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SPECTRAL DIAGNOSTICS OF BLAZAR CENTRAL ENGINES. III. SUBMILLIMETER FLARES IN BLAZARS

BRIAN PUNSLY
4014 Emerald Street, No. 116, Torrance, CA 90503
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ABSTRACT

This article investigates the difference in submillimeter flares in BL Lac objects and flat-spectrum radio quasars. It is shown that a strong distinction can be found in the low-frequency emission at centimeter wavelengths. This is ascribed to a mildly varying centimeter-peaked background spectral component that is far more powerful in quasar radio cores than in BL Lac objects. There is also a highly variable "millimeter peaked" component, the flaring component, which is similar in quasars and BL Lac objects. This analysis is supportive of the two-component spectral model discussed in Papers I and II of this series.

Subject headings: BL Lacertae objects: general — galaxies: active — galaxies: nuclei — quasars: general — radio continuum: galaxies

1. INTRODUCTION

The submillimeter flaring behavior of a sample of 13 blazars, five BL Lac objects, and eight flat-spectrum quasar radio cores reveals a difference between the two classes of objects at greater than 99.6% significance level (according to a Wilcoxon rank sum test). This distinction can be ascribed to the existence of a second spectral component, peaked at centimeter wavelengths, that is only mildly variable. The centimeter-peaked emission is relatively powerful in quasars and relatively weak in BL Lac objects.

The sample is drawn from the 17 blazars that were monitored from submillimeter to radio wavelengths in Stevens et al. (1994). Of these, 13 were deemed suitable for this study, the requirements being good frequency coverage and identification as either a quasar or BL Lac object. The object 0316+413 is a radio galaxy and 0430+052 is a Seyfert 1 galaxy, so they are not eligible for this analysis. The BL Lac object 1308+326 has huge relative errors in the 375 GHz data, and the quasar 1921−293 has no low-frequency monitoring. This leaves 13 objects for the following study.

2. ANALYSIS

The analysis is summarized in Table 1. Column (1) is the source name. The second column is the approximate date of the submillimeter flare, defined by a local flux density maximum as a function of time for the 375 GHz emission. The strength of the flare is measured relative to a baseline flux density at 375 GHz. This baseline is the flux density of the blazar during quiescent stages, F_Q. The relative strength of the submillimeter flare, $P(375)$, is defined as the ratio of the peak flux density, $F_\nu(\nu = 375\ \mathrm{GHz})$, and the quiescent flux density at 375 GHz, $F_Q(375)$:

$$P(375) \equiv [F_\nu(\nu = 375\ \mathrm{GHz})/F_Q(375)] \ . \tag{1}$$

The relative peak strengths of the submillimeter flares (defined as a flux density maximum more than 3 dB above the quiescent baseline), $P(375)$, are tabulated in column (3) for all the flares that were monitored in Stevens et al. (1994). The fourth column is the baseline flux density, $F_Q(375)$. Columns (5), (6), and (7) are the same for the corresponding 22 GHz flare. The quiescent flux density, $F_Q(22)$, is listed in column (7) for each blazar. The relative peak strength, $P(22)$, is found in column (6):

$$P(22) = [F_\nu(\nu = 22\ \mathrm{GHz})/F_Q(22)] \ . \tag{2}$$

Column (8) is the ratio of the relative peak strengths, R, for each flare:

$$R \equiv [P(375)/P(22)] \ . \tag{3}$$

When there is more than one monitored flare for an object, the R-values are averaged, $\bar{R}$ in column (9).

Question marks in the table indicate some uncertainty in the identification of the flare at that frequency. There are also two observations marked with note b. First, the 1988.8 375 GHz observation of 2251+158: To define a peak in flux density, one needs data just before and just after the maximum. These are not available for this observation; however, they are at 230 GHz. At 230 GHz, the peak of flare activity is at 1988.8. Thus, the 375 GHz data point at 1988.8 is considered the flux density maximum for that flare. Second, note the first entry for 0235+164. This submillimeter flare is monitored only at 230 GHz. This flare is included because it is clear that if it had been monitored at 375 GHz, all the conclusions of the following analysis would be weakened statistically. With so few flares (38 for 13 objects), this might be significant. If this measurement is not included, $\bar{R}$ for 0235+164 is 0.92 and the five BL Lac objects in the sample, 0235+164, 0735+178, 0851+202, 1413+135, and 2200+420, have the five lowest values of $\bar{R}$ in Table 1. According to a Wilcoxon rank sum test, the quasars have larger $\bar{R}$-values than BL Lac objects at the 99.9% significance level. If the 230 GHz flare for 0235+164 is included, this drops to a 99.6% significance level.

