PKS 0637–752 was also observed by the *Hubble Space Telescope* (Schwartz *et al.* 2000). The area where the three optical knots are located corresponds morphologically to the extraction region used for the X-ray analysis. The total optical flux density from the knots is $0.574\mu\text{Jy}$ at a frequency of 4.3×10^{14} Hz.

3. IC/CMB MODEL IMPLEMENTATION

We wish to fit the spectrum for the jet with a model of inverse Compton scattering of energetic electrons on the CMB. We assume that the spectrum of the entire X-ray jet is emitted by a spatially homogeneous population of electrons that collectively exhibit a bulk motion with Lorentz factor $\Gamma = (1 - \beta^2)^{-1/2}$. The random motion of the electrons (assumed isotropic in the jet rest frame) is described by the distribution of the Lorentz factor γ , such that the energy of any given electron in the jet rest frame is $\gamma m_e c^2$ (m_e : electron rest mass, c : speed of light; primed quantities refer to the jet rest frame, unprimed to the observer frame; exception: γ , which always refers to the jet rest frame).

This distribution is modeled as a power law between γ_{\min} and γ_{\max} , with a slope s ($n'(\gamma) \propto \gamma^{-s}$). The upper end of the distribution is chosen as a sharp cutoff; since we note that the high energy cutoff is not reached in the X-ray spectrum, the exact functional form doesn't affect the analysis as long as γ_{\max} is chosen sufficiently high. The shape of the low-energy cutoff, however, has a direct effect on the model spectrum. We investigate two options: a step function at γ_{\min} and a constant electron density below γ_{\min} . Neither of them is likely to be the actual shape of the low-energy cutoff, but they (together with the case when γ_{\min} is sufficiently small as to move the cutoff outside of the spectrum bandpass) provide three representative cases for the characterization of the electron distribution based on the available X-ray data.

Photons emitted at an energy E'_1 in the rest frame of the jet are observed at an energy $E_1 = \delta E'_1 / (1 + z)$, where $\delta = [\Gamma(1 - \beta\mu)]^{-1}$ is the jet Doppler factor (with $\theta = \cos^{-1}\mu$ the observer viewing angle of the jet) and z is the redshift of the quasar. Since for the determination of γ_{\min} we are only interested in the shape of the spectrum, and not its normalization, the observed spectral flux $j(E_1)$ can be set equal to the emissivity $j'(E'_1 = E_1(1+z)/\delta, \mu')$. $\theta' = \cos^{-1}\mu'$ is the scattering angle in the jet rest frame; one simplification thus already incorporated in this formalism is that the direction of the scattered photon in the jet rest frame is the same as the incident electron. For the observed spectrum, μ' is related to μ and β through $\mu' = (\beta - \mu) / (1 - \beta\mu)$, when the incident photons in the jet rest frame are traveling in the opposite direction to the jet.

The CMB soft photon spectrum is assumed to be mono-energetic at a photon energy (in the jet rest frame) of

$$E'_0 = (1 + z) \Gamma \sigma k T_{\text{CMB}}, \quad (1)$$

where $\sigma = 2.7$ is the average photon energy of a thermal spectrum in units of kT (Felten & Morrison 1966), and $T_{\text{CMB}} = 2.725$ K is the local CMB temperature (Fixsen *et al.* 1996). The spectrum of inverse Compton scattering of a population of electrons (number density in the jet rest frame $n'(\gamma)$) off a mono-energetic population of photons can then be expressed as

$$j'(E'_1, \mu') \propto E'_1 \int_{\gamma_0}^{\gamma_{\max}} \frac{n'(\gamma)}{\gamma^2} f(E'_1, E'_0, \gamma, \mu') d\gamma. \quad (2)$$

$f(E'_1, E'_0, \gamma, \mu')$ is the kernel for inverse Compton scattering, describing the spectrum of photons emitted for a single scattering event, and is very complex to be calculated in the most general case. Under the assumption that $\Gamma = \delta$, which is usually assumed for jets

seen at small viewing angles (as is the case for PKS 0637–752), $\mu = \beta$, and thus $\mu' = 0$. Different additional simplifying assumptions lead to different functional forms; we wish to compare the predictions of two kernels, because both of them have been used extensively in the literature.

The Blumenthal & Gould (1970) calculation assumes an isotropic electron *and* seed photon field, which is strictly speaking not applicable to a jet moving relativistically with respect to the CMB rest frame. The kernel does not depend on μ' and can be expressed as a function of a single variable $x = E'_1/(4\gamma^2 E'_0)$:

$$f(E'_1, E'_0, \gamma) = 2x \ln x - 2x^2 + x + 1. \quad (3)$$

$\gamma \gg 1$ is assumed throughout. From kinematics, γ_0 , which is the Lorentz factor of the least-energetic electrons that can contribute to the emission at energy E'_1 , is derived as

$$\gamma_0 = \frac{1}{2} \sqrt{\frac{E'_1}{E'_0}}. \quad (4)$$

By contrast, the Aharonian & Atoyan (1981) treatment is appropriate for the case when the bulk Lorentz factor of the jet Γ is sufficiently high that the incident photon field (isotropic in the observer frame) can be considered mono-directional (specifically, anti-parallel to the jet bulk velocity) in the jet rest frame. Adopting the notation of Stawarz *et al.* (2005), the kernel, expressed using the quantities $v' = 2(1 - \mu') E'_0 \gamma / (m_e c^2)$ and $w' = E'_1 / (\gamma m_e c^2)$ is

$$f(E'_1, E'_0, \gamma, \mu') = 1 + \frac{w'^2}{2(1-w')} - \frac{2w'}{v'(1-w')} + \frac{2w'^2}{v'^2(1-w')^2}. \quad (5)$$

