\(\gamma\)-Ray Generation in Microquasars: the link with AGN


Abstract. The link between the physical processes responsible for high energy emission from relativistic jets in AGN and microquasars is investigated. A Fortran code based on an existing inhomogeneous, synchrotron self-Compton (SSC) model, for AGN is presented. The code is then applied to the AGN 3C 279 and the microquasar LS5039. Spectral energy distributions (SED’s) are presented.

THE INHOMOGENEOUS SYNCHROTRON SELF-COMPTON MODEL

In order to predict gamma-ray emission from microquasar jets and to maintain the AGN-microquasar analogy, a code was produced based on an existing synchrotron self-Compton model for AGN jets [3][4]. The parameterisation of the jet follows the AGN model closely, although some of the functions contained within the emissivity and absorption coefficients vary at an insignificant level. The model is described fully within [3][4]. A basic outline is summarised here.

Jet Geometry and Parameterisation

The geometry of the jet is described by the relation between the distance along the jet, \(R\), and the radius of a surface orthogonal to that axis, \(r\), given by Eq.(1).

\[
r = r_0 \left( \frac{R}{R_0} \right)^\varepsilon = r_0 \lambda^\varepsilon \tag{1}
\]

For the purposes of predicting gamma-ray emission from microquasars, only processes in the inner part of the jet are considered as this is where the highest electron energies are assumed to exist. The parameters in Eq.(1) have to be chosen with great care to maintain a physical representation of a jet i.e. a small opening angle, \(\phi < 15^\circ\) [11] and a suitable shape. Assuming bulk acceleration throughout this region, \(\varepsilon < 1\), defines a parabolic shape [14]. Careful choice of the these parameters is necessary to produce physically realistic values for \(\phi\) or \(r_0\). In Eq.(1) as \(\varepsilon\) decreases, the smaller \(\phi\) becomes. Likewise,
as \( \left( \frac{R}{r_0} \right) \) increases, \( \phi \) again decreases but to a lesser effect. Assuming a value for \( \varepsilon \), \( R_{\text{max}} \) (the maximum extent of the jet often inferred from radio observations) and \( R_0 \), a relation between \( \phi \) and \( r_0 \) can be found, allowing suitable values to be chosen. As in [3][4], all physical parameters are constant on a plane orthogonal to the axis of the jet and vary along the jet according to simple power laws. The electron distribution \( N(\gamma) \) is given by,

\[ N(\gamma) = K\gamma^{-p} \tag{2} \]

where \( p \) is the spectral index of the electron distribution and is related to the synchrotron spectral index, \( \alpha_0 \), by \( p = 2\alpha_0 + 1 \).

\( K \) is the electron density parameter and is given by,

\[ K = K_0 x^{\varepsilon n} \quad \text{for } n > 0 \tag{3} \]

and \( \gamma \) is the local Lorentz factor of the electrons up to a maximum value \( \gamma = \gamma_{\text{max}} \) with,

\[ \gamma_{\text{max}} = \gamma_{\text{max}}(R_0)x^{-\varepsilon e} \quad \text{for } e > 0 \tag{4} \]

The bulk Lorentz factor, \( \Gamma \), describes acceleration throughout the jet and also follows a power law,

\[ \Gamma = \Gamma_0 x^g \quad \text{for } g > 0 \tag{5} \]

The magnetic field, \( B \), is described by,

\[ B = B_0 x^{-\varepsilon m} \quad \text{for } m > 0 \tag{6} \]

The electron scattering optical depth, \( \tau \), is given by,

\[ \tau = \frac{\sigma_T r}{K^2} = \frac{\sigma_T r}{r_0^2} x^{-\varepsilon(n-1)} \tag{7} \]

Using these definitions, the integrated synchrotron luminosity for the entire jet at a given frequency, \( \nu \) is given by,

\[ L_s(\nu) = 4\pi^2\varepsilon_s(\nu, 1) r_0^2 R_0 \int_{x_1(\nu)}^{x_2(\nu)} x^{\xi-1} [\delta(x, \theta)]^{2+\alpha_0} dx \tag{8} \]

where \( \varepsilon_s(\nu, 1) \) is the coefficient for synchrotron emissivity [7, and references therein]. The limits of integration are set to the extremes along the jet that contribute at the frequency \( \nu \) [4], \( [\delta(x, \theta)]^{2+\alpha_0} \) is the Doppler boosting factor for a jet with continuous injection of particles [11]. \( \xi - 1 = \varepsilon(2-n-m[1+\alpha_0]) \).

