3C 454.3 REVEALS THE STRUCTURE AND PHYSICS OF ITS "BLAZAR ZONE"

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ABSTRACT

Recent multiwavelength observations of 3C 454.3, in particular during its giant outburst in 2005, put severe constraints on the location of the "blazar zone," its dissipative nature, and high-energy radiation mechanisms. As the optical, X-ray, and millimeter light curves indicate, a significant fraction of the jet energy must be released in the vicinity of the millimeter photosphere; i.e., at distances where, due to lateral expansion, the jet becomes transparent at millimeter wavelengths. We conclude that this region is located at ~10 pc, which is also the distance that coincides with the location of the hot dust region. This location is consistent with the high-amplitude variations observed on a ~10 day timescale, provided that the Lorentz factor of a jet is \( \gamma > 20 \). We argue that dissipation is driven by the reconnection shock and demonstrate that X-rays and \( \gamma \)-rays are likely to be produced via inverse Compton scattering of near- and mid-IR photons emitted by the hot dust. We also infer that the largest gamma-to-synchrotron luminosity ratio ever recorded in this object, which took place during its lowest luminosity states, could be simply due to weaker magnetic fields carried by a less powerful jet.

Subject headings: galaxies: jets — gamma rays: theory — quasars: general — radiation mechanisms: nonthermal — X-rays: general

Online material: color figures

1. INTRODUCTION

Multiwavelength coverage of recent activity of the quasar 3C 454.3 has provided exceptional data with which to investigate the structure and physics of its blazar zone. Prior to the year 2000, this object spent most of its time in a low, relatively quiescent state. Starting in 2000, 3C 454.3 entered a highly active state, changing its optical flux by a factor of tens on timescales of a few months (Fuhrmann et al. 2006; Villata et al. 2006). The most powerful event to date took place in the middle of 2005 (Villata et al. 2006; Krichbaum et al. 2007). This event was monitored also in the X-ray bands (Swift XRT and BAT, Giommi et al. 2006; INTEGRAL, Pian et al. 2006; Chandra, Villata et al. 2006) and at millimeter wavelengths (Krichbaum et al. 2007).

These data allow us to construct a quasi-simultaneous broadband spectrum around the outburst peak. As is the case for other blazars, the spectrum is composed of two humps, the lower energy one produced via the synchrotron mechanism and peaking in the far-infrared band, and the higher energy one most likely generated by the inverse Compton process and peaking in the \( \gamma \)-ray band. The lack of coverage of the event by \( \gamma \)-ray observatories makes it impossible for us to determine the luminosity of the high-energy component. Nevertheless, X-ray data suggest that the luminosity ratio of the high-energy components to the low-energy components was much smaller during the outburst than it was during low states monitored in \( \gamma \)-rays by the Compton Gamma Ray Observatory (CGRO; Mukherjee et al. 1997; Hartman et al. 1999; Zhang et al. 2005).

This difference was theoretically investigated by Pian et al. (2006) and by Katarzyński & Ghisellini (2007). Pian et al. (2006) suggested that during the low states, the blazar zone is located inside the broad-line region (BLR) and that high-energy spectra are produced by the external radiation Compton (ERC) process, which involves the scattering of broad-line photons (via the scenario described in Sikora et al. 1994), while during the 2005 outburst, the dissipation zone moved outside the BLR, where the ERC becomes inefficient. In such a model, the production of the optical outburst does not require the jet power to increase. Similarly, in the scenario proposed by Katarzyński & Ghisellini (2007), the jet power is constant, and the drop in the luminosity of the high-energy component is explained by a decrease of the Lorentz factor.

