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TOTAL FLUX DENSITY VARIATIONS IN EXTRAGALACTIC RADIO SOURCES. II. DETERMINING THE LIMITING BRIGHTNESS TEMPERATURE FOR SYNCHROTRON SOURCES

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ABSTRACT

The maximum intrinsic brightness temperature $T_{b,\mathrm{lim}}$ for powerful synchrotron-emitting radio sources is usually assumed to be $\approx 10^{12}$ K, limited by the inverse Compton catastrophe. A lower value of $\approx 5 \times 10^{10}$ K, based on the equipartition brightness temperature, has been suggested by Readhead on the basis of $T_{b,\mathrm{obs}}$ distributions derived from VLBI observations. We present two new methods for estimating $T_{b,\mathrm{lim}}$ in extragalactic radio sources by using total flux density variations. A reasonable estimate of the value of $T_{b,\mathrm{lim}}$ for a source can be obtained by comparing the Doppler boosting factors derived from total flux density variations at 22 and 37 GHz with traditional estimates based on the radio and synchrotron self-Compton (SSC) X-ray fluxes. Another independent estimate of $T_{b,\mathrm{lim}}$ is obtained by comparing the brightness temperatures derived from variability data with the values calculated from VLBI observations. Using several data sets, we find that both methods yield a value of $\leq 10^{11}$ K, in accordance with the equipartition brightness temperature limit proposed by Readhead.

Subject headings: galaxies: photometry — radiation mechanisms: nonthermal — radio continuum: galaxies — X-rays: galaxies

1. INTRODUCTION

The observed brightness temperature in a source is

$$T_{b,\mathrm{obs}} \propto \frac{S}{\theta^2 \nu^2}\,, \tag{1}$$

where S is the flux, ν is the frequency, and θ is the angular diameter of the source. The angular size can either be measured directly with VLBI or computed from the flux density variability timescale. The observed brightness temperature can be transformed to the source proper frame by multiplying by $(1 + z)$ in the case of VLBI, and by $(1 + z)^3$ in the case of flux density variations.

The upper limit $T_{b,\mathrm{lim}}$ for the intrinsic brightness temperature $T_{b,\mathrm{int}}$ in incoherent synchrotron sources such as active galactic nuclei (AGNs) is usually taken to be $\approx 10^{12}$ K, independent of wavelength (Kellerman & Pauliny-Toth 1969). This limit marks the beginning of the inverse Compton (IC) process, which rapidly leads to catastrophic electron energy losses and the suffocation of synchrotron emission. Under nonstationary conditions, the 10^{12} K limit may be exceeded, and brightness temperatures up to 10^{15} K and more may be reached during the first few days after the injection of relativistic electrons (Slysh 1992). The IC process produces X-ray photons from a population of relativistic synchrotron electrons via the synchrotron self-Compton (SSC) mechanism. In a number of sources, the X-ray spectra follow the radio spectra smoothly in shape, strength, and simultaneous variations—an important feature in confirming the presence of the SSC process. Yet we observe sources with $T_{b,\mathrm{obs}} > 10^{12}$ K and no IC-scattered X-ray emission, although the high photon and relativistic electron densities imply a strong X-ray flux. The commonly accepted explanation for observed brightness temperatures exceeding the synchrotron limit is relativistic boosting in the source, which affects the observed properties. The relativistic speed of the jet in a radio source changes its apparent flux density, making it appear much brighter, blueshifts the radiation, and compresses the timescales. The Doppler boosting factor in a jet making an angle ϕ to the line of sight and having an intrinsic Lorentz factor Γ is

$$D = [\Gamma(1 - \beta \cos \phi)]^{-1}\ . \tag{2}$$

Relativistic beaming enhances the observed variability brightness temperature by a factor D^3, and the VLBI brightness temperature by a factor D. Consequently, if $T_{b,\mathrm{lim}}$ is known, an observed brightness temperature in excess of the limiting value can be used to calculate the Doppler boosting factor of the source and further to estimate its Lorentz factor and viewing angle using the VLBI expansion speeds (e.g., Teräsranta & Valtaoja 1994; Lähteenmäki & Valtaoja 1997).

