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PKS 2155-304

RELATIVISTICALLY BEAMED SYNCHROTRON RADIATION FROM A BL LAC OBJECT

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Abstract

The newly discovered BL Lac object, PKS 2155-304, has been observed with the medium and high energy detectors of the HEAO-1 A2 experiment. We confirm the variability by a factor of two in less than a day reported earlier by Snyder et. al. (1979). Two spectra, obtained a year apart, while the satellite was in scanning mode, are well fit by simple power laws with energy spectral index $\alpha_1 \sim 1.4$. A third spectrum, of higher statistical quality, obtained while the satellite was pointed at this source, has two components, and we get an acceptable fit using a two power law model, with indices $\alpha_1 = 2.0$ (+1.2,-0.6) and $\alpha_2 = -1.5$ (+1.5,-2.3). An interpretation of the overall spectrum from radio through x-rays in terms of a synchrotron self-Compton model gives a good description of the data if we allow for relativistic beaming. Thus, from a consideration of the spectrum, combined with an estimate of the size of the source, we infer the presence of jets without directly observing them.

Subject headings: BL Lacertae objects - radiation mechanisms - X-rays: sources - X-rays: spectra

Introduction

PKS 2155-304 is the second BL Lac object to be discovered as a result of its x-ray emission. A combination of x-ray error boxes obtained by the HEAO-1 A2 and A3 experiments (Agrawal and Riegler 1979, Schwartz et. al. 1979), revealed an optical candidate for identification with the x-ray source: a faint (~14th magnitude) stellar object. The optical spectrum (Wade, Szkody, and Cordova, 1978) was blue and featureless, and polarization of ~5% has been observed (Griffiths et. al. 1979). An improved radio position (Hjellming et. al. 1978) for the already catalogued source PKS 2155-304 (Shimmins and Bolton 1974) was found to be within a few arcseconds of the stellar object. Finally, variability in the flux has been observed in the radio, optical, ultraviolet, and x-ray bands, on timescales from years down to a day or less. (Shimmins and Bolton 1974, Hjellming et. al. 1978, Greenstein et. al. 1979, Maraschi et. al. 1980, Snyder et. al. 1979, Agrawal and Riegler 1979.) All of these properties are typical of BL Lac objects.

Other BL Lac objects, such as Mrk 421, PKS 0548-322, 1727+50 (=IZw187), and 1218+304 (=2A1219+305), exhibit short timescale variability and have similar spectra, (Mushotzky et. al. 1978, Mushotzky et. al. 1981, Worrall et. al. 1981, and Weistrop et. al. 1981). Their spectra consist of flat power laws in the radio, with a break somewhere in the optical or ultraviolet region, above which a steeper power law continues to x-ray energies, where another flat component is sometimes seen. The similarity of these BL Lac spectra suggests a common emission process. It has also been argued (cf. Stein, O'Dell, and Strittmatter 1976) that BL Lacs must be related in some way to QSOs and other active galactic nuclei since, to varying degrees, they share many of the same characteristics. The relativistic beaming hypothesis may explain the connection between these different objects.

Jets were first suggested to explain the transport of energy from the central powerhouse in QSOs out to the giant double radio lobes typically seen in these sources. Relativistic bulk motion in jets would then explain the superluminal expansion sometimes seen in the compact radio cores. Because the observed radio structures are fairly symmetric, the jet axis must be roughly perpendicular to our line of sight. Blandford and Rees (1978) took the jet hypothesis a step further by noting that jets should be randomly oriented on the sky, and asking what one might expect to see if the angle between the jet axis and line of sight were small. In fact, they predicted just those properties by which BL Lac objects are distinguished: high polarization, rapid variability, lack of observed line emission (presumably line emission from the core source would be swamped by the strong continuum from the jet), compact radio structures, and so on. As we shall see, bulk relativistic motion also removes the so-called Compton catastrophe, or brightness temperature problem. For these reasons, we find it natural to interpret the observed spectrum of PKS 2155-304 in terms of a relativistically beamed synchrotron model.

Observations

We present observations made with medium energy (argon) and high energy (xenon) detectors (MED and HED3, respectively) of the A2 experiment on HEAO-1[2]. These consist of two scanning observations, one during 11-16 November 1977, and the other a year later, on 11-16 November 1978, as well as a six hour pointed observation on 8 November 1978. PKS 2155-304 was also in our field of view during 11-16 May 1978, but we have less than 20% of the exposure of the November scans, due to satellite pointing maneuvers, so there are too few counts to analyze. The data presented cover the range from 2 to 45 keV, and were accumulated in 1.28 second bins (total counts) and 10.24 second bins (counts per energy channel). A complete description of the experiment is given in Rothschild et. al. (1979).

Variability

Data from the six day scan in 1977 show that the intensity of PKS 2155-304 changed by a factor of about two in less than one day, confirming the same event reported earlier by Snyder et. al. (1979). Figure 1a shows the light curve obtained by summing counts from both

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[2] The A2 experiment on HEAO-1 is a collaborative effort led by E. Boldt of GSFC and G. Garmire of CIT, with collaborators at GSFC, CIT, JPL, and UCB.

the MED and HED3 detectors.

We have looked for evidence of corresponding spectral changes, but are unable to detect them within the statistics. Figure 1b shows the ratio of counts from HED3 to counts from MED, for the same period as in the light curve. (This ratio can be related to the spectral index of the incident radiation, which is plotted as well.) Fitting a constant ratio to these data points gives an acceptable fit, but we note that between days 316 and 318, the spectral index seems to vary roughly in phase with overall intensity. The direction of this trend is that higher intensity corresponds to a harder (flatter) spectrum. This trend is a marginal result, since the reduction in the chi-squared statistic for a more detailed fit is not significant.

We do not see the one second flare reported by Agrawal and Riegler, who observed in the 0.15 to 3.5 keV range with the HEAO A2 low energy detectors (LEDs), but PKS 2155-304 has a higher photon flux below 2 keV than in our energy range, and therefore they have much better statistics with the same exposure.

Neither the pointing data nor the scanning data from November 1978 indicate any significant variation in intensity individually, but there is a change in 2 to 10 keV flux of about 40% between 8 November 1978 (the pointed observation) and 11-16 November 1978 (the second scanning observation). There is also a difference of about 20% between the averages of the two different scanning observations; that is, on the timescale of a year.

X-Ray Spectrum

A two component model is suggested by the x-ray spectrum obtained during the pointed observation on 8 November 1978. A simple one component model, whether thermal or power law in nature, does not give an acceptable fit to the data. The high energy component can be described by a power law with energy index $-4 \lesssim \alpha_2 \lesssim 0$, ($F_\nu \sim \nu^{-\alpha}$), while the low energy component can be fit by either a power law with index $1.4 \lesssim \alpha_1 \lesssim 3.2$ or a thermal bremsstrahlung with temperature 3 +/- 2 keV. (Errors quoted are 90% confidence.) The two spectra obtained from summing the six days of each scanning observation are of lower statistical quality, due to shorter on-source time, and are adequately fit by single power law (or thermal) components. The latter spectra are not inconsistent, however, with the two component spectrum.