The idea of a constant jet power might be challenged by the most recent optical outburst of 3C 454.3, which in 2005 July was also detected in \( \gamma \)-rays by AGILE (Vercellone et al. 2007). The bolometric luminosity of this outburst was 43\( \times \)5 times larger than the bolometric luminosity of 3C 454.3 during its low optical states, and the radiative output was strongly dominated by the \( \gamma \)-ray flux. The currently available millimeter-band light curves (Krichbaum et al. 2007) do not indicate any significant delay of the millimeter flux after the bolometric flux as inferred from the infrared and optical data presented in Bach et al. (2007). All of the above motivated us to investigate a different scenario, in which the origin of the high-energy peak involves the scattering of broad-line photons (via the scenario described in Sikora et al. 1994), while during the 2005 outburst, the dissipation zone moved outside the BLR, where the ERC becomes inefficient. In such a model, the production of the optical outburst does not require the jet power to increase.

2. MODEL ASSUMPTIONS

2.1. Location of the Blazar Zone

Optical and millimeter light curves show that the "2005 outburst" of 3C 454.3 was actually preceded by a long-term gradual increase in flux that started in 2004 August and continued until the middle of 2005 (Villata et al. 2006; Krichbaum et al. 2007). The optical flux reached maximum around 2005 May 9 and then...
dropped very rapidly, but this drop was associated with several local "wiggles." The millimeter light curve reached maximum about 18 days later and continued at that level for ~3 months, with fluctuations on a timescale of ~10 days. The outburst ceased by 2005 August and September. The lack of a high-luminosity plateau in the optical light curve suggests that the millimeter outburst lags the optical one by ~3 months. However, no such long delay is seen in the growing part of the outburst. Furthermore, the optical spectrum is steep and very variable, which makes the optical flux a very poor tracer of the bolometric luminosity. The latter, according to data presented by Bach et al. (2007), presumably reached its maximum (with a peak located in the far-IR) by the end of 2005 June, roughly in the middle of the millimeter plateau. This, coupled with large millimeter luminosities that require an in situ energy dissipation rate that is comparable to the rate required in order to account for the optical emission, as well as similar short-term variability timescales in both spectral bands, suggests that the regions of the optical and millimeter emission are not spatially detached.

If the above is indeed the case, it is possible to make unambiguous estimates of the location of the blazar zone (with respect to the central black hole) on the basis of the variability timescales, and this in turn can be verified by using millimeter data and calculations of the synchrotron self-absorption opacity of the source. Since the spectral slope measured in the millimeter band during the outburst is typically within the range 0.0 < \( \alpha_{\text{mm}} \) < 0.5, the blazar zone is expected to be partially opaque at these wavelengths. The resulting size of the source, \( R_{\text{mm}} \), and its distance from the center, \( r_{\text{mm}} \), depend on the specific model parameters, and for those models presented in Table 1, these values are calculated to be \( R_{\text{mm}} \sim 0.5 \) pc and \( r_{\text{mm}} \sim 9 \) pc (see Appendix B).

### 2.2. Dissipation Scenario

While it is relatively well established that the endpoints of most quasar jets correspond to "hot spots" that presumably involve terminal shocks, there is no consensus regarding the mechanism responsible for the energy dissipation within the flow and, in particular, in the blazar zone. The most popular, presumably because it is the easiest to treat quantitatively, is the internal shock scenario. In this scenario, jets are radially inhomogeneous in both density and velocity, and shocks are formed by collisions between jet portions propagating with different Lorentz factors (Sikora et al. 1994; Spada et al. 2001). The internal shock scenario is attractive for blazars because it predicts parallel polarization (electric vector position angle [EVPA] parallel to the jet) of the synchrotron radiation, which is in agreement with observations in the optical, infrared, and millimeter bands (Impey et al. 1991; Stevens et al. 1996; Nartallo et al. 1998; Jorstad et al. 2007). This prediction is independent of whether the magnetic field is dominated by the toroidal component, which is determined by poloidal electrical currents, or by turbulent magnetic fields compressed in the transverse shocks (Laing 1981). However, internal shocks are known to dissipate energy very inefficiently: modulation of a jet Lorentz factor by at least a factor of 4 is required to reach a few percent of efficiency.