3. THE SOURCE OF THE BIMODAL BEHAVIOR OF $\bar{R}$

This behavior of R is attributable to a stronger quiescent baseline at 22 GHz in the quasar population. To see this, note that averaging the relative strength of the submillimeter flares, $\langle P(375)\rangle$, the quasars have only slightly larger values than the BL Lac objects in Table 1:

$$\langle P(375)\rangle_{\mathrm{quasar}} = 4.25 \pm 1.44 \ , \tag{4a}$$

$$\langle P(375)\rangle_{\mathrm{BL}} = 3.83 \pm 0.91 \ , \tag{4b}$$

TABLE 1

RELATIVE STRENGTH OF SUBMILLIMETER FLARES[a]

	375 GHz Flare			22 GHz Flare				
Source (1)	Date (2)	$P(375)$ (3)	Quiescent Flux Density (Jy) (4)	Date (5)	$P(22)$ (6)	Quiescent Flux Density Jy (7)	R (8)	$\bar{R}$ (9)
0235+164.....	1989.15[b]	5.86 (230 GHz)	0.70 (230 GHz)	1989.8	2.40	1.00	2.44	(1.30)[c]
	1990.2	3.50	0.60	1990.5	3.70	1.00	0.95	0.92
	1991.2	3.83	0.60	1991.2	3.85	1.00	0.99	0.92
	1992.8	5.00	0.60	1992.8	6.10	1.00	0.82	0.92
0420−014.....	1990.5	4.43	0.70	1990.5	1.79	2.90	2.47	2.35
	1991.8	5.43	0.70	1991.8	2.44	2.90	2.23	2.35
0735+178.....	1989.6	4.31	0.65	1989.3	4.32	1.2	1.00	1.01
	1990.8	4.00	0.65	1991.0	3.92	1.2	1.02	1.01
0736+017.....	1990.05	3.05	0.40	1990.2	2.71	0.85	1.13	1.24
	1991.6	2.00	0.40	1991.9	2.14	0.85	1.05	1.24
	1992.2	3.05	0.40	1992.4	2.92	0.85	1.86	1.24
	1993.95	3.50	0.40	1993.95	1.88	0.85	0.93	1.24
0851+202.....	1989.45	4.38	0.80	1989.45	3.33?	1.8	1.32	1.04
	1990.0	3.20	0.80	1990.0	3.89	1.8	0.82	1.04
	1991.25	3.00	0.80	1991.85	3.78	1.8	0.79	1.04
	1993.95	2.00	0.80	1993.8	1.61	1.8	1.24	1.04
1156+295.....	1990.4	4.10	0.25	1990.6	2.12	0.85	1.94	1.76
	1993.1	3.64	0.25	1993.1	2.29	0.85	1.59	1.76
1226+023.....	1988.2	6.50	3.00	1988.9	1.80	20.0	3.60	2.63
	1990.45	7.00	3.00	1991.1	1.85?	20.0	3.78	2.63
	1991.2–1991.5	5.33	3.00	1991.7	2.80	20.0	1.90	2.63
	1992.2	3.67	3.00	1992.4	2.20	20.0	1.67	2.63
	1993.3	4.67	3.00	1993.9	2.21	20.0	2.22	2.63
1253−055.....	1988.2	5.29	3.50	1988.7	1.75	8.00	3.02	2.25
	1990.8	5.43	3.50	1991.2	2.00	8.00	2.71	2.25
	1993.4	2.60	3.50	1993.8	2.56	8.00	1.01	2.25
1413+135.....	1990.0	3.50	0.60	1990.9?	7.92	0.50	0.44	0.44
	1991.9	3.75	0.60	1991.9	8.53	0.50	0.44	0.44
1641+399.....	1991.8	5.78	0.90	1991.9	3.11	4.70	1.86	...
2200+420.....	1989.9	3.72	0.78	1989.9	4.20	1.20	0.87	0.85
	1993.25	3.59	0.78	1993.25	4.30	1.20	0.83	0.85
2223−052.....	1988.7	6.47	0.85	1988.9	2.78	2.70	2.33	1.82
	1990.0	5.18	0.85	1990.4	3.96	2.70	1.31	1.82
2251+158.....	1988.8[b]	3.55	1.90	1989.1	2.14	5.00	1.66	1.34
	1991.1	2.56	1.90	1991.1	1.50	5.00	1.70	1.34
	1992.25	2.21	1.90	1992.5	2.12	5.00	1.04	1.34
	1993.2	3.00	1.90	1993.2	2.75	5.00	1.10	1.34
	1994.0	3.55	1.90	1994.0	2.92	5.00	1.22	1.34

[a] Relative strengths of flares at 375 GHz, $P(375)$, and at 22 GHz, $P(22)$, for a sample of blazars.
[b] See text for detailed discussion.
[c] Includes the 230 GHz observation in the calculation of the mean ratio of relative peak strengths.