Similarly the integrated inverse Compton luminosity (using the synchrotron photons as the seed photons) is given by,

\[ L_s(\nu) = \frac{3\pi}{8} \varepsilon_{ic}(\nu) r_0^2 R_0 \int_{x_1(\nu)}^{x_2(\nu)} x^{\nu-1} [\delta(x, \theta)]^{2+\alpha_0} ln \left[ \frac{v_2(x)}{v_1(x)} \right] dx \tag{9} \]
where $\epsilon_{ic}(\nu) = c_1(\alpha_0)A(\alpha_0)\tau_0 K_0 B_0^{\nu_0} v^{-\alpha_0}$. The coefficients $c_1(\alpha_0)$ and $A(\alpha_0)$ are derived from [1]. The limits of integration are the extremes of the jet which produce synchrotron frequencies that can contribute to a given inverse Compton frequency, $\nu_{ic}$. $
u_1(x)$ and $\nu_2(x)$ are the minimum and maximum contributing synchrotron frequencies that can contribute to $\nu_{ic}$ for a given point in the jet and $l - 1 = \epsilon(3 - 2n - m[1 + \alpha_0])$.

**APPLICATION OF THE CODE TO 3C 279**

3C 279 is a well studied blazar, an AGN whose jets are aligned with the observer’s line of sight, which lies in the constellation Virgo at a distance $z = 0.538$. It was the first quasar in which apparent superluminal motion was observed [15]. It has proved to be a violently variable object and has been detected by EGRET aboard the Compton Gamma Ray Observatory in the energy range 30MeV to 5GeV [5, and references therein]. 3C

![Graph](image)

**FIGURE 1.** Synchrotron Self-Compton Model Applied to AGN 3C 279: The parameters used for the high and low state spectrum are the same as in [10] and are given at the end of this section. Again this is done to provide a direct comparison between two independent codes describing the same model.

3C 279 was the object selected to test the code, since the model was originally designed for AGN jets, and 3C 279 is such a well studied blazar. More importantly, this model has previously been used to describe 3C 279 [10] and so a direct comparison of the output of two independent codes may be made. Figure 1 shows the synchrotron spectrum obtained for 3C 279 using this code. Data points are adapted directly from [10] in which there is an analogous graph. Direct comparison of the two spectra shows the synchrotron
TABLE 1. Parameters Used in the Code as Applied to 3C 279. Values for $\gamma_{\text{max}}(R_0)$ are calculated using equation Eq.(4). Values for $K_0$ are calculated using equation Eq.(7). The local synchrotron spectrum is assumed to have a power law of 0.5 and is the same throughout the jet. The integrated spectrum from the whole jet varying due only to the difference in the local values of $\nu_s$ and $\nu_{s\text{max}}$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Common to High State and Low State</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon$</td>
<td>0.5</td>
</tr>
<tr>
<td>$R_0$</td>
<td>$2 \times 10^{15}$ cm</td>
</tr>
<tr>
<td>$R_{\text{max}}$</td>
<td>$4 \times 10^{18}$ cm</td>
</tr>
<tr>
<td>$r_0$</td>
<td>$2 \times 10^{15}$ cm</td>
</tr>
<tr>
<td>$B_0$</td>
<td>8G</td>
</tr>
<tr>
<td>$m$</td>
<td>1</td>
</tr>
<tr>
<td>$n$</td>
<td>1.5</td>
</tr>
<tr>
<td>$e$</td>
<td>0.5</td>
</tr>
<tr>
<td>$\eta$</td>
<td>1</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>5.5 at $R_0$ to $\sim 25$ at $R_{\text{max}}$ ($\gamma = 0.2$)</td>
</tr>
<tr>
<td>$d = \frac{c}{H_0}$</td>
<td>3225Mpc with $H_0 = 50$km$s^{-1}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>High State</th>
<th>Low State</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_{s\text{max}}(R_0)$</td>
<td>$4 \times 10^{15}$ Hz</td>
</tr>
<tr>
<td>$\gamma_{\text{max}}(R_0)$</td>
<td>$1.3365 \times 10^4$</td>
</tr>
<tr>
<td>$\tau_0$</td>
<td>$2 \times 10^3$</td>
</tr>
<tr>
<td>$K_0$</td>
<td>$1.5 \times 10^6$</td>
</tr>
<tr>
<td>$\nu_{s\text{max}}(R_0)$</td>
<td>$3 \times 10^{14}$ Hz</td>
</tr>
<tr>
<td>$\gamma_{\text{max}}(R_0)$</td>
<td>$3.66 \times 10^3$</td>
</tr>
<tr>
<td>$\tau_0$</td>
<td>$1 \times 10^3$</td>
</tr>
<tr>
<td>$K_0$</td>
<td>$7.5 \times 10^5$</td>
</tr>
</tbody>
</table>