A more promising dissipative scenario involves reconfiguration of magnetic fields (Komissarov & Falle 1997; Sokolov et al. 2004). Such shocks keep a pressure balance between the jet and its environment and are formed wherever the density gradient of the external medium departs from the longitudinal density gradient in a jet. On subparsec scales, the environment is too weak to affect dynamically powerful jets, but at parsec and larger distances, the interaction of the jet with its environment is sufficiently strong to modify the jet’s opening angle and, in the case of a nonaxisymmetric external matter density distribution, also its direction of propagation (see, e.g., Appl et al. 1996). The reconfiguration shock scenario provides interesting constraints on the structure and intensity of magnetic fields. In such shocks, the compression of chaotic magnetic fields leads to a perpendicular EVPA, but if the magnetic field intensity is dominated by the toroidal component, the EVPA is parallel to the jet, which is in agreement with observations.

### 2.3. Radiative Mechanisms and Model Input Parameters

The synchrotron mechanism and the inverse Compton process are known to be the basic radiative processes in relativistic jets. The latter involves scatterings of both “internal” synchrotron photons (the synchrotron self-Compton [SSC] process) and “external” photons (the ERC process). The ERC process is expected to dominate strongly over the SSC process, provided that the radiative environment is strong and the jets are highly relativistic (Dermer et al. 1992; Dermer & Schlickeiser 1993; Sikora et al. 1994; Blandford & Levinson 1995). At parsec distances, which correspond to the likely location of the blazar zone in 3C 454.3 (see §2.1), the external diffuse radiation field is dominated by near- and mid-infrared radiation of hot dust (Cleary et al. 2007 and references therein), and therefore such dust is very likely to provide the dominant source of seed photons for the inverse Compton process (Blažejowski et al. 2000; Arbeiter et al. 2002). This is in fact the scenario suggested for the origin of the high-energy peak in MeV blazars (a class of blazars that also
The values of these parameters are determined by our model assumptions and by the relations between these parameters and the observables. The latter, in the form of approximate formulas, are presented in Appendix A. Analytically estimated parameters are used to start an iterative procedure to numerically fit the observed spectrum. Because the 2005 outburst was not observed in the γ-ray band and because of uncertainties regarding the distribution and opacity of the hot dust, the set of input parameters cannot be determined uniquely. This in particular concerns the value of the jet Lorentz factor, which we assumed to be $\Gamma_j = 20$. Using such a large value allows us to avoid the softening of the X-ray spectrum from the contribution of the SSC process in the soft and midγX-ray bands. Such a large value of $\Gamma_j$ is also implied when we adopt the assumption of the domination of the toroidal magnetic component over the turbulent one. The value $\Gamma_j = 20$ is larger than that deduced from the VLBI observations of the superluminal expansion (see Jorstad et al. 2001 and references therein), but the latter may be underestimated due to its not taking into account the effects of the divergence of a jet (Gopal-Krishna et al. 2006).

3. MODELING THE 2005 OUTBURST

Results from modeling the spectrum observed in 2005 May, when the optical flux was at its maximum, are shown in Figure 1, and the input and output parameters are specified in Table 1. As is apparent, the entire spectrum can be reproduced using a single power law for the electron injection function, with a slope index of $p = 2$. The X-ray spectrum is produced by electrons that cool on a timescale longer than the blazar zone crossing time, and therefore this results in a slope of $\alpha_X = (p - 1)/2 \approx 0.5$. The synchrotron spectrum is produced in the fast-cooling regime and results in a slope of $\alpha_{\text{syn}} = p/2 \approx 1.0$, but in the optical band, it significantly steepens due to the high-energy cutoff in the injection function. It hardens at the millimeter wavelengths due to synchrotron self-absorption.