Again, the condition $\gamma \gg 1$ has to be satisfied. γ_0 with this kernel evaluates to

$$\gamma_0 = \frac{E'_1}{2m_e c^2} \left\{ 1 + \left(1 + \frac{2m_e^2 c^4}{(1 - \mu') E'_0 E'_1} \right)^{1/2} \right\}. \quad (6)$$

We proceed to implement custom XSPEC (Arnaud 1996) models that compute spectra based on the above formulas. The numerical integration is done using a modified version of the `qsimp` routine in Press *et al.* (1992). The two adjustable model parameters are s (the electron distribution power law index) and γ_{\min} . The additional parameters that are

not adjusted in the fit are γ_{\max} , δ , Γ , and z . γ_{\max} is kept fixed at 10^5 (corresponding to a high-energy cut-off around 850 MeV); $z = 0.651$.

Following Tavecchio *et al.* (2000) and Schwartz (2007), we assume $\Gamma = \delta = 10$, which sets $E'_0 = 1.05 \times 10^{-5}$ keV. From the δ -function approximation to the energy spectrum of a single inverse Compton scattering event, the location of any features in the IC/CMB spectrum scales as $(\Gamma \delta)^{-1/2}$. The same behavior is expected for the two kernels used in the models, although this was not investigated in detail. We will thus report all results for γ_{\min} with this scaling in mind.

It is worth noting that the custom IC/CMB models are computationally intensive, since they are relying on numerical integration to compute the model spectra. Many of the investigations done routinely within XSPEC, such as using `steppar` liberally to investigate the behavior of the fitting statistic as a function of one or more model parameters, are either not feasible or require a significant time to complete. We made sure that the best fits returned by XSPEC had converged to within reasonable tolerance, but the shape of the minimum in the fitting statistic was at most investigated with respect to one model parameter, most often γ_{\min} . The computing-intensive nature of the models also precludes an investigation of the effects of assuming that the incident CMB photon spectrum is mono-energetic, as the proper treatment that includes the blackbody shape of the CMB spectrum would require two numerical integrations.

4. RESULTS

Given that each individual spectrum has only a small number of counts over the bandpass of interest and was therefore grouped to have a minimum of only two counts per channel, χ^2 is not appropriate as a fitting statistic. Instead, the C-statistic implemented in XSPEC was used. Unfortunately, this statistic does not allow for a goodness-of-fit test, in the way the reduced χ^2 is commonly used. However, a visual inspection of the fits reveals a very good agreement between the data and the model. In any case, the important discriminant will be the changes in the fitting statistic with the model parameters as well as between models.

All subsequent results use a simultaneous fit to all 21 individual spectra, keeping one model normalization for all spectra. We also report all results for both the 0.3–7 keV and 0.55–7 keV bandpass. The calibration of *Chandra* at low energies has always been somewhat uncertain, and it is likely that not enough calibration products are available for the period of observations before the loss of low-energy sensitivity to significantly improve the calibration of the early *Chandra* observations.

Insofar as the phenomenological fits to the full 0.3–7 keV bandpass return results consistent with other investigations, we believe that the calibration products generated with the CIAO tools are adequate for the low signal-to-noise spectra obtained for this source. We used the alternative calibration files generated in Section 2 to constrain the magnitude of the systematic uncertainties on our results expected from calibration. Specifically, the fits to the power law model (Section 4.1) and to the IC/CMB model with the Blumenthal & Gould (1970) kernel and sharp cutoff in the electron distribution (Section 4.2) were repeated with each of the calibration files. Even though the low-energy response is slightly different in each of the cases, the parameters for the best fits for both the power law model and the IC/CMB model are the same to within uncertainties, and there is furthermore no significant change in the behavior of the fitting statistic as a function of γ_{\min} , such that the same statistical limits are obtained as for the nominal calibration products. We believe, but have not investigated, that the results for the untested cases that have not been included in the tests are equally unaffected. Therefore, even though we are not able to place a quantitative measure on the amount of systematic uncertainty expected from variations in the calibration, the expected uncertainty is smaller than the differences in the limits on γ_{\min} introduced by the choice of IC/CMB model and shape of the electron distribution.

The 0.55–7 keV bandpass is much better calibrated and should serve as an additional comparison to the more uncertain results from the wider bandpass. We also found that the effective area calculated for the calibration files for the individual spectra vary widely below 0.55 keV, but are consistent to within about 10% above that energy. (The effective area for each individual observation seems to be appropriate for that observation, however, since no significant residuals are found in the fits at low energies.) It is possible that the differences in effective area are caused by the varying position of the source on the CCD chip; however, the good agreement above 0.55 keV strengthen the reliability of the results obtained for the restricted bandpass.

4.1. Phenomenological Fits

We first fit the spectra in the 0.3–7 keV bandpass with a single power law, modified by neutral Galactic absorption. If n_{H} is allowed to be free, a best-fit value of $(9.1 \pm 0.8) \times 10^{20} \text{ cm}^{-2}$ is returned, and the best-fitting power law energy index is $\alpha = 0.76 \pm 0.04$. These values correspond very well with the expected values: the absorbing column with the value reported by Dickey & Lockman (1990) ($9.1 \times 10^{20} \text{ cm}^{-2}$), and the power law index with both the results from earlier investigations of the *Chandra* spectrum of this source (Chartas *et al.* 2000, $\alpha = 0.85 \pm 0.08$,) and the radio spectral index (Schwartz *et al.* 2000). The same power

law index (to within uncertainties) is obtained by fixing $n_{\text{H}} = 9.1 \times 10^{20} \text{ cm}^{-2}$ before fitting. The best-fit C-statistic value is 886.3 for 958 bins.

