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Blue Quasars and Blazar Unification Schemes

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ABSTRACT

Blue quasars (BQs) are sources with strong broad emission lines and flat hard X-ray spectra, properties that resemble classical flat spectrum radio quasars (FSRQs), and high peak frequencies and steep soft X-ray spectra, properties that resemble intermediate or high peak frequency BL Lacertae objects (IBLs and HBLs respectively). BQs challenge our understanding of blazar properties in terms of a luminosity sequence, which makes their incorporation into current blazar unification schemes problematic. In this work we show that this situation can be remedied if, in addition to the intrinsic luminosity, the orientation of the blazar jet is explicitly considered. We show, using published data, that the recently studied BQs are relatively misaligned blazars, and we examine the predicted aligned population. We examine both possible cases, sources with pure synchrotron spectra and sources with an optical–UV thermal contribution, for both constant velocity and accelerating jets. We show that the aligned sources are similar to FSRQs, and we suggest ways to distinguish between constant velocity and accelerating flows. We point out that IBLs are more aligned and less powerful than BQs and we address the very different emission line properties of these sources which display similar spectral energy distributions.

Subject headings: galaxies: active — galaxies: jets — BL Lacertae objects: general — radiation mechanisms: non-thermal

1. INTRODUCTION

Blazar–type active galactic nuclei (AGNs) are characterized by a luminous and rapidly variable spectral energy distribution (SED) extending from radio up to GeV and TeV energies (Urry & Padovani 1995). The blazar SED is characterized by two components. The first one peaks at IR to X-ray energies and it is most probably synchrotron radiation from electrons in a relativistic jet pointing close to the line of sight. The second one peaks at GeV–TeV energies and, according to leptonic models (for a recent review see Böttcher 1999), is inverse Compton (IC) emission from the

same electron population, synchrotron self Compton (SSC) scattering in the case of synchrotron seed photons and external Compton (EC) scattering in the case of external seed photons.

Unified schemes attempt to understand the properties of blazar samples using physical models coupled to scaling and/or geometrical arguments. One of the first unification problems was the differences between two types of BL Lacertae objects (BLs, blazars with weak broad emission lines), the high peak frequency BLs (HBLs) and the low peak frequency BLs (LBLs). Maraschi et al. (1986) proposed that these differences could be explained assuming that the jet flow is accelerating and that LBLs form a smaller angle between the jet axis and line of sight than HBLs. Sambruna, Maraschi, & Urry (1996) argued that the range of observed properties in blazars cannot be reproduced solely under the different orientation hypothesis, and that physical changes need to be invoked to explain the gradual change of observed properties going from flat spectrum radio quasars (FSRQs) to LBLs to HBLs. The gap between HBLs and LBLs was filled with the discovery (Laurent-Muehleisen et al. 1999) of the intermediate BLs (IBLs), sources with peak frequencies at optical-UV energies and with properties intermediate between those of HBLs and LBLs. Georganopoulos & Marscher (1998) proposed a unification scheme for BLs based on two parameters, the intrinsic luminosity of the source and the orientation of the jet relative to the observer.

Fossati et al. (1998) and Ghisellini et al. (1998) pointed out a sequence of blazar properties as a function of source power. As the source power increases, the emission line luminosity and the ratio of Compton to synchrotron luminosity are increasing, while the synchrotron peak frequency ν_s and the IC peak frequency decrease. Recent multiwavelength studies support this scheme (e.g. Kubo et al. (1998)). Under this scheme, sources with strong emission lines should have low ν_s and IC-dominated flat X-ray spectra, and sources with high ν_s should be lineless and have steep X-ray spectra dominated by the high energy tail of the synchrotron emission. Recent observations (Sambruna (1997); Perlman et al. (1998); Sambruna, Chou & Urry (2000)) revealed a population of high energy peaked FSRQs, dubbed blue quasars (BQs), with properties that challenge the above scheme. These are sources with *ROSAT* (0.1–2.4 KeV) spectra steeper than those of FSRQs, similar to those of HBLs. At the same time they exhibit strong emission lines and, those observed with *ASCA* (Sambruna et al. 2000), flat hard X-ray (2–10 KeV) spectra similar to classical FSRQs. Sambruna et al. (2000) presented SEDs and *ASCA* observations of 4 BQs. As they note, these sources are peaking at optical–UV energies (although with the current data the location of the SED peak is still somewhat uncertain), and it is not clear if the optical to UV emission is synchrotron as in BLs or if it has a thermal emission component as in sources like 3C 273. They also point out that while these BQs have similar SEDs and *ASCA* spectral indices ($\alpha_{2-10 \text{ KeV}} \approx 0.8$) to IBLs, they have much stronger broad emission lines. In this work we address the unusual properties of BQs and their implications on blazar unification.

