X- AND GAMMA RAY EMISSION FROM INTRA-DAY VARIABLES

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ABSTRACT

We re-examined the brightness temperature ($T_{\rm B}$) problem posed by rapidly varying blazars, known as intra-day variables (IDV's), such as $S5\ 0716+714$, which often display $T_{\rm B} > 10^{12}$ K, far exceed the limit imposed by inverse Compton cooling. Several of such IDV's have also shown a high degree of circular polarisation (CP) of the order of $\sim 1\%$, much higher that predicted by the conventional synchrotron theory. We adopted a synchrotron model that replaces the conventional power-law electron spectrum with a mono-energetic electron distribution, and found that a brightness temperature as high as $T_{\rm B} \sim 10^{14}$ K can be reached with a moderate Doppler factor of $\mathcal{D} \sim 10$. The predicted intrinsic degree of CP is of the order of 1%, in agreement with observations. With a predicted spectrum of $I_\nu \propto \nu^{1/3}$ between the radio and the infra-red frequencies, this model provides a good spectral fit to the IDV $S5\ 0716+714$ in the radio band.

Key words: galaxies: active – galaxies: high redshift – galaxies: jets.

1. INTRODUCTION

Rapid variability in radio flux have been observed in several extra-galactic sources, implying a very high brightness temperature [1]. Variability at higher frequencies have also been observed for some of these so called intra-day variables (IDV's), providing the mean for studying processes extrinsic to the source as the cause of the variability. For example, cases such as $PKS\ 1519-273$ and $PKS\ 0405-385$, the variability is identified as interstellar scintillation [2, 3]. Diffractive scintillation was discovered in $J\ 1819+3845$ [4]. These external effects mean that the brightness temperature at the source is in fact considerably lower, however, for these sources, $T_{\rm B} > 10^{13}$ K for the former two and $T_{\rm B} > 2\times10^{14}$ K for the latter are still required to account for the observed flux.

Such high brightness temperatures cannot be explained within the scope of the standard synchrotron models, in which the radiating electrons are assumed to have a power-law distribution. Kellermann and Pauliny-Toth [5] showed that the maximum brightness temperature that a source can sustain is limited by the cooling due to inverse Compton scattering in the Thomson regime, which rises rapidly when the source exceeds $T_{\rm B} > 3\times10^{11}$ K. As pointed out by Crusius-Waetzel [6], brightness temperatures higher than 10^{12} K can be produced by mono-energetic electron, since the GHz photons can emerge from the source without being absorbed by low energy electrons. The parameters of such a synchrotron model are discussed in Section 2.

In Section 3, we show that brightness temperature as high as $T_{\rm B} = 10^{14}$ can be reached. We also address another observational trend shown by several of these high brightness temperature sources − a high degree of circular polarisation (CP) at 1% level or above [e.g. 7]. In standard synchrotron theory, the degree of CP is estimated to be $r_{\rm c} \sim mc^2/(k_{\rm B}T_{\rm B})$, where $k_{\rm B}$ is the Boltzmann's constant. For a source of $T_{\rm B} = 10^{13}$ K, $r_{\rm c} = 0.06\%$.

Using $S5\ 0716+714$ as an example, we computed the synchrotron and the corresponding inverse Compton spectra, and compare it with the simultaneous multi-frequency study by Ostoreroe et. al. [8] in Section 4. The results will be discussed in Section 5.

2. MODEL PARAMETERS

We consider an idealised model with a mono-energetic electron distribution with Lorentz factor γ and number density $n_{\rm e}$, embedded in a uniform magnetic field B. The source is characterised by a single linear length scale R, and Doppler boosting factor $\mathcal{D} = \sqrt{1-\beta^2}/(1-\beta\cos\phi)$, where $c\beta$ is the source speed with respect to the rest frame of the host galaxy and ϕ is the angle between the velocity and the line of sight.