Figure 2 superimposes all three spectra, and shows the two parameter joint confidence contours for each power law fit. (Plotted for the two scans are spectral index versus hydrogen column density along the line of sight. For the pointed observation, where a two component power law model was used, we plot one spectral index versus the other.) The best-fit power law spectral indices for each observation are listed in Table 1. The value $\alpha_1 = 1.5$ (+1.7, -0.7) for the 1977 scan is consistent with that found by Agrawal and Riegler (1979) for the x-ray spectrum below 3 keV, implying a single, smooth spectrum across the x-ray band. In particular, if we use the upper limit for hydrogen column density obtained by Agrawal and Riegler (1979), which is more stringent than our own, we find $\alpha_1 = 1.4$ (+0.4,-0.6).

Discussion

(1) Composite Spectrum

The composite spectrum of PKS 2155-304, from radio through x-ray frequencies, is shown in Figure 3. Unfortunately, the various data plotted were not obtained simultaneously. The radio, infrared, optical, and hard x-ray portions date from November and December of 1978, while the ultraviolet spectrum was taken almost a year later, in October 1979. The soft x-ray spectrum is based on data published by Agrawal and Riegler 1979 (obtained in November 1977) with the following modifications: (1) the effect of absorption by matter along the line of sight, presumably not intrinsic to the source, has been removed, and (2) the overall intensity has been corrected by a factor of 0.7, to correspond to the change in intensity of the hard x-ray flux between November 1977 and November 1978. (See Table 1.) We cannot claim, therefore, that the spectrum plotted represents the true emission of the source at a single moment, particularly because PKS 2155-304 is known to be variable. However, given that the spectrum is displayed on a log-log scale, factors of a few in intensity and/or slight changes in slope will not radically change its appearance.

(2) Canonical Synchrotron Self-Compton Model

Bearing these reservations in mind, we suggest that all of the observed emission can be explained by a single process. The infrared flux is consistent with a single power law of slope $\alpha \sim 0.2$ extending from the radio data. Similarly, the soft x-ray flux and the soft part of the hard x-ray flux seem to be a smooth extension of the ultraviolet spectrum. In fact, the entire spectrum from 10^9 Hz to 10^{19} Hz looks remarkably like simple homogeneous models based on the synchrotron and self-Compton processes, (SSC models). (Cf. Jones, O'Dell, and Stein 1974, hereafter JOS.) The low energy self-absorption turnover is not seen, presumably because the turnover frequency, ν_m, lies below 10^9 Hz. The so-called break frequency, ν_b , is $\sim 10^{15}$ Hz, with the ultraviolet and low energy x-ray photons lying in the broken part of the synchrotron spectrum, and the flat x-ray tail corresponding to the self-Compton photons.

From the characteristics of the radio part of the spectrum and the angular size of the emitting region, it is possible to calculate various parameters of interest, including the expected strength of the self-Compton x-ray emission. We know of no VLBI measurements of the angular size of this source, so we infer the angular size from the observed variability and redshift (assuming that it implies distance according to the Hubble law). Detailed observations of variability have not been done in the radio; the only published radio fluxes, made with different instruments, indicate a change in intensity of about 10%, (which is just outside the quoted errors), in 7.5 years. (Shimmins and Bolton 1974, Hjellming et. al. 1978.) We assume that the radio emitting and x-ray emitting regions are roughly coincident, and that the x-ray variability reported above gives some indication of the size.

This may not be true, since some models predict a dependence of the emitting region on wavelength, (cf. Marscher 1980). Such a wavelength dependence cannot be too strong, however, if the SSC model is to be self-consistent. That is, if the high energy x-rays are produced by up-scattering the radio synchrotron photons off the same energetic electrons which produced them, then the radio photons, x-ray photons, and electrons must be roughly co-spatial.

Charles et. al. have reported a redshift of 0.17 for PKS 2155-304, which implies a distance of about 1 Gpc. If this redshift is correct, then this BL Lac object is one of the intrinsically brightest extragalactic sources known, with a luminosity of $\sim 10^{47}$ erg/sec (from 10^{9} to 10^{19} Hz), dominated by the ultraviolet and soft x-ray synchrotron emission. In our view, this redshift is still tentative, since one observer has reported a confirmation (Maraschi et. al. 1980) while others, observing with sensitivity equal to or better than that of Charles et. al., have been unable to confirm it, (Snyder et. al. 1979, Griffiths et. al. 1979). At this point, we proceed using the value $z = 0.17$, and later we will detail the dependence of our result on z.

From the light curve in Figure 1a, it can be seen that the x-ray flux more than doubles in about a day. This gives an angular size $\phi \lesssim 0.0015\,\delta$ milliarcseconds, where $\delta = \Gamma^{-1}(1 - \beta\cos\theta)^{-1}$ is the kinematical Doppler factor in the case of relativistic expansion, β = velocity of expansion, θ = angle between the line of sight and the direction of expansion, and $\Gamma = (1 - \beta^2)^{-1/2}$. (Unless otherwise stated, all calculations in this paper are based on the formulae of JOS, and/or Marscher et. al. 1979. They differ due to disparate geometrical factors raised to high powers. Where the difference is large, the numbers from JOS are used, as they require a lesser degree of relativistic beaming.)

The available upper limit of 10^{9} Hz for ν_m gives, in this single component model, a lower limit to the expected self-Compton x-ray flux, which is proportional to $\nu_m^{-(5+3\alpha)}$. Using equations 19 and 33 of JOS, and including the appropriate factors of δ, (cf. Marscher et. al. 1979), we derive the following expression for the SSC x-ray flux:

$$S_\nu^{sc} \approx 6.5 \times 10^{-8} (5.5 \times 10^{3})^{\alpha} f(\alpha) \ln\frac{\nu_b}{\nu_m} S_m^{2(2+\alpha)} \nu_m^{-(5+3\alpha)} \varphi^{-2(3+2\alpha)} (1+z)^{2\alpha} \delta^{-2(\alpha+2)} \nu^{-\alpha} \quad Jy,$$

where ν_m, ν_b, δ, and φ are defined above, z = redshift, α = optically thin radio spectral index, S_m = flux at the turnover frequency, and $f(\alpha)$ has values $f(0.0)=0.50$, $f(0.2)=2.84$, and $f(0.5)=28.8$. Fluxes are in Jy, (1 Jy = 10^{-23} ergs/cm^{2}/sec/Hz), frequencies are in GHz, and φ is in milliarcseconds. For PKS 2155-304, using observed values of α and ν_b, and estimated values (given above) for ν_m, φ, and S_m, the expected x-ray flux at 10^{18} Hz is $\gtrsim 3 \times 10^{8}$ Jy, if there is no relativistic expansion or bulk motion ($\delta \sim 1$). The observed flux is $\lesssim 2 \times 10^{-6}$ Jy, some 14 orders of magnitude below the predicted flux. The result goes as a very high power of angular size, φ, and so is very sensitive to errors in that quantity. However, the discrepancy is so great that φ would have to be over two orders of magnitude larger than our estimate, which was already somewhat conservative, in order for the expected x-ray flux to be comparable to the observed flux. In either case, φ is too small ($\lesssim$ 0.2 milliarcseconds) to resolve, even using VLBI techniques. The Compton catastrophe described above is a problem in other extragalactic sources as well. (See Marscher et. al. 1979.)