Readhead (1994) has argued that instead of the inverse Compton catastrophe limit, a more reasonable upper value for the intrinsic brightness temperature is $\leq 10^{11}$ K, based on the assumption that the sources are near equipartition of energy between the radiating particles and the magnetic field. Readhead has pointed out that the inverse Compton catastrophe occurs only in conditions requiring enormous departures from the equipartition and minimum-energy conditions, and further suggested that some as yet unknown mechanism may instead maintain the sources close to equipartition. For such a source, the corresponding intrinsic brightness temperature, called the equipartition brightness temperature T_{eq} by Readhead, is weakly dependent on the redshift, the observing frequency, the observed flux, and the spectrum of the source. For reasonable values of these parameters, T_{eq} is within a factor of 2 of 5×10^{10} K. In support of this equipartition limit, Readhead has analyzed VLBI data for samples of compact powerful radio sources, which appear to show an upper cutoff in the observed brightness temperature distribution consistent with T_{eq}, if modest Doppler boosting is also assumed to be present. Such a value for $T_{b,\mathrm{lim}}$, an order of magnitude lower than the commonly accepted limit of $\approx 10^{12}$ K, would among other things mean that the amounts of Doppler boosting in compact radio sources have hitherto been systematically underestimated, with important implications for source physics and unification scenarios.

In principle, $T_{b,\mathrm{int}}$ can be estimated from simultaneous total flux density and VLBI observations by calculating $T_{b,\mathrm{obs}}$(VLBI) and $T_{b,\mathrm{obs}}$(var), and then eliminating the common unknown factor D. Alternatively, if the value of D is known, then $T_{b,\mathrm{int}}$ can be calculated from either value of $T_{b,\mathrm{obs}}$. The upper limit $T_{b,\mathrm{lim}}$ can then be estimated from the distribution of the $T_{b,\mathrm{int}}$ values. Güijosa & Daly (1996) have compared the SSC Doppler boosting factors calculated from radio and X-ray data with equipartition Doppler boosting factors calculated from $T_{b,\mathrm{obs}}$(VLBI) and T_{eq}. Using a sample of 105 sources, they found that D_{SSC} and D_{eq} are, in general, comparable, supporting the equipartition limit hypothesis. However, the calculated SSC and equipartition boosting factors are not independent, since the same observed quantities (frequency, flux, apparent size) are used in the calculation of both.

In this paper we instead attempt to solve the crucial question of the true value of $T_{b,\mathrm{lim}}$ by using the total flux density variation data at 22 and 37 GHz obtained in the Metsähovi quasar monitoring program (Teräsranta et al. 1992, 1998), presented in § 2. In § 3 we compare the brightness temperatures of sources with simultaneous VLBI and total flux density observations in order to obtain estimates for $T_{b,\mathrm{int}}$. In § 4 we use traditional Doppler factors based on observed SSC X-ray fluxes to calculate the intrinsic brightness temperatures $T_{b,\mathrm{int}}$ for a number of sources. We estimate the observed variability brightness temperatures $T_{b,\mathrm{obs}}$(var) by modeling the total flux density variations with exponentially growing and decaying flares. This method, presented in Valtaoja et al. (1998, hereafter Paper I), provides a good description of major total flux density variations. We have adopted the operative definition that major radio variations exceed 10% of the total flux density and have timescales exceeding 10 days. This is sufficient to exclude intraday and other rapid small-scale variations at 22 and 37 GHz that may have different origins (Wagner & Witzel 1995). By excluding smaller variations occurring in timescales of days, we also avoid possible strongly nonstationary situations (Slysh 1992). As §§ 3 and 4 show, our results strongly indicate that the equipartition brightness temperature proposed by Readhead does provide a good estimate for the limiting intrinsic brightness temperature in strong, compact extragalactic radio sources. Preliminary results of this study have earlier been presented in Lähteenmäki & Valtaoja (1998). In Lähteenmäki et al. (1998, hereafter Paper III) we will consider the implications of this result for the Doppler boosting factors, the viewing angles, and the unified models of AGNs.

2. THE DATA AND THE CALCULATION OF VARIABILITY BRIGHTNESS TEMPERATURES

The almost 20 yr of continuum monitoring of active galaxies with the Metsähovi 13.7 m radio telescope has resulted in an extensive database at 22 and 37 GHz. It consists of ≈ 130 sources, many of which have been observed since 1980. Monitoring data prior to 1990.5 have been published by Salonen et al. (1987) and Teräsranta et al. (1992).