In the restricted 0.55–7 keV bandpass, the fit with both the power law index and the absorbing column free returns $n_{\text{H}} = 3.0 \times 10^{20} \text{ cm}^{-2}$ (with large uncertainties) and $\alpha = 0.63 \pm 0.05$. The C-statistic at the minimum is 808.2 for 860 bins, but it is clear that the low value for the absorption and the resulting fit is spurious, as the restricted bandpass is not very sensitive to the absorption column density. If $n_{\text{H}} = 9.1 \times 10^{20} \text{ cm}^{-2}$ is fixed before fitting, the power law index increases to $\alpha = 0.84 \pm 0.02$, once more consistent with previous values. The minimum value of the fitting statistic is 817.2 for 860 bins. In all subsequent fits, the absorbing column is kept fixed at the Galactic value.

The normalization of the power law component (before absorption) is in all cases equal to about $(3.1 \pm 0.5) \times 10^{-5} \text{ photons/cm}^2/\text{s/keV}$, corresponding to a flux density of $(21 \pm 3) \text{ nJy}$ at 1 keV. This is slightly smaller than, but probably within 1σ of, previous measurements (Schwartz *et al.* 2000), which could be due to differences in the extraction region or the background subtraction.

4.2. IC/CMB Model Fits

4.2.1. Upper Limit on γ_{min} from X-ray Spectrum

We now wish to investigate whether a better fit can be obtained by letting the IC/CMB spectrum cut off before the low-energy end of the bandpass under consideration. It is expected that if $\gamma_{\text{min}} (\Gamma_{10} \delta_{10})^{1/2} \lesssim 40$ ($\Gamma_{10} = \Gamma/10$, $\delta_{10} = \delta/10$), the cutoff will be too low in energy to affect the 0.3–7 keV bandpass; obviously, this limiting value of γ_{min} will be higher for the 0.55–7 keV bandpass.

We proceed to fit the spectra with the custom IC/CMB models developed in Section 3. For the 0.3–7 keV bandpass, the best fit for both the Blumenthal & Gould (1970) and the Aharonian & Atoyan (1981) kernel, and for both the sharp cutoff in the electron distribution or the flat segment case (cases (1) and (2) in Figure 4), is such that the best-fitting γ_{min} is above the limiting value. In fact, plotting the fitting statistic as a function of γ_{min} leads to Figure 2, which shows that a cutoff due to γ_{min} appears to be detected about 2σ statistical confidence for two of the four cases. Note that the differences in C-statistic values are equivalent to differences in χ^2 , such that the same $\Delta\chi^2$ values may be used to determine the confidence regions of fitted parameters.

The best-fit values of the fitting statistic and the constraints that we are able to place

on γ_{\min} are shown in Table 2. In all cases, the fit is as good as the unbroken power law fit or better. The y-axis in Figure 2 is normalized to have a $\Delta(\text{C-statistic})$ of 0 for the best fit. We expect the previous fit to the unbroken power law to be recovered by pushing γ_{\min} below the limiting value. In detail, the IC/CMB models do not revert exactly to a power law even if γ_{\min} is very low; furthermore, slight differences in the value of the fitting statistic are expected near the minimum, given the minimization algorithm employed by XSPEC. The limiting value of the fitting statistic as $\gamma_{\min} \rightarrow 1$ can therefore be slightly different from the value obtained for the unbroken power law fit above.

The power law index for the electron distribution is returned in all four cases as $s = 2.6 \pm 0.1$, consistent with the measurement of the energy index measured for the power law fit ($\alpha = (s - 1)/2$). The index is systematically lower for the case of the flat electron distribution, but the difference to the index for the sharp cutoff in the electron distribution is not statistically significant. There is almost no degeneracy between the power law index and γ_{\min} .

As expected, restricting the analysis to the 0.55–7 keV bandpass eliminates the minimum in the fitting statistic, and only upper limits on γ_{\min} are obtained. The behavior of the fitting statistic as a function of γ_{\min} for the restricted bandpass is shown in Figure 3. Again, the relevant data on the best fits and on the γ_{\min} constraints are included in Table 2.

It is worth noting that, contrary to expectations, the upper limits on γ_{\min} from the restricted bandpass are as tight as from the full 0.3–7 keV bandpass. The reason for this might be that the residuals to the fit in the restricted bandpass favor an unbroken power law down to the lowest bins and are very sensitive to changes in the shape at the low-energy end, while the residuals in the bins between 0.3–0.55 keV are more ambivalent about the shape of the model in that range.

4.2.2. Lower Limit on γ_{\min} from Optical Flux Measurement

Figure 4 shows the optical and X-ray measurements of PKS 0637–752 as well as the predicted IC/CMB spectra based on $\gamma_{\min} (\Gamma_{10} \delta_{10})^{1/2} = 60$ and the best-fit value of the power law index $s = 2.6$. As γ_{\min} becomes smaller, the low-energy extension of the model fitted to the X-ray observations will approach and at some point over-predict the observed optical flux (Schwartz *et al.* 2000). This gives us an opportunity to place lower limits on γ_{\min} .

The sum of the individual knots’ optical flux density is $0.574 \mu\text{Jy}$, and we estimate a conservative error on that measurement of $0.1 \mu\text{Jy}$. The observed X-ray flux density at 1

keV is (21 ± 3) nJy. The ratio of optical to X-ray flux densities thus evaluates to 29.0 ± 9.7 .

The IC/CMB models developed in the previous section were adapted to return the ratio of optical to X-ray flux as a function of γ_{\min} . The effect of the uncertainty on the power law index measurement was included by always calculating the minimum ratio over the confidence region of the power law index. The calculation of the ratio in the case of the flat electron distribution below γ_{\min} requires the caveat that the assumption $\gamma \gg 1$ is violated, as $\gamma_0 \sim 3$ for energies corresponding to the optical data point.

