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TOTAL FLUX DENSITY VARIATIONS IN EXTRAGALACTIC RADIO SOURCES. I. DECOMPOSITION OF VARIATIONS INTO EXPONENTIAL FLARES

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ABSTRACT

We show that 22 and 37 GHz total flux density variations in compact extragalactic radio sources can to a good accuracy be modeled by superposition of a small number of flare components. Both the rise and the decay of these flares are exponential, with a characteristic decay timescale 1.3 times longer than the rise timescale. The properties of the individual model flares derived from these flux decompositions are in agreement with data obtained from VLBI observations of the corresponding new shock components. The total flux density decompositions can be used to search correlations between radio and other regimes, to calibrate and to interpret VLBI observations, and to derive physical parameters of the shocks. In particular, the associated brightness temperatures of the flares can be used to estimate the amount of Doppler boosting in each source and, using additional VLBI data, to derive the intrinsic brightness temperatures, the Lorentz factors and the viewing angles of the sources.

Subject heading: radio continuum: galaxies

1. INTRODUCTION

After the discovery of radio variability in active galactic nuclei (Dent 1965; Sholomitskii 1965) it was soon realized that the variations are not random, and that at least the major outbursts are sufficiently similar to be modeled by a single physical process. The first spherical expanding source models have since been replaced by shocked jet models (e.g., Marscher & Gear 1985). The high-frequency radio outbursts that have been studied in more detail have been found to develop in accordance with the shocked jet model predictions, with no clear cases of counterexamples demanding alternative mechanisms (see the reviews by Valtaoja 1994, 1996 and Robson 1996, and references therein). This result holds for major radio variations, while smaller scale flickering and intraday variability may have different origins (Wagner & Witzel 1995). For the purposes of this paper we adopt the operative definition that major radio variations exceed 10% of the total flux density and have timescales exceeding 10 days, which is sufficient to exclude intraday and other rapid, small-scale variations.

Inherent in the shocked jet concept is the idea that the radio flux density variations can be decomposed into separate contributions from the underlying jet and from the shocks forming in the jet. Although not strictly true (van der Walt 1993), in the first approximation the flux density of the underlying jet (often called the base or the quiescent flux) remains constant, and the growth and decay of each shock constitute a separate event corresponding to a single radio flare, or outburst, and to the ejection of a new VLBI component from the radio core.

Even though the individual outbursts are produced by the same mechanism, there is little a priori reason to expect that they would be very similar, considering the number of independent parameters even in the simplest shocked jet models and the conceivably very wide range of physical conditions in the sources. It is therefore slightly surprising that, in general, the total flux density (TFD) outbursts seem to have quite simple, and similar, flux curves. Legg (1984) found that the outburst profiles in six different sources, when scaled in time and flux density, all had similar shapes that could be fitted reasonably well with the function $S(t) = S_0 t^n e^{-t/\tau}$, where $n > 3$ and τ is the timescale. The outbursts have also been modeled in terms of the so-called generalized shock models (Valtaoja, Lähteenmäki, & Teräsranta 1992; Litchfield et al. 1995), which explain the overall shape of the flare but do not give an exact form for the $S(t)$ dependence.

In studying the millimeter variability using the extensive Metsähovi flux density monitoring database, Teräsranta & Valtaoja (1994) found that the logarithmic variability timescale (Burbidge, Jones, & O'Dell 1974), defined as

$$\tau_{\rm obs} = \frac{dt}{d \ln S} , \quad (1)$$

appeared to remain constant during the flux changes, with decay timescales slightly longer than the rise timescales. In other words, both the flux increases and the flux decreases were exponential, with a sharp peak in between.

In this paper we continue this approach and decompose the 22 and 37 GHz total flux density variations of the AGN monitored at Metsähovi from 1980 onward into a small number of exponential flares. We show that such a simple approach produces a good model for the major flux density variations in most sources. For a given source, the range of the derived variability timescales and the associated apparent brightness temperatures of well-defined flares (i.e., isolated, single outbursts) is rather narrow. Each source thus has its own characteristic associated variability brightness temperature $T_{b,\rm obs}$, in most cases exceeding 10^{12} K. The most straightforward explanation is that we are seeing effects of Doppler boosting in the shocked jets.