By using this unique high-frequency total flux density variation data, we have calculated the intrinsic variability brightness temperature and the Doppler boosting factor for each source in the database. The method is described thoroughly in Paper I. First we subtracted the quiescent flux level of the source from the total flux density, to account for the contribution of the constant flux from the nonvariable components. For each source, we then identified the well-defined outbursts and fitted each of them with the commercial PeakFit program, using a function with an exponential rise, a sharp turnover, and an exponential decay with a timescale 1.3 times longer than the rise timescale. For such an exponential outburst, the logarithmic variability timescale

$$\tau_{\mathrm{obs}} = \frac{dt}{d(\ln S)} \quad (3)$$

remains constant during the growth (or decay) stage. Next we calculated the observed variability brightness temperature (in the source proper frame),

$$T_{b,\mathrm{obs}}(\mathrm{var}) = 5.87 \times 10^{21}\, h^{-2}\, \frac{\lambda^2 S_{\mathrm{max}}}{\tau_{\mathrm{obs}}^2} (\sqrt{1+z} - 1)^2 \,, \quad (4)$$

where λ is the observed wavelength in meters, S_{max} is the maximum amplitude of the outburst in janskys, z is the redshift, and τ_{obs} is the observed variability timescale in days. (The numerical factor in eq. [4] corresponds to using $H_0 = 100\, h$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$, and to assuming that the source is a homogeneous sphere.) The observed variability brightness temperature is related to the Doppler boosting factor D_{var} and to the intrinsic brightness temperature $T_{b,\mathrm{int}}$ by

$$D_{\mathrm{var}} = \left[\frac{T_{b,\mathrm{obs}}(\mathrm{var})}{T_{b,\mathrm{int}}}\right]^{1/3} . \quad (5)$$

To get optimal results, we chose only the sources that had at least one strong radio outburst with good data coverage and that could be fitted reliably, giving us 76 sources for which $T_{b,\mathrm{obs}}$(var) could be calculated for one or more outbursts.

For comparison with VLBI-derived values of $T_{b,\mathrm{obs}}$(VLBI), we did a similar fitting at the epoch of each VLBI observation. Instead of S_{max} in equation (4), we used ΔS, the amplitude of the flare at the time of the VLBI observation, thus obtaining the associated $T_{b,\mathrm{obs}}$(var) for comparison with simultaneous $T_{b,\mathrm{obs}}$(VLBI). Altogether, we used three different VLBI data sets, obtaining a total of 48 individual pairs.

3. ESTIMATING $T_{b,\mathrm{lim}}$ FROM SIMULTANEOUS VLBI AND VARIABILITY DATA

We have compared the total flux density variation brightness temperatures $T_{b,\mathrm{obs}}$(var) at 22 GHz with brightness temperatures from simultaneous 22 GHz VLBI observations using three different VLBI data sets: the VSOP Pre-Launch Survey (hereafter PLS; Moellenbrock et al.

1996), and those of Bloom et al. (1998) and Wiik et al. (Wiik et al. 1998; Wiik & Valtaoja 1998). The PLS sample is constructed of 140 compact flat- or inverted-spectrum extragalactic radio sources observed at 22 GHz. It was motivated by the VLBI space satellite mission VSOP (VLBI Space Observatory Program), launched in 1997 February with the satellite *HALCA*, and was intended to provide guidelines for the VSOP scientific observing program at 22 GHz as well as for future space VLBI missions and for millimeter VLBI. However, for almost half of the 140 sources, only the lower limit of $T_{b,\mathrm{obs}}$(VLBI) is available. Furthermore, simultaneous data from Metsähovi sufficient for estimating $T_{b,\mathrm{obs}}$(var) exists for only a fraction of the PLS sources. Altogether, this leaves a total of 33 sources for comparisons with the PLS sample. The Bloom et al. (1998) sample consists of multiwaveband observations of 30 flat-spectrum quasars and radio galaxies with strong millimeter-wave emission, 17 of which were observed with VLBI at 22 GHz. Finally, there are 15 bright AGN in the Wiik et al. (1998) sample, previously unobserved with 22 GHz VLBI. Here, too, the lack of simultaneous Metsähovi data reduces the number of sources. In addition, we could not always identify a clear VLBI shock component for comparison with the continuum flare data. The total number of useful sources in the Bloom et al. sample is 10, and in the Wiik et al. sample there are five.