In all cases, the ratio is monotonically increasing with decreasing γ_{\min} as long as the departure from power law behavior occurs at an energy below the reference X-ray energy, i.e. when $\gamma_{\min} (\Gamma_{10} \delta_{10})^{1/2} \lesssim 75$ as determined by the spectral investigation above. For $\gamma_{\min} (\Gamma_{10} \delta_{10})^{1/2} = 50$, the ratio evaluates to less than 10 and is safely below the observed ratios quoted above. Lower limits on γ_{\min} are thus obtained by inverting the optical/X-ray ratio vs. γ_{\min} relation and reading off γ_{\min} at the appropriate statistical upper limits on the ratio. The lower limits on γ_{\min} thus obtained will actually underestimate the true lower limits, since the two-sided errors on the optical to X-ray flux ratio, and not the one-sided upper limits, are used.

Table 3 summarizes the lower limits on γ_{\min} thus obtained. Note that at 99% confidence, the lower limit in all cases relaxes to the minimum possible value for γ_{\min} of 1.

5. DISCUSSION

Tables 2 and 3 summarize the constraints on γ_{\min} that we are able to place. If the full bandpass of 0.3–7 keV is used, marginal evidence for a break in the spectrum at around $\gamma_{\min} (\Gamma_{10} \delta_{10})^{1/2} = 40$ –55 emerges, depending on the model for the electron distribution and the kernel for inverse Compton scattering. Given the uncertainties with the low-energy calibration of *Chandra*, the bins below 0.55 keV might want to be excluded from analysis, in which case only upper limits can be placed on γ_{\min} from the X-ray spectrum alone, to wit $\gamma_{\min} (\Gamma_{10} \delta_{10})^{1/2} \lesssim 80$, again depending on the choice of model.

In the detected minimum of the fitting statistic with respect to γ_{\min} , the column of Galactic absorption would need to be increased to about $1.4 \times 10^{21} \text{ cm}^{-2}$ (an increase of over 50%) to mask the minimum and have the fitting statistic increase monotonically with γ_{\min} . The behavior of n_{H} in the vicinity of PKS 0637–752 was investigated by visually inspecting the IRAS 100 μm map (Wheelock *et al.* 1994). No evidence for any Galactic molecular clouds was found that would average out in the large-beam radio surveys resulting in a spurious high value for n_{H} reported in Dickey & Lockman (1990). Their value for n_{H} is about 15% higher

than the one reported from the Leiden/Argentine/Bonn Survey of Galactic HI (Kalberla *et al.* 2005).

In Figure 4, it can be seen that, for the same value of γ_{\min} , the point at which the spectrum deviates from power law shape is at a lower energy for the Aharonian & Atoyan (1981) kernel for inverse Compton scattering compared to the Blumenthal & Gould (1970) kernel, by about a factor of 3. This results in tighter lower limits on γ_{\min} for the Aharonian & Atoyan (1981) kernel, but correspondingly less-strict upper limits.

The Aharonian & Atoyan (1981) kernel is the more appropriate one for the situation of a jet moving relativistically through a homogeneous and isotropic distribution of seed photons, as is the case for the cosmic microwave background. The comparison to the other kernel can serve to illustrate the order of magnitude of the uncertainty introduced by the choice of the inverse Compton scattering formalism.

We only investigate two possible shapes of the cutoff at γ_{\min} : a sharp cutoff such that there are no electrons below γ_{\min} (case 1 in Figure 4), and an electron distribution that has a constant density below γ_{\min} (case 2 in the same figure). The real shape of the cutoff is likely to be more complicated than in either of these models, but these two distributions bracket the range of expected real distributions, where the cutoff is probably less sharp than in case 1, but the electron distribution does cut off more quickly than to a constant distribution below γ_{\min} . As expected, if the cutoff is sharp, the fitting statistic increases rapidly as γ_{\min} increases, while the increase is slower for the case of the flat distribution below γ_{\min} , since the X-ray spectrum in this case exhibits a correspondingly milder cutoff.

The finding that $\gamma_{\min} (\Gamma_{10} \delta_{10})^{1/2} \lesssim 80$ has notable consequences. The radio spectrum is expected to extend unbroken down past 2 MHz and into the hundreds of kHz, for the estimated jet rest-frame magnetic field $B = 10\mu\text{G}$, which is close to the equipartition value for the assumed γ_{\min} and δ (Schwartz 2007). Furthermore, the possibility that γ_{\min} is in fact as high as 50 leads to a relaxation of the total power requirement for this jet. Tavecchio *et al.* (2000) reported a total kinetic power of the PKS 0637–752 jet of $L = 3 \times 10^{48} \text{ erg s}^{-1}$ for $\gamma_{\min} = 10$, which requires PKS 0637–752 to be among the more powerful jet sources.

If $\gamma_{\min} = 50$ instead of 10, the electron energy density in the jet is reduced by a factor of 2.6, while their number density drops by a factor of 13. Assuming a jet composed of only hot electrons and cold protons, and preserving charge neutrality, the dominant reduction in the overall jet kinetic power results from the reduction in the number density of protons. The overall factor evaluates to 12, meaning that the jet might exhibit a kinetic power as small as $2.5 \times 10^{47} \text{ erg s}^{-1}$.