(3) Relativistic Beaming

Several authors (Rees and Simon 1968, Burbidge, Jones, and O'Dell 1974, Blandford and Rees 1978, Blandford and Konigl 1979, Scheuer and Readhead 1979, Marscher 1980, Königl 1981) have suggested that a resolution to this problem lies in relativistic expansion and/or beaming of the synchrotron source. The latter two authors have developed detailed models, with magnetic field and particle density as functions of radius. The model we consider now is much simpler, with a single blob of synchrotron- emitting material moving relativistically at some angle to our line of sight. Because of light travel time effects, the observed variability is therefore much faster than the intrinsic variability. Anisotropic radiation also implies reduced energy output. As shown in the above equation, the predicted self-Compton flux goes as a very high power of δ; namely, to the power $2(5+3\alpha)$. (Note that ϕ is proportional to δ.)

For PKS 2155-304, the required value for δ is in the range 20 to 70, with allowances for errors and differences in formulae. Such a large value implies that θ, the angle of our line of sight relative to the expansion direction, is less than about 2°, and that β, the velocity of expansion, is greater than 0.997. This result is shown in Figure 4, where we have plotted allowed values of β and θ for various values of δ.

Since the redshift for PKS 2155-304 is uncertain, we also investigated the variation of these quantities with z. The results are summarized in Table 2. Even for $z = 0.01$, $\delta \gtrsim 5$, $\theta \lesssim 10^{\circ}$, $\beta \gtrsim 0.93$, and $\Gamma \gtrsim 2.7$. At this redshift, a typical galaxy would be about one arcminute in extent, and could be clearly resolved. Since BL Lac objects are typically embedded in elliptical galaxies, (cf. Weistrop et. al. 1981), and the optical image of PKS 2155-304 is nearly stellar, this object is either in an unusually faint elliptical galaxy or its redshift is larger than 0.01 .

(4) Consequences of the Simplest SSC Model

The lifetime of radiating electrons against synchrotron losses, which is inversely proportional to the electron energy and the square of the magnetic field strength, (e.g. see Pacholczyk 1970), is on the order of 10^{10} years. Only a small fraction of electrons lose their energy via inverse Compton radiation, but it is interesting to calculate their lifetime against Compton losses. It varies inversely with electron energy, E, and photon energy density, u_{ph}. The latter is not well determined, but we can estimate it from the luminosity of the source and its size. That is,

$$u_{ph} \approx \frac{\text{(Luminosity)(travel time of photon in source)}}{\text{(Volume of source)}}$$

$$\approx \frac{L\ R\psi/c}{(R\psi)^2 R} \sim \frac{F\Omega\, d^2 R\psi}{R^3\,\psi^2 c} \sim \frac{F\pi\,\psi^2 d}{cR\,\psi} \sim \frac{\pi F\, d^2\,\psi}{c\ R^2}\ ,$$

where R is roughly the length of the jet, Ω is the solid angle subtended by the jet, ψ is the opening angle of the jet, F is the flux we measure, and d is the distance to the source. Pacholczyk gives $\tau_c \approx \frac{25}{u_{ph} E}$ seconds. So $\tau_c \approx \frac{10c}{FE\psi}\left(R/d\right)^2$. With $R \sim 10^{18}$ cm ($R \sim c\, t\,\delta$, where t is the characteristic variability time, a few light days, and δ is the kinematical Doppler factor), $F \sim 10^{-10}$ ergs/cm^2/sec, (see Table 1), $d \sim 1$ Gpc, $E \sim 10^{-3}$ ergs ($\gamma \gtrsim 10^3$), and $\psi \sim 10^0$, the loss time is $\lesssim$ 30 days, within an order of magnitude or so. We expect Compton loss times to be on the order of a few days since that is the timescale for x-ray variability.

One of the most uncertain quantities in the above timescale calculations is the appropriate value for the energy of a relativistic electron. We estimate it using the relation $\nu_s \sim \gamma'^2 \nu_B$ where $\nu_B = \frac{eB}{2\pi mc} \sim 10$ Hz and/or $\nu_c \sim \gamma'^2 \nu_s$. The observed synchrotron photons extend from 10^9 to 10^{18} Hz, indicating a range for γ' of 10^4 to 3×10^8, if the magnetic field is on the order of a few microgauss. Since we can't know what the original synchrotron frequency was for a given Compton frequency, it is more difficult to find γ' from the second relation. We can set a lower limit to γ', however, because we do not see a break in the Compton part of the spectrum. Photons with frequencies just greater than the break frequency, ν_b, must be scattered to higher frequencies than in our spectrum. Thus, $\gamma' \gtrsim 10^2$, and could be as much as 10^5 or more.

This γ' gives the approximate energy of a relativistic electron in the rest frame of the blob which is itself moving toward us with Lorentz factor Γ. This is a small effect compared to the uncertainty of the appropriate value for B, or the change in frequency of an inverse-Compton scattered synchrotron photon. In any case, it is clear that the timescale calculations are only good to within an order of magnitude or two.

In principle, spectral indices of power laws in each energy band should be related. Tucker (1975) relates the spectral index above the break frequency, α_1, to the optically thin radio spectral index, α, via $\alpha_1 \approx \frac{4}{3}\alpha + 1$, where he has assumed no injection of new particles, and no re-isotropization of pitch angles. If, however, continuous reacceleration occurs, the steeper index, in this simple two power-law approximation, is given by $\alpha_1 \approx \alpha + 0.5$. In fact, the spectrum we have shown in figure 3 consists of a series of gradually steepening power laws with indices 0.2, 0.4, 0.65, 1.0, and 1.6 in the radio, infrared, optical, ultraviolet, and soft x-ray regimes, respectively. If we approximate this by the two power laws $\alpha = 0.2$ and $\alpha_1 = 1.5$, with a break between 10^{15} and 10^{16} Hz, then the observed steepening is greater than either of the above relations would suggest. We cannot say this is a real inconsistency, however, given the seeming complexity of the spectrum and, more importantly, the non-simultaneity of the various observations.