A notable limitation to our method arises from the quality of the VLBI data. Most of the data used here (the PLS sample) provide us with the brightness temperature of the whole source rather than brightness temperatures of separate components, since no maps were made. Fortunately, the Bloom et al. (1998) and Wiik et al. (1998) samples include 22 GHz VLBI maps, allowing us to identify the shocks and thus determine the VLBI brightness temperature of the component corresponding to the total flux density flare and the associated variability brightness temperature. This provides us with much more accurate estimates of $T_{b,\mathrm{int}}$, but the number of sources is small. However, a note of caution is necessary even here. Generally, the source structure is completely resolved in only a few VLBI measurements. Even if actual brightness temperatures (instead of lower limits) are derived from the data, some of them may still be underestimated, since the sources may contain more compact unresolved components. In order to minimize such underestimates, we have used only global 22 GHz data.

For each source, we calculated $T_{b,\mathrm{obs}}$(var) at 22 GHz from our variability data at the epoch of the corresponding 22 GHz VLBI observation. Because of the different dependence of $T_{b,\mathrm{obs}}$(var) and $T_{b,\mathrm{obs}}$(VLBI) on the Doppler factor, $T_{b,\mathrm{int}}$ can be estimated. For VLBI, the formula for the observed brightness temperature is

$$T_{b,\mathrm{obs}}(\mathrm{VLBI}) = T_{b,\mathrm{int}}(\mathrm{VLBI})D_{\mathrm{VLBI}} . \quad (6)$$

For continuum observations,

$$T_{b,\mathrm{obs}}(\mathrm{var}) = T_{b,\mathrm{int}}(\mathrm{var})D_{\mathrm{var}}^3 . \quad (7)$$

Assuming that both the total flux density and the VLBI observations relate to the same component, we can eliminate D and get $T_{b,\mathrm{int}}$ for each source:

$$T_{b,\mathrm{int}} = \sqrt{\frac{T_{b,\mathrm{obs}}(\mathrm{VLBI})^3}{T_{b,\mathrm{obs}}(\mathrm{var})}} . \quad (8)$$

We find that the observed variability and VLBI values of $T_{b,\mathrm{obs}}$ correlate with the probability $P_{\mathrm{Spearman}} < 0.00005$. Figure 1 shows $T_{b,\mathrm{obs}}$(VLBI) versus $T_{b,\mathrm{obs}}$(var). At the upper end of the $T_{b,\mathrm{obs}}$ distribution, the variability brightness temperatures are much larger than the VLBI brightness temperatures, as expected if the sources are Doppler boosted ($D > 1$; eqs. [6] and [7]). At the lower end, the VLBI brightness temperatures are larger, again as expected if these sources are Doppler deboosted ($D < 1$). In an ideal case, the data would lie along a straight line with a slope of $\frac{1}{3}$. Even in the real world, the data points are nearly all

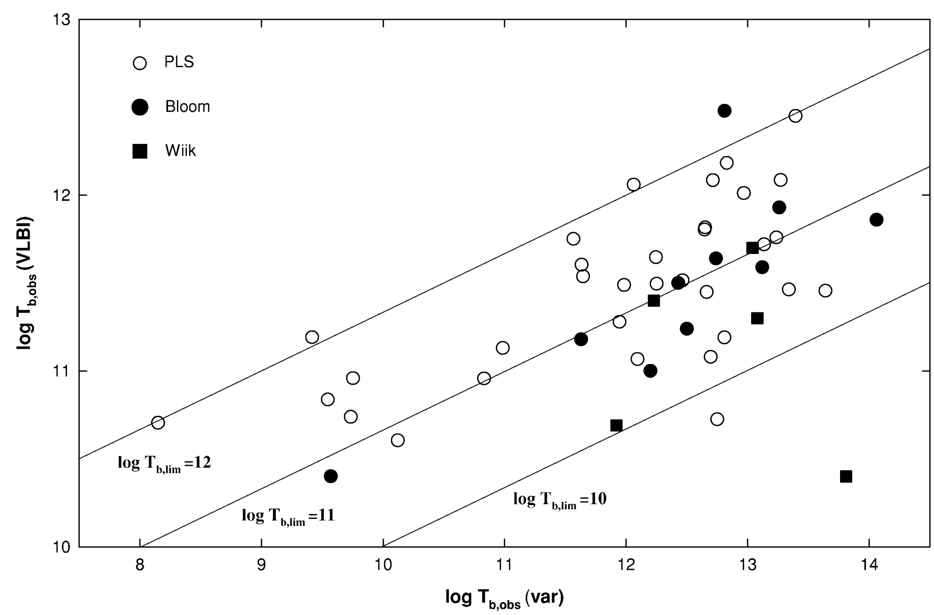

FIG. 1.—Observed brightness temperatures (source frame) derived from VLBI data and from total flux density variations. *Open circles*: VSOP Pre-Launch Survey of Moellenbrock et al. (1996). *Filled circles*: Bloom et al. (1998) survey. *Filled squares*: Wiik et al. (1998) survey. The straight lines correspond to intrinsic brightness temperatures of 10^{12} K, 10^{11} K, and 10^{10} K.