2. BLUE QUASARS

In Table 1 we present published data for the 4 BQs of Sambruna et al. (2000) and for two IBLs with sufficient observations, which we use for comparison purposes: source name, source type, ratio R of the extended (nonbeamed) to core (beamed) radio power, which is a measure of the alignment between the jet axis and the line of sight, extended radio power P_{ext} , and broad line region (BLR) power L_{BLR} . The smaller R and the higher P_{ext} and L_{BLR} of BQs indicate that BQs are more powerful and less aligned than IBLs. Additional evidence for the relative misalignment of 0923+392 (Kollgaard, Wardle & Roberts 1990) and 0405-123 (Morganti, Killeen & Tadhunter 1993) comes from the FR II like radio morphology of these sources. Given the relative misalignment of BQs we ask how the SED of the aligned version of these sources looks, and how these aligned sources compare with sources found in current blazar samples. We examine both cases for the optical–UV flux being only synchrotron or having an additional thermal contribution from an accretion disc. We use the jet formalism of ?, modified to include IC losses due to an external photon field and an angle dependent emission for both a constant Lorentz factor and an accelerating jet (Georganopoulos & Marscher 1998). In this work the IC emission is not modeled. Modeling the hard X-ray emission, which is probably due to SSC (Kubo et al. 1998), is highly complicated for the inhomogeneous jets studied here. Although we cannot address the hard X-ray emission quantitatively, we can discuss qualitatively the scaling of the observed hard X-ray flux of the BQs as a function of beaming, since the beaming behavior of the IC component is well understood (Dermer 1995).

2.1. Case A: Thermal component

We study first a constant Lorentz factor Γ jet together with a thermal component modeled as black body (BB) radiation. In Figure 1 we plot the SED for a range of angles θ between the jet axis and the line of sight. The jet emission is strongly affected by Doppler boosting and, as θ decreases, the non-thermal SED shifts mostly upward to higher apparent luminosities with a slight shift to higher peak frequencies, since $L \propto \delta^{3+\alpha} L_0$ and $\nu \propto \delta \nu_0$, where α is the spectral index, δ is the usual Doppler factor $\delta = 1/(\Gamma(1 - \beta_\Gamma \cos \theta))$, and the subscript 0 refers to quantities in the flow comoving frame. Since the BB and the BLR emission are not a function of θ , the relative contribution of the thermal component and the equivalent width (EW) of the emission lines (which are not plotted here, but are assumed to have a fraction of the BB luminosity) are reduced as θ decreases. We expect the IC ASCA component to either follow the increase of the synchrotron one if it is due to SSC emission or to increase even faster if it is due to EC emission, since $L_{SSC} \propto \delta^{3+\alpha}$ and $L_{EC} \propto \delta^{4+2\alpha}$ (Dermer 1995). In both cases, and depending on L_{BLR} , the aligned source will look like an LBL or a classical FSRQ, possibly similar to 3C 279, a source showing evidence of a thermal component in its optical–UV spectrum (Pian et al. 1999). It is interesting to note that for 3C 279, $\log L_{BLR} = 44.76 \text{ erg s}^{-1}$ (Cao & Jiang 1999), in the L_{BLR} range of the BQs examined here.

We study now the case of an accelerating jet. Higher frequencies emerge closer to the base of the jet, are characterized by lower Γ , and are therefore less sensitive to angle variations compared to the lower frequencies (Georganopoulos & Marscher 1998). As can be seen from the solid lines in Figure 2, as θ decreases, the non-thermal SED shifts upward to higher apparent luminosities, but this time with a large shift to lower ν_s , since the higher Γ of the low-frequency emitting plasma results to a larger increase in the low-frequency boosting. The relative contribution of the thermal component and the EW of the emission lines drop as the source becomes more aligned, although this is more gradual compared to the apparent luminosity and ν_s changes observed due to the frequency-dependent Doppler boosting. The IC *ASCA* component must be mostly due to the same plasma responsible for the sub-mm-IR emission, and is characterized by a Γ higher than the Γ of the X-ray emitting plasma. Therefore, as the source becomes more aligned, the IC component will progressively dominate over the synchrotron at lower frequencies. Qualitatively, the aligned population in this case is similar to the one predicted for a constant Γ jet. A discriminator between the two cases could be the detailed form of the SED for low R (more misaligned) objects. One would expect the synchrotron and the BB peak frequencies of the SED to be further apart in the constant Γ case, since in this case the synchrotron peak frequency has to be $\nu_s \sim 10^{12.5-13.5}$ Hz, close to the synchrotron peak frequency of classical FSRQs and LBLs, and the BB peak frequency $\sim 10^{15}$ Hz.

