Toward a Handle on the Low-energy End of the Electron Distribution in Large-scale Jets: The Case of PKS 0637-752

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Motivation: Unknown Behavior of the Electron Distribution at Low Energies

The Uniqueness of the Chandra observations of PKS 0637-752:
PKS 0637-752 is a z = 0.651 quasar with a prominent radio/optical/IR/X-ray jet and was observed by Chandra as part of the initial focusing period (Schwartz et al. 2000). This early in the mission, there was no loss of sensitivity in the soft X-ray band due to contamination of the optical blocking filter or the CCDs. We thus have an opportunity with this object to potentially push the X-ray spectrum to lower energies than is possible for other large-scale jets that were observed later. A big caveat is the lack of good calibrations for the soft X-ray band for early observations taken at a focal plane temperature different from the current -120°C.

Broad-band spectra of large-scale jets:
Investigations of large-scale jets reveal power law spectra in both the radio and X-ray, with the optical and IR flux (if measured) falling below the line connecting the radio and X-ray flux points. In the scenario of the X-ray emission being produced by inverse Compton scattering of energetic electrons on the cosmic microwave background (IC/CMB), the same electron population is also responsible for the radio to optical emission and therefore needs to be cut off both at the high end, so as not to overproduce the optical emission, and the low end, to keep the synchrotron component dominant over the IC/CMB component at optical frequencies.

Motivation: (cont.)

Broad-band spectra of large-scale jets: (cont.)
For PKS 0637-752, the high-energy cutoff needs to be around $\gamma_{max} = 4\times10^5$ (Chartas et al. 2000, Tavecchio et al. 2000). In this work, we are interested in placing limits on the low-energy cutoff γ_{min}.

Constraining the low-energy cutoff in PKS 0637-752:
Investigations into the low-energy cutoff using the broad-band spectrum cannot make use of the radio synchrotron component, as the frequency at which deviations from power law shape are expected to occur is too low to permit observations. Instead, limits on γ_{min} have to be found using optical and X-ray measurements. (Tavecchio et al. 2000, Uchiyama et al. 2005)

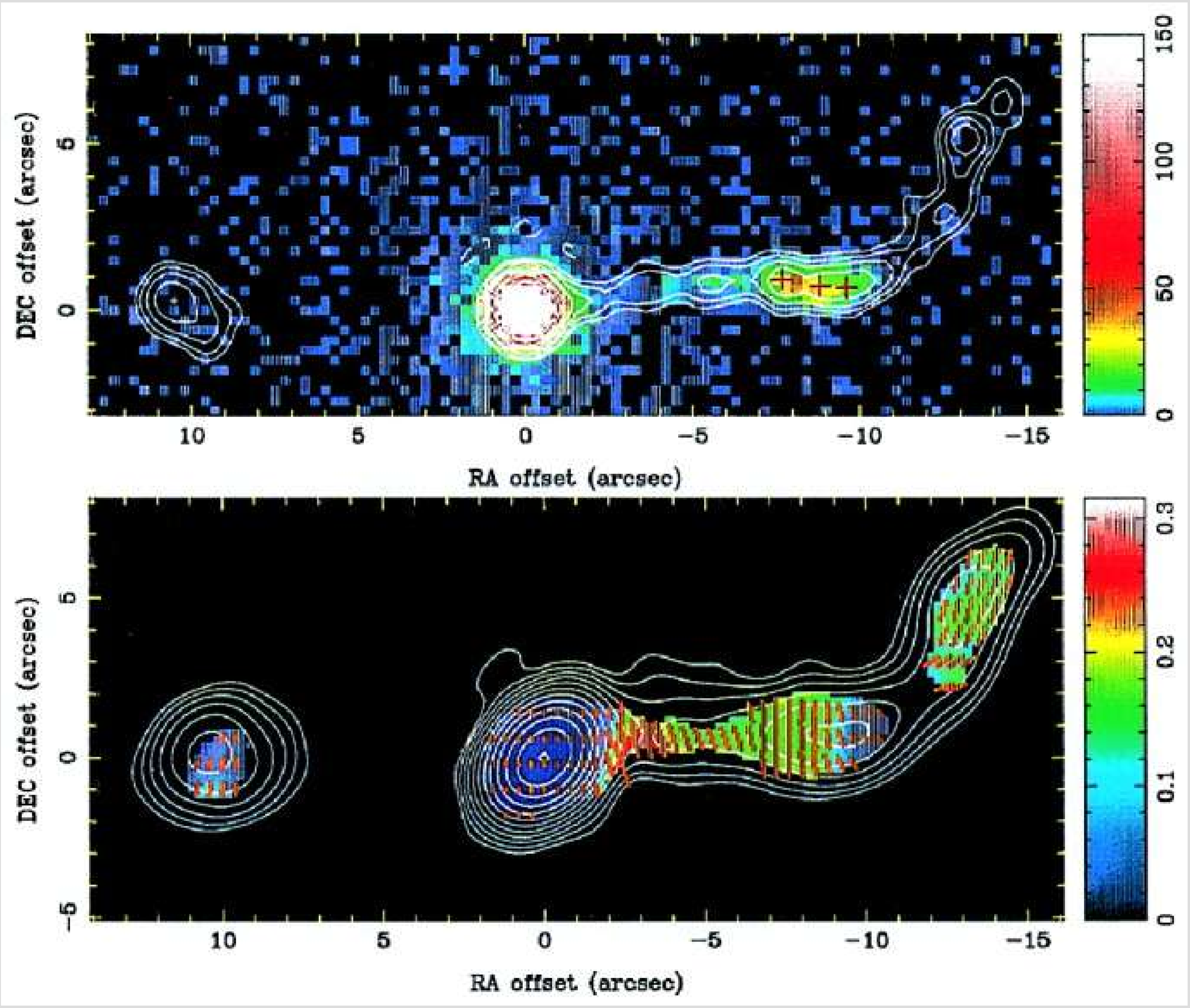
γ_{min} cannot be too low, because the optical flux measurement would then be violated by the IC/CMB component. γ_{min} cannot be too high, either, since, as γ_{min} increases, the departure from power law shape moves into the soft X-ray band accessible to current instruments like Chandra, which would change both the observed radio to X-ray flux ratio and the X-ray power law index (which agrees with the radio spectral index).

