High energy emission processes in OJ 287 during 2009 flare

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ABSTRACT

The broad-band spectrum of a BL Lac object, OJ 287, from radio to γ-rays obtained during a major γ-ray flare detected by Fermi in 2009 is studied to understand the high energy emission mechanism during this episode. Using a simple one-zone leptonic model, incorporating synchrotron and inverse Compton emission processes, we show that the explanation of high energy emission from X-rays to γ-rays, by considering a single emission mechanism, namely, synchrotron self-Compton (SSC) or external Compton (EC), requires unlikely physical conditions. However, a combination of both SSC and EC mechanisms can reproduce the observed high energy spectrum satisfactorily. Using these emission mechanisms we extract the physical parameters governing the source and its environment. Our study suggests that the emission region of OJ 287 is surrounded by a warm infrared emitting region of ~9 pc. This supports the claim that the γ-ray emission from OJ 287 during the 2009 flare arises from a location far away from the central engine as deduced from millimetre–γ-ray correlation study and very long baseline array images.

Key words: radiation mechanisms: non-thermal – galaxies: active – BL Lacertae objects: individual: OJ 287 – galaxies: jets – X-rays: galaxies.

1 INTRODUCTION

BL Lacs are a class of radio loud active galactic nuclei (AGN) with no/weak emission line features (Urry & Padovani 1995). They are classified along with flat spectrum radio quasars (FSRQ) as blazars. BL Lacs are characterized by a non-thermal spectra extending from radio to γ-rays with many of them detected even up to GeV/TeV energies (Wystan Benbow for the VERITAS Collaboration 2011).1 Their spectral energy distribution (SED) is bimodal with a low-energy peak in infrared (IR)–X-ray wavelength and a high-energy one at γ-rays. Based on the location of low-energy peak they are classified as low-energy peaked BL Lacs (LBL), intermediate-energy peaked BL Lacs (IBL) and high-energy peaked BL Lacs (HBL; Padovani & Giommi 1995; Fossati et al. 1998). The observed short time variability of the order of days to minutes and detection of very high energy (VHE) γ-rays demand the emission to arise from a relativistic jet close to the line of sight of the observer (Dondi & Ghisellini 1995). Moreover, the constraints obtained from the variability time-scale suggest the emission region to be located at sub-parsec scales from the central engine. The strong polarization observed in radio and optical bands, and the non-thermal nature of the spectrum indicate that the radio-to-X-ray emission is of synchrotron origin due to cooling of a power-law distribution of electrons in a magnetic field. The higher energy emission is then generally attributed to synchrotron self-Compton (SSC) emission where the population of electrons responsible for synchrotron emission will further scatter off the synchrotron photons to higher energies by inverse Compton process. However, for certain BL Lacs one needs to consider the inverse Compton scattering of photons external to the jet in order to explain the high energy emission (Abdo et al. 2011; Ackermann et al. 2012). Besides these models, there also exist other models where the high energy emission is believed to be the result of hadronic processes (Mannheim 1998; Mücke et al. 2003; Böttcher, Reimer & Marscher 2009).

The relativistic jets of a few BL Lacs are resolved in the high-resolution radio maps and often show knot-like features (Giroletti et al. 2004; Marscher & Jorstad 2011). In many misaligned AGN jets, Fanaroff and Riley type I and II (FR I and FR II; Fanaroff & Riley 1974), such knots are even observed in optical and X-ray maps at kiloparsec scales (Pesce et al. 2001; Sambruna et al. 2002). Often the location of these optical/X-ray knots is coincident with the ones seen in radio. For these knots, the radio-to-optical emission is generally attributed to synchrotron emission whereas X-ray emission can be an extension of synchrotron radiation itself or arise due to inverse Compton scattering of soft target photons (Tavecchio et al. 2000).

If X-ray flux is above the extrapolation of radio to optical flux, then X-ray emission is explained through inverse Compton process else synchrotron emission model is accepted (Sambruna et al. 2002). For

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the case when X-ray emission is due to inverse Compton processes, SSC interpretation requires large jet power and magnetic field lower than the equipartition value (Chartas et al. 2000). On the other hand, inverse Compton scattering of external photons may be a viable option. At kiloparsec scales the plausible external photon field for the inverse Compton scattering can be the cosmic microwave background radiation (CMBR). Explanation of X-ray emission through inverse Compton scattering of CMBR (IC/CMBR) requires less jet power and near equipartition magnetic field (Tavecchio et al. 2000) and this process is widely accepted though it faces various criticisms (Atoyan & Dermer 2004; Harris & Krawczynski 2006). At parsec scales, the high energy emission can be due to inverse Compton scattering of radiation from the nuclear region and/or starlight (Stawarz et al. 2006). When X-ray emission is due to synchrotron process, the underlying particle distribution requires a broken power law in order to explain the observed spectrum (Wilson & Yang 2002; Liu & Shen 2007). A broken power-law particle distribution can be formed by a continuous injection of plasma into a cooling region or through multiple acceleration processes (Sahayanathan et al. 2003; Sahayananathan 2008).