However, the 22 GHz flares have very different relative strengths:

$$\langle P(22)\rangle_{\rm quasar} = 2.36 \pm 0.55\ , \tag{5a}$$

$$\langle P(22)\rangle_{\rm BL} = 4.43 \pm 1.90\ . \tag{5b}$$

Both equations (4) and (5) incorporate the 230 GHz flare in 0235+164.

It might be conjectured that equation (5) is simply a consequence of the fact that the flares in quasars decay at higher frequencies (see Stevens et al. 1994) than BL Lac flares (quasar flares are intrinsically different than BL Lac flares). However, if this phenomenon exists, it can be shown that its effect on the behavior of "R" is relatively minor. To demonstrate this, using Table 1, one can compute the flux excess over the quiescent value at both 375 GHz and 22 GHz during a flaring event:

$$F_\nu(\nu = 375\ {\rm GHz}) - F_Q(375)\ , \tag{6a}$$

$$F_\nu(\nu = 22\ {\rm GHz}) - F_Q(22)\ , \tag{6b}$$

respectively (where F_ν is the flux evaluated during the peak of flare activity). From this one can generate a ratio, to obtain the relative flare strength at 22 GHz, FS:

$$\mathrm{FS} \equiv \frac{F_\nu(\nu = 22\ {\rm GHz}) - F_Q(22)}{F_\nu(\nu = 375\ {\rm GHz}) - F_Q(375)}\ . \tag{6c}$$

There are 13 BL Lac flares in Table 1 that were sampled at both 22 GHz and 375 GHz. The average flare strength, $\overline{\mathrm{FS}}$, of this group of 13 spectra is

$$\overline{\mathrm{FS}}(\text{BL Lac objects}) = 1.96 \pm 0.58\ . \tag{7a}$$

Similarly, for the 23 quasar flares sampled at both 22 GHz and 375 GHz,

$$\overline{\mathrm{FS}}(\mathrm{quasars}) = 1.67 \pm 0.76 \ . \tag{7b}$$

The flare strength, FS, of the BL Lac flares is larger than those of quasars with only an 85% statistical significance (Wilcoxon rank sum test). One might think that this result is not accurate because there are more flares of certain objects than others, so these heavily sampled objects would weight the statistics unfairly. Thus, we compute alternatively the average flare strength, FS, from the flares of each object to obtain a single value of each object. Thus, there are 13 of the average flare strengths (eight average flare strengths for quasars and five for BL Lac objects). Using the average flare strength for each of the objects, the average flare strength of BL Lac objects is only larger than that of quasars at the 78% significance level (Wilcoxon rank sum test).

The flare strengths in equation (7) can be used to compute the average effective index of the flares between 22 GHz and 375 GHz, $\bar{\alpha}_{\mathrm{FS}}$ (the convention chosen in this paper is that a positive spectral index corresponds to a negative logarithmic spectral slope):

$$\bar{\alpha}_{\mathrm{FS}}(\mathrm{BL\ Lac\ objects}) = 0.238 \ , \tag{8a}$$

$$\bar{\alpha}_{\mathrm{FS}}(\mathrm{quasars}) = 0.181 \ . \tag{8b}$$

The effective spectral index of the flares (eq. [8]) and the flare strength (eq. [7]) do not distinguish quasar flares from BL Lac flares.