Our results show that even a very moderate energy density of the dust radiation is sufficient to provide strong domination of the ERC luminosities over the SSC luminosities. This is due to a

| Parameter | Model 1 | Model 2 | Model 3 | Model 4 |
|-----------|---------|---------|---------|---------|
| $\gamma_{\text{min}}$ | 1 | 1 | 1 | 1 |
| $\gamma_{\text{in}}$ | $4 \times 10^3$ | $4 \times 10^3$ | $4 \times 10^3$ | $9 \times 10^3$ |
| $\gamma_{\text{max}}$ | $\ldots$ | $\ldots$ | $\ldots$ | $80$ |
| $p$ | 2.0 | 2.0 | 2.0 | 1.7 |
| $q$ | 2.0 | 2.0 | 2.0 | 2.5 |
| $K_{\gamma}$ (s$^{-1}$) | $3.0 \times 10^{49}$ | $1.5 \times 10^{49}$ | $2.3 \times 10^{49}$ | $3.0 \times 10^{48}$ |
| $\Gamma_j$ | 20 | 20 | 20 | 17 |
| $\theta_j$ (rad) | 0.05 | 0.05 | 0.05 | 0.05 |
| $\phi_{\text{obs}}$ (rad) | 0.05 | 0.05 | 0.05 | 0.05 |
| $r_0 = \Delta r_0$ (cm) | $10^{19}$ | $2 \times 10^{19}$ | $2 \times 10^{19}$ | $2 \times 10^{19}$ |
| $B_0$ (G) | 1.4 | 0.50 | 0.63 | 0.27 |
| $\nu_{\text{min}}(r_0)$ (erg cm$^{-3}$ s$^{-1}$) | $1.24 \times 10^{-4}$ | $1.24 \times 10^{-4}$ | $1.24 \times 10^{-4}$ | $1.24 \times 10^{-4}$ |
| $h\nu_{\text{IR}}$ (eV) | 0.34 | 0.34 | 0.34 | 0.34 |
| $\nu_{\text{X}}^2(2\nu_{\text{X}})$ (erg cm$^{-3}$ s$^{-1}$) | $3.25 \times 10^{-3}$ | $4.06 \times 10^{-4}$ | $6.22 \times 10^{-4}$ | $1.95 \times 10^{-4}$ |
| $\nu_{\text{X}}^2(2\nu_{\text{X}})$ (erg cm$^{-3}$ s$^{-1}$) | $1.95 \times 10^{-2}$ | $2.49 \times 10^{-3}$ | $3.95 \times 10^{-3}$ | $7.25 \times 10^{-4}$ |
| $L_{\text{jet}} > L_\beta$ (erg s$^{-1}$) | $7.35 \times 10^{47}$ | $3.75 \times 10^{47}$ | $5.96 \times 10^{47}$ | $1.10 \times 10^{47}$ |
| $\gamma_{\text{in}} - 1$ | $<0.17/\eta_\nu$ | $<0.16/\eta_\nu$ | $<0.16/\eta_\nu$ | $<0.26/\eta_\nu$ |
| $\gamma_{\text{in}}$ | 8.3 | 8.3 | 8.3 | 13.0 |
| $\eta_{\text{a}}/\eta_{\text{p}}$ | $<37.5/\eta_\nu$ | $35.3/\eta_\nu$ | $35.3/\eta_\nu$ | $<37.9/\eta_\nu$ |
| $\delta_{\text{tot}} = \delta_{\text{kin}} + \delta_{\text{rad}}$ | $5.88/\eta_\nu/\eta_\beta$ | $6.25/\eta_\nu/\eta_\beta$ | $6.25/\eta_\nu/\eta_\beta$ | $3.72/\eta_\nu/\eta_\beta$ |
large value of \( \Gamma_j \) and the strong dependence of the \( L_{\text{ERC}}/L_{\text{SSC}} \) ratio on \( \Gamma_j \). The spectrum shown in Figure 1 is obtained for an active zone enclosed within a distance range of \( 10^{19} \text{Y}2 \times 10^{19} \) cm. Jets within this distance range are opaque at millimeter wavelengths.

In order to get a spectrum with the observed slopes and fluxes in the millimeter band, it is necessary to assume a larger distance for the blazar zone, as well as smaller optical luminosities. In Figure 1 we show the broadband spectrum produced within a distance range of \( 2 \times 10^{19} \text{Y}4 \times 10^{19} \) cm. The optical luminosity is smaller there by a factor of \( \sim 5 \), but when we assumed that the magnetic energy flux was proportional to the flux associated with matter flow, it was possible to accommodate this by decreasing the electron injection function by only a factor of \( 2 \) (see parameters in Table 1). The optical luminosity produced within this distance range corresponds to optical fluxes recorded during the millimeter plateau period. The results from Figure 1 indicate that the most powerful portions of the jet start to dissipate energy closer to the center than do the less powerful ones, but the energy dissipation extends, albeit with decreasing efficiency, up to the region where the plasma becomes transparent at millimeter wavelengths.