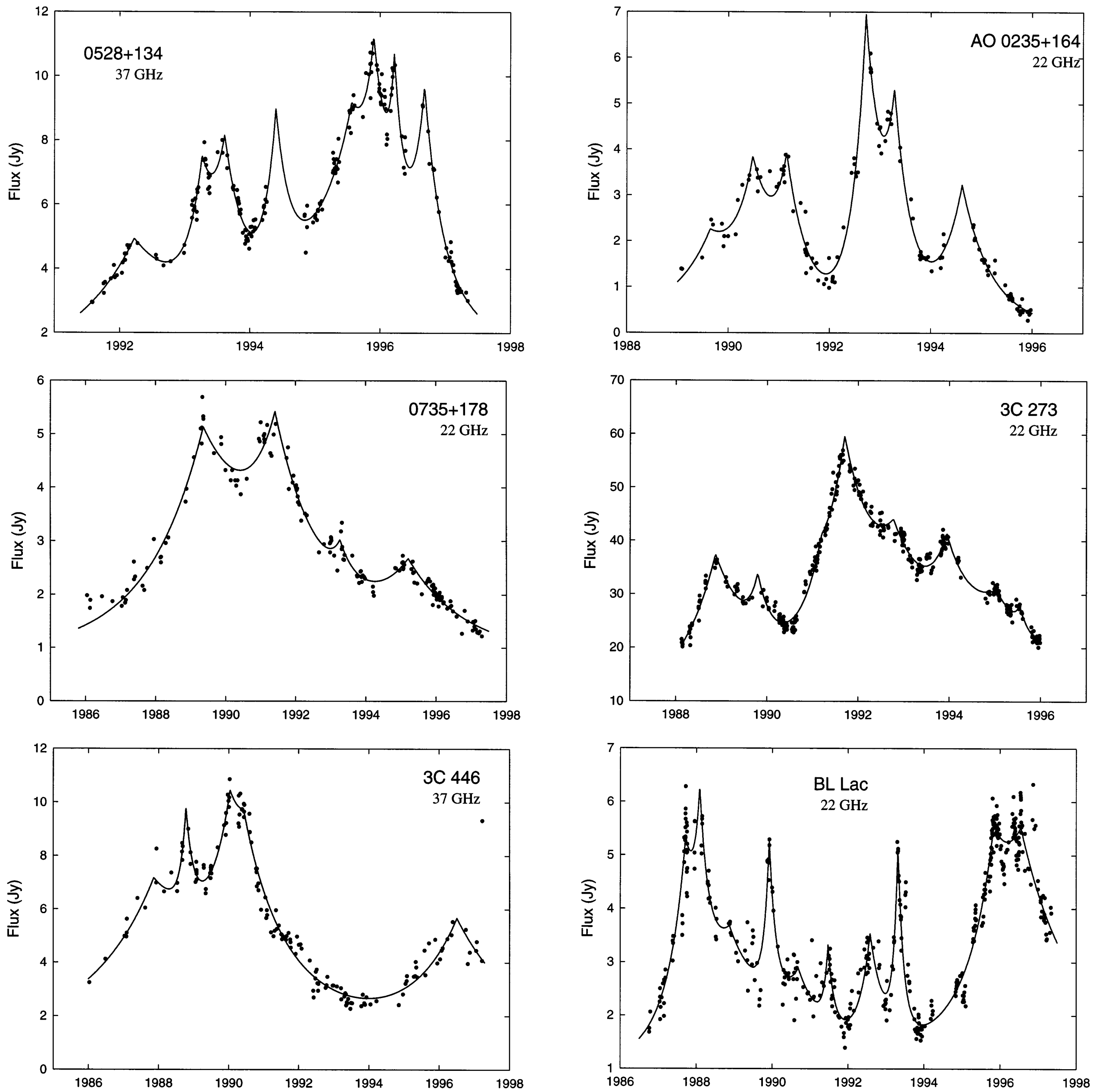

FIG. 1.—22 and 37 GHz total flux density curves of six well-observed sources from the Metsähovi monitoring program, with superposed exponential flare model fits.