The limits on γ_{\min} are particularly interesting with respect to the question about the

composition of the jet and the mechanism for the emission resulting in high-contrast knots and inter-knot regions. For the adopted jet angle with respect to the line of sight of 6.4° , the deprojected length of the X-ray jet is on the order of 900 kpc. With the estimated magnetic field strength of $10 \mu\text{G}$, the cooling time (taking both IC/CMB and synchrotron losses into account) for electrons with $\gamma \lesssim 8,500$ is larger than the travel time along the jet (Equation D1 in Stawarz *et al.* 2004). It would be possible therefore to produce these electrons in the central core of this source and propagate them at the bulk velocity to the sites of X-ray emission. Higher energy electrons, on the other hand, would have had to be accelerated locally in the jet.

There are several problems with this interpretation, though. There is little reason to expect that the energy density in the centrally produced electrons matches onto the spectrum of the locally accelerated electrons, such that the two populations combine to produce an X-ray spectrum without an observable jump in intensity at some cross-over energy. Also, the high inner-jet-to-knots contrast argues against the presence of a significant number of electrons with γ -factors in the range of hundreds to thousands, as they would radiate in the observed X-ray band via IC/CMB all along the jet.

If all the electrons that are responsible for the knots are produced locally in the jet, the morphology of the X-ray emission might then be expected to show evidence of a cooling population, such that the spectrum should soften with increasing distance along the jet after the onset of the knot emission. The observations on this source are however not good enough to investigate a spatially resolved X-ray spectrum.

6. CONCLUSION

As far as we are aware, this work represents the first attempt at placing confidence limits on the low-energy electron distribution cutoff in a jet based on a fit to its X-ray spectrum. Usually, papers investigating the broad-band spectra of jet sources simply quote a value for γ_{min} that happens to make the model pass through the measured data points. It is very hard to conduct observations in the radio that are able to constrain γ_{min} (Gopal-Krishna, Biermann & Wiita 2004), especially for the kpc-scale jets where the Doppler factor becomes too low to make the cutoff accessible above the synchrotron self-absorption frequency. Thus, the soft X-ray spectrum as well as any measured optical fluxes are the best tools to shed light on the behavior of the low-energy end of the electron distribution.

We find that $\gamma_{\text{min}} (\Gamma_{10} \delta_{10})^{1/2} \lesssim 80$, which is significantly higher than the value of 10–20 usually assumed in energetics modeling of this source. The kinetic power requirement is

therefore lessened, but the questions of jet composition and X-ray emission mechanism are not addressed conclusively with this finding.

The present work did not consider other proposed emission mechanisms for the X-ray spectrum, such as direct synchrotron or synchrotron self-Compton. Based on the above considerations, however, IC/CMB remains a viable model for the X-ray emission in PKS 0637–752.

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Table 1. *Chandra* ACIS-S Observations of PKS 0637–752 Used in this Investigation^a

ObsID	Exposure Time (ks)	ObsID	Exposure Time (ks)
472	5.52	1062	0.62
473	3.54	1063	1.22
474	4.64	62549	6.25
475	4.64	62550	5.20
476	2.39	62551	5.32
1051	1.02	62552	5.07
1052	1.02	62553	4.88
1055	2.01	62554	11.22
1056	1.73	62555	4.91
1058	1.51	62556	4.84
1060	0.62	Total	78.20

^aMore information on the individual observations is available in Table 1 of Chartas *et al.* (2000).

Table 2. Constraints on γ_{\min} Obtained from the X-ray Spectrum

X-ray bandpass	IC/CMB kernel ^a or power law model	e ⁻ distr. ^b	best-fit C-statistic	$\gamma_{\min} (\Gamma_{10} \delta_{10})^{1/2}$ (1 σ)	$\gamma_{\min} (\Gamma_{10} \delta_{10})^{1/2}$ (99%)
0.3–7 keV	power law	...	886.3		
	BluGou	case (1)	879.4	49 \pm 2	49 \pm 6
		case (2)	881.5	57 \pm 4	< 67
	AhaAto	case (1)	881.8	63 \pm 2	< 67
		case (2)	880.2	72 \pm 3	72 \pm 10
0.55–7 keV	power law	...	817.2		
	BluGou	case (1)	818.6	< 50	< 54
		case (2)	817.2	< 55	< 63
	AhaAto	case (1)	817.3	< 67	< 70
		case (2)	817.3	< 73	< 79

^aBluGou = Blumenthal & Gould (1970), AhaAto = Aharonian & Atoyan (1981)

^bCases (1) and (2) refer to the different electron distributions in Figure 4.

Table 3. Lower Limits on γ_{\min} Obtained from Optical and X-ray Flux Measurement

IC/CMB kernel ^a	e ⁻ distr. ^b	$\gamma_{\min} (\Gamma_{10} \delta_{10})^{1/2}$ (1 σ)	$\gamma_{\min} (\Gamma_{10} \delta_{10})^{1/2}$ (99%)
BluGou	case (1)	> 4.2	> 1
	case (2)	> 6.1	> 1
AhaAto	case (1)	> 4.8	> 1
	case (2)	> 7.7	> 1

^aBluGou = Blumenthal & Gould (1970), AhaAto = Aharonian & Atoyan (1981)

^bCases (1) and (2) refer to the different electron distributions in Figure 4.