4. MODELING DIFFERENT SPECTRAL STATES

One important observable characterizing the double-hump spectra of blazars is the luminosity ratio of the high-energy component to the low-energy component. If the production of a high-energy component is dominated by the ERC process, then this ratio is \( L_{\text{ERC}}/L_{\text{syn}} \sim \Gamma_j^2 \mu_{\text{BR}}/\mu_{\text{B}} \), where \( \mu_{\text{B}} \) is the energy density of the magnetic field in the blazar zone of a jet. If we note that the energy flux of the magnetic field in a jet is \( L_B \approx c \mu_{\text{B}} \pi R^2 \Gamma_j^2 \) and that \( \mu_{\text{BR}} = \xi_{\text{BR}} L_{\text{disk}}/(4\pi r^2 c) \), and if we assume that \( L_B \propto L_{\text{jet}} \) and \( \theta_j = R/r \sim 1/\Gamma_j \), this ratio is

\[
\frac{L_{\text{ERC}}}{L_{\text{syn}}} \propto \frac{\Gamma_j^2 \xi_{\text{BR}} L_{\text{disk}}}{L_{\text{jet}}}. \tag{1}
\]

Hence, for a fixed disk luminosity, the luminosity ratio of the two components depends mainly on three parameters: \( \Gamma_j \), \( \xi_{\text{IR}} \), and \( L_{\text{jet}} \). All of them can be a function of distance in a jet, and \( \Gamma_j \) and \( L_{\text{jet}} \) can also vary with time. With our basic assumption that the blazar zone is related to the location of the reconfinement shock and that this location does not change significantly with time, changes of the luminosity ratio from epoch to epoch can be just a function of \( L_{\text{jet}} \) and \( \Gamma_j \). We demonstrate in Figures 2 and 3 that spectra of 3C 454.3 taken at two epochs, during the outburst and during the quiescent phase, can be reproduced just by assuming changes in \( L_{\text{jet}} \) and making some modifications to the shape of the injection function. From inspection of these spectra (including Fig. 1), it is apparent that differences between synchrotron luminosities at different states are much larger than differences between bolometric luminosities. This results from the fact that for \( L_{\text{ERC}} > L_{\text{syn}} \), \( L_{\text{ERC}} \propto L_{\text{bol}} \propto L_{\text{jet}} \), and when this is combined with equation (1), it gives \( L_{\text{syn}} \propto L_{\text{jet}}^2 \).

5. DISCUSSION AND CONCLUSIONS

We have demonstrated in this paper that broadband spectra of 3C 454.3 can be reconstructed if we assume that they are produced at distances of \( r \sim 3Y9 \) pc. At the end of this distance range, the jet becomes transparent at millimeter wavelengths. Blazar activity has historically been defined via observations in the IR and optical bands, whereas the “blazar zone” is often considered to be located deeply within the millimeter photosphere. However, the optical and millimeter light curves seem to indicate a significant overlap of the blazar zone with a region where the jet becomes transparent at millimeter wavelengths (see § 2.1). This is further supported by very large millimeter luminosities that require a high in situ dissipation rate of energy,
and it is consistent with timescales of the fastest high-amplitude variations, which are on the order of 10 days in both spectral bands. Furthermore, at such distances the cospatial model self-consistently incorporates the production of X-rays and $\gamma$-rays via scatterings of near- and mid-IR photons emitted by hot dust.