Our main aim is not to provide perfect model fits to the long-term flux curves but rather to develop a tool for various investigations utilizing TFD variations. The flux decompositions have several potential uses, described in § 4, which we will explore in more detail in future papers. In Papers II and III of the series (Lähteenmäki, Valtaoja, & Wiik 1998a, hereafter Paper II; Lähteenmäki et al. 1998b, hereafter Paper III) we will derive an estimate for the limiting synchrotron brightness temperature $T_{b,\mathrm{lim}}$ from comparisons of total flux density, VLBI, and X-ray data, and will further calculate the intrinsic Lorentz factors and the viewing angles for a sample of bright radio sources.

2. THE DATA AND THE FLUX DECOMPOSITIONS

We use the monitoring data at 22 and 37 GHz obtained with the Metsähovi radio telescope between 1980 and 1997, totaling over 30,000 total flux density measurements of over 100 compact extragalactic radio sources (Teräsranta et al. 1992, 1998). At still higher frequencies no comparable radio variability data exist. At lower frequencies abundant data are available from the Michigan monitoring program (Aller et al. 1985), but these are more difficult to use for simple flux decompositions because the outbursts are typically much slower, with smaller amplitudes, and blend together in total flux density variations, making the identification and the separation of the individual flares difficult. These problems persist also at higher frequencies, but with typical variability timescales of months instead of years the blending of flares is much less severe.

Our method is quite straightforward. First, we subtract the quiescent level flux, assumed to remain constant during the whole period for which we model the flares. The quiescent flux must naturally be smaller than, or equal to, the lowest observed flux level, but its value cannot be determined from TFD data alone. However, the exact value is not crucial to the flare fits. In Teräsranta & Valtaoja (1994) half of the observed minimum flux was subtracted from the total flux density prior to estimating the variability timescales. We have found that in general this alternative results in the best agreement between the observed TFD flare fluxes and the VLBI component fluxes. A likely explanation is that with outbursts occurring typically once a year, the true quiescent level is usually not reached before the next flare starts.

Next we fit an exponential curve of the form

$$\Delta S(t) = \begin{cases} \Delta S_{\max} e^{(t - t_{\max})/\tau} , & t < t_{\max} , \\ \Delta S_{\max} e^{(t_{\max} - t)/1.3\tau} , & t > t_{\max} , \end{cases} \tag{2}$$

to the first outburst. The fitting parameters are $\Delta S_{\max}$, the maximum amplitude of the flare (after the quiescent flux subtraction), the flare rise timescale τ, and the epoch of the flare maximum, $t_{\max}$. The best-fit model flare flux is then subtracted from the TFD flux curve, and a second flare is fitted to the first peak in the remnant data. The procedure is repeated as long as flares are visible. In essence, we thus perform a one-dimensional CLEAN algorithm to find the most significant flare components. By experimenting we have found that it makes little difference to the end result whether we start with the first well-defined peak in the flux curve and proceed forward in time, or with the highest peak and proceed to smaller ones.

We initially also let the decay timescale remain a free parameter. However, we found that while there are some variations in the decay/rise timescale ratio, for virtually all flares both at 22 and at 37 GHz a good model fit could be obtained using $\tau_{\rm fall} = 1.3\tau$. Consequently, we have used this ratio in all the model fits. Although the timescale τ varies from outburst to outburst in a given source, the spread is not large. Each source appears to have a typical timescale, and a corresponding characteristic brightness temperature.

The decomposition of the TFD flux curve is in most cases not unique, since two or even more flares are often superposed and their sum cannot be uniquely decomposed into individual components, given the accuracy of the data. Additional uncertainties are introduced by smaller flickering, which may either be a sign of superposed smaller flares or, alternatively, be produced by some other mechanism. Also, even with the best available data, the flux curves are still undersampled and contain a number of gaps. Nevertheless, having two independent data sets and decompositions at two nearby frequencies helps in identifying the most likely alternatives.

