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Correlation between the γ-ray and the radio emissions

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Abstract. In this paper, the correlation between the γ-ray and the radio bands is investigated. The results show that there is a closer correlation between the γ-ray emission and the high frequency (1.3mm, 230GHz) radio emission for maximum data than between the γ-ray and the lower frequency (5GHz) radio emissions, which means that the γ-ray is associated with the radio emission from the jet.

Key words: galaxies: active – quasars: general – gamma rays. observations – radio continuum: galaxies

1. Introduction

The most important result of the CGRO/EGRET instrument in the field of extragalactic astronomy is the discovery that blazars (i.e., flat-spectrum radio quasars–(FSRQs) and BL Lac objects) emit most of their bolometric luminosity in the high γ-ray ($E >$100 MeV) energy range. Many of the γ-ray emitters are also superluminal radio sources (von Montigny et al. 1995). The common properties of these EGRET-detected AGNs are the following: The γ-ray flux is dominant over the flux in lower energy bands; The γ-ray luminosity above 100 MeV ranges from less than 3×10^{44} erg/s to more than 10^{49} erg/s; Many of the sources are strongly variable in the γ-ray band on timescales from days to months, but large flux variability on short timescales of < 1 day has also been detected (see 0716+714 for instance, Cappi et al. 1994) and the photon spectrum in the EGRET energy range (30 MeV to 30 GeV) are generally well represented by power laws with an average photon spectral index of 2.0.

Various models for γ-ray emission have been proposed: (1) the inverse Compton process on the external photons (ECS), in which the soft photons are directly from a nearby accretion disk (Dermer et al. 1992; Coppi et al. 1993) or from disk radiation reprocessed in some region of AGNs (e.g. broad emission line region) (Sikora et al. 1994; Blandford & Levinson 1995); (2) the synchrotron self-Compton model (SSC), in which the soft photons originate as synchrotron emission in the jet (Maraschi et al. 1992; Bloom & Maraschi 1992, 1993; Zdziarski & Krolik 1993); (3) synchrotron emission from ultrarelativistic electrons and positrons produced in a proton-induced cascade (PIC) (Mannheim & Biermann 1992; Mannheim 1993; Cheng & Ding 1994). From these models it is clear that the γ -ray emission is from the jet. Observations suggest that most of the objects in the EGRET sample show superluminal motion, which yields also strong evidence that the γ-ray radiation from these objects comes from the relativistic jets and is strongly beamed.

As the models indicate, there is no consensus yet on the dominant emission process (see $3C273$ for instance, von Montigny et al. 1997). It is well known that the emission might imply various relations among wave bands that can be used to distinguish among a variety of emission mechanisms. Dondi & Ghisellini (1995) have studied the correlation between emission in the γ-ray and in the lower energy bands, and found that the γ-ray luminosity is more correlated with the radio luminosity than with other bands luminosities (e.g. optical and X-ray band); but M$\ddot{u}$cke et al. (1997) reported that there is no correlation between the γ-ray and the radio bands. Xie et al. (1997) found that the luminosity correlation between the γ-ray and the infrared band is closer than that between the γ-ray and the optical or the X-ray band. Fan (1997) has investigated the correlation between the γ-ray band and the lower energy bands by means of the multiple regression method. He found that there is an indication of a correlation between the γ-ray flux and the radio flux while there is no correlation between the γ-ray flux and the optical flux or between the γ-ray flux and the X-ray flux, and proposed that the γ-ray emission is from the SSC process and that the correlation between the γ-ray and the radio bands is probably due to the fact that both the γ-ray and the radio emissions are beamed. Observations show that there is a correlation between the γ-ray and radio bands (Valtaoja & Ter$\ddot{a}$sranta 1995) although there is no simple one-to-one relation between them (Pohl et al. 1996; M$\ddot{u}$cke et al. 1996a). We think that the reason for these different results comes from the following factors: 1) Luminosity-luminosity correlation can not be considered as a true correlation because of the known fact that luminosity depends on redshift; 2) The lower frequency radio emission is not only from the jets and is variable; 3) The γ-ray emissions show large flux variation (von Montigny et al. 1995, see also Hartman 1996). These facts suggest that the correlation between the γ-ray and the radio bands is difficult to conclude. So, we will propose that it is necessary to use the high frequency radio data to investigate the association between the γ-ray and the radio band emissions. Here we will use the observed maximum data in the γ-ray and radio bands, the sources are listed in Table 1. In Sect. 2, we give the data and the correlation between the γ -ray and the radio bands; In Sect. 3, we give some discussion.