It should be emphasized here that the input-parameter set for ERC models is not unique and that high-energy spectra can also be reproduced by the scattering of broad emission photons if this takes place in the subparsec region. However, then the high-energy nonthermal radiation should be accompanied by bulk Compton features (Sikora & Madejski 2000; Moderski et al. 2004; Celotti et al. 2007), which so far have not been observationally confirmed. Their absence or weakness can be explained by assuming that the toroidal magnetic field over chaotic or turbulent magnetic fields. However, it should be noted that the domination of the toroidal magnetic field over chaotic or turbulent magnetic fields together with optical polarization data, implies the domination of the lobe energetics (Rawlings & Saunders 1991), as well as from Chandra and HST observations of $\gamma$-ray blazars (Tavecchio et al. 2007).

We identify the blazar zone with a reconfinement shock. This, together with optical polarization data, implies the domination of the toroidal magnetic field over chaotic or turbulent magnetic fields. However, it should be noted that the domination of the toroidal component does not necessarily indicate the domination of the Poynting flux over the matter energy flux. It is very likely that the conversion of a Poynting flux dominated jet into a matter-dominated jet, and hence the jet acceleration process, is accomplished on subparsec scales (Sikora et al. 2005; Komissarov et al. 2007). Similar conclusions are reached by Jorstad et al. (2007), following multiwaveband polarimetric observations of 15 AGNs.

During its 2005 outburst, 3C 454.3 was the most luminous object ever recorded in the optical band. To explain such an outburst, a jet power of more than $7 \times 10^{47}$ erg s$^{-1}$ is required (see Table 1). Is this feasible? Noting that estimates of the black hole mass in this object are $\sim 4 \times 10^9 M_\odot$ (Gu et al. 2001), we infer that the jet power is on the order of the Eddington luminosity. This, however, is at least a factor of few larger than the accretion luminosity, which in turn, as determined from the optical luminosity of the thermal component detected during the low state (Smith et al. 1988), and after application of the bolometric correction, is likely to be on the order of $10^{47}$ erg s$^{-1}$. 3C 454.3 is in this respect not exceptional among most powerful radio-loud quasars: jet powers of larger than $10^{47}$ erg s$^{-1}$ have been inferred for several other quasars from analysis of the lobe energetics (Rawlings & Saunders 1991), as well as from Chandra and HST observations of $\gamma$-ray blazars (Tavecchio et al. 2007).

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APPENDIX A

ANALYTICAL APPROXIMATIONS OF THE MODEL PARAMETERS

A1. INJECTION FUNCTION

The normalization factor $K_e$ of the electron injection function $Q$ can be derived using approximate formulas for the production of the X-ray spectrum via the ERC process in the slow-cooling regime (see Moderski et al. 2003):

$$\nu_X L_{\nu_X} = \frac{1}{2} \gamma N_\gamma \left| \gamma \right|_{\text{ ERC}} (\theta_{\text{obs}}) m_e c^2 D^4,$$

where

$$\left| \gamma \right|_{\text{ ERC}} (\theta_{\text{obs}}) = \frac{c \sigma_T}{m_e c^2 u_{\text{IR}}} \left( \frac{D}{\Gamma_j} \right)^2,$$

$$N_\gamma = Q \frac{\Delta \nu}{c \Gamma_j},$$

$$u_{\text{ext}}^\prime = \frac{4}{3} \frac{\Gamma_j^2 u_{\text{ext}}}{\Gamma_j},$$

$$D = \frac{1}{\Gamma_j (1 - \beta \cos \theta_{\text{obs}})}.$$  

In the slow-cooling regime, the slope $p$ of the electron injection function is $p = 2 \alpha_X + 1$, and for $\Delta \nu = \nu$, the above equations give

$$K_e = \frac{3}{2} \frac{\nu_X L_{\nu_X}}{\sigma_T u_{\text{IR}}^\prime} \frac{\Gamma_j}{D^{\alpha_X + 2}} \left( \frac{u_{\text{ext}}}{\nu_X} \right)^{1 - \alpha_X}.$$  


In one of our models, a break in the injection functions is introduced in order to get a better fit of the observed spectrum:

\[ Q = K_e \frac{1}{\gamma^q + \gamma_{br}^{-q}} \]  

(A7)

where \( \gamma_{br} \) is the break energy and \( q \) is the spectral index of the injection function at the high-energy limit.