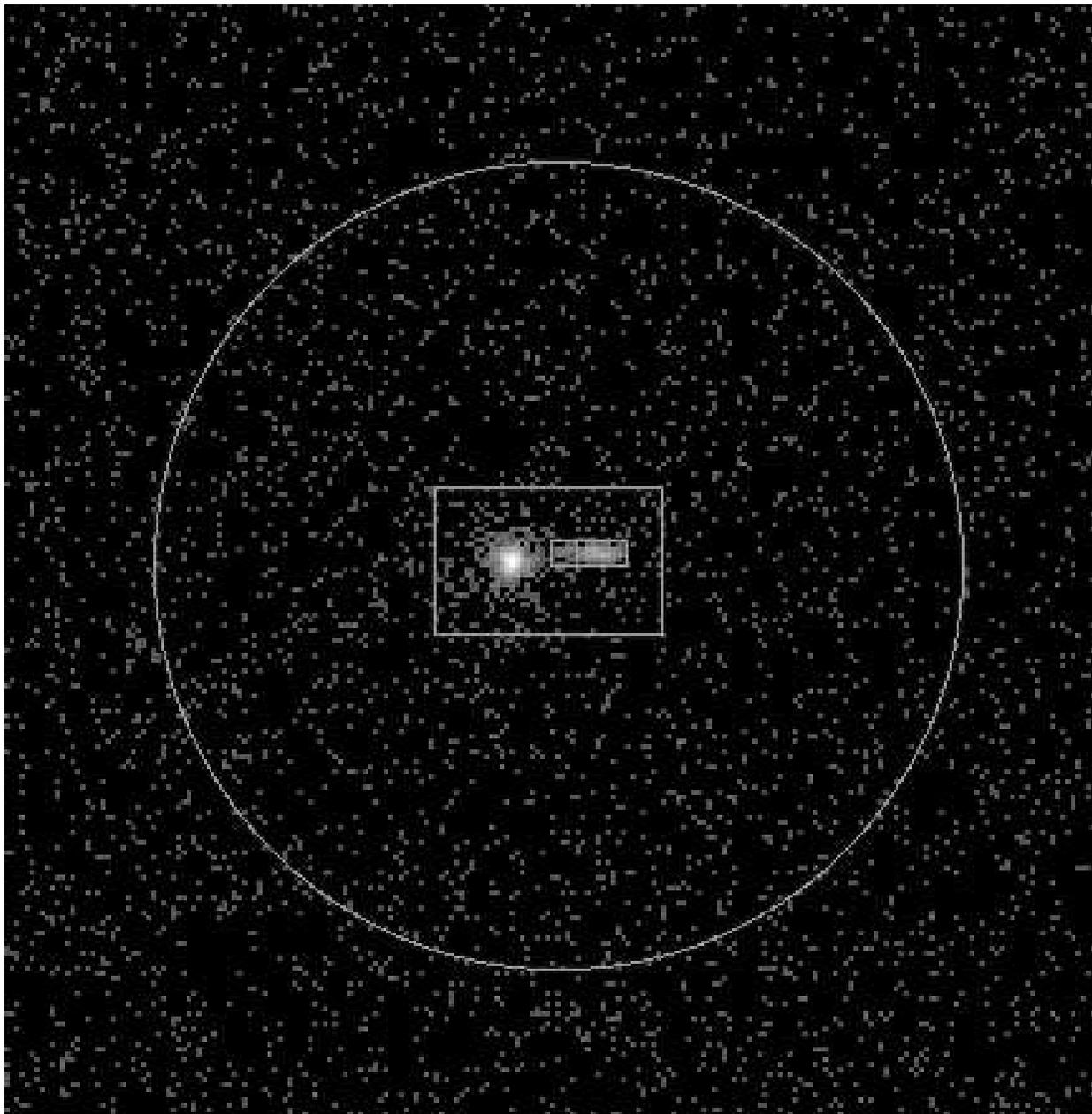


Fig. 1.— Extraction regions superimposed on one of the exposures of PKS 0637–752 (ObsID 62554). The inner and outer jet regions are the two rectangular regions straddling the jet; the background was extracted from the elliptical region while excluding the counts from within the larger rectangular box. These extraction regions are representative of the regions used for all observations; however, the change in focus for some of them necessitated larger boxes for the inner and outer jet, which were then chosen to again just straddle the image of the jet.