2. Correlation

2.1. Data

Blazars are known to be strongly variable in the γ-ray as well as in the radio band on time scales of days to months (von Montigny et al. 1995). Therefore, simultaneous observations should be adequate for a correlation analysis (M$\ddot{u}$cke et al. 1997). Unfortunately, there is scarity of such simultaneous observations. So, we can only choose the observed maximum high frequency data in the radio band at 230GHz and the observed maximum data in the γ-ray band to investigate the correlation between the γ-ray and the radio emission. Radio data obtained after 1990 have been chosen because this corresponds to the operation period of EGRET.

In this paper, we discuss 44 γ-ray loud AGNs with available high frequency radio (230 GHz) flux densities (see Table 1). 35 are FSRQs (19 highly polarized quasars – HPQs with $P > 3\%$; 11 are lowerly polarized quasars–LPQs with $P < 3\%$; and 5 objects have no available polarization measurements); 9 of which are BL Lac objects and are marked with a †. Col.1 gives the name of the source; Col. 2, the redshift, Col.3, the observed maximum γ -ray photon in 10^{-7}photon/cm^2/s with the error, Col. 4, the spectral index; Col.5, reference for Col. 3 & 4; Col. 6, the radio flux in Jy at 5GHz; Col. 7, reference for Col. 6 (see also Comastri et al. 1997; M$\ddot{u}$cke et al. 1997); Col. 8 the observed maximum high frequency radio flux in Jy and the error, Col. 9 references for Col. 8. As in the paper of Comastri et al. (1997), the adopted γ-ray data of 1622-297 is not the peak value of (210±70)$\times 10^{-7}$photon/cm^2/s (Mattox & Wagner 1996) but the data compiled by Mukherjee et al. (1997). It is found that the γ-ray spectrum tends to harden with increasing γ-ray flux for EGRET sources (Mücke et al. 1996b). A strong correlation has also been found for the spectral index and the integral flux above 100MeV for 3C273 (von Montigny et al. 1997). So, we chose the flat spectral index if there are more than one spectral index available for the sources considered in the paper.

2.2. Analysis results

The observed photons are converted to flux densities at 1GeV. It is done as follows: If the the photon density is expressed as $n(\nu) = n_0\nu^{-(\alpha_\gamma+1)}$, then the flux density can be expressed as $f_\nu = n(\nu)h\nu \propto n_0\nu^{-\alpha_\gamma}$. n_0 can be determined from the observation result (N photon/cm^2/s), N photon/cm^2/s should be equal to $\int_{100MeV} n(\nu)d\nu$. So, we obtained a formula to convert the observed photons to the flux densities at 1 GeV,

$$f_{1GeV}(pJy) = N_{(>100MeV)}\alpha_\gamma 10^{(2-\alpha_\gamma)}$$

where $N_{(>100MeV)}$ is in a unit of 10^{-7} photons/cm^2/s. The flux densities are k-corrected according to $f_\nu = f_\nu^{ob.}(1+z)^{\alpha-1}$,