For 85 of our sources we have sufficient data to model at least one outburst. In some active, well-observed sources, up to 10 major outbursts between 1980 and 1996 can be fitted with exponential flares. In Figure 1 we show the 22 and 37 GHz data between 1986 and 1996 for six sources, all among the most frequently observed ones in the Metsähovi monitoring program. For each source individual large outbursts are quite well fitted with exponential flares, and the TFD variations over the years can be modeled with a small total number of flare components. With an unlimited number of components, all variations could of course be modeled to any given accuracy, but such a decomposition would not be physically meaningful. Also, we are not attempting to provide a perfect model fit for all the data, but just to identify the major components contributing to the TFD variations and to model them with exponential flares. There are clearly epochs when the decomposition into a few components fails to provide a good fit (e.g., for BL Lac during 1996), because of either insufficient data, too densely superposed flares, or the rapidity of variations. However, the exponential nature of the major flares in each source is well demonstrated.

3. COMPARISON WITH VLBI DATA

If the model flares found in the decompositions correspond to real physical components, we should be able to identify them with evolving shocks seen in the VLBI maps. The best test of our method would therefore be to compare the decomposed model flux curves with the evolution of the VLBI component fluxes over the same time interval.

Unfortunately, only very little 22 GHz VLBI monitoring data have been published. In Figure 2 we show the arguably best observed source, 3C 345. We have joined published VLBI data with as yet unpublished new data to construct the flux evolution of the various VLBI components between 1980 and 1996 (Biretta, Moore, & Cohen 1986; Zensus, Cohen, & Unwin 1995; Leppänen 1995 and 1998 private communication; Lobanov 1996 and 1998 private communication; Lobanov & Zensus 1998). Figure 2 also shows our TFD decomposition model, made as described above with no reference to VLBI data.

It can be seen that the correspondence between VLBI and TFD data is quite good. The three major high-frequency VLBI components, C4, C5, and C7, correspond to TFD flares peaking in 1982.6, 1986.7, and 1992.8, respectively. A new component, C8, seen in the last 1994.45 map (Leppänen 1995), seems to correspond to the beginning of

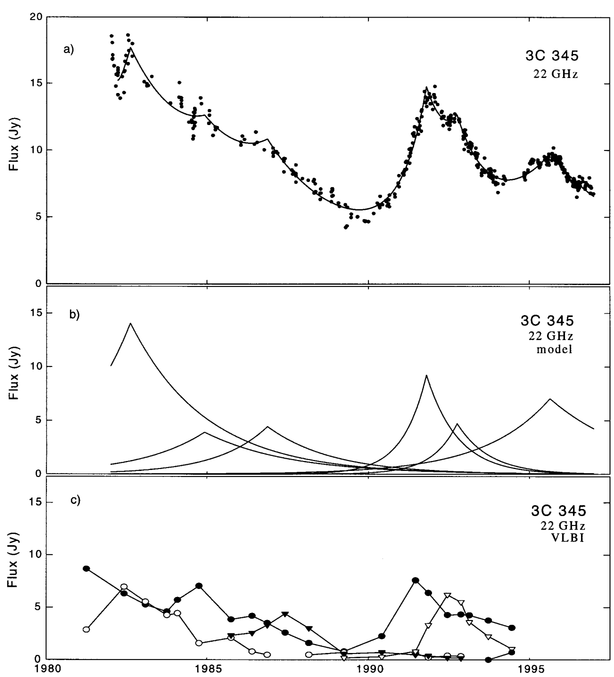

FIG. 2.—(*a*) 22 GHz total flux density evolution of 3C 345 between 1980 and 1996 from the Metsähovi monitoring program, with superposed model fit. (*b*) Model fit decomposed into individual flare components. (*c*) Evolution of the VLBI component fluxes (see the main text for references). Note the good correspondence between the major VLBI components and the model flares. Symbols: C4, *open circles*; C5, *filled triangles*; C7, *open triangles*; D, *filled circles*.

the latest TFD flare peaking in 1995.7. The flux density evolution of each component, as seen in the VLBI data, is in good accordance with the TFD model decompositions, especially considering the uncertainties inherent in making and in calibrating VLBI maps. The TFD model flare peaking in 1991.8 is identified as a "brightening of the core D" in the VLBI maps; however, it seems likely that in this case a new shock responsible for the flux changes has not been well resolved from the core. Indeed, multifrequency monitoring shows that the 1991 radio outburst evolved similarly to other outbursts seen in 3C 345 (Stevens et al. 1996), and so the outburst was unlikely to be a "core" brightening (i.e., brightening of the underlying jet; see Valtaoja 1996). Similarly, the 1984.9 TFD flare is seen only as a "core brightening" in the VLBI maps.