Motivation: (cont.)

Problems with earlier reported results on PKS 0637-752:
Lacking in these earlier measurements of γ_{min} is a discussion of the statistical significance of the quoted range. Also, the IC/CMB model used is most likely a δ-function approximation to the spectrum of a single scattering between an electron and a photon—this leads to incorrect limits, as the low-energy behavior of the IC/CMB component is modified once the proper kinematic treatment is introduced. In our investigation, we intend to do a much more careful study of γ_{min}, reporting on both the approximations that went into the IC/CMB model used in our case and the statistical significance of the limits we're able to place on γ_{min}.

Different approach to placing an upper limit on γ_{min}:
A different way to derive an upper limit on γ_{min} is to fit the low-energy end of the X-ray spectrum (instead of simply using the X-ray flux measurement) to constrain the presence of a cutoff due to γ_{min}. Depending on how far into the soft X-ray band we are able to push the spectrum, this should allow us to place the best-possible upper limit on γ_{min}.

It will also permit us to constrain the presence of additional emission components that are sometimes proposed to exist in the observationally inaccessible region in the electromagnetic spectrum between optical and soft X-rays. Specifically, in the scenario of knot formation due to internal shocks in the jet, the bulk of the electrons could be present in the form of a mildly relativistic, quasi-thermal distribution (γ factors of a few), which would give rise to an additional IC/CMB component at UV energies whose high-energy tail might be detectable with Chandra.



Schwartz et al. 2000

Data Reduction

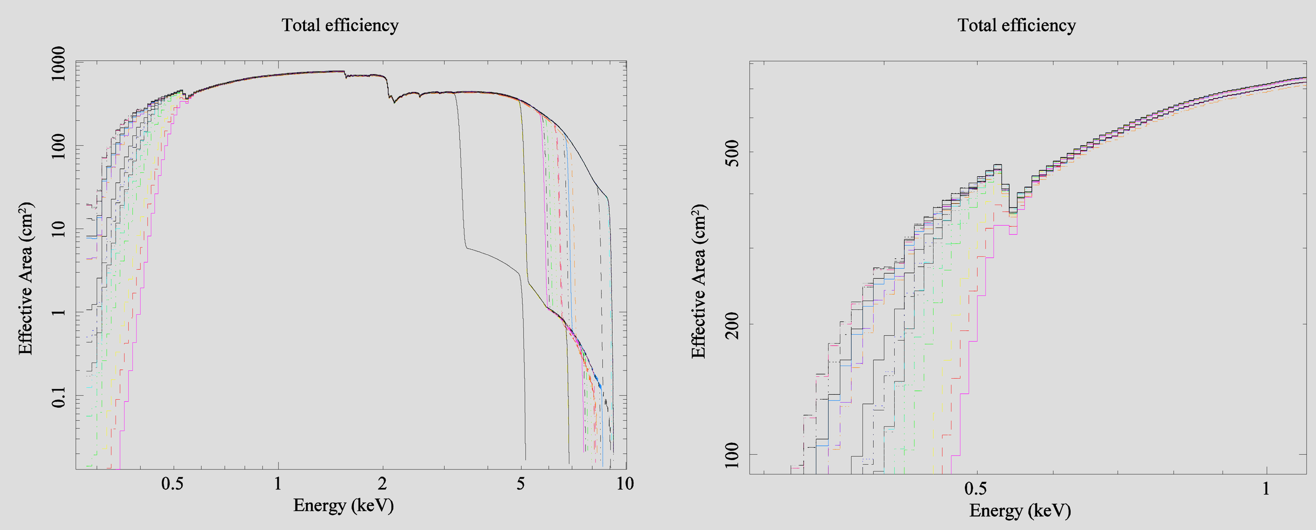
- 21 observations of PKS 0637-752 with the source on the ACIS S-3 chip, adding up to about 78ks, observation dates between August 14–20, 1999
- evt2 event file recreated from the evt1 file to pick up newer calibrations (CIAO 3.3/CALDB 3.2.4) than original pipeline processing (no changes expected with CIAO 3.4/CALDB 3.4.1)
- CTI and time-dependent gain adjustments do not apply
- source and background spectra of the jet in the individual observations extracted using dmextract
- RMFs and ARFs constructed using mkwarf and mkrmf (the latter using the FEF weights output by mkwarf)
- simultaneous fits to all individual spectra in Xspec, checking agreement between chi-squared and C statistic (low number of counts per bin)