There may be reasons to expect a steeper fall-off. Particles with larger pitch angles lose energy faster than those with small pitch angles, and so are depleted more rapidly, leaving an empty region in phase space. If there is some means of re-isotropization of pitch angles, such as might result from the accelerator mentioned above, or from a disordered field, then the spectrum above the break will be steeper than $\frac{4}{3}\alpha + 1$. (Tucker 1975.)

One can see from Table 2 that both the magnetic field strength and the energy density of relativistic electrons are only weak functions of the assumed redshift. Thus, unless we are very wrong about the size of the source, we find that the particle energy density is many orders of magnitude greater than the magnetic field energy. This is consistent with the jet picture, in which the magnetic field presumably is not strong enough to confine the very energetic electrons, which are therefore free to stream outward in jets.

(5) Consequences of a Specific Jet Model

Although our discussion above involved a simple, locally homogeneous blob of synchrotron -emitting material, there is evidence, notably the very flat radio spectrum, that an inhomogeneous jet would be a more physically realistic model. Königl (1981) has calculated the emission spectrum from a conical jet with electron density and magnetic field varying smoothly as a function of radius. The synchrotron radiation is approximated by a series of power laws with indices α_{s1}, α_{s2}, $\alpha_0 + 0.5$, and α_{s3}, where α_0 is the index of the spectrum that would be produces by the same electron power law in a homogeneous medium. Choosing $\alpha_{s1} = 0.2$, $\alpha_{s2} = 0.6$, and $\alpha_{s3} = 1.5$, we find $\alpha_0 = 0.47$, so that the third power law has $\alpha \sim 1.0$, corresponding to the ultraviolet spectral index. Solving for the radial dependences of magnetic field and electron density, we find $B = B_0 r^{-1.31}$ and $N = N_0 r^{-1.35}$, respectively. Since equipartition would require $B \sim r^{-1}$ and $N \sim r^{-2}$, we see that in this model as well, particles dominate the field.

The above choice of power law indices is probably correct, and within the context of this model, the radial exponents are thus well-determined. We would like to take the model a step further, and find the coefficients B_0 and N_0, as well as r_M, the innermost radius from which optically thin emission is observed. Unfortunately, there are more free parameters in the model than there are observable quantities, so that a small amount of guesswork is required. We assume that we know the following quantities reasonably well: (1)the break frequency in the synchrotron regime, (where the α_{s1} and α_{s2} power laws meet), $\sim 10^{14}$ Hz; (2)the flux density at that frequency, ~0.03 Jy; (3)the redshift, 0.17, and the distance to the source, ~1 Gpc; and (4)the turnover frequency in the inverse-Compton part of the spectrum, which, if we assume that the hard x-ray tail is actually rising, should be about 10^{20} Hz. Further, in keeping with the simple model presented earlier, we guess that $\delta \sim 10$ and $\theta \sim 6^{\circ}$, so that $\beta \sim 0.99$ and $\Gamma \sim 7$. Finally, we assume a cone opening angle of 5°, (the cone angle must be smaller than the angle to the line of sight). The results, (using Königl's equations 5, 6 and 12), are $B \approx 7 \times 10^{-5} r^{-1.31}$ gauss and $N \approx 8 \times 10^{4} r^{-1.35}$ cm^{-3}, where r is in parsecs, and $r_M \approx 2 \times 10^{-5}$ pc $\approx$ .5 light-hours. As a consistency check, we calculate the ratio of the Compton flux to the synchrotron flux, using Königl's equations 12 and 13, and find that it is a few times 10^{-4}, which is roughly what is observed. Thus, while these parameter choices are not unique, they do lead to a self-consistent set of physical conditions, and they are characteristic of the kinds of numbers expected for beamed sources. Observations at higher energies would test our assumptions, since our calculations predict that above the Compton turnover, which we have assumed is 10^{20} Hz, or 400 keV, the spectral index should be ~0.6.

The magnetic field strength varies from 100 gauss at r_M, to 70 μgauss at 1 pc, to 0.008 μgauss at 1 kpc, while the corresponding particle densities are 10^{11} cm^{-3}, 10^{6} cm^{-3}, and 10 cm^{-3}. It is difficult to judge whether or not these are reasonable numbers, but we can note two things about them. First, the values at 1 pc are comparable to those from the simpler model (shown in Table 2), and second, at any given radius, the electron energy density is many orders of magnitude greater than the magnetic field energy density, as in the simple model.

Finally, we calculate the lifetime of electrons against synchrotron losses in this model, (see Königl's eqn. 10). We find $t_{synch} \approx 6 \times 10^{5}$

$r^{2.62}$ years, with r in parsecs. (Because the magnetic field has a radial dependence, so has the cooling time.) This means lifetimes of 10 seconds, 6×10^{5} years, and 4.4×10^{13} years at r_{M}, 1 pc, and 1 kpc, respectively. Of course, the underlying assumption in the model is that there is some sort of continuous injection of energy from the core of the source, so that short lifetimes at the nozzle of the jet are presumably not a problem.

(6) Other Possible Models

A power law spectrum can be produced by mechanisms other than the synchrotron self-Compton process. A multi - temperature thermal bremsstrahlung spectrum could be a power law over a limited bandwidth. Some authors have suggested thermal photon/Compton scattering models, (Shapiro, Lightman, and Eardley 1975, Katz 1976). These usually have the virtue that energy comes directly from accretion onto a massive object, thus obviating the need to imagine a source for large numbers of energetic particles. One is forced, however, to assume that different parts of the spectrum arise from separate components in the source, radiating according to different mechanisms. The radio emission from compact extragalactic objects is well-explained by the synchrotron picture, and the composite spectrum of PKS 2155-304 is striking in its resemblance to canonical synchrotron spectra; it practically duplicates the spectrum of a Crab Nebula weaker by a factor of one thousand. Besides, if the x-ray emission is thermal while the radio emission is synchrotron radiation, one still faces the problem of explaining why the self-Compton process is suppressed.

Based on the data for PKS 2155-304, we cannot distinguish conclusively between the different possible models. Observations of spectral changes as a function of time may provide a way to do so. In homogeneous synchrotron models, an increase in intensity should result from an injection of energetic particles, and the entire spectrum should rise uniformly, possibly becoming slightly harder above the break frequency, where the "new" electrons will not have had time to lose much energy. In multi-temperature thermal models, however, it is almost impossible to have the spectrum change uniformly. Emission at different frequencies would come from components at different temperatures, probably spatially separate, and coherent change would be precluded by signal propagation requirements. If, then , an object gets brighter while its spectrum softens, simple synchrotron models can probably be ruled out. Of course, in the case of an inhomogeneous, synchrotron emitting jet, the evolution of the spectrum depends critically upon the model under consideration and we cannot predict here what form it would take.