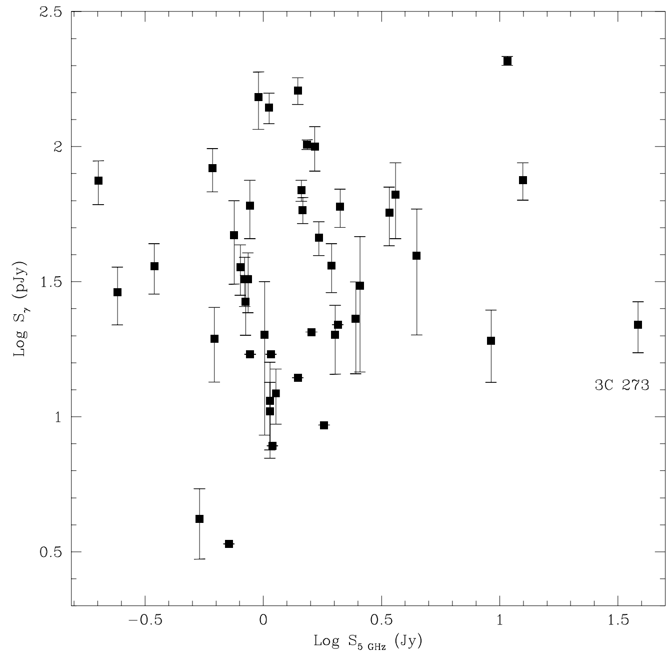

Fig. 1. The diagram of γ-ray flux density in pJy against the radio flux density in Jy at 5 GHz

where α is the spectral index at the frequency ν ($f_\nu \propto \nu^{-\alpha}$). The spectral index is set to 0.87 and 1.25 for BL Lac objects and FSRQ (Comastri et al. 1997) for which the γ-ray spectral index is unknown, and it is chosen to be 0.0, following M$\ddot{u}$cke et al. (1997) for radio band. For BL Lac object 0716+714, a lower limit of $z = 0.3$ has been adopted, and for 0446+112, a redshift of 1.0 has been used because the redshift is about 1.0 for most objects listed in the table. When the linear regression analysis is performed on the data, the following results are obtained:

$$logf_\gamma = (0.15 \pm 0.02)logf_{5GHz} + (1.49 \pm 0.001) \quad (1)$$

with a correlation coefficient of $r = 0.16$ and a possibility of the relationship having occurred by chance $p = 36\%$.

$$logf_\gamma = (0.28 \pm 0.01)logf_{230GHz} + (1.55 \pm 1.8 \times 10^{-4}) \quad (2)$$

with $r = 0.347$ ($p = 1.7\%$), where f_γ stands for the observed maximum γ-ray flux density in pJy, f_{5GHz} and f_{230GHz} stand for the observed radio flux density in Jy at 5 GHz and 230 GHz respectively. The results are shown in Figs. 1 and 2.

3. Discussion

Observations show that the γ-ray loud AGNs are clearly associated with compact, flat radio spectrum sources. These objects show evidence for superluminal motion (von Montigny et al. 1995). Schachter & Elvis (1993) reported that there is a correlation between the γ-ray and radio emission at 6cm (5GHz), but a negative result was reported by M$\ddot{u}$cke et al. (1997). We think that the problem is from the facts mentioned in the introduction. For large γ-ray flares in blazars, they only occur when the sources are in a high state, and many blazars are detected only

Table 1. A sample of γ-ray loud AGNs with available high frequency radio data at 230 GHz.