located between lines corresponding to 10^{10} K < $T_{b,\mathrm{int}}$ < 10^{12} K. With three exceptions, the most reliable data points (from the Bloom et al. 1998 and Wiik et al. 1998 samples) are close to the 10^{11} K line. The medians for the three samples are, as listed in Table 1:

1. For the PLS sample, $\log T_{b,\mathrm{int}} = 11.24 \pm 0.10$ ($N = 33$).
2. For the Bloom et al. (1998) sample, $\log T_{b,\mathrm{int}} = 10.89 \pm 0.17$ ($N = 10$).
3. For the Wiik et al. (1998) sample, $\log T_{b,\mathrm{int}} = 10.41 \pm 0.43$ ($N = 5$).

In order to estimate the errors in the brightness temperatures shown in Figure 1, we have made a series of tests. We have made a number of independent model fits to the Wiik et al. (1998) sample sources using both spherical and ellipsoidal components, and with Gaussian and uniform brightness distributions. From fits to 19 different VLBI components, we find that the median uncertainty in $\log T_{b,\mathrm{obs}}$(VLBI) caused by the choice of the model component geometry alone is ± 0.20. Considering calibration and other errors inherent in the VLBI observations, this must be a very conservative lower limit to the true error in the component brightness temperatures derived from VLBI data. In the case of the PLS, where only brightness temperatures integrated over the whole source are available, the uncertainty is larger still.

One possible source of error in estimating $T_{b,\mathrm{int}}$ from Figure 1 is the fact that the VLBI brightness temperatures are systematically underestimated because of insufficient resolution. This would lead to a higher value of $T_{b,\mathrm{int}}$. However, the Bloom et al. (1998) and Wiik et al. (1998) sample values are derived from careful model fits to resolved shock components, so a systematic underestimation is not likely.

For the total flux density estimates, the largest uncertainty in the case of well-defined isolated flares comes from the subtraction of the quiescent flux, which cannot be accurately determined from total flux density monitoring alone (cf. Paper I). This affects both the estimated flare flux $S_{\max}$ (or ΔS) and the variability timescale τ_{obs} (eq. [4]). We have made model fits to 45 representative flares using the two extreme alternatives: no quiescent flux removal before the exponential flare fit, and removal of the whole observed minimum flux density before the fitting process. The median difference between the two calculated values for $T_{b,\mathrm{obs}}$(var), $\Delta T/T$, is 0.50, which gives a conservative *upper* limit to the error in $T_{b,\mathrm{obs}}$(var), comparable to the *lower* limit of $T_{b,\mathrm{obs}}$(VLBI). (For some individual total flux density flares, however, the errors may be larger because of uncertainties in the model fitting procedure.)

Comparing these error estimates with the data in Figure 1 and the median errors of the samples given above, we conclude that all our data are consistent with the assumption that *all* sources have intrinsic brightness temperatures close to the equipartition limit of $\approx 10^{11}$ K. One should note that this result is independent of the actual amounts of Doppler boosting in the sources, and seems to hold both for the highly Doppler boosted sources (Fig. 1, *upper right corner*) and for the Doppler "deboosted" sources with $T_{b,\mathrm{obs}} \ll T_{b,\mathrm{int}}$ (Fig. 1, *lower left corner*).