The code produced for this work seems to give a better fit to the low state inverse Compton data than [10]. The fit to the high state data appears equally good in both works. It is worth noting that [10] also attempts to fit the high state inverse Compton spectrum to EGRET data points, whereas this work does not. The EGRET data are not contemporaneous with the other data sets, and there are no simultaneous data at lower frequencies to support the EGRET data, to allow the fit at other wavelengths. A second point worth noting is the lack of any fit to data at the frequencies lower than $10^{12}$ Hz. This again is to be expected, as this work is concerned with predicting gamma ray emission and only takes into account the inner part of the jet where electron energies are at the highest. To fit the low frequency data points would require extra code which includes the outer part of the jet where acceleration is no longer present and where the jet shape becomes a truncated cone with $\varepsilon = 1$. Here the electrons have much lower energies than at the base of the jet and would be responsible for the radio synchrotron emission.
To upscatter these photons to gamma ray frequencies would require unphysically large electron local Lorentz factors at the source of production and so they are not relevant to this discussion.

THE MICROQUASAR LS5039

Microquasars are a class of X-ray binary with a basic morphology similar to that of some AGN, only on much smaller length and time scales i.e. a central compact object, an accretion disk and collimated jets of relativistic particles. Providing the analogies are more than just morphological, studies of microquasars could give an insight to the processes occurring over much longer time scales in AGN.

LS5039 is a high mass X-ray binary, lying close to the Galactic plane, containing an O7V spectral type star and an as yet undetermined, compact object. Previous work shows that it has an highly eccentric, short period orbit [8] and that accretion is likely to be by stellar wind capture as oppose to Roche lobe overflow [9]. Radio frequency studies have indicated that LS5039, which lies within the 95% confidence contour of the EGRET source 3EG J1824-1514, has persistent radio jets rather than the more common transient type [12] [13]. Some of the physical parameters used in the model are those derived from these radio observations.

Figure 2 shows the fit of the synchrotron self-Compton model to the EGRET data on LS5039 [2].
(adapted from [2]) for 3EG J1824-1514. The jet is defined as paraboloid in shape. The opening angle of the jet is kept deliberately small to ensure the radius at the base of the jet is kept physical. The variables in the code are matched to values observed or derived for LS5039 wherever possible and are indicated. The angle of the jet to the observers line of sight, $\theta = 30^\circ$, $R_o = 1.272 \times 10^{13}$ cm, $B_0 = 12$ G and $\varepsilon = 0.5$ are taken from [13] and references therein. The bulk Lorentz factor $\Gamma$ is varied from 1 at $R_0$ to 1.012 at $R_{\text{max}} = 1.5 \times 10^{16}$ cm, which is equivalent to $\beta = 0.2c$, again in keeping with [13]. The power law index of $B$ is set to 1, that for $K$ is set to 2. This allows a constant ratio of magnetic field energy density to particle energy density throughout the jet [6]. $K_0$ and $\gamma$ are allowed to vary to fit the data. It is worth noting that the parameters used to fit the EGRET data produce a cut off in the inverse Compton spectrum at $\sim 25$ GeV. Additional multiwavelength data is required on LS5039 to further constrain the parameters and energy cut-offs.

**CONCLUSION**

An inhomogeneous SSC model for high energy emission from AGN [3][4], is shown to fit data for the AGN 3C 279. The model is then applied to data for the EGRET source 3EG J1824-1514, the 95% contour of which includes the microquasar LS5039. The model is applied to this data and a reasonable fit is found. Contemporary radio, optical and X-ray data are sought on LS5039 to further constrain the model as applied to microquasars.

**REFERENCES**