OJ 287 ($z = 0.306$) is one of the well-studied BL Lac object (LBL) with a peculiar periodic outbursts at an interval of roughly 12 yr (Sillanpää et al. 1996a). This behaviour suggested the possible presence of a binary supermassive black hole (SMBH) system at the nucleus of OJ 287. Sillanpaa et al. (1988) explained these outbursts as a result of tidal disturbances in the accretion disc of the primary black hole caused by the secondary. Later Sillanpaa et al. (1996b) performed a detailed study of the optical light curves during these periodic episodes and found that the outbursts are double peaked. They explained this feature as a result of the double impact of the secondary black hole on the accretion disc of the primary while orbiting around the latter in the binary black hole system (Lehto & Valtonen 1996). This model later modified to accommodate new data obtained during 2005–2007 outburst (Valtonen et al. 2006, 2009, 2011; Valtonen 2007).

Recently OJ 287 was observed extensively through several campaigns during 2005–2010 (Valtonen & Sillanpää 2011 and references therein). The observations were primarily oriented towards the detection of the outburst around, confirming the prediction of binary black hole system originally proposed by Sillanpää et al. (1988). Agudo et al. (2011) studied the $\gamma$-ray flare of OJ 287 during 2008–2010 along with observations in other energy bands around the same period. They found a strong correlation between $\gamma$-ray and the millimetre emission during the two major $\gamma$-ray flares. Further the Very Long Baseline Array (VLBA) study suggested that the millimetre flares are associated with the ejection of superluminal patterns from a stationary knot C1 (Agudo et al. 2011). Based on these facts they argued that the location of the $\gamma$-ray emission is linked with the knot C1. From the separation between knot C1 and an inner knot C0, located close to the nucleus, they concluded that the $\gamma$-ray emission region must be at a distance >14 pc from the central engine. At such a distance, $\gamma$-ray emission mechanism can be due to either SSC or external Compton (EC) scattering of IR photons from a dusty torus (EC/IR).

In the present work we have studied the plausible high energy (X-ray and $\gamma$-ray) emission mechanisms in OJ 287 during a major flare in 2009. As suggested by Agudo et al. (2011), this emission may also be associated with the ejection of superluminal patterns from the knot C1. We divided the flare light curve during this period into three different states and obtained their average flux in various energy bands. A simple emission model was then used to study the observed broad-band spectrum corresponding to different states. We have exploited the available information obtained through simultaneous/contemporaneous multiwavelength observations which are sufficient to extract the physical parameters of the source. We analysed the possibility of reproducing the broad-band SED of OJ 287 considering different combinations of emission mechanisms like (i) synchrotron and SSC, (ii) synchrotron and EC/IR and (iii) synchrotron, SSC and EC/IR and present our results here. Below we first describe the data analysis technique (Section 2). In Section 3 we study the processes responsible for the high energy emission mechanism. We discuss the results obtained in Section 4. A flat $\Lambda$ cold dark matter ($\Lambda$CDM) cosmology with $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$ and $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$ is assumed throughout the paper.

2 DATA ANALYSIS

We have used the publicly available multi-wavelength data from Fermi-Large Area Telescope (LAT) and Swift-X-Ray Telescope (XRT) along with optical and radio data from various blazar monitoring programs during the flaring episode (MJD: 55110–55185) of OJ 287 in 2009.

2.1 $\gamma$-ray data

The LAT on the Fermi Gamma-ray Space Telescope is a pair production telescope sensitive to $\gamma$-rays energies from 30 MeV to >300 GeV (Atwood et al. 2009). Its periodic ~3 h (two orbits) scan of the entire sky makes it the best instrument to monitor the evolution of GeV sources as well as any high energy (HE) phenomenon down to the scanning time-scale thereby helping to understand and constrain the HE physics and associated emission processes.

LAT data of OJ 287 obtained during 2009 flare (MJD: 55110–55185) were analysed using f ermi science tool version v9r23p1, latest publicly available release during the time of data analysis. Only ‘source class events’ (evclass 2) having energy above 100 MeV from photon data were considered with the recommended time interval$^2$ to make sure that the spacecraft was in normal science data acquisition mode, avoiding Earth’s limb, South Atlantic Anomaly (SSA) and pointed observations. Unbinned maximum likelihood analysis (Mattox et al. 1996) method was used to model the photons from a region of interest (ROI) of $1^\circ$ centred on the location of OJ 287 to reconstruct the source energy spectrum. Effects of time selection, energy cut, variation of LAT area with azimuth angle and point spread function (PSF) corrections were accounted for while generating the exposure map from an annular region of $10^\circ$ around ROI. Sources in the region were modelled using LAT second catalogue (Nolan et al. 2012).$^3$ Pass 7 instrument response function with galactic diffuse emission model (gal$\_\text{2year}$v6$\_\text{0.fit}$) and isotropic background model (gal$\_\text{2year}$v6$\_\text{0.fit}$) provided by the LAT science team were used to model the source spectrum (0.1–300 GeV) keeping integral flux and photon index as free parameters.