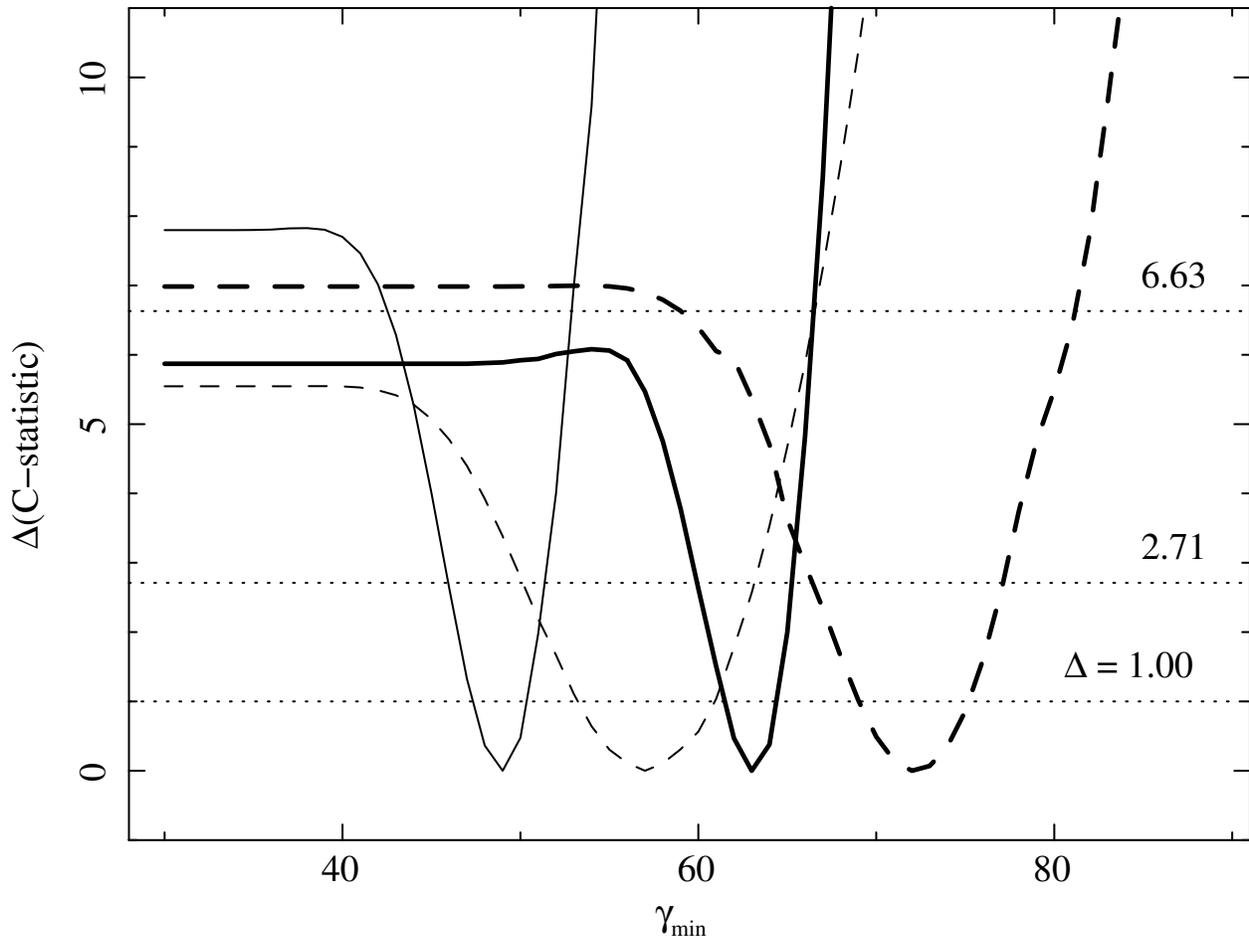


Fig. 2.— Confidence limits on γ_{\min} for the IC/CMB model fits, obtained from the 0.3–7 keV X-ray spectrum. The bold lines are for the Aharonian & Atoyan (1981) kernel, the thin lines for the Blumenthal & Gould (1970) kernel. In both cases, the solid line is for the electron distribution with the sharp cutoff at γ_{\min} (case (1) in Figure 4), and the dashed line for the constant segment below γ_{\min} (case (2) in Figure 4). The three dotted lines mark the $\Delta(\text{C-statistic}) = 1.00$, 2.71 and 6.63 levels corresponding to the 68.3, 90 and 99% two-sided confidence limits on γ_{\min} .