Conclusion

As noted above, the spectra of several other BL Lac objects are very similar to that of PKS 2155-304. In particular, Mrk 421, 0548-322, 1727+50, and 1218+304 are all compact radio sources with broken power law spectra, strong x-ray variability, and weak or unobserved x-ray Compton tails. This is exactly what is predicted for relativistically beamed sources where we are nearly looking down the jet, (Königl 1981). We have investigated two different models: the single, bright, homogeneous blob and the continuous, inhomogeneous cone, both moving toward us at relativistic speeds. In a sense, these two pictures are extremes of the range of models which represent the jet phenomenon. We therefore expect that the results obtained for particle densities, magnetic fields, and kinematical factors are limits to the true values in a real relativistic jet.

We conclude that if x-ray emission from BL Lac objects is due to the SSC process, they are probably expanding relativistically, possibly with jet structures. In order to be more certain of this, we need simultaneous broad band spectral observations, extending to lower frequencies in hopes of seeing the synchrotron self-absorption turnover. (Several simultaneous ultraviolet/ soft x-ray observations have been made, and will be reported in a future paper.) We also need a determination of angular size using VLBI. The available upper limit of 0.3 arcseconds for PKS 2155-304 from the VLA observation of Hjellming et. al. is not a severe enough limit. Finally, searches for possible intensity-spectral correlations should be made, as this is the most direct way of comparing the efficacy of the simplest SSC process and multi-temperature thermal processes as models for the emission of PKS 2155-304.

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Table 1. X-Ray Intensity of PKS 2155-304

Date of Observation	Mean Intensity (x 10^{-10} ergs /cm^2/sec)		Spectral Index	
	2-10 keV	0.25-40 keV	for N_H free	for $N_H \leq 10^{21}$ atoms/cm^2
11-16 November 1977[a]	1.45 +/- 0.05	2.45 +/- 0.05	$\alpha_1 = 1.5$ (+1.7,-0.7)	$\alpha_1 = 1.4$ (+0.4,-0.6)
11-16 November 1978[a]	1.2 +/- 0.2	2.2 +/- 0.4	$\alpha_1 = 1.4$ (+1.4,-0.7)	$\alpha_1 = 1.2$ (+0.4,-0.5)
8 November 1978[b]	0.85 +/- 0.15	4.0 +/- 0.0	$\alpha_1 = 2.0$ (+1.2,-0.6)	
			$\alpha_2 = -1.5$ (+1.5,-2.3)	

[a] scanning [b] pointing

Table 2. Allowed Ranges for Parameters of a Relativistically Beamed Synchrotron Model for PKS 2155-304, as a Function of Assumed Redshift

Assumed Redshift, z	Kinematic Doppler Shift, δ	Jet Angle, θ (degrees)	Magnetic Field,[a] B (μgauss)	Relativistic Electron Energy Density[a] (ergs cm^{-3})
0.01	5-15	5-10	10-60	20
0.05	15-30	2-4	2-10	10
0.10	20-45	1-3	1-6	10
0.17	25-60	1-2	0.7-4	10
0.25	30-70	0.8-2	0.5-3	10
large, ~1	45-100	0.5-1.5	0.2-1	150

[a] See Marscher et. al. (1979), formulae (2) and (4).

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Figure Captions

Figure 1a. 2-45 keV intensity of PKS 2155-304 as a function of time during 11-16 November 1977 scan (=days 315-320).

Figure 1b. Spectral index versus time for the same period.

Figure 2. X-ray photon spectra for PKS 2155-304, (✦ 11-16 November 1977, + 8 November 1978, ◇ 11-16 November 1978), plus associated contours for 90% confidence intervals. For the scanning data, plotted contours are for spectral index versus hydrogen column density. For the pointing data, which requires a two component fit, the contour plotted is for one spectral index versus the other, with hydrogen column density as a free parameter.

Figure 3. Composite spectrum of PKS 2155-304. Radio data are from Hjellming et. al. 1978; infrared, Persson 1979; optical, Griffiths et. al. 1979; ultraviolet, Maraschi et. al. 1979; low energy x-ray, Agrawal and Riegler 1979; high energy x-ray, present paper.

Figure 4. Velocity of expansion versus jet angle for a relativistic beam model, for different values of δ.