The assumed energy distribution captures the relevant properties of a power-law electron distribution with a lower energy cut-off, if the distribution rises towards the cut-off faster than $\mathrm{d}\ln n/\mathrm{d}\ln\gamma > -1/3$. Distribution of this type can account for the lack of Faraday depolarisation in parsec-scale emission regions [9, 10], and which has recently been discussed in connection with statistical trends in the observed distribution of superluminal velocities as a function of observing frequency and

redshift [11]. Similar models have been considered in connection with high brightness temperature sources by Crusius-Waetzel [6] and Protheroe [12]. Slysh [13] has also considered a model with mono-energetic electrons, but restricted his treatment only to optically thick sources and did not allow for multiple scattering.

The source model has five parameters: $\mathcal{D}$, R, B, $n_{\rm e}$ and γ. $\mathcal{D}$ and R can be constrained either by variability, which puts an upper limit to the quantity $R/\mathcal{D}^2$, or separately from independent observations. Surveys of superluminal motion [14] suggest that $\mathcal{D} \leq 10$ for most sources, and for a few, up to 30 or 40. An upper limit of R can be obtained if scintillation is present.

The rest of the parameters, B, $n_{\rm e}$ and γ can be constrained by eliminating them with three new parameters. Denoting the Thomson optical depth corresponding to the monenergetic electrons by $\tau_{\rm T} = n_{\rm e} R \sigma_{\rm T}$, the first of the three new parameters is the optical depth to synchrotron absorption $\tau_{\rm s}$ is

$$\tau_{\rm s} = \frac{\sqrt{3}\tau_{\rm T} m_{\rm e} c^3 K_{5/3}(x)}{8\pi e^2 \nu_{\rm s} \gamma^3} \quad (1)$$

[e.g., 15]. Here, $K_{5/3}(x)$ is the modified Bessel function,

$$x = \nu(1+z)/(\mathcal{D}\nu_{\rm s}) \quad (2)$$

ν is the observing frequency, $\nu_{\rm s} = 3eB\sin\theta\gamma^2/(4\pi m_{\rm e} c)$ is the synchrotron characteristic frequency, for an angle θ between the line of sight and the magnetic field B in the rest frame of the source, and z is the redshift of the host galaxy.

The observed brightness temperature $T_{\rm B}$ measured at frequency ν is related to the specific intensity of radiation I_ν by $T_{\rm B} = c^2 I_\nu/(2\nu^2 k_{\rm B})$, and is therefore

$$\frac{k_{\rm B} T_{\rm B}}{m_{\rm e} c^2} = \frac{\mathcal{D}}{1+z}\left(\frac{\gamma F(x)}{2x^2 K_{5/3}(x)}\right)\left(1 - {\rm e}^{-\tau_{\rm s}}\right) \quad (3)$$

where $F(x) = x\int_x^\infty {\rm d}t K_{5/3}(t)$ is the standard synchrotron function in the Airy integral approximation [see e.g. 16, Chapter 6].

The second new parameter, ξ, determines the inverse Compton luminosity, and is defined as the ratio of the energy density in synchrotron photons to the magnetic energy density (and thus the ratio of the energy densities in consecutive generation of scattered photons), assuming the scattering occurs in the Thomson regime. This quantity is somewhat sensitive to the geometry and homogeneity of the source [17]. For a uniform source that can be characterised by a single length scale R we have, in the optically thin case of relevance here,

$$\xi = 4\gamma^2 \tau_{\rm T}/3 \quad (4)$$

When $\xi > 1$, the energy contained in successive generations of inverse Compton scattered photons increases, provided the scattering remain in the Thomson regime. As a consequence, the energy radiated formally diverges, a phenomenon that has acquired the name *Compton Catastrophe*. Therefore, to avoid large Compton losses, we require $\xi \leq 1$, which in turns ensures that $\tau_{\rm T} \ll 1$.

