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# Variability in the X-ray Flux of Quasar 3C345: Inverse-Compton Emission from the Parsec-scale Jet?

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**Abstract.** We present the results of the first systematic study of *variability* in the X-ray emission from the 'superluminal' quasar 3C 345. Its power-law 1-keV X-ray emission varies by a factor of two on a timescale of years, but with no change in spectral index, closely following the high-frequency radio flux. Using VLBI images, we show that one of the superluminal 'knots' in the jet (at a distance of $\approx 15$ pc from the nucleus), rather than the nucleus, produces most of the observed X-rays, via the synchrotron self-Compton process. We show that this knot accelerates as it moves away from the nucleus, along along a path at $\approx 10°$ from the line of sight.

## 1. Introduction

The quasar 3C 345 ($z = 0.595$) is a well-known 'superluminal' radio source (apparent proper motion $\beta_{\rm obs} > 1$). Its evolution has been monitored with VLBI imaging at cm-wavelengths since the late 1970s. All the VLBI images show a relativistic jet, which appears one-sided, due to Doppler-boosting. Figure 1 shows representative images; most of the identifiable parsec-scale components (or 'knots') persist several years, and yield measurable proper motions (Zensus, Cohen & Unwin 1995).

3C 345 is also a non-thermal X-ray source; the X-rays are believed to originate in the jet via inverse-Compton scattering of low-energy photons. Previous studies (e.g., Unwin et al. 1994) have shown that (1) superluminal motion, and (2) synchrotron self-Compton X-ray emission, both require the jet to be relativistic, from which a self-consistent picture of the jet kinematics can be built. By examining time-variability in the relation between X-ray and radio properties, we can eliminate many systematic errors resulting from over-simplified modeling—we are more interested in *changes* in derived parameters than their absolute values.