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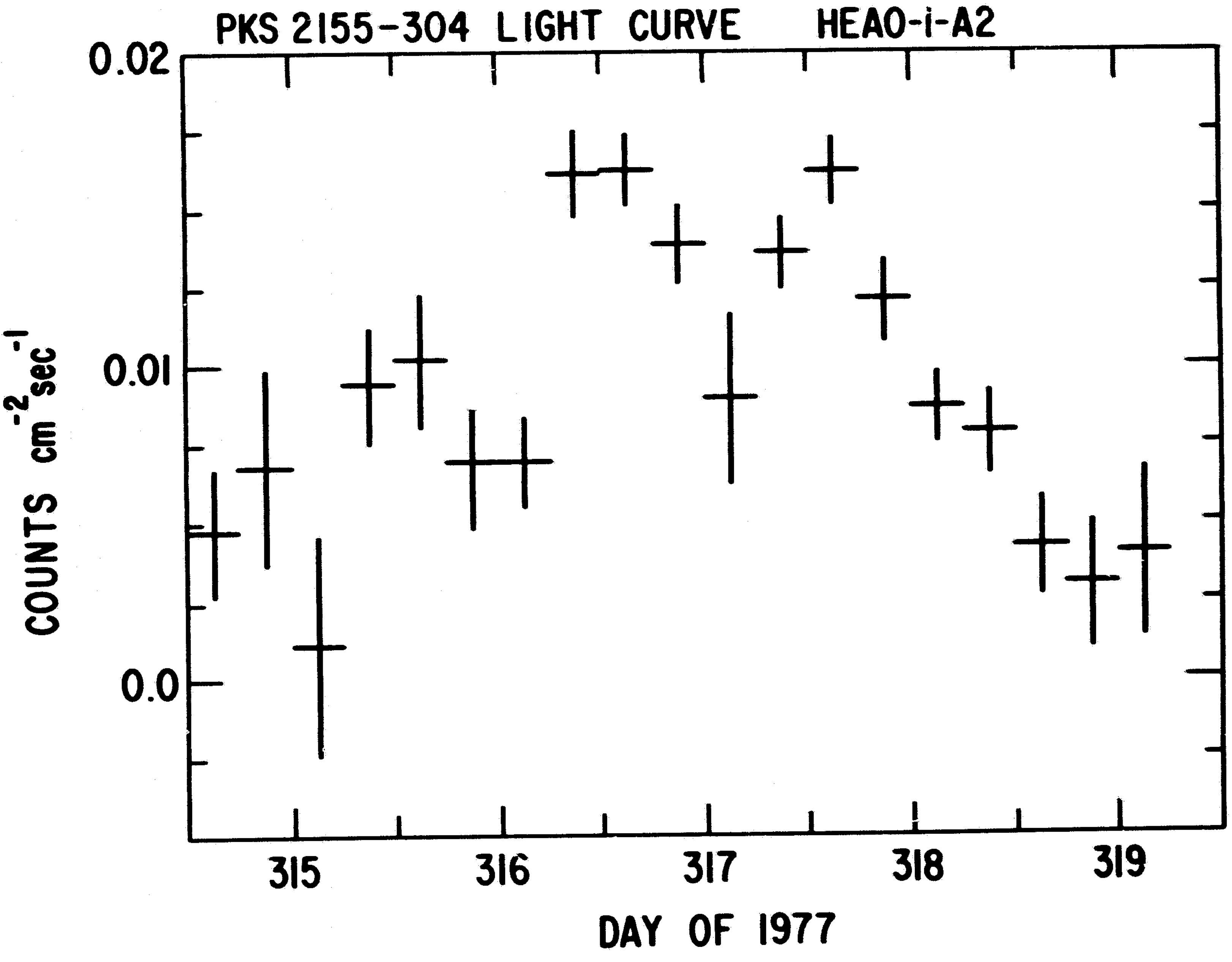
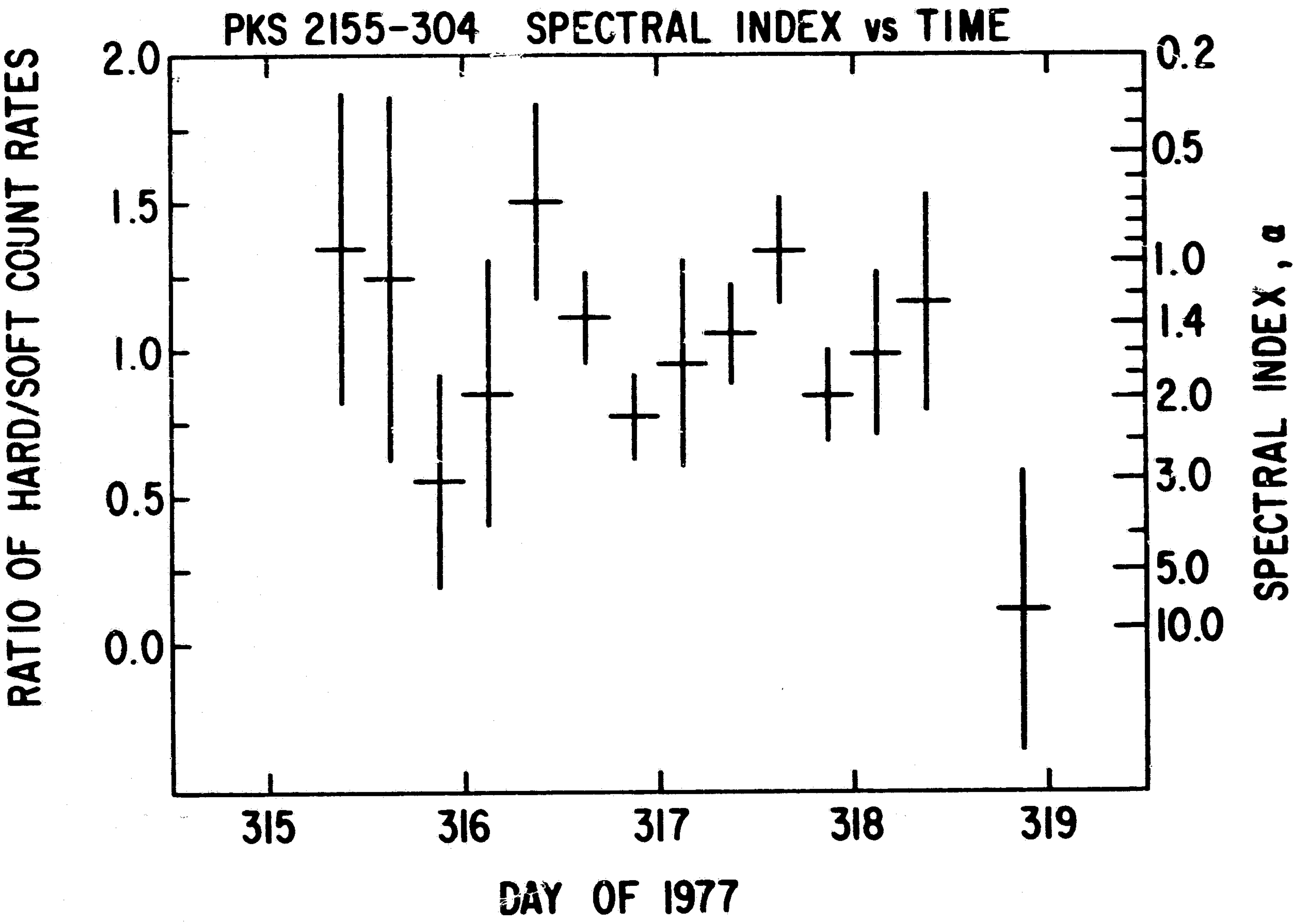