Eliminating the parameters $\tau_{\rm T}$, $\nu_{\rm s}$ and γ from Eq. (3) using Eqs. 1, 2 and 4, the brightness temperature can be written as

$$\frac{k_{\rm B} T_{\rm B}}{m_{\rm e} c^2} = \left(\frac{3^{3/2} m_{\rm e} c^3}{4^5 \pi e^2 \nu}\right)^{1/5} \left(\frac{\xi \mathcal{D}^6}{(1+z)^6}\right)^{1/5} \left(\frac{1-{\rm e}^{-\tau_{\rm s}}}{\tau_{\rm s}^{1/5}}\right) \left(\frac{F(x)}{x^{9/5} K_{5/3}^{4/5}(x)}\right) \quad (5)$$

The first term in parentheses on the right-hand side of Eq. 5 is independent of the source parameters. The third term in parentheses reaches a maximum of the order of unity at $\tau_{\rm s} \sim 1$. The fourth, however, diverges for small x as $x^{-2/15}$. Thus, even with $\xi < 1$ and $\mathcal{D} < 10$, it is possible to find source parameters for which this formula gives an arbitrarily high brightness temperature at any specified observing frequency. Ultimately, when $x \lesssim \gamma^{-3}$, the Airy integral approximation to the synchrotron emissivity, on which Eq. (5) is based, loses validity, because the harmonics of the gyro frequency $\nu_{\rm L}/\gamma$ cease to merge into a smooth continuum. However, there is a tighter constraint from observations.

This model predicts an optically thin synchrotron spectrum of $I_\nu \propto \nu^{1/3}$ between the observing frequency ν and the frequency ν/x. Optical observations of, for example, PKS 1519 −273, PKS 0405 −385 and S5 0716+714 ([18, 8] and Wagner, priv. comm.) suggest that the optically thin synchrotron radiation cuts off above $\sim 10^{14}$ Hz. This can be quantified by introducing the third new parameter, $\nu_{\rm max} = \nu/x$, such that the optically thin synchrotron emission stretches from ν up to $\nu_{\rm max} \lesssim 10^{14}$ Hz.

3. BRIGHTNESS TEMPERATURE AND CIRCULAR POLARISATION

Rewriting Eq. (5) in terms of the three new parameter $\tau_{\rm s}$, ξ and $\nu_{max,14} = \nu_{\rm max}/10^{14}$ Hz, the brightness temperature is independent of the source size, and only weakly dependent on the other parameters:

$$T_{\rm B} = 1.2\times10^{14}\left(\frac{\mathcal{D}_{10}^6 \xi}{(1+z)^6}\right)^{1/5}\left(\frac{1-{\rm e}^{-\tau_{\rm s}}}{\tau_{\rm s}^{1/5}}\right)\nu_{max,14}^{2/15}\nu_{\rm GHz}^{-1/3}\,{\rm K} \quad (6)$$

where $\mathcal{D}_{10} = \mathcal{D}/10$ and $\nu_{\rm GHz} = \nu/10^9$, and the approximations $F(x) \approx 2.15x^{1/3}$ and $K_{5/3}(x) \approx 1.43x^{-5/3}$ for $x \ll 1$ are used. According to Eq. 6, brightness temperatures of up to $\sim 10^{14}$ K at GHz frequencies can be achieved with moderate Doppler boosting factors of $\mathcal{D} \sim 10$.

A particularly interesting source property is the degree of intrinsic circular polarisation $r_{\rm c}$. Assuming a pure

electron-proton plasma,

$$r_{\rm c} = \frac{1}{3}\left(\frac{2}{x\gamma^3}\right)^{1/3} \cot\theta\,\Gamma(1/3) \quad (7)$$

$$= 1.9\times\left(\frac{\tau_{\rm s}}{\mathcal{D}_{10}\xi}\right)^{1/5} \nu_{max,14}^{1/5}\cot\theta\,\% \quad (8)$$

[19]. In the case of a power-law electron distribution, $r_{\rm c}$ changes sign when entering the optically thick regime, but we have found no such calculation for the mono-energetic case so far. To order of magnitude, the peak value of $r_{\rm c}$ can be estimated using this expression, which is remarkably insensitive to the source parameters except the magnetic field direction.