Conversely, look at the ratio of the quiescent spectral fluxes at 22 GHz and 375 GHz, R_Q:

$$R_Q \equiv [F_Q(22)/F_Q(375)] \ . \tag{9}$$

There are five BL Lac objects in Table 1, and the average ratio of quiescent fluxes, $\bar{R}_Q$, is computed from the table using equation (9) to be

$$\bar{R}_Q(\mathrm{BL\ Lac\ objects}) = 1.63 \pm 0.53 \ . \tag{10a}$$

Similarly, for the eight quasars,

$$\bar{R}_Q(\mathrm{quasars}) = 3.71 \pm 1.57 \ . \tag{10b}$$

A Wilcoxon rank sum test shows that R_Q is larger for quasars than for BL Lac objects at the 99.84% significance level. Converting equations (10a) and (10b) to average spectral indices of the quiescent spectra between 22 GHz and 375 GHz, $\bar{\alpha}_Q$, one finds

$$\bar{\alpha}_Q(\mathrm{BL\ Lac\ objects}) = 0.173 \ , \tag{11a}$$

$$\bar{\alpha}_Q(\mathrm{quasars}) = 0.463 \ . \tag{11b}$$

Equations (7) and (10) make it clear that the distinction between $\langle P(22)\rangle_{\mathrm{quasar}}$ and $\langle P(22)\rangle_{\mathrm{BL}}$ in equation (5) is a consequence of the fact that the background quiescent spectra in quasars have a large centimeter excess compared to those in BL Lac objects. This means ultimately that this excess quiescent centimeter emission in quasars is also the reason for the distinction of R values between quasars and BL Lac objects. By contrast, equation (7) and the related nonparametric statistical analysis reveal that the flares in BL Lac objects and quasars have similar flare strengths. Gear et al. (1994) also found that BL Lac objects have flatter spectra than quasars. However, due to a limited number of measurements for each object (generally three observations or less for each blazar), the flaring behavior could not be segregated from the quiescent background flux, as is accomplished in this analysis.

4. INTERPRETING R IN A TWO-COMPONENT MODEL

In Paper I (Punsly 1996a) and Paper II (Punsly 1996b), it was argued that two distinct jets are required to explain the γ-ray luminosity of quasars with strong extended radio structure (§ 6, Punsly 1996a) and the observed polarization properties in the optical and radio of compact radio sources (Björnsson 1993 and § 5 of Punsly 1996a). The two-jet model was able to explain various correlations of the radio to far-infrared spectra with seemingly unrelated physical observables (optical polarization, radio polarization, extended radio luminosity, and redshift). In Punsly (1996b), it was shown that much of this behavior can be anticipated from extant hydromagnetic models of the central engine. Furthermore, these models and the predicted correlations are consistent with many evolutionary properties of powerful radio sources as well. It is posited in Punsly (1996a) that the putative "millimeter peak" in the spectra of compact radio sources is associated with the "blazar jet." There is another jet (associated with a disk in the ergosphere of a black hole) that radiates a spectrum peaked at centimeter wavelengths. This ergosphere driven jet is the primary radiative component in VLBI jets that feed strong FR II radio emission. In a typical BL Lac object with an FR I extended luminosity, this second jet is weak and the "blazar jet" is at least equally prominent on VLBI scales. In quasars (and not generally in BL Lac objects), the ergosphere-driven jet is the primary source of the centimeter spectral peak.

The results of Table 1 combined with equations (4), (5), (7) and (10) have a natural interpretation within the two-component model described in Papers I and II. Note first that the average spectral indices of the flares, $\bar{\alpha}_{\mathrm{FS}}$ in equation (8), are very similar to the average spectral index of the quiescent emission in BL Lac objects, $\bar{\alpha}_Q$ (BL Lac objects) in equation (11a). The putative "blazar jet" is ubiquitous in compact radio sources, and it is highly variable. In Papers I and II, FR I BL Lac objects are considered to be nearly naked "blazar jets." Therefore, as mentioned above in relation to equations (8) and (11a), a spectral index $\alpha \approx 0.2$ from 22 GHz to 375 GHz is expected. (This also follows from Table 1 of Punsly 1996a.) This suggests that typically strong submillimeter flares are associated with the "blazar jet" in both quasars and BL Lac objects. During flaring stages, the variable component constitutes the dominant portion of the total luminosity at 375 GHz in both BL Lac objects and quasars. Equation (8) suggests that the flares have fairly flat spectra between 22 GHz and 375 GHz for the most part. The centimeter emission from the flaring "blazar jet" provides spectral variability at 22 GHz as well. There is a second component, the ergospheric disk–driven jet, and it is very strong in quasars. This second jet is primarily responsible for the centimeter emission in the quiescent spectra of quasars (in BL Lac objects the second jet is weak, so the "blazar jet" contributes significantly at centimeter wavelengths as well). The flux density of the second jet is peaked at centimeter wavelengths and is only mildly variable in comparison with the "blazar jet." This strong centimeter component dilutes the relative strengths of the flares at 22 GHz in quasars, explaining equations (5), (7), and (10) (consistently with eq. [8]) and therefore the lower R values of BL Lac objects compared to quasars in Table 1.