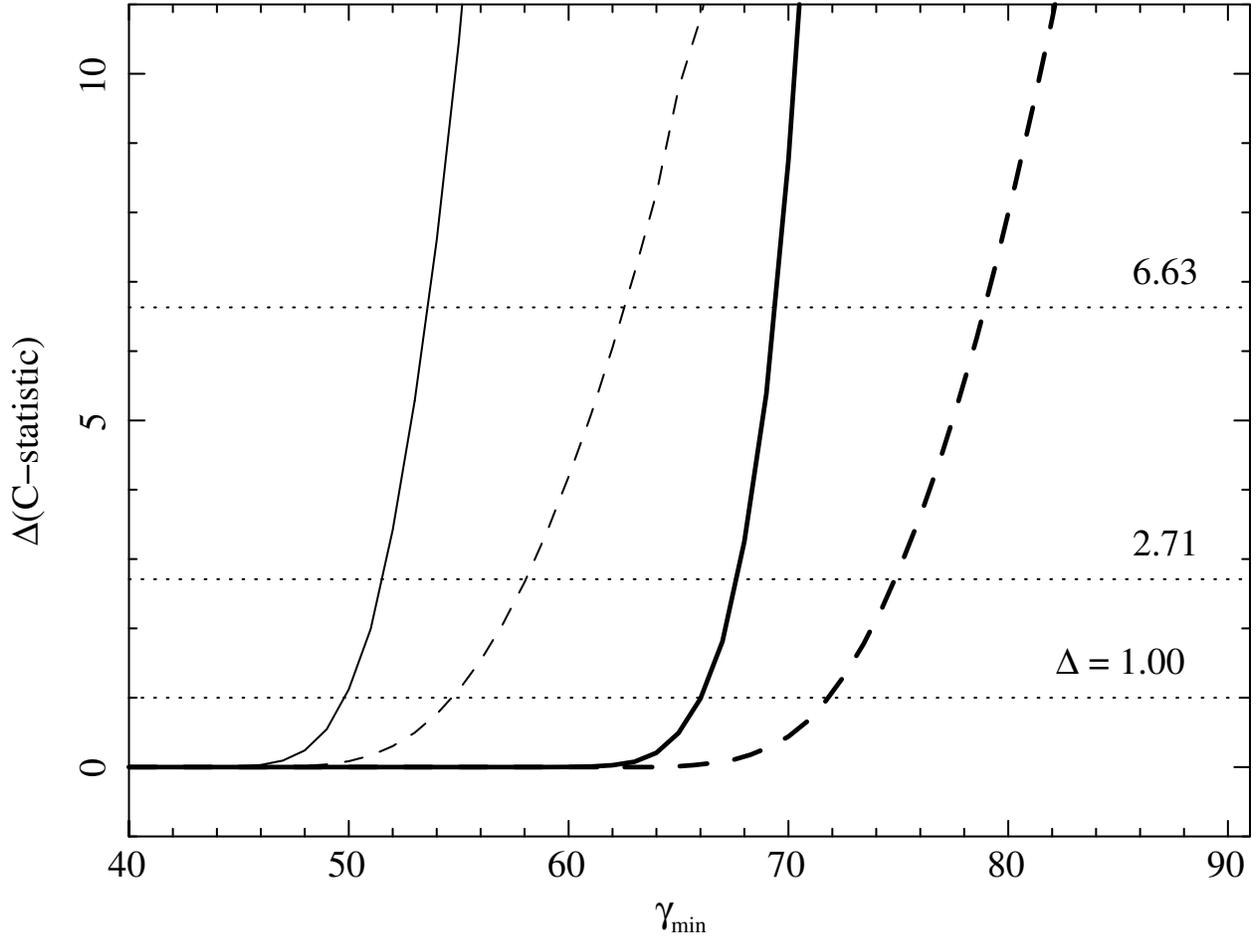


Fig. 3.— Confidence limits on γ_{\min} for the IC/CMB model fits, obtained from the X-ray spectrum using the restricted 0.55–7 keV bandpass. The same conventions as for Figure 2 apply.

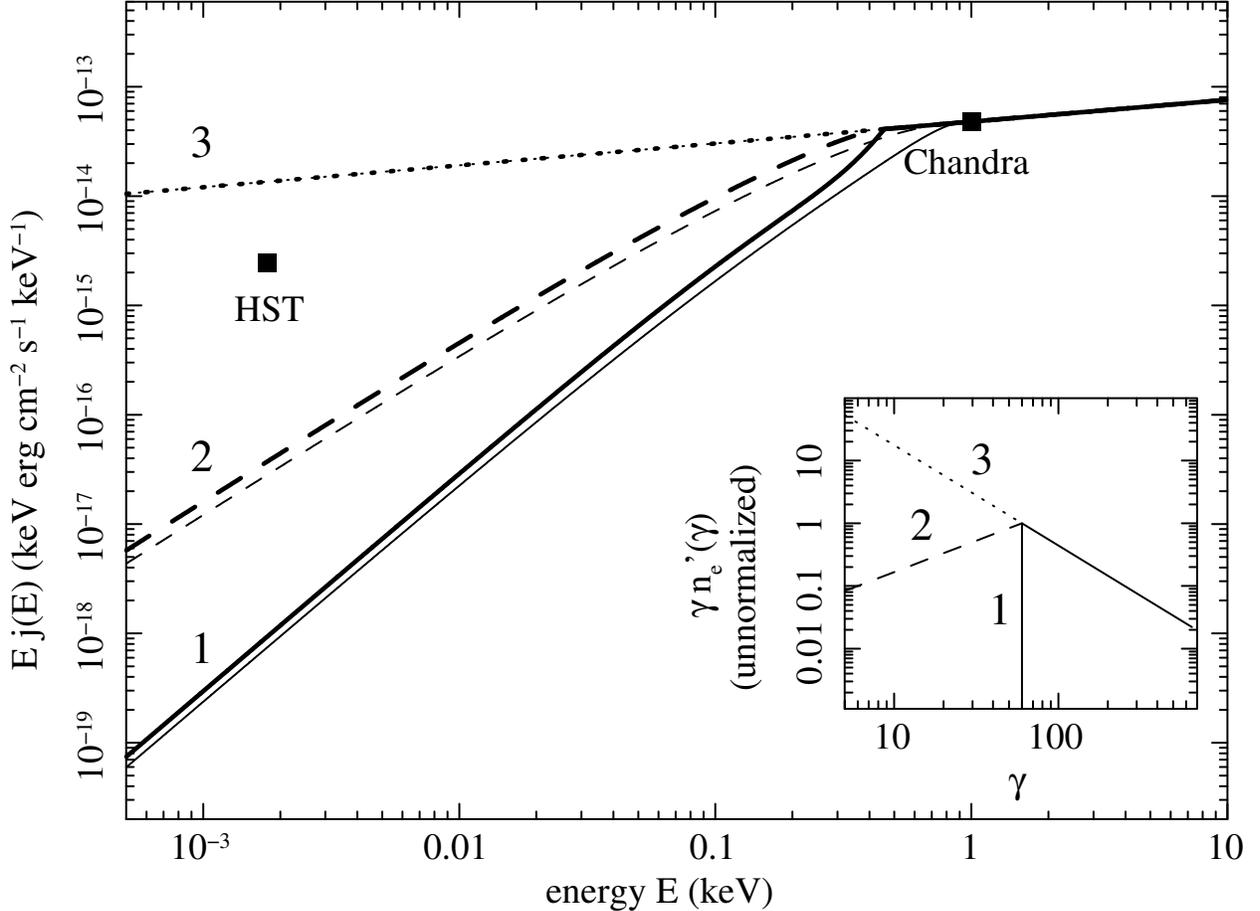


Fig. 4.— Predicted flux of the CMB inverse Compton models developed in Section 3. The adjustable parameters are set to $\gamma_{\min} = 60$ and $s = 2.6$. The inset plot shows the selected electron density distributions, which are all described as a power law with slope s above γ_{\min} . Note that the normalization of the y axis is arbitrary. The two cases with a modification of the spectrum at γ_{\min} are characterized by either the step-function cutoff at γ_{\min} (1) or the constant density below γ_{\min} (2). Case 3 results when γ_{\min} is chosen sufficiently low such that the cutoff in the photon spectrum moves outside its bandpass. The spectra based on the Aharonian & Atoyan (1981) kernel are shown as bold lines, the ones based on the Blumenthal & Gould (1970) kernel as thin lines. The spectra for the two models coincide for case (3). Both sets of spectra have been normalized to the observed X-ray flux. The optical data point is also plotted and is violated by the models without a cutoff in the electron distribution. The allowable range of γ_{\min} , such that the cutoff occurs below the X-ray data point, and the optical flux from the IC/CMB model does not over-predict the optical detection, is approximately 5–80.