A2. MAGNETIC FIELD INTENSITY

The ERC-to-synchrotron peak luminosity ratio

\[ \frac{L_{\text{ERC}}}{L_{\text{syn}}} = \frac{u_{\text{ext}}'(D/\Gamma_j)^2}{u_B'} \]  

(A8)

gives us a magnetic field intensity of

\[ B' = D \sqrt{\frac{32}{3} \frac{L_{\text{ERC}}}{L_{\text{syn}}}} \]  

(A9)

and a magnetic energy flux of

\[ L_B = c u_B' \pi R^2 \gamma_j^2 = \pi c u_B'^2 (\theta_j \Gamma_j)^2, \]  

(A10)

where \( u_B' = B'^2/8\pi \) is the magnetic energy density. With known values of \( B' \), we can estimate the maximum energy of the injected electrons:

\[ \gamma_{\text{max}} \simeq 5.2 \times 10^{-4} \sqrt{\frac{u_{\text{syn, max, obs}}(1+z)}{B'D}}. \]  

(A11)

A3. ELECTRON ENERGY DENSITY

Due to light-travel effects, sources moving with relativistic speeds are seen on the sky as being stretched by a factor of \( D/\Gamma_j \), which means that only a fraction \( 1/(D/\Gamma_j) \) of the particles is seen at a given instance to be enclosed within the distance range \( \Delta r \). Hence, the volume of the jet segment into which electrons are injected at the “observed” rate \( Q \) is \( \pi R^2 \lambda' \), where \( \lambda = \Delta r/(D/\Gamma_j) \). The amount of energy injected into this segment during its propagation through the \( \Delta r \) zone is

\[ E_{e,\text{inj}}' = \frac{\Delta r}{\Gamma_j} \int Q \gamma m_e c^2 d\gamma, \]  

(A12)

and the energy density of the injected electrons is

\[ u_{e,\text{inj}}'(r_0 + \Delta r = 2r_0) = \frac{E_{e,\text{inj}}'}{\pi R^2 \lambda'} = \frac{D}{\Gamma_j} \frac{\int Q \gamma m_e c^2 d\gamma}{\pi c R^2} = \frac{m_e c D \Gamma_j}{4 \pi r_0^2 (\theta_{\text{obs}} \Gamma_j)^2}, \]  

(A13)

where \( \lambda' = \lambda \Gamma_j \).

A4. ENERGY DISSIPATION EFFICIENCY

In jets dominated by the inertia of protons, the acceleration of electrons is powered by protons, and we have

\[ u_{e,\text{inj}}' = \eta_p u_p' (\tilde{\gamma}_p - 1), \]  

(A14)

where \( \tilde{\gamma}_p - 1 < 1 \) is the fraction of the proton bulk kinetic energy that is converted to “thermal” proton energy, which we hereafter call the efficiency of the energy dissipation, and \( \eta_p \) is the fraction of the proton thermal energy that is tapped by electrons. The condition of having a matter-dominated jet implies that \( u_p' > u_B' \), and the combination of this condition with the previous equation gives

\[ \tilde{\gamma}_p - 1 < \frac{u_{e,\text{inj}}'}{u_B' \eta_e}. \]  

(A15)
A5. PAIR CONTENT

Using the definition of particle energy densities \( u = m c^2 \gamma \), and noting that \( \gamma \gg 1 \) (throughout our paper, \( \gamma \equiv \gamma_c \)) and \( \bar{\gamma} - 1 \ll 1 \), we obtain a pair content of

\[
\frac{n'_p}{n'_0} = \frac{m_p}{m_e} \frac{\bar{\gamma} - 1}{\gamma} \approx \frac{m_p}{m_e} \frac{u'_{e,\text{inj}}}{u'_0},
\]

where equation (A15) was used and \( \bar{\gamma} \equiv \int Q(\gamma) d\gamma/\int Q d\gamma \).