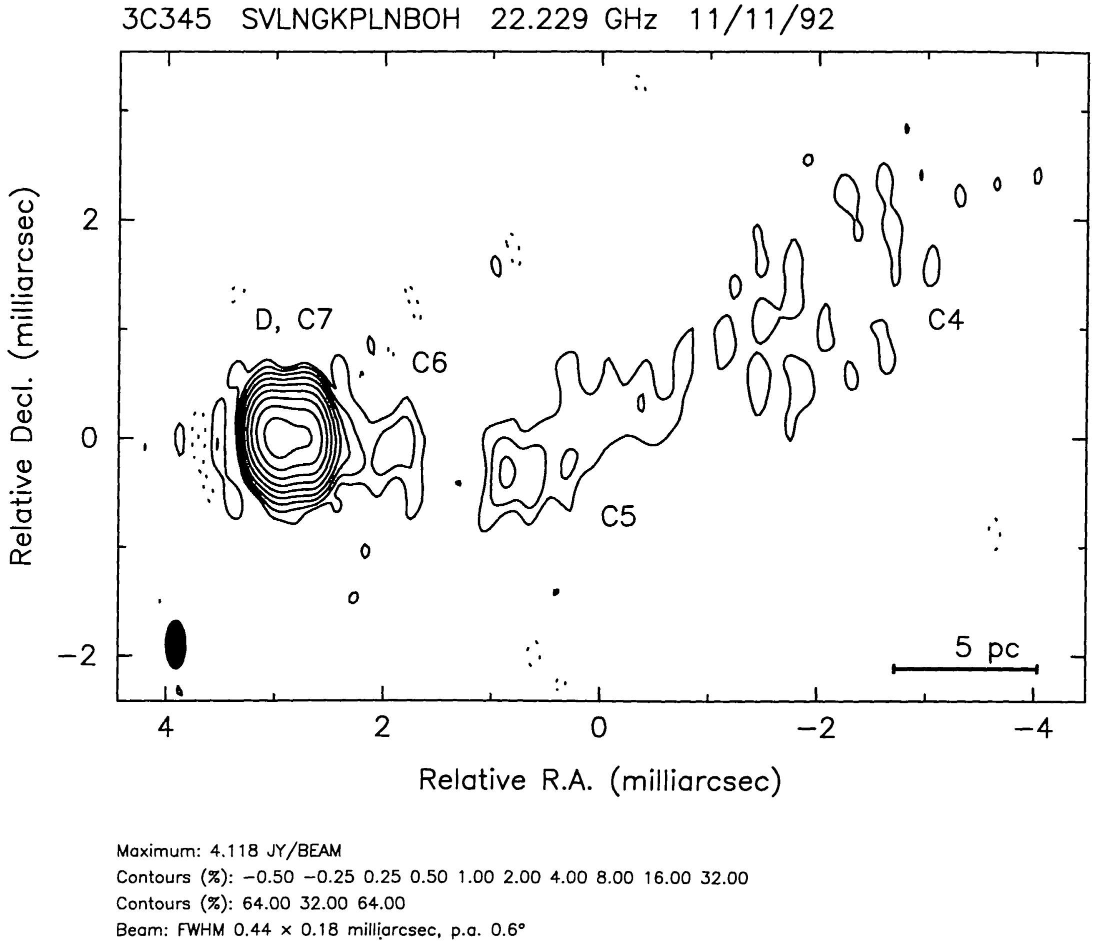

Figure 1. VLBI image of 3C 345 at 22 GHz, at a resolution of 0.7 pc, at epoch 1992.86. This image is representative of a long series of monitoring experiments at 5, 8, 11, and 22 GHz. Labeled features are the nucleus 'D', and superluminal jet components 'Cn', which are identified at other epochs and frequencies, allowing us to follow their spectral evolution.

Some of the questions we can answer with variability data are the following: How variable are the power-law X-rays from 3C 345, and is there any variation in spectral index? Are X-ray variations correlated with radio properties, such as total flux density at different frequencies? Are X-ray variations associated with individual components in the relativistic jet, and do they correlate with angular size or spectral shape? Can variability provide any new information on the geometry and dynamics of the parsec-scale jet?

## 2. X-ray monitoring results

3C 345 was observed by the ROSAT PSPC instrument (0.2–2.0 keV) instrument 5 times, during 1990–1993. All were reduced in a uniform way, which reduces systematic errors between epochs to a low level. Figure 2 shows the X-ray and

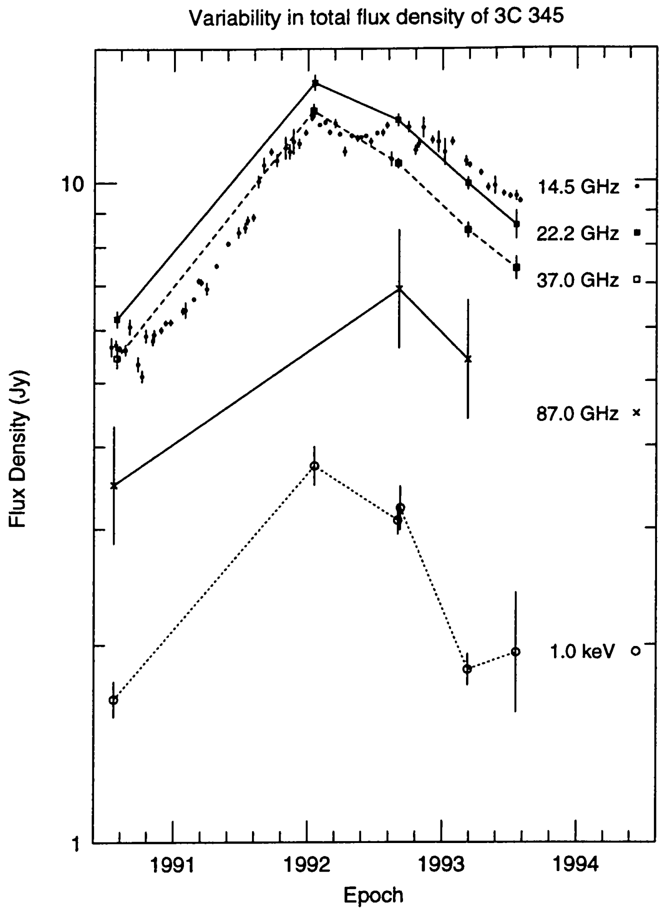

Figure 2. X-ray and radio flux monitoring of 3C 345, during 1990–1993. (X-ray flux densities scaled by 4 × $10^6$ before plotting).

high-frequency radio flux density measurements vs. time. A constant Galactic column $N_{\mathrm{H}} = 7.4 \times 10^{19}\,\mathrm{cm}^{-2}$, and constant spectral index $\alpha = -0.75$ ($S_\nu \propto \nu^\alpha$) were assumed in fitting the X-ray spectra, since there was no evidence between epochs for variability in either parameter.