Calibration of Chandra ACIS low-energy response:
There is significant concern that the calibrations of the early observations (at a focal plane temperature of -100°C, not at the current setting of -120°C) might introduce uncertainties into the spectral analysis below 1 keV. As a first step, therefore, we limited our analysis to between 1–7 keV.

It is highly desirable to extend the investigation of the X-ray spectrum of PKS 0637-752 to below 1 keV. Understandably, most of the efforts to calibrate ACIS have gone into the later periods of the Chandra mission. However, if efforts are underway to use the available calibration data obtained for ACIS in order to arrive at the best-possible calibration products for early observations like the current one, this project would benefit immensely in the science that can be extracted from the observational data.

Data Reduction (cont.)

Unexpected behavior of the effective area at low and high energies:



Effective area as a function of energy for the Chandra observations of PKS 0637-752. The plot is an overlay of the curves for the 21 individual response matrices. Between about 0.55-3 keV, there is good agreement between all the curves. Outside of that interval, however, large deviations are seen. Since the generation of these matrices does not include any time-dependent factors, as would be the case for later observations (incorporating the time-dependence of the ACIS gain and CTI), the reason for these deviations has to be found in the realization that the object was at different positions on the detector in the individual observations.

A preliminary fit of an absorbed power law to the set of 21 observations, using these response matrices, and extending the fit from 0.3-7 keV reveals that the matrices *are* appropriate for each respective data set, as no major residuals are seen.

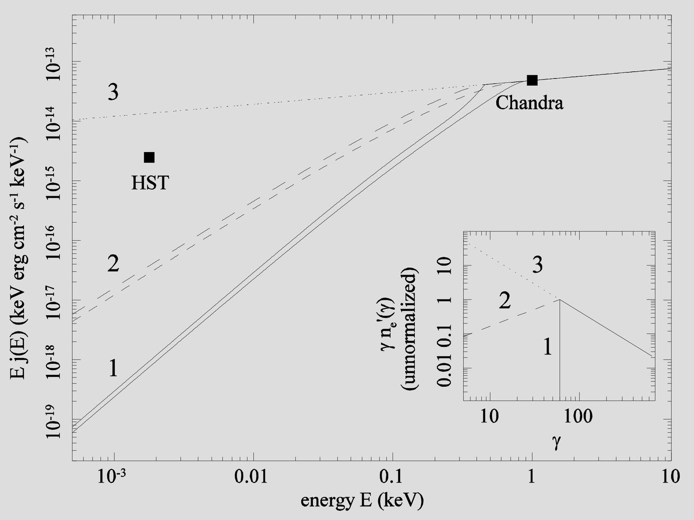
IC/CMB Model

- assumed jet bulk Lorentz factor Γ = 10, and jet Doppler factor $\delta = \Gamma$
- two different kernels for IC scattering describing the outgoing photon spectrum obtained from a single scattering of an electron and a photon: Blumenthal & Gould (1970), Aharonian & Atoyan (1981)
- CMB photon field assume monoenergetic; further assumption: isotropic in jet restframe (Blumenthal & Gould), monodirectional, opposite to jet bulk motion (Aharonian & Atoyan)

Emitted IC/CMB spectrum (in jet rest frame):