Several extra-galactic high brightness temperature sources such as those mentioned above have been observed with circular polarisation at the percent level [7]. With a conventional power-law electron distribution, PKS 0405−385, for example, would have $r_{\rm c} \approx 0.06\%$, far too small to explain the observation. However, according to Eq. 8, the typical value of $r_{\rm c}$ for a mono-energetic electron distribution is of the order of 1%.

4. SYNCHROTRON AND INVERSE COMPTON SPECTRA

Following the approach of Georganopoulos et. al. [20], in the observer's frame, photons with energy $h\nu_{i-1}$ are scattered by a uniform distribution of electrons with number density $n_{\rm e}$ at a rate

$$\left(\frac{{\rm d}N_p}{{\rm d}t{\rm d}\nu_i}\right)=\int_0^{4\pi}{\rm d}\Omega\int_0^{R/2}n_{\rm e}{\rm d}^3r\int_0^{\infty}\frac{{\rm d}\nu_{i-1}}{c}\left(\frac{{\rm d}n_p}{{\rm d}t{\rm d}\nu_i}\right)\frac{\zeta I_{\nu_{i-1}}}{h\nu_{i-1}} \quad (9)$$

where ζ is a constant arises from the geometry of the source, typically of the order of unity, and for the model discussed here, $\zeta = 2/3$. $({\rm d}n_p/{\rm d}t{\rm d}\nu_i)$ is the rate of scattering per photon frequency interval from a single electron for the ith generation scattered photons, defined in [20] Eq. (4) as

$$\left(\frac{{\rm d}n_p}{{\rm d}t{\rm d}\nu_i}\right) = \frac{3\sigma_{\rm T}c}{4\nu_{i-1}\gamma^2}f(y) \quad (10)$$

and the function $f(y)$ is defined in Eq. (7) of [20], which takes into account of the Klein-Nishina effect.

Assuming the synchrotron emission is isotropic,

$$I_{\nu_i}^{\rm SC} = \left(\frac{{\rm d}E}{{\rm d}t{\rm d}\nu_i{\rm d}r^2{\rm d}\Omega}\right) = \frac{h\nu_i}{4\pi}\left(\frac{{\rm d}N_p}{{\rm d}t{\rm d}\nu_i}\right)\frac{1}{4\pi(R/2)^2}$$

$$= \frac{1}{4}\tau_{\rm T}\frac{\nu_i}{\gamma^2}\int_0^{\infty}\frac{{\rm d}\nu_{i-1}}{\nu_{i-1}^2}I_{\nu_{i-1}}f(y) \quad (11)$$

We evaluate Eq. 11 numerically over the frequency range $10^7 \le \nu \le 10^{25}$ Hz, and the results are shown in Fig. 1.

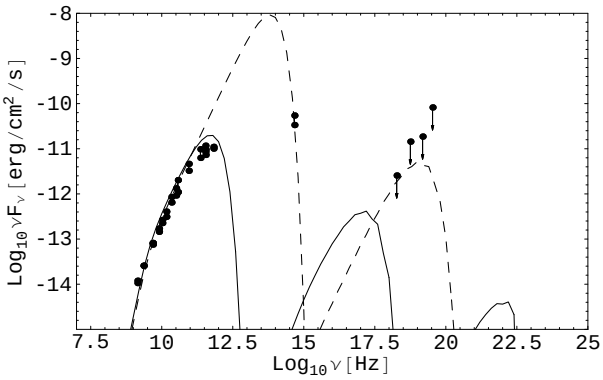

Figure 1. Spectral energy distribution of S5 0716 +714 from observations (black dots, variation ranges are indicated by vertical bars and upper limits by arrows) and as predicted by this model. Doppler factors $\mathcal{D}$ are 8 (dashed) and 10 (solid), Lorentz factors γ are 319 (dashed) and 349 (solid), magnetic field strength B are 20G (dashed) and 0.1G (solid). We adopted an angular size of 0.16mas [21], corresponding to 0.7pc at $z = 0.3$.