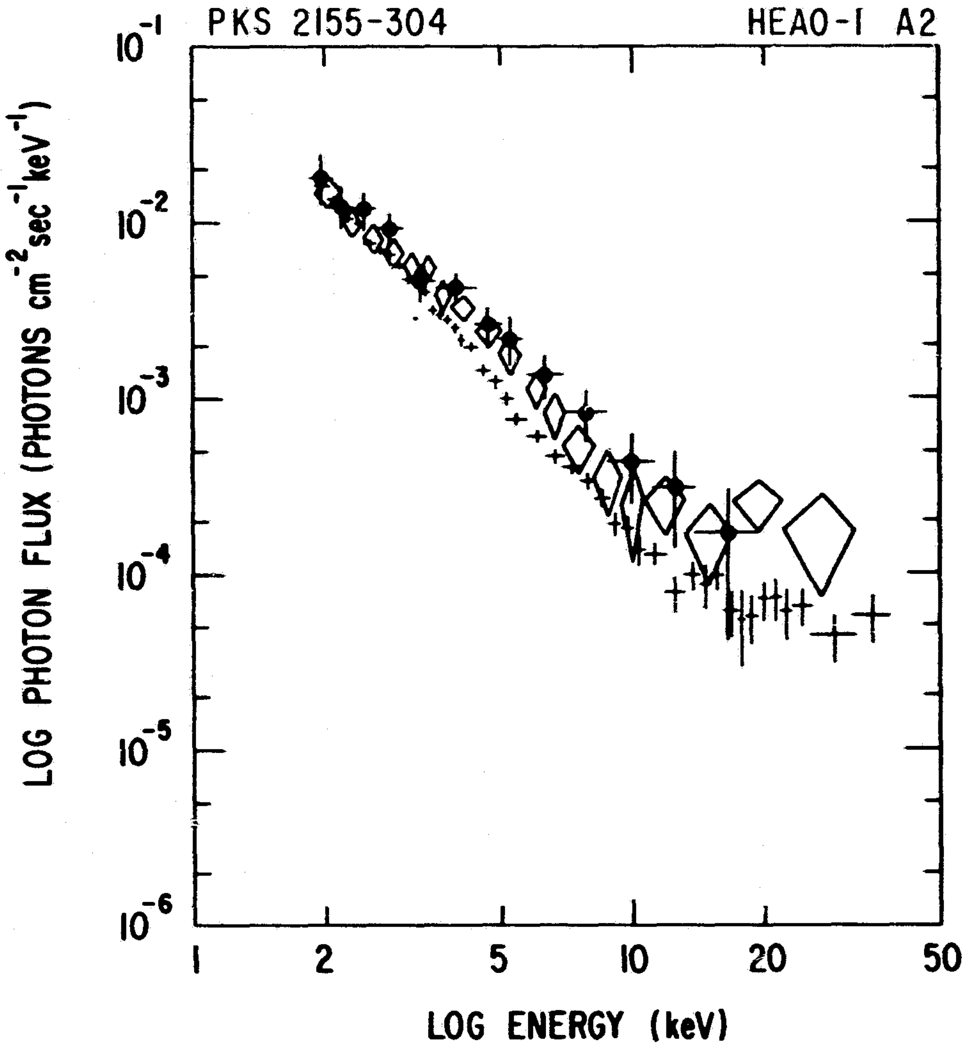
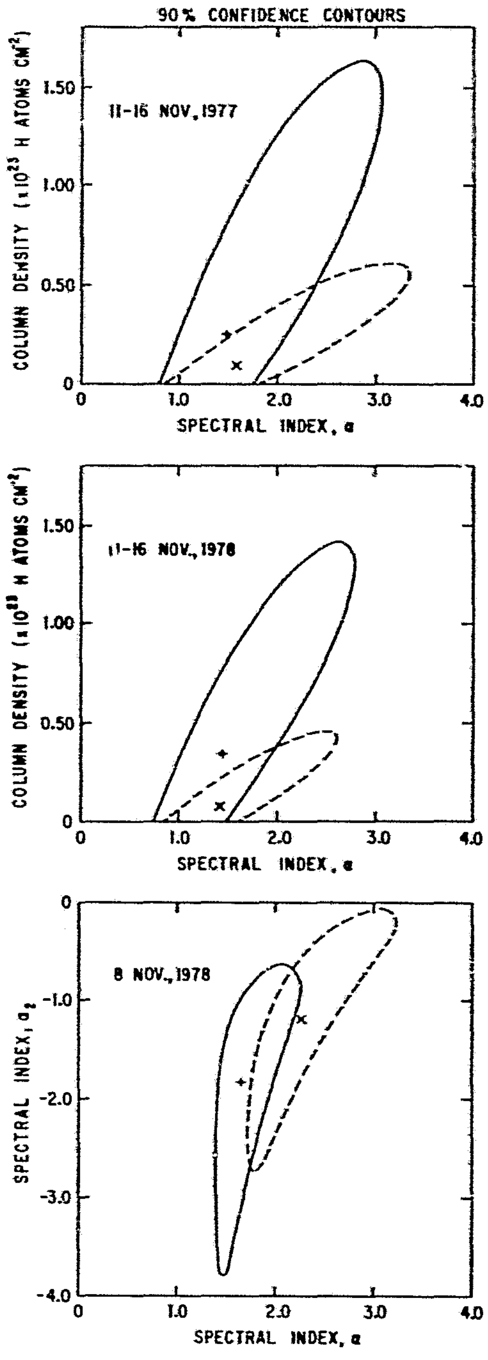
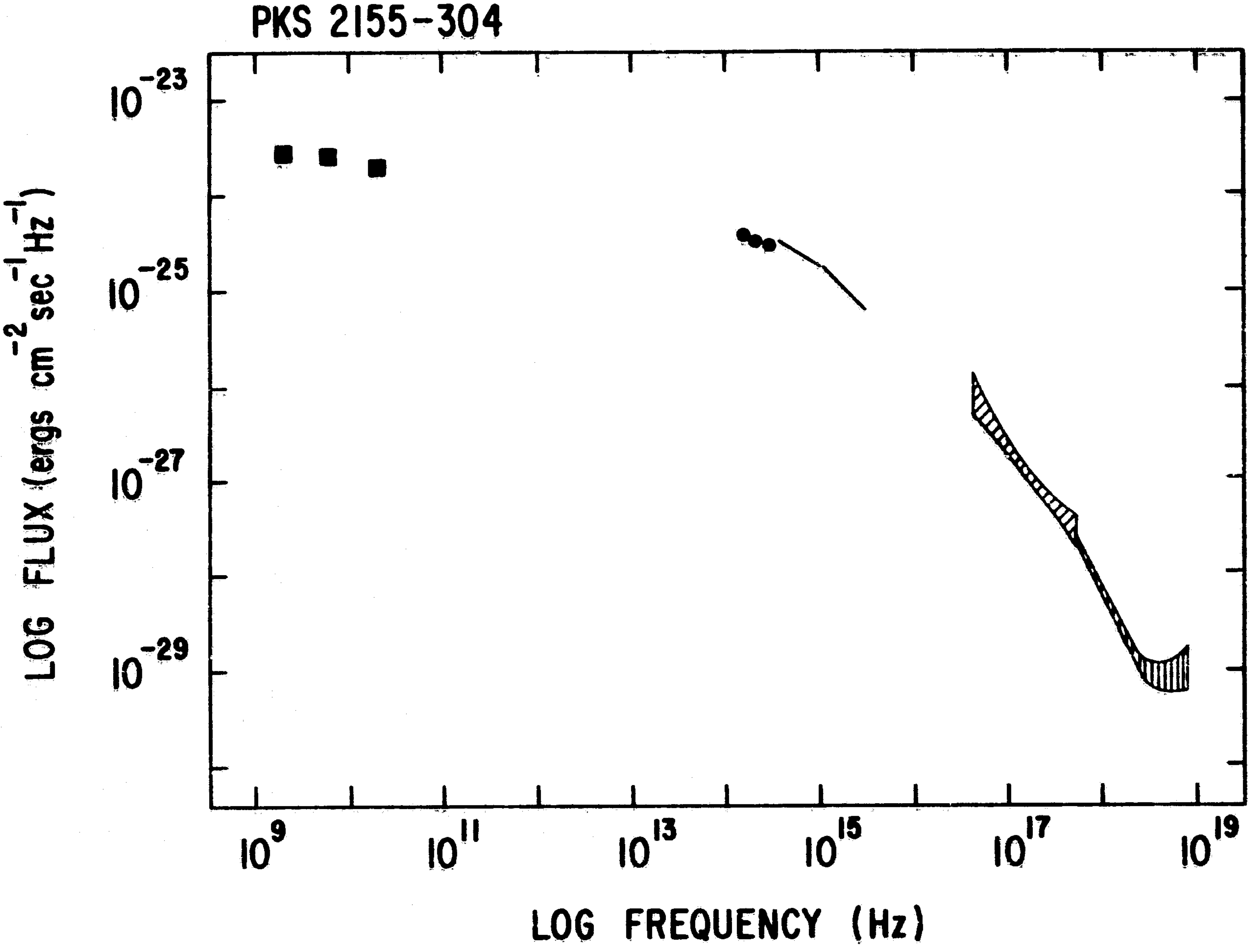