Source fluxes in different energy ranges (100–300 MeV, 300 MeV–1 GeV, 1–3 GeV, 3–10 GeV) were then extracted by freezing the photon index to the best-fitting value obtained by the analysis of 0.1–300 GeV data. Finally, time averaged SED data points were extracted by combining LAT data over the mentioned period (see Section 2.4) following the procedure as described above.

$^2$ http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Data_Exploration/Data_preparation.html

$^3$ OJ 287 is fitted with a simple power-law model.
2.2 X-ray data

The XRT (Burrows et al. 2005) onboard Swift is a grazing incidence Wolter type 1 focusing X-ray telescope sensitive to soft X-ray energies (0.3–10 keV). We have used the photon counting (PC) pointed data with normal clocking and default window configuration for this study.

Event files obtained from Swift-XRT data base were calibrated and cleaned with standard filtering criteria using XRTPipeline (SWXRT-DAS version 2.8.0) task and latest calibration files from Swift CALDB. Source photons for spectral analysis were extracted using a circular region of 20 pixels (~47 arcsec, 90 per cent PSF at 1.5 keV; Moretti et al. 2005) centred on the source, and background photons from multiple uncontaminated regions around the source. CCD defects and PSF corrections were applied using auxiliary response file (ARF) generated from XRTKMARC task. The data in the energy bins of the resultant spectrum file (0.5–10 keV) were re-binned using GRPPHA with a minimum 5σ significance (statistical only) and fitted with a power-law model modified by an absorber (PHABS) within XSPEC (version 12.7.1) by freezing the neutral hydrogen column density \( N_\text{H} \) to its Galactic value of 2.38 \( \times 10^{20} \) cm\(^{-2} \) (Kalberla et al. 2005) in the direction of OJ 287. For SED analysis, individual XRT event files during the considered period (see Section 2.4) were combined using the XSELECT task and an average spectrum was extracted. The extracted SED data points were then corrected for Galactic absorption.

2.3 Optical and radio data

Contemporaneous optical and radio data used in this study were taken from archives of various multiwavelength programs supporting Fermi observatory. The optical data include V-band photometric data from Arizona-Steward\(^4\) and near-IR–optical photometric data from Yale-Small and Medium Aperture Research Telescope System (SMARTS)\(^5\) project. The radio data at 15 and 43 GHz were obtained from Caltech-Owens Valley Radio Observatory (OVRO)\(^6\) and Boston-VLBA\(^7\) project, respectively.

The details of data selection and analysis procedure for Yale-SMARTS, Arizona-Steward, Caltech-OVRO and Boston-VLBA data are described in Bonning et al. (2012; and references therein), Smith et al. (2009), Richards et al. (2011) and Jorstad et al. (2005), respectively.

2.4 Multiwavelength SEDs

Fig. 1 shows the multiwavelength light curves of OJ 287 during the flare in 2009 as observed by various satellites and ground-based observatories (mentioned above). The daily binned LAT light curve (top panel) corresponds to a detection criteria of 3σ (TS > 9; Mattox et al. 1996) followed by X-ray, IR, optical and radio light curves. The inset of Fig. 1 shows the 7 d binned LAT photon flux with TS > 9 for MJD: 55152–55166.

The near correlated variation in different energy bands (visible in the LAT and the optical V-band data around MJD 55126 with a hint in X-rays as well) suggests a co-spatial origin of radiation emphasizing that a single electron population may be responsible for emission throughout the electromagnetic spectrum, i.e. from mm (below this frequency different regions are believed to be contributing to the radio fluxes; Maraschi et al. 1994) to γ-ray energies.

3 HIGH ENERGY EMISSION MECHANISM

To understand the X-ray and the γ-ray emission from OJ 287 during the flare, we adopt a simple model where the emission region is assumed to be a sphere of radius \( R \) moving down the jet at relativistic speed (\( \beta c \)) with bulk Lorentz factor \( \Gamma = (1 - \beta^2)^{-1/2} \) at an angle \( \theta \) with respect to the line of sight of the observer. The emission region is permeated with a tangled magnetic field \( B \) and populated by a broken power-law distribution of particles described by (primed quantities are measured in the rest frame of the emission region)

\[
N'(y') \, dy' = \begin{cases} \kappa \, y'^{q-p} \, dy', & \gamma'_\text{min} < y' < \gamma'_0, \\ \kappa \, y'^{q-p} \, dy', & \gamma'_0 < y' < \gamma'_\text{max}, \end{cases}
\]

with \( \kappa = K_y y'_\text{b}^{q-p} \). Here, \( \gamma'_\text{min}, m_e c^2 \) and \( \gamma'_\text{max}, m_e c^2 \) are the minimum and maximum energy of the particle distribution and \( \gamma'_0 m_e c^2 \) is the break energy with \( m_e \) being the rest mass of electron. The magnetic field and particle energy densities are related by