2.2. Case B: Synchrotron emission

We now assume that the observed SED of the BQs, with a peak at $\nu_s \sim 10^{14-15}$, is synchrotron radiation with no significant thermal contribution. As can be seen in Figure 3, aligning a constant Γ jet will boost up the apparent luminosity and will slightly increase ν_s . The EW of the emission lines (which are still assumed to be powered by an accretion disc) will be reduced, but the IC component will be boosted either as much as the synchrotron component (SSC case) or more (EC case). In both cases the aligned sources will be bright sources with $\nu_s \approx 10^{14-15}$, low EW emission lines, and a spectral flattening between *ROSAT* and *ASCA* energies, due to IC emission. Such high luminosity, high peak frequency sources, with hard X-ray IC spectra flatter than the synchrotron soft X-ray spectra have not been observed, and there is no obvious selection effect acting against detecting them. If such sources existed they would have been observed in X-ray selected BL samples. Therefore, the possibility of pure synchrotron emission and constant Γ jets is excluded for BQs.

The case of a synchrotron SED for an accelerating flow (Figure 2, broken line) is quite similar to the accelerating flow with the BB contribution and it is practically impossible to discriminate between the two without a detailed knowledge of the SED at optical-UV energies.

3. DIFFERENCES WITH IBLs

A question pointed out by Sambruna et al. (2000) is how can objects with similar SEDs like BQs and IBLs have so different emission line properties. The higher value of R and the smaller P_{ext} and L_{BLR} of the IBLs we present in Table 1 show that these are less powerful sources seen under a smaller angle. We can qualitatively ‘transform’ a BQ to an IBL with two translations, one in angle and one in intrinsic power: first align the BQ, then decrease its intrinsic power. The source resulting from the first translation will have smaller EW emission lines, since decreasing θ boosts the synchrotron component, but it will be more luminous than an IBL. The second step will reduce the luminosity of the source down to the IBL luminosity. The similar peak frequencies hold an interesting clue to the acceleration and cooling processes: since the aligned BQ will have $\nu_s \approx 10^{13}$ Hz regardless of an accelerating or constant velocity jet, the decrease of the intrinsic power must increase ν_s to typical values for IBLs ($\nu_s \approx 10^{14-15}$ Hz). This means that cooling becomes less efficient and/or particles are accelerated to higher energies as the intrinsic power of the source is reduced, something that has been previously argued by Ghisellini et al. (1998).

We now focus on the *ASCA* X-ray emission. Although the *ASCA* spectra of all the sources presented in Table 1 are flat ($\alpha_{2-10\text{ KeV}} \approx 0.8$), they differ in the following sense: while in the IBLs the hard X-ray luminosity is ≈ 100 times weaker than the peak luminosity of the first spectral component (Kubo et al. 1998), in the BQs this is at most 10 times weaker. Given now the difference in θ , if one was to align the BQs, this difference would either persist or would become even more pronounced. This is because the hard X-ray emission is either SSC ($L_{SSC} \propto \delta^{3+\alpha}$) or EC ($L_{EC} \propto \delta^{4+2\alpha}$) emission, while the apparent luminosity of the first component will at most increase as $\delta^{3+\alpha}$ if it is pure synchrotron emission with no contribution from a thermal component. If this difference in the hard X-ray luminosity relative level is also present in the peak IC luminosities, then the ratio of the photon to magnetic field energy density experienced by the emitting particles is higher in high power sources. Unfortunately, there are no *EGRET* detections of the BQs, although the two IBLs we compare them with have been detected with an IC luminosity practically equal to that of the synchrotron component (Kubo et al. 1998).