PKS 2155-304 LIGHT CURVE HEAO-i-A2
0.02
0.01
0.0
COUNTS $cm^{-2}sec^{-1}$
315
316
317
318
319
DAY OF 1977

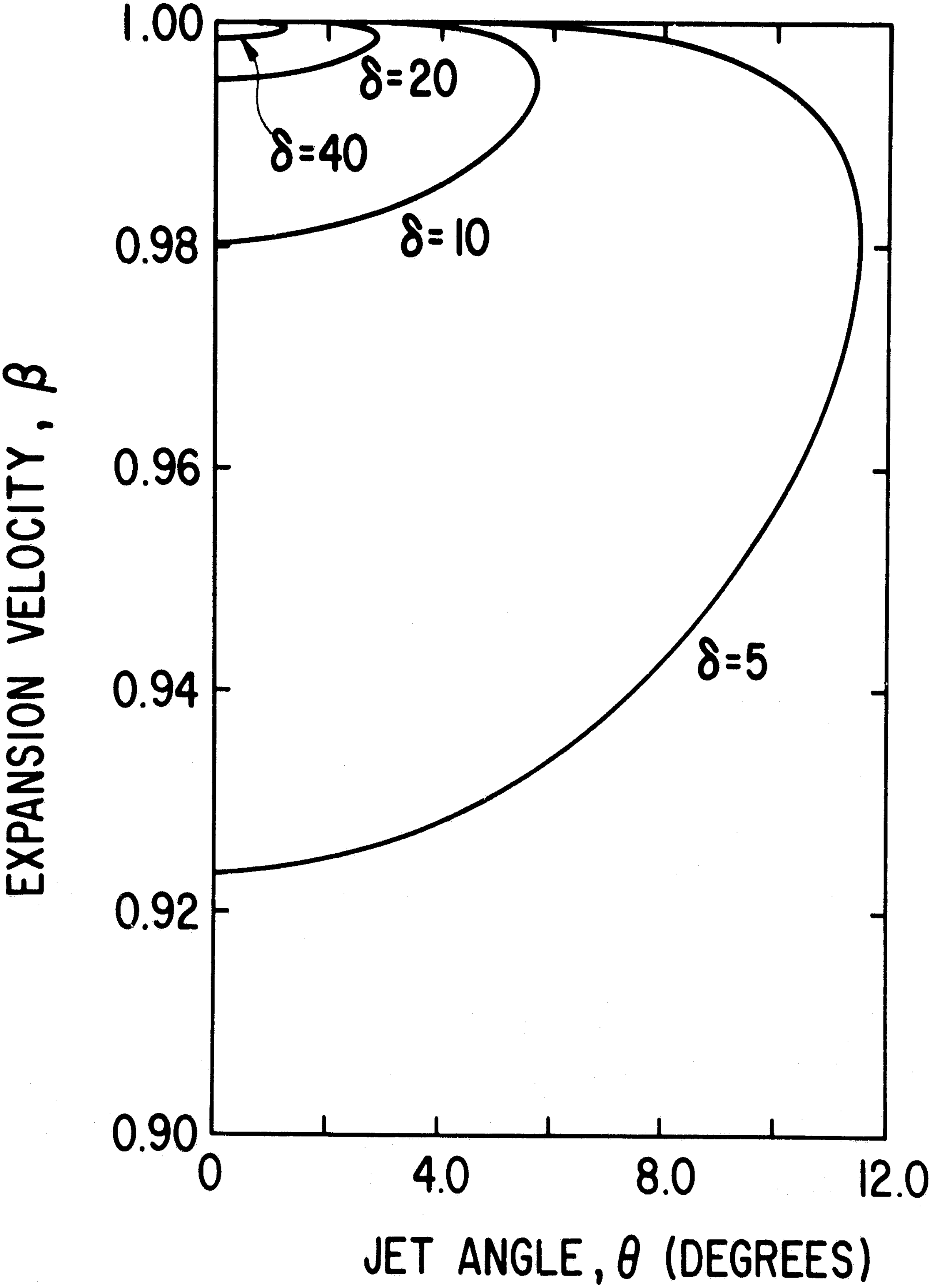


PKS 2155-304 SPECTRAL INDEX vs TIME


PKS 2155-304
HEAO-I A2
LOG PHOTON FLUX (PHOTONS cm^{-2}sec^{-1}keV^{-1})
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
1
2
5
10
20
50
LOG ENERGY (keV)


90% CONFIDENCE CONTOURS
11-16 NOV, 1977
COLUMN DENSITY ($\times10^{23}$ H ATOMS CM^2)
1.50
1.00
0.50
0
0
1.0
2.0
3.0
4.0
SPECTRAL INDEX, α
11-16 NOV., 1978
COLUMN DENSITY ($\times10^{23}$ H ATOMS CM^2)
1.50
1.00
0.50
0
0
1.0
2.0
3.0
4.0
SPECTRAL INDEX, α
8 NOV., 1978
SPECTRAL INDEX, α_2
0
-1.0
-2.0
-3.0
-4.0
0
1.0
2.0
3.0
4.0
SPECTRAL INDEX, α


PKS 2155-304
LOG FLUX (ergs cm^{-2} sec^{-1} Hz^{-1})
10^{-23}
10^{-25}
10^{-27}
10^{-29}
10^{9}
10^{11}
10^{13}
10^{15}
10^{17}
10^{19}
LOG FREQUENCY (Hz)


1.00
0.98
0.96
0.94
0.92
0.90
0
4.0
8.0
12.0
δ=20
δ=40
δ=10
δ=5
EXPANSION VELOCITY, β
JET ANGLE, θ (DEGREES)