TABLE 1

MEDIAN VALUES OF $\log T_{b,\mathrm{int}}$ FOR ALL DATA SETS

Method	Data Set	N	$\log T_{b,\mathrm{int}}$
VLBI & SSC......	3C 345	1	10.82 ± 0.41
VLBI..............	Wiik et al. (1998)	5	10.41 ± 0.43
VLBI..............	Bloom et al. (1998)	10	10.89 ± 0.17
VLBI..............	PLS	33	11.24 ± 0.10
SSC	Güijosa & Daly (1996)	48	11.30 ± 0.20

4. ESTIMATING $T_{b,\mathrm{int}}$ FROM DOPPLER BOOSTING FACTORS AND VARIABILITY DATA

4.1. *Synchrotron Self-Compton Estimates*

We have compared our Doppler boosting factors derived from variability brightness temperatures with the SSC Doppler factors from Güijosa & Daly (1996), based on the data originally collected by Ghisellini et al. (1993). This is the largest existing sample of SSC Doppler factors so far, giving D_{SSC} for 105 sources. For 48 of these sources, sufficient flux density data have been accumulated in the Metsähovi monitoring program to estimate the variability brightness temperature for at least one flare, at either 22 or 37 GHz. In the case of sources with more than one well-fitted flare, we have used the highest reliable value of $T_{b,\mathrm{obs}}$(var) in the comparisons.

If we assume that the variability and the SSC Doppler factors are equal (as they should be), the intrinsic brightness temperature can be calculated for each source:

$$D_{\mathrm{var}} = \left[\frac{T_{b,\mathrm{obs}}(\mathrm{var})}{T_{b,\mathrm{int}}}\right]^{1/3} = D_{\mathrm{SSC}} \qquad (9)$$

$$\Leftrightarrow T_{b,\mathrm{int}} = \frac{T_{b,\mathrm{obs}}(\mathrm{var})}{D_{\mathrm{SSC}}^{3}} . \qquad (10)$$

We again find a high correlation, this time between the variability and the SSC values of D, with probability $P_{\mathrm{Spearman}} = 0.0002$. Figure 2 shows the distribution of the variability and the SSC Doppler factors for the 48 sources. Although the data points are scattered because of the uncertainties, one can see that $T_{b,\mathrm{int}} \approx 10^{11}$ K provides the best general agreement between the two totally independent estimates of the Doppler boosting factors. The median value for $\log T_{b,\mathrm{int}}$ is 11.30 ± 0.20 (see Table 1), well below the inverse Compton limit and in agreement with the values derived in the previous section.

One problem with the SSC Doppler factors is that they are not very reliable. D_{SSC} depends strongly on the flux and the size of the source. Even small deviations in these observed quantities affect the final result severely. Even worse, the values used are often totally wrong. It is usually impossible to identify the component in which the X-ray originates. In addition, instead of the observing frequency and the corresponding observed flux, one should use the synchrotron turnover flux and frequency in the calculations. These have been accurately determined for only a handful of sources (e.g., Marscher & Broderick 1985), and most estimates of D_{SSC}, including those of Güijosa & Daly (1996), are based on whatever VLBI data happens to be available. Furthermore, the VLBI and X-ray observations are taken at different times, often years apart. The end result is that the values of ν, S, θ, S_{X}, etc., used in calculating the SSC Doppler factor usually bear little relation to the correct ones.

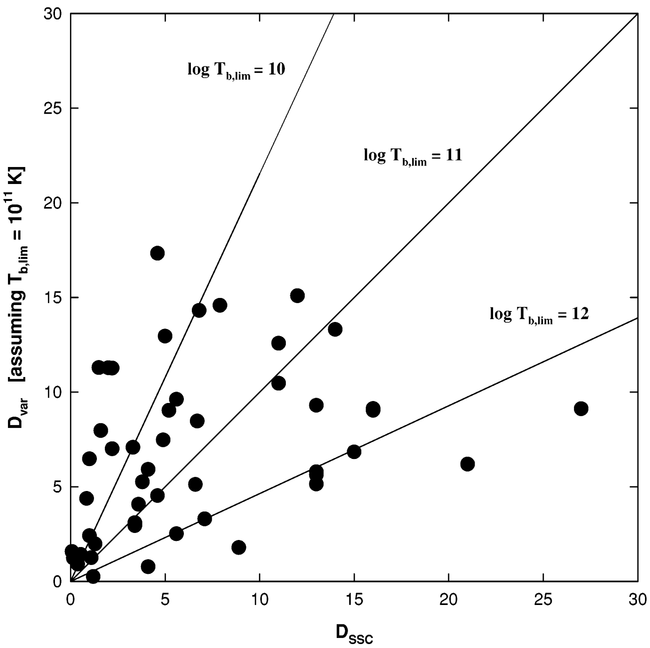

FIG. 2.—Doppler boosting factors derived from variability brightness temperatures vs. the SSC-derived boosting factors from Güijosa & Daly (1996). The $D_{\rm var}$ values have been calculated assuming $T_{b,\rm lim} = 10^{12}$ K. The straight lines show the expected dependence between $D_{\rm var}$ and $D_{\rm SSC}$ for various values of the intrinsic brightness temperature.