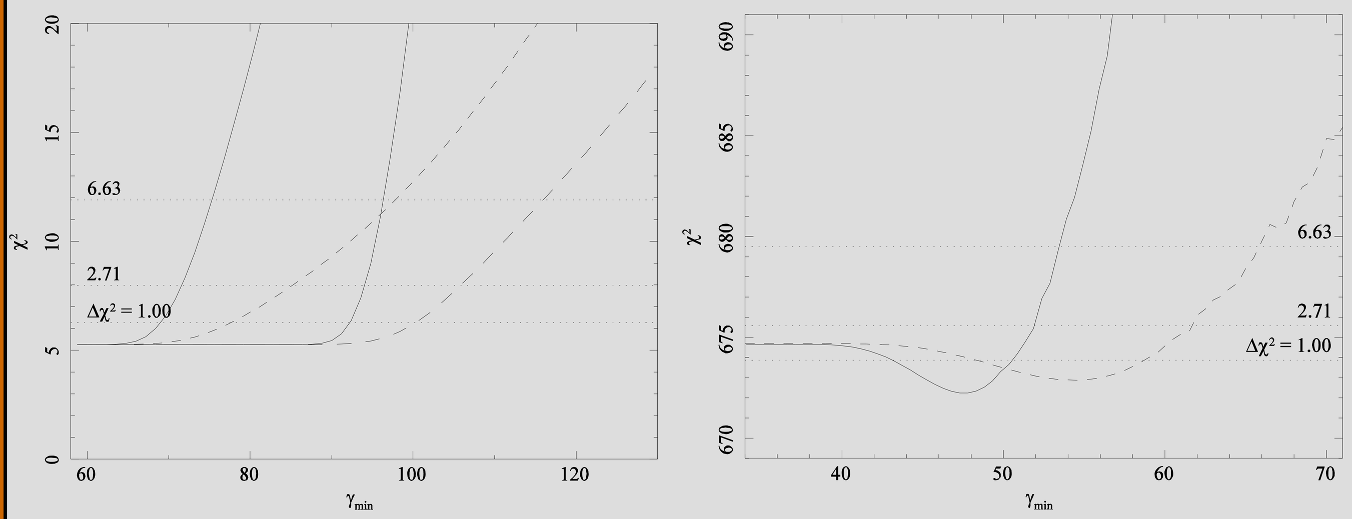
$$j'(E_1', \quad ') \propto E_1' \int_0^{max} \frac{n'(\quad)}{2} f(E_1', E_0', \quad, \quad ')\, d$$

E_1': photon energy in jet rest frame
$n'(\gamma)$: jet rest frame electron distr.
$f(E_1', E_0', \gamma, \mu')$: IC kernel



Predicted flux of the IC/CMB model for γ_{min} = 60, and electron distribution power law index 2.6 (corresponding to observed radio/X-ray energy index 0.8). The inset shows the corresponding electron distributions (case 1: sharp cutoff at γ_{min}, case 2: electron number density constant below γ_{min}, case 3: no cutoff). The Chandra and HST flux measurements are also included, which shows that the case of no cutoff is not allowed by the observed optical flux. IC kernel: bold lines: Aharonian & Atoyan; thin lines: Blumenthal & Gould.

Results: Upper Limit on γ_{min} from X-ray Spectrum



Upper limits on γ_{min} obtained from fitting the IC/CMB models to the X-ray spectrum between 1-7 keV. The power law and normalization are allowed to adjust as γ_{min} is varied. IC kernels: bold lines: Aharonian & Atoyan; thin lines: Blumenthal & Gould. Electron distributions: solid lines: sharp cutoff, dashed lines: constant segment below γ_{min}. Desired statistical upper limits on γ_{min} can be read off the graph; 68.3, 90, and 99% limits are indicated by the dotted lines.

If the calibration between 0.3-1 keV is trusted and the spectrum in that range included in the fit, the upper limits on γ_{min} are tightened, as expected. Note that these calculations have so far only been performed for one of the IC kernels (Blumenthal & Gould); the solid line again corresponds to the electron distribution with the sharp cutoff at γ_{min}, the dashed line to the constant segment below γ_{min}.

Results: Lower Limit on gamma_min from Optical Flux

- given measured X-ray flux, IC/CMB model predicts an increasing optical flux as γ_{min} becomes smaller
- lower limit on γ_{min} obtained when predicted optical flux exceeds measured flux
- taking uncertainties in both optical and X-ray flux measurement into account

Results:
at 1σ statistical significance, $\gamma_{min} > 4.2$ for the sharp cutoff in the electron distribution, $\gamma_{min} > 6.1$ for the constant segment below γ_{min}
(results weakly dependent on choice of IC kernel)

at 99% statistical significance, no useful limits on γ_{min} anymore, γ_{min} = 1 included in confidence range

Conclusion

- statistically sound confidence range placed on γ_{min}; range dependent on choice of IC kernel, shape of cutoff in electron distribution, and bandpass of X-ray spectrum
- values for γ_{min} used in Tavecchio et al. 2000 (γ_{min} = 10) and Uchiyama et al. 2005 (γ_{min} = 20) probably too low; higher values relax kinetic power carried by jet in PKS 9637-752 considerably