\[
U'_e = \eta U'_B, \quad \text{and} \quad U'_B = \frac{B_e^2}{8\pi},
\]

where \( U'_e \) is the particle energy density given by

\[
U'_e = m_e c^2 \int_{\gamma'_\text{min}}^{\gamma'_\text{max}} \gamma' N'(\gamma') \, d\gamma',
\]

and \( U'_B \) is the magnetic field energy density

\[
\eta \text{ is a parameter and equipartition condition corresponds to } \eta \sim 1. \quad \text{Particles lose their energy radiatively through synchrotron, SSC and/or EC processes. Because of relativistic motion and cosmological effects, the flux received by the observer on earth will be}
\]

\[
F(v) = \frac{\delta (1+z)}{d_L^2} V' \epsilon' \left( \frac{1+z}{\delta} V \right),
\]

where \( \delta = [\Gamma (1 - \beta \cos \theta)]^{-1} \) is the jet Doppler factor, \( d_L \) is the luminosity distance, \( V \) the volume of the emission region and \( \epsilon' \) is the source emissivity due to different radiative processes.

Among the various parameters deciding the observed flux, the size of the emission region can be constrained through the variability.
High energy emission processes in OJ 287

Figure 1. Multiwavelength light curves of OJ 287 during a flare in 2009 (October 6–December 20) from radio to γ-ray frequencies. The vertical lines delineate the three different states of OJ 287. The X-ray (Swift-XRT) and γ-ray (Fermi-LAT) data are from their respective data base. The IR–optical data are reproduced from Yale-SMARTS (filled circles) along with optical V-band data from Arizona-Steward (filled squares) Fermi follow-up programs. Radio data were obtained from Boston and OVRO blazars' monitoring program as labelled in the figure. The 7 d binned LAT data from MJD: 55152–55166 are shown in the inset with the same x-scale.

For the present work, we consider the viewing angle of the jet for OJ 287 to be ∼3° as estimated from VLBA studies (Jorstad et al. 2005) and the bulk Lorentz factor of the jet Γ is chosen to be 12 to obtain the observed superluminal velocity of 10.8c (Agudo et al. 2011). Under these assumptions and constraints, a plausible mechanism responsible for the high energy emission can be argued based on the observed fluxes in optical, X-ray and γ-ray energies.

\[ R' = \frac{\delta}{1+z^{1/3}} \]  

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(6)
We have chosen the spectrum corresponding to the State 1 for present study and used the approximate analytical solution for synchrotron and EC emissivities (Sahayanathan & Godambe 2012) to estimate the source parameters.

### 3.1 Synchrotron self-Compton

In the interpretation based on SSC mechanism being operative, we consider the X-ray and \( \gamma \)-ray emission as resulting from inverse Compton scattering of synchrotron photons by the particle distribution described by equation (1). The SSC peak \( (v_{\text{p,SSC}}) \) of the spectrum can then be related to the synchrotron peak \( (v_{\text{p,syn}}) \) as

\[
v_{\text{p,SSC}} = \gamma_b^2 v_{\text{p,syn}},
\]

with

\[
v_{\text{p,syn}} = \frac{\delta}{1 + \frac{z}{\delta}} \gamma_b^2 v_L.
\]

Here \( v_L = B^2/(2\pi mc^2) \) is the Larmor frequency.

The observed synchrotron flux for \( \nu > v_{\text{p,syn}} \) can be approximated as

\[
F_{\text{syn}}(\nu) \approx s(z,q)B^{\delta+5/2}2^{\nu+1/2}R^5 \nu^{-\delta}
\]

where \( s(z,q) \) is a function of \( z \) and \( q \) (for \( z = 0.306 \) and \( q = 3.54, s = 3.8 \times 10^{-47} \)). Substituting equation (6) in equation (9) and choosing \( p = 2.42 \) and \( q = 3.54 \) (corresponding to photon indices \( 1.71 \pm 0.05 \) and \( 2.27 \pm 0.10 \)), we can obtain the source magnetic field in terms of observed quantities as

\[
B' \approx 0.08 \left( \frac{F_{\gamma} \times 10^{-3} \text{Jy}}{6.6 \times 10^{-3} \text{Jy}} \right)^{0.44} \left( \frac{\delta}{17.2} \right)^{-3.20} \left( \frac{\nu}{2.5 \text{d}} \right)^{-1.32} \left( \frac{\kappa}{2.4 \times 10^9} \right)^{-0.44} \left( \frac{\nu}{5.5 \times 10^{-14} \text{Hz}} \right)^{0.56} G.
\]

The value of \( \kappa \) is chosen to reproduce the SSC flux of \((5.5 \pm 0.5) \times 10^{-11} \text{Jy} \) at 0.55 GeV. Considering \( v_{\text{p,syn}} \lesssim 10^{14} \text{Hz} \) (see Fig. 2) and using equations (8) and (10) we get \( \gamma_b' \approx 5.8 \times 10^3 \). These estimated parameters correspond to an equipartition parameter \( \eta \sim 215 \) for assumed \( \gamma_b'_{\text{min}} = 40 \).