A6. TOROIDAL VERSUS TURBULENT MAGNETIC FIELD

We have assumed in this paper that the magnetic field is dominated by the toroidal component. This assumption can be verified as follows. For \( u'_{B,\text{tor}} \gg u'_{B,\text{turb}} \), \( u'_{B,\text{tot}} \approx u'_{B,\text{tor}} \equiv u'_0 \) and

\[
u'_{B,\text{tor}} \approx \frac{u'_0}{u'_{e,\text{inj}}} = \frac{u'_0}{u'_{e,\text{inj}}}(\bar{\gamma}_p - 1).\]

For \( u'_{B,\text{turb}} \approx \eta_B u'_0(\bar{\gamma}_p - 1) \), this gives

\[
\frac{u'_{B,\text{tor}}}{u'_{B,\text{turb}}} = \frac{\eta_B u'_0}{\eta_B u'_{e,\text{inj}}}.\]

Note that all formulas that involve a Doppler factor apply for “mono-Doppler” sources only. In the case of conically diverging jets, the observed radiation is contributed by jet portions that are moving at different angles relative to the line of sight, and then analytical estimations differ significantly from numerical results. This in particular concerns the quantity \( K_e \) because of its strong dependence on \( D \). However, for values of \( \theta_{\text{obs}} \sim \theta_j \sim 1/\Gamma_j \), analytical estimates that are still reasonable are achievable if one uses \( D = 1.5 \Gamma_j \) instead of \( D = \Gamma_j \).

APPENDIX B

THE MILLIMETER PHOTOSPHERE

The optically thin synchrotron spectrum in 3C 454.3 and other quasar-hosted blazars is produced by electrons in the fast-cooling regime. In this regime, the electron distribution is steepened due to radiative losses, and for a single power-law injection function, \( Q \sim \gamma^{-p} \), the electrons reach a distribution with an index of \( s = p + 1 \). Below we provide an estimation of the millimeter photosphere distance, assuming that \( p = 2 \). For such a source, the synchrotron self-absorption opacity \( \tau(\nu'_{\text{abs}}) \) is at \( \nu'_{\text{abs}} \) equal to 1 for

\[
R_{\text{mm}} = 2.7 \times 10^{-15} \frac{\nu'^{3/2}}{c_\gamma B^5/2} \text{ cm},
\]

where \( c_{\gamma} = c_e \gamma^{-3} \) is the electron density energy distribution.

Noting that

\[
c_e = \frac{C_N}{\Gamma_f} = \frac{C_N \Gamma_f^2 D}{\pi r^3 (\Delta r/r)(\bar{\gamma}_f)(\Gamma_f)} \gamma^{3/2},
\]

where \( C_N = \gamma^3 N_\gamma \), and that

\[
N_\gamma = \frac{\int \gamma Q d\gamma}{|\gamma|_{\text{tot}}},
\]

where for \( L_{\text{ERC}} > L_{\text{syn}} \),

\[
|\gamma|_{\text{tot}} \approx \frac{16 c \sigma T \gamma^2 T_{\text{ext}}^2 u_{\text{ext}}}{9 m_e c^2},
\]

we obtain, for \( \theta_{\text{obs}} \Gamma_j = 1 \) and \( \Delta r = r \),

\[
R_{\text{mm}} \approx 1.9 \times 10^7 \frac{D^{9/5}}{\Gamma_j^{17/5}} \frac{B_0}{u_{\text{ext}} i_{\text{inj}}^{2/5}} \frac{K_e^{2/5}}{\nu_{\text{obs}}(1 + z)^{7/5}} \text{ cm},
\]

where

\[
K_e = \frac{c_e e^2}{m_e c^2}.
\]
and \( r_{mm} = R_{mm}/\gamma_f \). For \( \nu_{\nu, \text{obs}} = 3 \times 10^{11} \) Hz (\( \lambda_{\nu, \text{obs}} = 1 \) mm) and the parameters of model 1 (see Table 1), this gives values of \( R_{mm} \approx 1.4 \times 10^{18} \) cm and \( r_{mm} \approx 2.8 \times 10^{19} \) cm.

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