4. DISCUSSION & CONCLUSIONS

BQs seem to be relatively misaligned blazars with a relatively de-boosted synchrotron continuum. It is not clear if there is a thermal component in the optical–UV spectrum of the BQs (Sambruna et al. 2000). If there is, one can distinguish between an accelerating and constant Γ flow depending on the peak frequency ν_s of the synchrotron component. If $\nu_s \approx 10^{12.5-13.5}$ Hz, then the flow is most probably characterized by a single Lorentz factor. Otherwise, if ν_s is close to the peak of the thermal component, the flow is most probably accelerating. In both cases the aligned sources will be LBLs or FSRQs, possibly similar to 3C 279. On the other hand, if no significant thermal component can be detected in BQs, the possibility of a constant Γ jet is excluded, since

the aligned version would be a source similar to a bright HBL, but with a strong and flat IC hard X-ray spectrum. Such sources are not observed, and there are no obvious selection criteria against their detection. Clarification therefore of the nature of the SED can provide valuable insight on the flow characteristics.

Orientation aside, sources of different intrinsic power are different. The synchrotron frequency ν_s is lower for higher power sources. This suggests that cooling is stronger in high power sources. In addition, the relative level of the hard X-ray IC luminosity hints that the ratio of the comoving photon to magnetic field energy density is higher in high power sources. Measurements of the IC peak luminosity are needed though to check if this is really the case.

The fact that cooling is not invariant under an increase of the intrinsic power suggests that powerful sources are not simply scaled up versions of weak sources. Since both the orientation and the intrinsic power strongly affect the observed characteristics of a source, we are naturally led to a two-dimensional unification scheme for blazars. In this scheme, the BQs observed by Sambruna et al. (2000) appear to be intrinsically powerful sources, whose jet angle to the line of sight is relatively larger than that of typical blazars.

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Table 1. Observational data.

Source	Type	R	$\log P_{ext}$ (W Hz ⁻¹)	$\log L_{BLR}$ (erg s ⁻¹)
0405-123	BQ	0.57 ^d	27.4 ^d	46.02 ^a
0736+017	BQ	3.42 ^d	25.9 ^d	44.43 ^a
0923+392	BQ	0.44 ^e	26.85 ^e	45.88 ^a
1150+497	BQ	0.39 ^e	26.78 ^e	44.56 ^a
0235+164	IBL	61.4 ^b	25.7 ^b	43.92 ^a
0735+178	IBL	195 ^c	25.0 ^c	—