![Figure 2](https://example.com/f2.png)

**Figure 2.** Time averaged broad-band SED of OJ 287 obtained for MJD: 55124–55131 (State 1), MJD: 55131–55152 (State 2) and MJD: 55152–55184 (State 3) (see Fig. 1) during the 2009 \( \gamma \)-ray flare. State 1 SED corresponds to an average spectra from 2009 October 20–27. The brightest \( \gamma \)-ray flare happened on 2009 October 22 while the XRT data for this state correspond to 2009 October 25. State 2 SED corresponds to an average spectra from 2009 October 28–November 17 while the State 3 SED corresponds to 2009 November 18–December 19.

If we consider the SSC spectrum as a broken power law with indices \( \alpha_x = 0.71 \pm 0.05 \) and \( \alpha_\gamma = 1.27 \pm 0.10 \), then the peak SSC frequency in SED can be obtained through X-ray and \( \gamma \)-ray fluxes as

\[
v_{\gamma,\text{SSC}} = \left( \frac{F_{\gamma,\text{SSC}}}{F_{\gamma}} \right)^{\alpha_x/(\alpha_x - \alpha_\gamma)} \approx 3 \times 10^{22} \text{Hz}.
\]

From equation (7), this frequency corresponds to \( \gamma_b' \gtrsim 1.5 \times 10^4 \) which contradicts our earlier condition on \( \gamma_b' \). However, considering that the X-ray observation was performed during the falling edge of the \( \gamma \)-ray flare, the \( \gamma \)-ray flux of State 1 may be underpredicted.

If we increase the X-ray flux approximately five times, consistent with the factor of increase in the \( \gamma \)-ray flux corresponding to the highest and the lowest value, we can obtain \( \gamma_b' \approx 4 \times 10^4 \). This satisfies the \( \gamma_b' \) constraint obtained earlier (using equations 8 and 10). However, the parameters required to explain the SED deviate from the equipartition condition considerably.\(^9\) In Fig. 3, we plot the resultant spectrum due to synchrotron and SSC processes using the parameters described above. For the model plot presented in Fig. 3 and the ones following (Figs 4–7) we have used the exact description for radiative processes (Rybicki & Lightman 1986; Dermer 1995) rather than the approximate analytical expressions mentioned above and afterwards to analyse the different emission mechanisms.

### 3.2 External Compton

In the EC scenario, the emission region moves through an external photon field and the high energy emission is dominated by EC process rather than SSC process. For simplicity we assume the external radiation to be of blackbody origin corresponding to a temperature \( T_s \) (quantities with subscript \( s \) are measured in the AGN frame). In the rest frame of emission region, the Lorentz boosted external photon field is scattered to high energy through...
Model spectrum due to synchrotron, SSC and EC processes along with the SED corresponding to State 1. The high energy emission is interpreted as a result of EC process only. As in Fig. 3, the dashed and dotted curves represent synchrotron and SSC components, respectively. The EC spectrum is represented by dash–dotted curve and the solid line is total spectrum due to all these emission processes.

\[ F_{\nu, EC} = \frac{\delta}{1 + z} \gamma_p^2 (\Gamma \nu_p) \]

where \( \nu_p = 2.82K_B T_e / h \) with \( K_B \) and \( h \) being Boltzmann and Planck constants. The observed EC flux for \( \nu > \nu_{p, EC} \) can be written as

\[ F_{\nu, EC} \approx c(z, q) \kappa_\nu (\nu - \nu_{\min, EC})^{-2} \frac{F_{\nu, EC}}{h} (\nu_{\min, EC}^2)^{-2} \frac{\nu_{\min, EC}}{6.6 \times 10^{-3}} \]

Figure 4. Model spectrum due to synchrotron, SSC and EC processes along with the SED of State 1. The high energy emission is interpreted as a result of both SSC and EC processes. The dashed, dotted and the dash–dotted curves represent the synchrotron, SSC and EC spectral components, respectively. The solid curve is the total emission from all the spectral components.

\[ B' \approx 0.3 \left( \frac{F_{0.55 \text{GeV}}}{5.5 \times 10^{-11} \text{ Jy}} \right)^{0.5} \left( \frac{F_{3.5 \times 10^{14} \text{ Hz}}}{6.6 \times 10^{-3} \text{ Jy}} \right)^{-0.5} \left( \frac{\nu_{p, EC}}{1.4 \times 10^{22} \text{ Hz}} \right)^{-2.14} \left( \frac{G}{3 \times 10^{22} \text{ Hz}} \right)^{2.14} \]