We have also compared single-epoch 22 GHz VLBI observations with our flux decompositions. The largest published 22 GHz VLBI sample is the VSOP prelaunch survey of Moellenbrock et al. (1996), consisting of single-epoch observations of 140 AGNs. For 58 of these sources we have simultaneous TFD monitoring data from which the flare flux could be estimated and compared with the correlated flux found in the VLBI survey. The survey did not produce any VLBI maps, and so individual components cannot be identified. Also, the data are not of uniform resolution and quality. Nevertheless, as Figure 3 shows, a good correlation between the correlated VLBI flux and the TFD flare flux is found. This is in accordance with our earlier result comparing correlated 22 GHz VLBI fluxes with TFD flare fluxes (Valtaoja et al. 1992).

Figure 3 also includes data from the VLBI surveys of Bloom et al. (1997), Wiik & Valtaoja (1998), and Wiik et al. (1998). In both surveys 22 GHz maps are produced, and so we can in most cases compare the TFD flare fluxes with corresponding individual VLBI component fluxes, not just with the integrated values as in the case of the Moellenbrock et al. (1996) survey. Again, a good correlation is found.

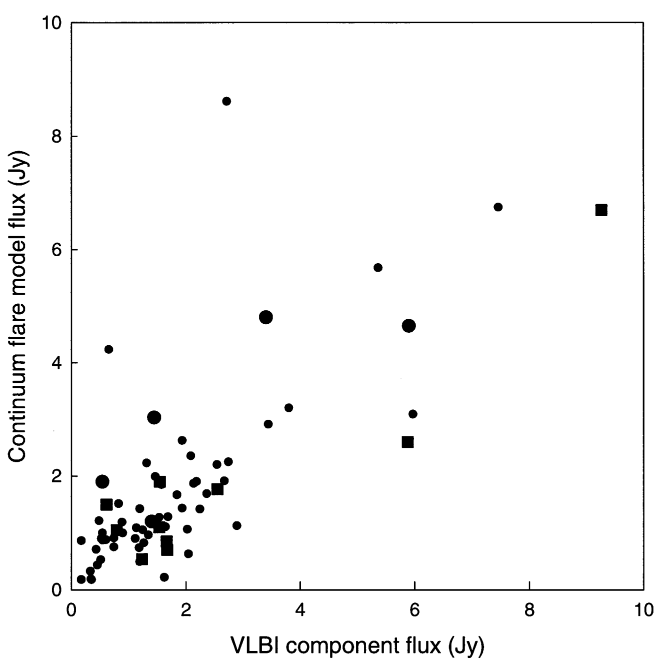

FIG. 3.—Correlated 22 GHz VLBI total flux density of 56 sources from the survey by Moellenbrock et al. (1996) compared with the flare fit model flux ΔS at the time of the VLBI observations (*small circles*); the 22 GHz fluxes of the VLBI components from the Bloom et al. (1997) survey compared with the fluxes of model flares identified with the VLBI components (*large squares*); and similar data from the Wiik et al. (1998) survey (*large circles*). Two strong, complex sources in the Moellenbrock et al. survey are not shown: 3C 84 (VLBI flux 1.6 Jy, ΔS 15.8 Jy) and 3C 273 (VLBI flux 7.79 Jy, ΔS 15.3 Jy).

In summary, we find that our TFD decomposition flare components do seem to correspond to VLBI components within the accuracy allowed by the uncertainties in both the TFD monitoring data, the VLBI data, and the simple model used. The model flares can therefore be used to trace the evolution of the shocked regions, in particular their total flux densities, variability timescales (and variability sizes), brightness temperatures, and the epochs of their creation ("the epochs of zero separation" in the VLBI parlance).

4. DISCUSSION

We have found that a simple decomposition of TFD variations at 22 and 37 GHz into a small number of exponential flares provides a good description both of the individual flares and of the total flux density variations over the years. The flux density of an individual decomposed flare component at any given time corresponds well to the flux density of the VLBI component identified with the flare. In the case of 3C 345, the only source for which sufficient data are presently available, the flux evolution of the individual flares also corresponds well to the flux evolution of the corresponding VLBI components.