^a Cao & Jiang 1999

^b Kollgaard et al. 1996

^c Perlman & Stocke 1994

^d Morganti et al. 1997

^e Hooimeyer et al. 1992

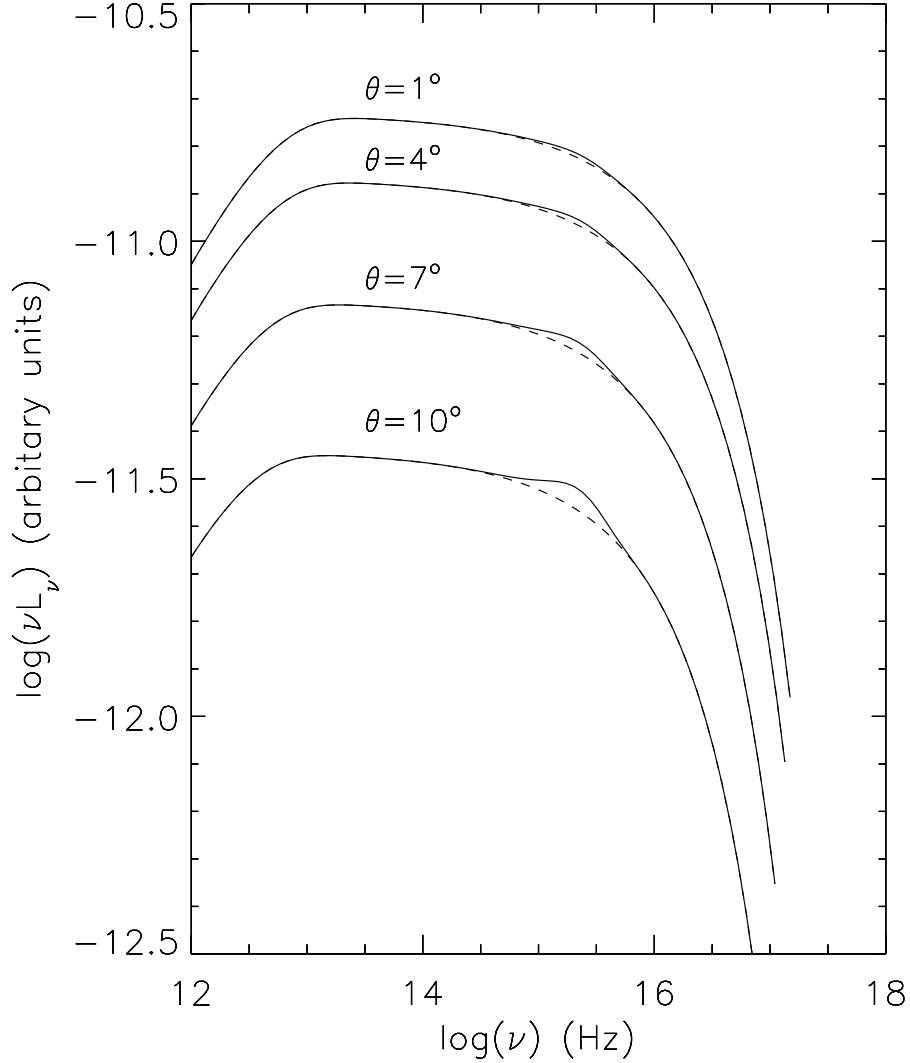


Fig. 1.— The SED of a constant Lorentz factor jet for a range of angles $\theta = 1^\circ, 4^\circ, 7^\circ, 10^\circ$ between the jet axis and the line of sight. The solid line corresponds to the total emission, including the BB emission, while the broken line corresponds to the synchrotron emission only. We assume here, as in all the models that include a BB, that the BB luminosity is equal to the kinetic power in the jet. Model parameters: Bulk motion Lorentz factor $\Gamma = 5$, jet cross section radius $R = 10^{16}$ cm, magnetic field $B = 1.0$ G, maximum electron energy $\gamma_{max} = 5 \cdot 10^4$, external photon energy density $U_{ext} = 0.1 U_B$, where $U_B = B^2/8\pi$ is the magnetic field energy density, jet length $Z = 2 \cdot 10^{17}$ cm.