Then from equation (8) and (12)

\[ v_* \approx 1.5 \times 10^{13} \left( \frac{F_{0.55 \text{GeV}}}{5.5 \times 10^{-11} \text{ Jy}} \right)^{0.5} \left( \frac{F_{3.5 \times 10^{14} \text{ Hz}}}{6.6 \times 10^{-3} \text{ Jy}} \right)^{-0.5} \left( \frac{\nu_{p, EC}}{1.4 \times 10^{22} \text{ Hz}} \right)^{1.14} \left( \frac{\nu_{p, EC}}{3 \times 10^{22} \text{ Hz}} \right)^{-1.14} \]

where \( \nu_{p, EC} \) is obtained by considering the EC spectrum as a broken power law (refer equation 11). The lowest photon frequency of EC spectrum will then be

\[ \nu_{\min, EC} = \frac{\delta}{1 + z} \gamma_{\min}^2 (\Gamma \nu_p) \]

\[ \approx 3.4 \times 10^{13} \left( \frac{\delta}{17.2} \right) \left( \frac{\Gamma}{12} \right) \left( \frac{\gamma_{\min}}{12} \right)^2 \left( \frac{v_*}{1.5 \times 10^{17}} \right) \text{ Hz} \]

However, this frequency is larger than the minimum observed frequency at X-ray energies \( (1.2 \times 10^{17}) \) unless one assume \( \gamma_{\min} < \Gamma \) which is unphysical under shock acceleration theory (Kino, Takahara & Kusunose 2002; Kino & Takahara 2004). Alternatively,
and there were no $\sim 3 \times 10^{40}$ and maximum Lorentz factor of the electrons $\gamma_{\text{max}} = 3 \times 10^4$. Columns (2)–(7) are the parameters governing the broad-band spectrum of different states of the source, whereas columns (9) and (10) are the jet and radiated power derived from these parameters.

$\gamma_{\text{min, EC}}$ can be lowered by reducing $\Gamma$ and $\delta$. However, this demands an increase in $K$ to explain the observed EC flux. Since the SSC flux has a quadratic dependence on $K$ (Sahayanathan & Godambe 2012), this will result in dominant SSC emission at X-ray energies and hence our EC interpretation fails. Furthermore, the $\gamma_0'$ required to produce an EC peak frequency at $3 \times 10^{22}$ Hz by scattering of the soft photons at frequency $\nu_s$ is $\approx 3.4 \times 10^4$. This again contradicts our constraint obtained earlier (see Section 3.1). Hence the interpretation of high energy emission by EC process alone may not be a viable option though the deviation of the deduced quantities from the observed ones is marginal. The estimated value of $B'$ corresponds to an equipartition parameter $\eta = 2.3$ for $\gamma_{\text{min}} = 12$. The resultant spectrum due to synchrotron and dominant EC processes is shown in Fig. 4.

### 3.3 SSC and EC processes for high energy emission

We consider the case where high energy emission is an outcome of both the SSC and EC processes since individually either of these processes is unable to explain the observations satisfactorily. Under this scenario, the X-ray emission is attributed to SSC process and the $\gamma$-ray emission to EC process. Then using equations (2), (9) and (13) for $\eta \sim 1$ we obtain the temperature of the external photon field as

$$T_* \approx 280 \left( \frac{F_{\nu}}{5.5 \times 10^{-11} \text{ Jy}} \right)^{0.23} \left( \frac{F_{\nu}}{6.6 \times 10^{-3} \text{ Jy}} \right)^{-0.23} \left( \frac{B_{\text{eq}}}{0.4 \text{ G}} \right)^{0.53} \left( \frac{\Gamma}{12} \right)^{-0.53} \text{K}. \quad (17)$$

The value of $B'$ is chosen to reproduce the SSC flux of $(9.1 \pm 0.5) \times 10^{-3}$ Jy at 2 keV. The resultant spectrum of OJ 287 due to synchrotron, SSC and EC during State 1 is shown in Fig. 5 along with the observed data. The physical parameters of the source governing the spectrum are given in Table 1. An exercise similar to one described above for State 1 is repeated for States 2 and 3 and we have found that their high energy spectra can be explained only if both SSC and EC processes are included. The resultant spectrum due to these emission processes is shown in Figs 6 and 7 and the corresponding parameters are given in rows 2 and 3 of Table 1. The spectrum of State 2 is reproduced using the equipartition parameter $\eta \sim 1$ whereas for State 3, during which the source was almost in quiescent state, we need to consider $\eta \sim 0.2$ to reproduce the observed spectrum. Incidentally, we obtain almost similar temperature for the external photon field ($\sim 250$ K) in all the states. The radio fluxes of all the states lie on synchrotron self-absorbed regime in the model plots (as is the case for most of the blazars) and the low energy break seen in the counterpart spectrum is due to synchrotron self-absorption effect.