We have not found any clear examples of well-defined single radio outbursts that cannot be adequately modeled with flares having an exponential rise, a sharp turnover, and an exponential decay with a timescale approximately 1.3 times longer than the rise timescale. We never see a flare with a flat top plateau, such as the original (Marscher & Gear 1985) model predicted. The lack of the plateau stage has been known from previous investigations, and our study emphasizes the generality of this result (e.g., Valtaoja et al. 1992; Litchfield et al. 1995; Stevens et al. 1995).

Other functions could of course be made to fit the data. In particular, we note that functions of the form $S(t) = S_0 t^n$, with $n > 3$, resemble exponential functions over a limited range, and could be made to fit the rise stages of the flares, as was done by Legg (1984). However, our exponential function, with fewest free parameters, provides the simplest acceptable fit to the radio flares.

The exponential character is not explicitly predicted by the shock models, although generalized shock model light curves (Valtaoja et al. 1992; Litchfield et al. 1995) do show approximately exponential rise and decay stages. The exponential character of both the rise and the decay stages (i.e., the constancy of the variability timescale during the shock growth or decay) can be taken as a new observational input for theoretical models. In the model of Marscher & Gear (1985) the shock starts as a thin cylindrical slice of the jet and subsequently expands along the jet. Because of relativistic aberration, we preferentially see the jets at right angles to the axis, and so the constancy of the variability timescale τ could be understood if the transverse width of the jet does not change appreciably along the length traversed by the shock during its early development.

Flux decomposition is a simple but potentially very useful way of modeling high radio frequency variations and using the variability data in various applications.

1. The flux decomposition provides a simple characterization of the general radio state of the source at any given time (rising flare, peaking flare, decaying flare, quiescent time), and gives the phases and the amplitudes of the flares. This can be used to advantage in comparing radio variations with other regimes, for example gamma rays where paucity of data excludes correlation analysis (Valtaoja & Teräsranta 1995, 1996; Lähteenmäki et al. 1997, 1998c).

2. The decompositions can be used to estimate shock variability timescales (τ) and sizes ($L \propto c\tau$), associated apparent brightness temperatures ($T_b \propto \Delta S/\tau^2$), and required Doppler boostings [$D = (T_b/T_{b,\mathrm{lim}}^{1/3})$]. This approach has already been used in Teräsranta & Valtaoja (1994) and Valtaoja & Teräsranta (1994), and will also be further explored in Paper III. The derived Doppler boosting factors are arguably more accurate than the ones derived by traditional methods, e.g., from synchrotron self-Compton (SSC) estimates. Together with expansion speeds v/c derived from VLBI observations, they can be used to estimate the intrinsic Lorentz factors and the viewing angles of the sources (Teräsranta & Valtaoja 1994; Lähteenmäki & Valtaoja 1997a; Paper III).

3. The shock components found by flux decomposition can be identified with components seen in VLBI maps (component fluxes and zero epochs), facilitating the often uncertain identification of the VLBI components and helping to avoid the stroboscopic effect in interpreting the motions from sparsely sampled VLBI maps. Since the dependence of the observed parameters (flux, size, brightness temperature) on Doppler boosting and the intrinsic brightness temperature is different for TFD variations and for VLBI observations, both D and $T_{b,\mathrm{int}}$ of a shock component can be estimated from comparisons of simultaneous TFD and VLBI data (Wiik & Valtaoja 1998; Wiik et al. 1998).

4. The limiting synchrotron brightness temperature $T_{b,\mathrm{lim}}$ (corresponding to the highest $T_{b,\mathrm{int}}$ found in the sources) can be estimated from comparisons with VLBI data as described above. Alternatively, Doppler boosting factors derived by some other method independent of the assumed value of $T_{b,\mathrm{lim}}$ (such as SSC estimates) can be compared with variability-derived Doppler factors dependent on the assumed value of $T_{b,\mathrm{lim}}$, giving an estimate of the limiting brightness temperature (Lähteenmäki & Valtaoja 1998; Paper II).

Finally, it would be interesting to see whether higher frequency variations, from millimeter to optical and beyond, could also be modeled with a single universal exponential flare shape. At present, however, the sampling of the flux curves is not sufficient for such comparisons.

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