$Name$	$Redshift$	$N_{(100MeV)}(\sigma)$	α_γ	References	f_{5GHz}	Ref	$f_{230GHz}(\sigma)$	Reference
0202+149	1.202	2.6(0.60)	1.50	F94	2.49	K81	0.85(0.07)	T96
0208-512	1.003	13.19(2.47)	0.70	T95,M97	3.31	K81	2.60(0.21)	T96
0234+285	1.213	2.91(1.13)	1.70	T95	2.36	P82	2.66(0.30)	S92
0235+164†	0.940	8.25(0.91)	0.90	T95	2.85	S91	3.82(0.31)	T96
0336-019	0.852	18.62(0.76)		M97	2.84	K81	1.35(0.12)	T96
0420-014	0.915	5.12(1.05)	0.90	T95,M97	3.72	P82	5.34(0.38)	T96
0440-003	0.844	8.44(1.20)		M97	3.17	W85	0.78(0.07)	S92
0446+112		11.3(2.06)	0.80	T95	1.22	K81	1.39(0.12)	T96
0454-234	1.009	1.40		vM95	2.20	L85	0.88(0.06)	T96
0454-463	0.858	2.90	0.90	vM95	2.97	K81	0.51(0.04)	T96
0458-020	2.286	3.08(0.95)		M97	2.04	L85	0.92(0.10)	T96
0506-612	1.093	0.60		vM95	1.50	K81	0.45(0.04)	T96
0521-365	0.055	3.75(1.12)	1.2	T95,M97	9.70	K81	3.98(0.32)	T96
0528+134	2.070	30.76(3.46)	1.30	T95,M97	4.30	P82	4.21(0.35)	T96
0537-441†	0.894	8.98(1.45)	1.00	T95,M97	4.00	S91	5.73(0.46)	T96
0716+714†		4.40(1.1)	0.90	T95,M97	1.12	K81	3.03(0.31)	S92
0735+178†	0.424	4.09(2.13)		M97	3.65	G94	0.92(0.11)	T96
0827+243	0.939	6.81(1.44)	1.30	M97,F94	0.67	B91	1.33(0.11)	T96
0836+710	2.172	4.53(1.13)	1.40	T95	2.67	P82	0.93(0.09)	S93
0851+202†	0.306	2.90		Sh96	2.70	K81	2.50(0.26)	T96
0906+430	0.670	3.20		C97	1.80	K81	0.40(0.04)	S88
0954+658	0.368	1.43(0.40)	0.90	T95	1.46	K81	0.54(0.05)	S88
1127-145	1.187	9.27(2.29)	1.15	S96	7.46	K81	1.22(0.09)	T96
1156+295	0.729	22.86(5.48)	1.0	T95	1.65	G94	0.83(0.08)	T96
1219+285†	0.102	1.7	0.40	vM95	0.97	G91	0.19(0.04)	T96
1222+216	0.435	8.29(2.02)	0.90	T95	1.26	G91	0.45(0.04)	T96
1226+023	0.158	5.57(1.19)	1.40	T95,M97	44.59	K81	26.18(1.80)	T96
1229-021	1.045	1.41(0.41)	1.92	S96,T95	1.10	K81	0.18(0.03)	T96
1253-055	0.538	28.70(1.09)	0.90	T95	16.58	K81	15.26(1.07)	T96
1406-076	1.494	12.7 (2.34)	1.0	M97,T95	0.5	C97	0.76(0.06)	T96
1510-089	0.361	4.83(1.80)	1.3	T95	3.35	K81	2.42(0.37)	T96
1606+106	1.227	6.03(1.28)	1.20	T95	1.78	K81	0.64(0.30)	T96
1622-297	0.815	24.56(3.18)	1.2	M97	1.92	K81	1.0	M96
1633+382	1.814	10.51(0.94)	0.90	T95	4.08	W85	1.4 (0.15)	S93
1730-130	0.902	13.69(4.29)	1.39	T95	6.90	Gr94	2.61(0.19)	T96
1739+522	1.375	5.38(1.11)	1.2	T95	1.98	K81	0.56(0.09)	S88
1741-038	1.054	3.40	2.00	vM95	3.72	K81	1.43(0.12)	T96
1933-400	0.966	9.66(3.3)	1.40	T95	1.48	K81	0.63(0.05)	T96
2005-489†	0.071	1.8		vM95	1.50	C97	0.79(0.07)	T96
2052-474	1.489	3.76(2.16)	1.40	T95,M97	2.52	K81	0.66(0.05)	T96
2155-304†	0.117	3.23(0.78)	0.71	V95,M97	0.27	L85	0.33(0.03)	T96
2200+420†	0.07	7.81(3.83)	1.21	Ca97,M97	4.77	K81	5.4 (0.6)	S93
2230+114	1.037	4.90(1.4)	1.60	L96,T95	4.10	P82	2.28(0.16)	T96
2251+158	0.859	13.17(2.07)	1.20	L96,T95	23.30	W85	10.80(0.87)	T96

†: BL Lac object

References:

B91: Becker et al. (1991); Ca97: Catanese et al.(1997); C97: Comastri et al(1997); F94: Fichtel et al.(1994); G91: Gregory & Condon (1991); G94: Gear et al. (1994); Gr94: Griffith et al. (1994); K81: K$\ddot{u}$hr et al. (1981); L85: Ledden & O'Dell (1985); L96: Lin et al. (1996); M96: Mattox & Wagner (1996); M97: Mukherjee et al. (1997); P82: Perley (1982); S88: Steppe et al.(1988); S91: Stickel et al. (1991); S92: Steppe et al.(1992); S93: Steppe et al.(1993); S96: Sreekumar et al.(1996); Sh96: Shrader et al.(1996); T95: Thompson et al.(1995); T96: Tornikoski et al.(1996); V95: Vestrand et al.(1995); vM95: von Montigny et al.(1995); W85: Wall & Peacock (1985)

in a flare state (Hartman 1996; also see McHardy 1996). So, a γ-ray emitter is more easily detected when it is in a flare state. If the γ-ray emission is from the SSC model, there should be a correlation for the fluxes in the flare between the radio flux and the γ-ray flux. The $f_\gamma - f_{radio}$ correlation places an observational constraint on the γ-ray radiation mechanism and can be applied to test the radiation models of the emitting region. It is clear from Sect. 2 that there is a correlation for the maximum

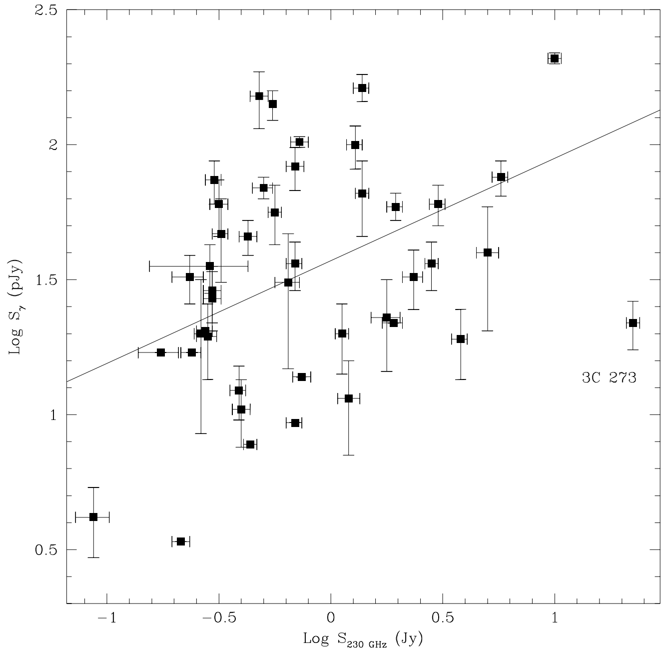

Fig. 2. The diagram of γ-ray flux density in pJy against the radio flux density in Jy at 230 GHz, the solid line shows the best fit with $3C273$ excluded

fluxes between the γ-ray and the 230GHz bands, but the correlation between the γ-ray and the radio emission at 5 GHz is weaker.

It is well known that both the radio radiation of blazars and the γ-ray emission are strongly beamed, which means that there should be a correlation between the γ-ray and the radio data in the jets, and it is hard for us to get a good correlation between the γ-ray and the (5 GHz) radio band since the 5 GHz radio flux is not wholly from the jet. That may be why different results have been reported.

From the figures, we can see that $3C273$ lays at bottom right, which suggests that the object was not in its flare state when it was observed. If we exclude this object, a better correlation: $logf_\gamma = (0.38 \pm 0.02) logf_{230GHz} + (1.57 \pm 4 \times 10^{-4})$ with $r = 0.421 (p = 5.0 \times 10^{-3})$ shows up (see the straight line in Fig. 2), which means that the γ-ray is associated with the high frequency radio emission or with the radio emission in the jets and suggests that the γ-ray emission is likely from the SSC process in this case. From the correlation, letting $\alpha_\gamma = 1.0$, we would expect that the flare value of 3C273 is about 20×10^{-7}photon/cm^2/s in the $E >$100MeV band.

The association between the γ-ray and the radio bands has been further investigated. Recently, Valtaoja & Teräsranta (1995) found a correlation between the initial phase of a mm-wavelength outburst and the EGRET γ-ray flaring phase of high optically polarized quasars. Our results is consistent with theirs.

There is a correlation for the maximum data between the γ-ray and the high frequency radio emissions, which suggests that the high frequency radio emission (or radio emission in the jet) is very important for γ-ray emission.

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