### 4 DISCUSSION

Our study suggests that the broad-band spectra of OJ 287 observed during different stages of the $\gamma$-ray flare in 2009 cannot be explained by considering the synchrotron and the SSC processes alone unless unlikely physical conditions are assumed. Hence an additional emission component is required to explain the high energy emission. A plausible candidate for this additional component can be the EC scattering of soft photons external to jet. We assume this external photon field to be a blackbody radiation. With this addition in the emission mechanisms we are able to reproduce the SED of OJ 287 obtained during the different stages of the flare successfully. This result is similar to the conclusion obtained through the empirical SED modelling of various LBL observed by Fermi-LAT (Abdo et al. 2010). Models involving inverse Compton scattering of IR photons (EC/IR) from a dusty torus, proposed by the unified picture of the AGN (Urry & Padovani 1995), are also used to explain the VHE emission from 3C 66A (Abdo et al. 2010) and ON 231 (Abdo et al. 2010). The EC/IR interpretation is also proposed for the BL Lac object AO 0235+164 since the SSC interpretation requires a very small covering factor of the broad line regions (BLR) and IR dusty torus compared to the typical values of quasars (Ackermann et al. 2012). Earlier simultaneous observations of OJ 287 in X-ray and VHE during 2007 optical outbursts were modelled by Seta et al. (2009). No significant excess was reported at VHE during these observations and they explained the broad-band spectrum from radio to X-rays using synchrotron and SSC emission models. These observations were done before the launch of Fermi and there were no instruments available to observe the source at MeV–GeV energies. However, inclusion of MeV–GeV flux, due to later observations by Fermi, requires an additional emission component to explain the broad-band SED (fig. 8 of Seta et al. 2009).

The physical parameters extracted by reproducing the observed spectrum of OJ 287 through synchrotron, SSC and EC processes can be used to estimate the total power of the jet. To do so we assume the jet is loaded with cold protons with their number density being equal to that of non-thermal electrons. The power of the jet can then be approximated as (Celotti, Padovani & Ghisellini 1997)

$$P_{\text{jet}} = \pi R^2 \gamma^2 \beta c (U'_p + U'_H + U'_e),$$

where $U'_p$ is the cold proton energy density. For the chosen set of parameters we find $P_{\text{jet}} \approx 10^{36}$ erg s$^{-1}$ which is approximately four orders of magnitude larger than the total power released as radiation $P_{\text{rad}} \approx 10^{42}$ erg s$^{-1}$ (Table 1). Hence the radiative processes are inefficient and most of the jet power can be carried to large scales. The X-ray jet of OJ 287 seen by Chandra X-ray Observatory has been studied by Marscher & Jorstad (2011). Using parsec scale viewing angle of $\sim 3:2$, they derived the de-projected length to be greater than mega-parsec. The X-ray emission from this mega-parsec scale jet is modelled as a result of IC/CMBR since at these.
length scales the dominant external photon field will be CMBR. The jet power estimated through their study is consistent with the one obtained above (Table 1).

The Fermi $\gamma$-ray spectrum obtained through the data analysis described in Section 2 during the flare episode (States 1 and 2 combined) falls steeply beyond 10 GeV. In our model, the highest observed $\gamma$-ray photon energy is decided by $\gamma'_{\text{max}}$ provided the inverse Compton scattering happens in Thomson regime. In order to explain the X-ray spectrum as a result of inverse Compton emission, the synchrotron spectrum should fall before the X-ray energies (Fig. 5). This can constrain $\gamma_{\text{min}}$ of the particle distribution which in our case is found to be $3 \times 10^4$. This high energy cut-off in the particle spectrum at $\gamma'_{\text{max}}$ is reflected in the $\gamma$-ray spectrum at $\sim$10 GeV consistent with the observed Fermi spectrum. This conclusion also states that the 2009 flare of OJ 287 is beyond the detectable threshold of ground-based atmospheric Cherenkov telescopes operating at VHE. This result is consistent with the non-detection of OJ 287 by Major Atmospheric Gamma-ray Imaging Cherenkov (MAGIC) telescope during 2007 optical outbursts (Seta et al. 2009).

Our analysis described in the previous section demands the presence of a warm region at temperature $\sim$250 K around the emission region to explain the high energy emission from OJ 287. If we assume this region to be a spherical cloud surrounding the emission region, then the extent of this region can be estimated from the flare time-scale as

$$R_{\text{IR}} \approx \frac{\Gamma^2 c t_{\text{fl}}}{1 + z} \approx 0.23 \left(\frac{\Gamma}{12}\right) \left(\frac{t_{\text{fl}}}{2.5 \text{ d}}\right) \text{ pc.} \quad (19)$$