5. THE TAXONOMY OF FLARING BEHAVIOR

There is a whole panoply of flaring behaviors observed in compact radio sources. The most common flare has a time delay on the order of 2–3 months between the peak of the 375 GHz emission and the peak of the 22 GHz emission (Stevens et al. 1994). The magnitude of the flare flux (the flux magnitude of eqs. [6a]–[6b]) is usually larger at 22 GHz than 375 GHz, as indicated by equation (7). Sometimes there is no evidence of a time delay between the 22 GHz and 375 GHz peaks. Also about $\frac{1}{5}$ of the time the 375 flare flux (see eqs. [6a]–[6b]) is larger than (this occurs primarily in quasars) the flux at 22 GHz. Some submillimeter flares do not appear to become centimeter flares (I. Robson 1993, private communication).

The most common type of flare has a description in terms of the Marscher & Gear (1985) shock propagation model as demonstrated in Stevens et al. (1994). One or a series of radiative blobs are generated at the base of the "blazar jet." The blobs initially have a strong peak in the submillimeter that dominates emission at 375 GHz. As the blobs propagate along the "blazar jet," they expand and radiate more prominently at centimeter wavelengths, yielding the time delay between the 22 GHz and 375 GHz flares. In quasars, at 22 GHz there is a strong centimeter quiescent component from the second (ergospheric disk–driven) jet. This dilutes the relative strength of the 22 GHz quasar flare as implied by equations (7) and (10).

Shock propagation in the "blazar jet" is not the only flaring behavior available to the two-jet system. The ergospheric disk–driven jet can also flare, but this flaring should be more mild relative to quiescent levels. Also, changes in the environment near the central engine can cause both jets to flare simultaneously. For example, according to the hydromagnetic models in Punsly (1996b), if a large amount of magnetic flux is accreted toward the putative central black hole, both jets would become stronger. An interesting related theoretical concern is the dynamical interaction of the energy exchange between the flaring "blazar jet" and the ergospheric disk jet on parsec scale distances from the central engine (i.e., does the flare in the "blazar jet" ultimately cause the other jet to flare at centimeter wavelengths?). Perhaps all these possibilities are needed to explain all the observed flaring behaviors—yet shock propagation in the "blazar jet" along the lines of Marscher & Gear (1985) is the most common radiative effect.

6. CONCLUSION

Both BL Lac objects and quasars have strong submillimeter flares that dominate high-frequency emission during active phases. This component is associated with the jet that radiates the "millimeter peak" found in blazar spectra. The millimeter peaked or flaring component is highly variable at all frequencies. The low-frequency spectrum of these flares becomes prominent at centimeter wavelengths as well as it propagates along the jet. However, there is a second jet that has a spectrum that is peaked at centimeter wavelengths, and it is less variable. This centimeter-peaked component is relatively weak in BL Lac objects and strong in quasars. In quasars, this jet is primarily responsible for the centimeter peak in the spectra, except during flaring stages. The strong emission from this second jet in quasars at centimeter wavelengths dilutes the strength of the flares at 22 GHz and is responsible for the statistically significant difference in the peak flux ratio, R of equation (3), between BL Lac objects and quasars.

The only evidence favoring the two-component model presented in this paper is that the flares in both BL Lac objects and quasars have very flat spectra (see eq. [8]). The spectral indices of the flares are similar to the spectral indices of the BL Lac quiescent spectra, not quasar quiescent spectra (see eq. [10] and Table 2 of Paper I). This suggests that

1. The flare-generating mechanism is common to quasars and BL Lac objects.
2. The radiative properties of the flares are similar to those of the VLBI core-jet emission seen in quiescent BL Lac objects as opposed to the quiescent emission in the VLBI core jet of quasars.

Combining points 1 and 2, one expects a jet common to all compact radio sources that supports the flares, and it is the type of jet that is prominent in BL Lac objects. In quasars, this jet is buried within another radiative component that has a strong centimeter excess. This is consistent with the discussions of Papers I and II that the "blazar jets" in BL Lac objects and quasars are similar (the flares are similar). The jet with a strong centimeter excess is very weak in BL Lac objects; they are nearly naked "blazar jets" (BL Lac objects have a flatter quiescent spectrum). Thus, the flares are a probe of the "blazar jet" in both BL Lac objects and quasars.

It has yet to be shown that shock propagation models in a single jet can explain all the observed flaring behaviors discussed in § 5. The two-component model offers more parameters for describing the wide variety of flaring behaviors observed.

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