We will discuss the reliability of SSC Doppler boosting factors in more detail in Paper III. Here we only note that plotting $D_{\rm SSC}$ values derived by various authors from different data sets for the same sources generally results in almost pure scatter diagrams. Comparing the sources common to Madejski & Schwartz (1983), Zhang & Bååth (1996), and Güijosa & Daly (1996), we find that only in about half the cases do the derived Doppler boosting factors agree within a factor of 2, and for a significant fraction the values differ by an order of magnitude. This alone is sufficient to explain most of the scatter in Figure 2. In contrast, the formal errors in $D_{\rm var}$ are much smaller, since it depends only on the third root of the observed variability brightness temperature. However, variability data clearly show that $D_{\rm var}$ does not always stay constant from one outburst to another. Ideally, one should compare $D_{\rm SSC}$ and $D_{\rm var}$ calculated from simultaneous X-ray, VLBI, and total flux density observations. Use of noncontemporaneous data thus also increases the scatter in Figure 2 beyond the errors of the variability and SSC estimates.

In view of the uncertainties associated with the SSC Doppler boosting values shown in Figure 2, we again conclude that our data is in agreement with the hypothesis that all sources have intrinsic brightness temperatures close to the equipartition limit.

4.2. *Doppler Boosting Factors for 3C 345*

Other methods for estimating the Doppler factors in radio sources have also been suggested, all involving various assumptions (see Readhead 1994). Probably the best-studied radio source is 3C 345, for which various estimates of Doppler boosting factors have been presented in a very comprehensive study by Unwin et al. (1994). They applied several different methods for estimating the amount of Doppler boosting. They concluded that the Doppler factor for the brightest knot in the jet, also likely to be the origin of the X-ray emission, lies in the range $5.5 \leq D \leq 10.5$, with $D = 7.5$ as the best value. Based on contemporaneous X-ray multifrequency VLBI and other data, this is arguably the most reliable "traditional" estimate yet obtained for the amount of Doppler boosting in a radio source. From our monitoring data, we derive a value of 2.8×10^{13} K for the highest observed brightness temperature in 3C 345, corresponding to $T_{\rm int} = 2.8 \times 10^{13}/7.5^3 = 6.6 \times 10^{10}$ K. Once more, this is in agreement with the equipartition limit. (We note that if the intrinsic brightness temperature in 3C 345 were instead $\approx 10^{12}$ K, we should expect to see extremely spectacular rapid total flux density variations, corresponding to $T_{b,\rm obs}({\rm var}) \approx 4 \times 10^{14}$ K. These would appear very different from the ones actually seen in our total flux density monitoring of 3C 345.)

5. SUMMARY

We have calculated intrinsic brightness temperatures $T_{b,\rm int}$ for several samples of radio sources from total flux density variations using the Metsähovi 22 and 37 GHz continuum monitoring data and two different methods. $T_{b,\rm int}$ can be estimated by comparing the observed VLBI component brightness temperatures with the corresponding observed variability brightness temperatures (eq. [8]). Alternatively, $T_{b,\rm int}$ can be calculated from $T_{b,\rm obs}({\rm var})$ if we also have an estimate for the source's Doppler boosting, usually derived from SSC estimates (eqs. [9] and [10]).

In Figure 3 we show the distribution of $T_{b,\rm int}$ for each of the data sets. Most of the individual $T_{b,\rm int}$ values derived from all the different data sets are below 10^{12} K, clustering around the equipartition limit of $\approx 10^{11}$ K, in accordance with Readhead (1994). The numerical results for each data set are compiled in Table 1.