5. DISCUSSION

The most important feature of this model is the lack of low energy electrons, which would otherwise absorb the GHz emission. This can be in the form of a mono-energetic distribution, where all electrons have Lorentz factor $\gamma = \gamma_0$, or in the form of a quasi-mono-energetic distribution, such that ${\rm d}\ln n/{\rm d}\ln\gamma > -1/3$ for $\gamma < \gamma_0$. For example, a relativistic thermal distribution rises at low energy as γ^2. The addition of a power-law tail to higher energy would not affect this assumption.

Continuous re-acceleration prevents the accumulation of low energy electrons, but once evacuated from the acceleration zone, the particles are subsequently cooled by synchrotron and inverse Compton scattering. Therefore, the quasi-mono-energetic assumption is only self-consistent if these particles escape the source in a time shorter than the radiative cooling time.

For the scenario discussed here, where the Thomson optical depth $\tau_{\rm T} \ll 1$, the dominant cooling process is synchrotron radiation. As it was shown in [22], the ratio of the synchrotron cooling time $t_{\rm cool}$ to the light crossing time R/c is

$$\frac{ct_{\rm cool}}{R} = 2.9\left(\frac{\mathcal{D}_{10}^{13}\xi^3}{(1+z)^{13}\tau_{\rm s}^3}\right)^{1/5}\sin^2\theta R_{-2}^{-1}\nu_{max,14}^{-8/5}\nu_{\rm GHz}^{-1} \quad (12)$$

where the source size is written as $R = R_{-2}\times 0.01\,$pc.

Fig. 1 shows the simultaneous data (black dots) obtained by Ostoreroe et. al. [8], and the theoretical spectra of S5 0716+714. Dashed lines represent the synchrotron and inverse Compton spectra produced by mono-energetic electrons of Lorentz factor 319, with optically thin synchrotron emission between $\nu_{\rm GHz} = 4\,$GHz

and $\nu_{\max} = 10^{13.7}$ Hz. The synchrotron spectrum gives a reasonable fit at radio frequencies, going through the optical points at $\sim 10^{14.5}$ Hz, although the break in the power law spectrum at $\sim 10^{11.5}$ Hz cannot be fitted. The first order inverse Compton spectrum gives emission in x-ray frequencies, and the second order inverse Compton spectrum falls outside the Thomson regime and therefore no gamma ray emission is produced. This parameter set is ruled out, however, since the ratio of the synchrotron cooling time to the light crossing time is $\ll 1$, implying that the relativistic electrons are cooled by scattering before they leave the acceleration region. The shape of the electron spectrum will therefore change from being mono-energetic with (quasi-mono-energetic with a low energy cut-off at) $\gamma = \gamma_0$ to one which is $\propto \gamma^{-2}$, extending to energy lower than $\gamma_0 m_{\rm e} c^2$.

The solid lines show the synchrotron and inverse Compton spectra produced by electrons of Lorentz factor 349. Here the optically thin spectrum is only between $\nu_{\rm GHz} = 4$ GHz and $\nu_{\max} = 400$ GHz. The synchrotron spectrum shows good agreement with the data points at radio frequencies. However, the optical points cannot be fitted with parameters that are consistent with the mono-energetic assumption. The first order inverse Compton spectrum gives emission in the x-ray frequencies, and the second order spectrum gives gamma-ray emission up to ~ 0.1 GeV energies, higher orders are then cut off by the Klein-Nishina effect.

To summarise, synchrotron radiation from a mono-energetic electron distribution reproduces the very high brightness temperatures observed in extra-galactic variable radio sources, as well as the high degree of circular polarisation. Testable predictions of the theory are a hard radio to infra-red spectrum, x-ray emission and possibly gamma-ray emission in the MeV to GeV range, depending on the specific values of the parameters.

REFERENCES

[1] S. J. Wagner and A. Witzel. Intraday Variability In Quasars and BL Lac Objects. *ARA&A*, 33:163–198, 1995.