- At all epochs the photon count data in 0.2–2.0 keV are well fitted by a single power law, with constant absorbing column equal to the Galactic value, and weighted mean spectral index $\alpha = -0.75 \pm 0.17$.
- There is no evidence for spectral curvature, nor evidence for variability in the spectral index, during 1990–1993. This argues against the X-ray emission arising from two components, say, a hard and a soft component, each with different time histories.
- Two of the epochs each comprised data blocks separated by $\approx 1$ week in time. We can place a limit of $< 5\%$ on any variability on that timescale.
- The X-ray flux history is directly correlated with the total flux density at 14.5 GHz and higher frequencies (Fig. 2), both in amplitude range and

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variability timescale. Since the radio variability is known to arise in the parsec-scale components imaged directly with VLBI, this is strong evidence for a causal relation between VLBI and X-ray.

## 3. VLBI monitoring results

With VLBI imaging, we can track the spatial and spectral evolution of compact features in the parsec-scale jet (Fig. 1); more than a dozen VLBI images went into the spectral analysis we discuss here. Lobanov (1996), and Zensus et al. (in preparation) present most of the observational material, with an analysis of the component kinematics. We concentrated on the 'core' component ('D'), and the brightest most compact jet component ('C7'), since these are the most likely to produce significant inverse-Compton X-ray emission.

We fitted spheres to the components at each epoch to derive flux densities, and angular sizes, then interpolated the results to the epochs at which X-ray flux densities were measured. At each of these epochs, spectral turnovers were determined for each component by fitting homogeneous spheres to the 'knots', and a Königl (1981) model to the nucleus.

## 4. Inverse-compton X-ray calculation

From previous VLBI results, we know that the core ('D') is inhomogeneous, with a slowly-rising spectrum in the radio, whereas C7 and the other 'knots' can be represented by homogeneous spheres. We believe that shocks play a role in the knots, but the observations do not resolve them enough to justify a more-complicated model; therefore we computed the expected (self-) Compton X-ray emission from scattering of synchrotron photons in a homogeneous sphere. We assumed a spectral index $\alpha = -0.75$ for the optically-thin side of the sphere's spectrum; this is the same as the measured X-ray index, as required in this model; the predictions are a weak function of $\alpha$.

For the core, we used the inhomogeneous conical-jet model of Königl (1981), in which the particle density and magnetic field fall as power-laws with radius. The rising synchrotron spectrum in the radio results from superposition of locally-homogeneous emission regions with varying 'turnover' parameters.

**Core component ('D')** For all epochs, the Königl model *under-predicts* the X-ray emission by more than 2 orders of magnitude for a wide variety of parameters. Only solutions with a very large angle to the line of sight ($\theta > 25°$) even approached the measured value, and we regard such a large angle as implausible for other reasons (Zensus, Cohen, & Unwin 1995).

**Jet component ('C7')** The homogeneous-sphere model *over-predicts* the X-ray emission from Component C7, unless there is bulk relativistic motion ($\delta \gg 1$). In terms of the jet energetics, the most conservative assumption is that C7 *is* the origin of the observed X-rays, and that the Doppler factor must be such as to lower the predicted flux to match the observed flux.

Since jet components are known to move 'superluminally' (with $\beta_{\rm obs} > 1$), we can derive the jet kinematics—the angle $\theta$ to the line of sight, and the bulk Lorentz factor $\gamma$. Figure 3 shows the geometric relation between these quantities.