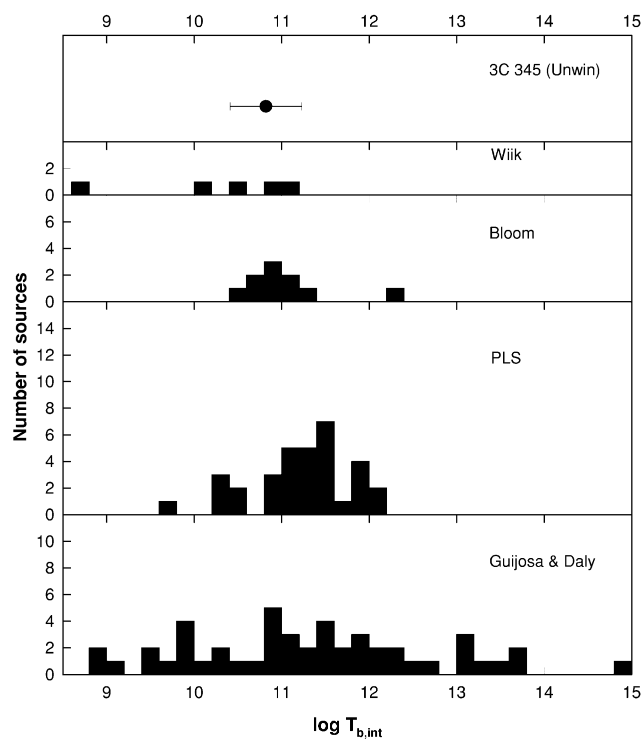

FIG. 3.—Intrinsic brightness temperatures calculated from the various data sets (see text for details).

In the case of the first method (the Wiik et al. 1998, Bloom et al. 1998, and PLS samples), the errors in the calculated values of $T_{b,\mathrm{int}}$ for individual sources can be estimated from equation (8), using the errors for $T_{b,\mathrm{obs}}$(var) and $T_{b,\mathrm{obs}}$(VLBI) estimated in § 3. We find that typically $(d \log T_{b,\mathrm{int}}) \geq 0.50$. This is comparable to the standard deviations of the individual measurements in the three samples. The second method (the Güijosa & Daly 1996 sample), with $T_{b,\mathrm{int}}$ calculated from equation (10), is less accurate because of the large uncertainty in D_{SSC}, enhanced by the third power. We estimate (see § 4) that $(d \log T_{b,\mathrm{int}}) \geq 1$, again comparable to the individual standard deviation in the sample. We therefore conclude that the spreads in the calculated values of $T_{b,\mathrm{int}}$ in the four data sets are most likely not caused by a spread in the true values of $T_{b,\mathrm{int}}$ between some 10^{10} K and 10^{12} K. Instead, essentially all the spread in $T_{b,\mathrm{int}}$ comes from the uncertainty in $T_{b,\mathrm{obs}}$(var), in $T_{b,\mathrm{obs}}$(VLBI), and in D_{SSC}, and the data are in accordance with the hypothesis that $T_{b,\mathrm{int}}$ is very close to 10^{11} K in all sources. In other words, all the synchrotron-emitting shocks in the relativistic jets of various AGNs appear to be initially as bright as they can be, close to the equipartition brightness temperature upper limit. After the growth and the maximum phases, lasting from a few months to a few years at frequencies ≥ 22 GHz, the shocks expand and decay, and their brightness temperatures eventually drop below T_{eq}, as both VLBI and total flux density observations at lower frequencies demonstrate.

Our data indicate that for every source, during high radio frequency flares $T_{b,\mathrm{int}}$ is close to 10^{11} K, with very little intrinsic scatter. We therefore argue that this limiting intrinsic brightness temperature $T_{b,\mathrm{lim}} \approx T_{\mathrm{eq}}$ can be used to obtain reliable estimates of the Doppler boosting factors D directly from the observed variability brightness temperatures (eqs. [4] and [5]). The viewing angle θ and the intrinsic Lorentz factor Γ of the flow can be determined if the Doppler boosting factor D and the apparent superluminal speed β_{app} (measurable from VLBI monitoring) are known (e.g., Ghisellini et al. 1993; Teräsranta & Valtaoja 1994; Guerra & Daly 1997). A correct value of D is therefore essential for obtaining estimates of the main source parameters. Using $T_{b,\mathrm{lim}} = 10^{12}$ K instead of 10^{11} K underestimates D by a significant factor of 2 in the case of total flux density variations and by a factor of 10 in the case of VLBI data (eqs. [6] and [7]).

In conclusion, we find that the limiting intrinsic brightness temperature for synchrotron sources is the equipartition value $T_{\mathrm{eq}} \approx 10^{11}$ K, as has been proposed by Readhead (1994), not the inverse Compton value of $\approx 10^{12}$ K. In addition, during the early phases of their evolution, *all* shocks seem to reach this limit, making it possible to accurately estimate their Doppler boosting factors from total flux density variation data alone. The results of these estimates will be presented in Paper III (Lähteenmäki et al. 1998).

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