[2] J.-P. Macquart and L. Kedziora-Chudczer, et. al. Strong, Variable Circular Polarization in PKS 1519-273. *ApJ*, 538:623–627, August 2000.

[3] B. J. Rickett, L. Kedziora-Chudczer, and D. L. Jauncey. Interstellar Scintillation of the Polarized Flux Density in Quasar PKS 0405-385. *ApJ*, 581:103–126, December 2002.

[4] J.-P. Macquart and G. de Bruyn. Diffractive Interstellar Scintillation of the Quasar J1819+3845 at 21cm. *ArXiv Astrophysics e-prints*, October 2005.

[5] K. I. Kellermann and I. I. K. Pauliny-Toth. The Spectra of Opaque Radio Sources. *ApJ*, 155:L71, February 1969.

[6] A. R. Crusius-Waetzel. High radiation brightness temperatures in active galactic nuclei. *A&A*, 251:L5, November 1991.

[7] J.-P. Macquart. Circular polarization in relativistic jets. *New Astronomy Review*, 47:609–612, October 2003.

[8] L. Ostorero and S. J. Wagner, et. al. Testing the inverse-Compton catastrophe scenario in the intra-day variable blazar objectS5 0716+71/object. *A&A*, 451:797–807, June 2006.

[9] J. F. C. Wardle. Upper limits on the Faraday rotation in variable radio sources. *Nature*, 269:563–566, October 1977.

[10] T. W. Jones and S. L. Odell. Physical conditions in polarized compact radio sources. *A&A*, 61:291–293, October 1977.

[11] Gopal-Krishna, P. L. Biermann, and P. J. Wiita. Brightness Suppression of Relativistic Radio Jets of Quasars: The Role of the Lower Electron Energy Cutoff. *ApJ*, 603:L9–L12, March 2004.

[12] R. J. Protheroe. The brightness temperature problem in extreme intra-day variable quasars: a model for PKS 0405-385. *MNRAS*, 341:230–238, May 2003.

[13] V. I. Slysh. The synchro-Compton limit of the brightness temperature of nonstationary radio sources. *ApJ*, 391:453–455, June 1992.

[14] M. H. Cohen and M. A. Russo, et. al. Variability and Velocity of Superluminal Sources. In *ASP Conf. Ser. 300: Radio Astronomy at the Fringe*, page 177, 2003.

[15] M. S. Longair. *High energy astrophysics. Vol.1,2: Particles, photons and their detection*. Cambridge: Cambridge University Press, 1992, 2nd ed., 1992.

[16] G. B. Rybicki and A. P. Lightman. *Radiative processes in astrophysics*. New York, Wiley-Interscience, 1979. 393 p., 1979.

[17] R. J. Protheroe. Factors Determining Variability Time in Active Galactic Nucleus Jets. *Publications of the Astronomical Society of Australia*, 19:486–498, 2002.

[18] J. Heidt and S. J. Wagner. Statistics of optical intraday variability in a complete sample of radio-selected BL Lacertae objects. *A&A*, 305:42–+, January 1996.

[19] D. B. Melrose. *Plasma astrophysics: Nonthermal processes in diffuse magnetized plasmas. Volume 1 - The emission, absorption and transfer of waves in plasmas*. New York, Gordon and Breach Science Publishers, 1980. 276 p., 1980.

[20] M. Georganopoulos, J. G. Kirk, and A. Mastichiadis. The Beaming Pattern and Spectrum of Radiation from Inverse Compton Scattering in Blazars. *ApJ*, 561:111–117, November 2001.

[21] U. Bach and T. P. Krichbaum, et. al. Kinematic study of the blazar ¡ASTROBJ¿S5 0716+714¡/ASTROBJ¿. *A&A*, 433:815–825, April 2005.

[22] J. G. Kirk and O. Tsang. High brightness temperatures and circular polarisation in extra-galactic radio sources. *A&A*, 447:L13–L16, February 2006.