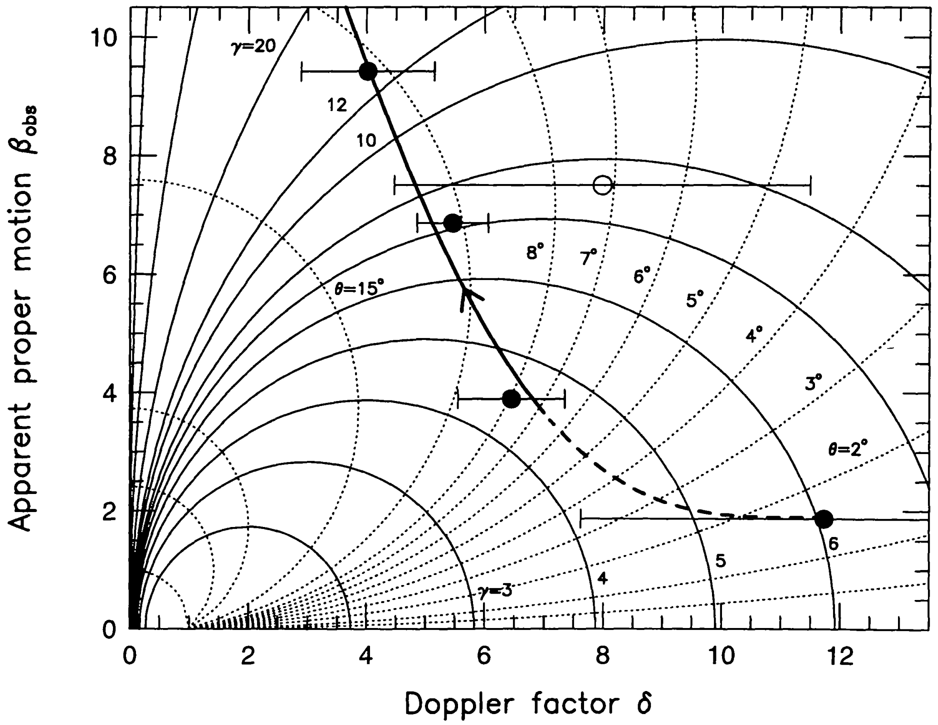

Figure 3. Geometry and kinematics of the jet in 3C 345. The Doppler factor $\delta$ (from X-rays) and $\beta_{obs}$ (from superluminal motion) are *observable* quantities. The angle $\theta$ to the line of sight, and the bulk Lorentz factor $\gamma$ are *derived* quantities. The track of C7 in this plane is indicated by the heavy line. The open circle represents C5, which dominated the jet in 1990 (Unwin et al. 1994).

We show measurements for C7 from our inverse-Compton X-ray calculations, using $\beta_{obs}$ from Lobanov (1996). Clearly, fixed values of $\theta$ and $\gamma$ for C7 are inconsistent with the X-ray and VLBI data: C7 must accelerate ($\gamma$ increasing) as it moves away from the nucleus. The first point (at $\delta = 11.7$ from epoch 1992.05) suggests that C7 may have started out closer to the line of sight, then bent away. If other mechanisms, or other components, make a significant contribution to the X-ray flux, then the heavy line in Fig. 3 traces a lower limit to $\delta$.

## 5. Conclusions

1. We have demonstrated a direct link between variations in parsec-scale jet structure and X-ray emission of a quasar for the first time—in 3C 345, a prototypical 'superluminal' radio source.

2. The core of 3C 345 (component 'D') can be modeled with a Königl jet, which explains the radio emission, but under-predicts the X-ray flux.

3. Jet component C7 (the brightest and most compact in 1992–1993) is the origin of the X-ray emission, unless the Doppler factor $\delta$ of the jet is even larger than the limits we derive.

4. The Doppler factor of C7 decreased from $\delta \approx 12$ to $\delta \approx 4$ during 1992–1993.

5. Combining X-ray and kinematic data for component C7, we conclude that C7 accelerates as it moves away from the nucleus, and its path probably bends away from the line of sight.

6. VLBI imaging with the VLBA, using several simultaneous frequencies, is now starting to provide better determinations of component spectra. With 43-GHz monitoring, we can probe the smallest jet scales, where we believe the X-ray emission is strongest.

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