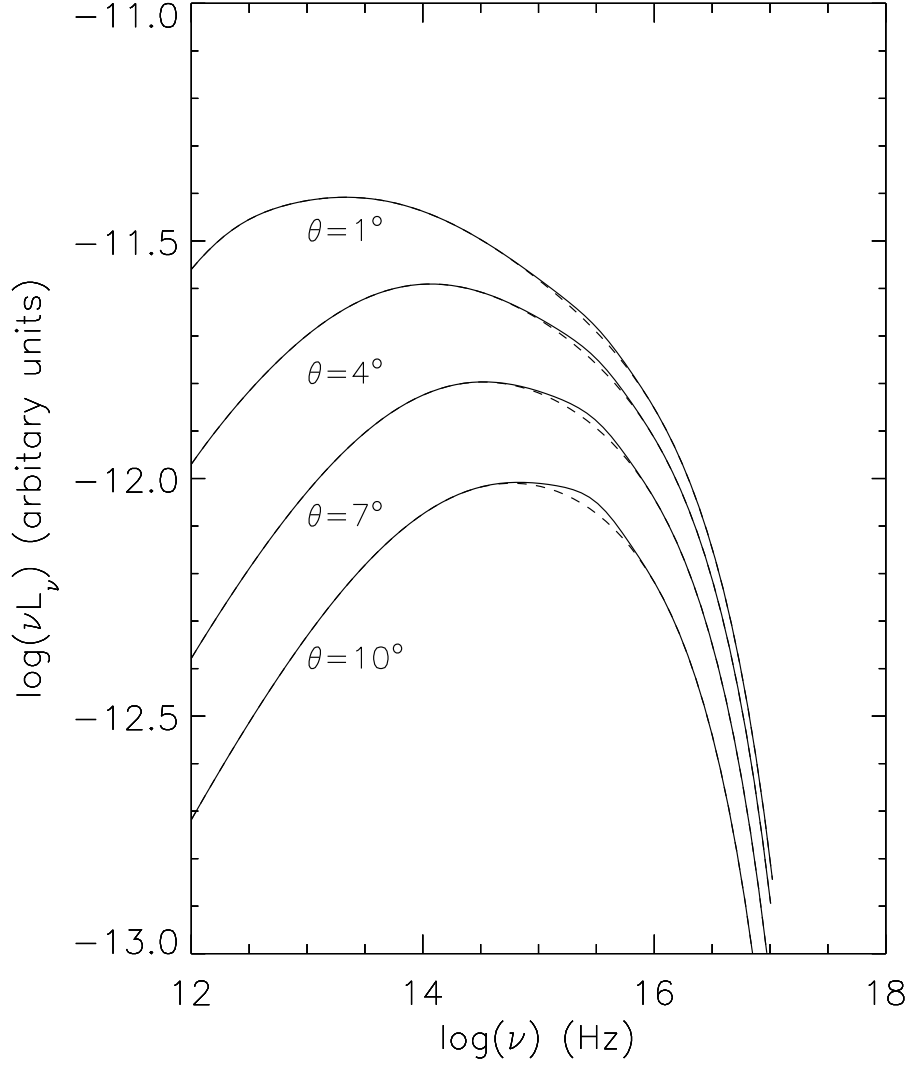


Fig. 2.— The SED for an accelerating jet. Description as in Figure 1. The bulk motion Lorentz factor Γ increases along the jet: $\Gamma = \Gamma_0(z/z_0)^{1/2}$. The jet has a parabolic form, and its radius is $R = R_0(z/z_0)^{1/2}$, where $\Gamma_0 = 3$, $R_0 = z_0 = 10^{16}$ cm. The magnetic field decays as $1/R$, $B = B_0(z/z_0)^{(1/2)}$, $B_0 = 1.0$ G. The rest of the parameters are the same as for the constant Lorentz factor model.

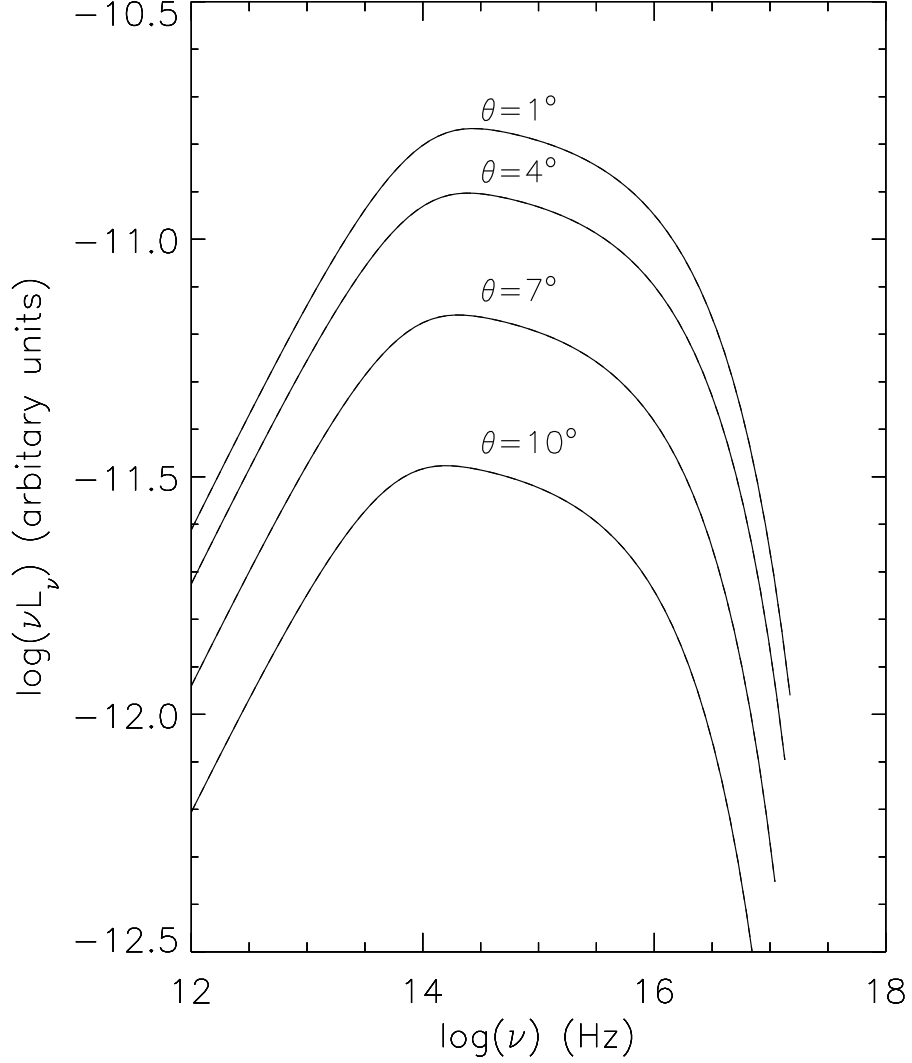


Fig. 3.— The SED of a constant Lorentz factor jet without a BB component for a range of angles $\theta = 1^\circ, 4^\circ, 7^\circ, 10^\circ$ between the jet axis and the line of sight. All the parameters are the same as in Figure 1, except that the external photon energy density is zero, and that the length of the jet is shorter, $Z = 5 \cdot 10^{16}$ cm.