The total IR luminosity of the cloud will then be

$$L_{\text{IR}} = 4\pi R_{\text{IR}}^2 \sigma_{\text{SB}} T_\nu^4 \approx 1.4 \times 10^{42} \text{ erg s}^{-1}, \quad (20)$$

where $\sigma_{\text{SB}}$ is the Stefan–Boltzmann constant. This thermal IR luminosity is too small compared to the continuum emission from the jet and hence the latter dominates the SED of OJ 287. Our result, therefore, is consistent with the understanding that the thermal IR emission is generally absent/weak in BL Lac objects and their unification counterpart, FR I radio galaxies (Urry & Padovani 1995; Chiaberge, Capetti & Celotti 1999; Plotkin et al. 2012). However, presence of a weak extended IR emission has been reported for the nearby FR I radio galaxies, Cen A (Romani et al. 2008) and M87 (Perlman et al. 2007). Furthermore, our estimated thermal IR luminosity is an order of magnitude smaller than the IR upper limit obtained for the BL Lac object ON 231 (Malmrose et al. 2011). If we assume that the IR emitting cloud is powered by the radiation from an accretion disc having ultraviolet (UV) luminosity, $L_{\text{UV}} \sim 10^{46} \text{ erg s}^{-1}$, then the covering factor of the IR cloud as can be estimated as $L_{\text{IR}}/L_{\text{UV}} \approx 10^{-4}$. Using this covering factor we can obtain the location of the emission region from the central engine: $D = 0.5 \left(\frac{L_{\text{UV}}}{L_{\text{IR}}}ight)^{1/2} \approx 9 \left(\frac{L_{\text{UV}}}{10^{46} \text{ erg s}^{-1}}\right) \left(\frac{T_s}{250 \text{ K}}\right)^{-4} \text{ pc.} \quad (21)$

This distance is comparable with the one obtained by Agudo et al. (2011) ($\sim$14 pc) through correlation study between 1 mm radio and Fermi $\gamma$-ray light curves and VLBI images. Hence, our study suggests the presence of a warm medium at temperature $\sim$250 K located at a distance $\sim$9 pc from the central engine of OJ 287. Previous studies of thermal emission from a dusty environment of blazars and non-blazars also suggest the presence of a hot dust at a temperature $\sim$800–1200 K extending up to a distance of $\lesssim$2 pc and a warm component at a temperature $\sim$150–300 K covering the hot region with the possible extension up to a few tens of parsec (Jaffe et al. 2004; Mor, Netzer & Elitzur 2009; Landt, Buchanan & Barnby 2010; Malmrose et al. 2011). A simulation study of this hot dust medium employing two-dimensional radiative transfer code and three-dimensional radiative transfer code using Monte Carlo technique also suggests a decrease in the temperature of the dust as one moves away from the central engine (Pier & Krolkin 1992; Schartmann et al. 2005). Thus, it is possible that the observation of OJ 287 presented in this paper probes the external regions of the dust emission. A treatment similar to the one presented in this paper was used by Sahayanathan & Godambe (2012) to conclude that the observed VHE emission from 3C 279 supports the EC/IR model. However, they obtained a temperature of the IR medium as $\sim$900 K which is consistent with the hot dust at inner region of the torus.

The 2009 Fermi $\gamma$-ray flare was also studied by Neronov & Vovk (2011) who suggested the jet of OJ 287 to be associated with the lesser massive black hole of the SMBH binary system. They used the fact that the observed variability time-scale is much smaller than the light crossing time of black hole with a mass of $1.8 \times 10^{10} M_{\odot}$ but comparable to the one with a black hole mass of $1.3 \times 10^{5} M_{\odot}$. Agudo et al. (2011), based on the luminosity ratio and simultaneity of optical and $\gamma$-ray flares, concluded that the $\gamma$-ray emission is consistent with both the SSC and the EC/IR scenario. However, they favoured the SSC process since thermal IR emission is not detected from BL Lac. Here we have studied the emission models in detail, estimating and constraining the governing parameters using various observational information, and as already pointed out that both SSC as well as EC are required to interpret the high energy emission.

### 5 CONCLUSIONS

We have analysed the archival X-ray and $\gamma$-ray observations of the BL Lac object OJ 287 during a $\gamma$-ray flare observed by Fermi in 2009. Supplementing these data with the radio and near-IR–optical data during the same period, we divided the multwavelength light curve into three parts: the flaring state, moderately active state and the quiescent state. The broad-band SED corresponding to each state is then obtained and modelled using synchrotron and inverse Compton emission processes. The main conclusions drawn from studies are the following.

1. The simple SSC interpretation of X-ray and $\gamma$-ray emission requires a broken power-law particle distribution with a large break energy. However, this is not supported by the synchrotron spectrum in the near-IR–optical energy bands.
2. Interpretation of high energy emission based on EC process requires particles with Lorentz factor smaller than the bulk Lorentz factor of the jet to explain the lowest observed X-ray energy. However, this is not supported by the shock acceleration theory. Though the deviation of minimum particle energy with the bulk flow encountered in this case is marginal, still the demand for the same cannot be achieved.
3. The high energy spectra, involving X-ray and $\gamma$-ray energies, can be readily explained by considering both SSC and EC processes together. Under this scenario the X-ray emission is attributed to the SSC process and the $\gamma$-ray emission to EC process. To explain the $\gamma$-ray flux through EC process, we need the emission region to be buried inside a warm dusty region at a temperature of $\sim$250 K. If we consider the dusty environment of blazars to be illuminated by an accretion disc, then the location of the emission region should be $\sim$9 pc from the central engine. This distance is consistent with the constraints obtained from the millimetre–$\gamma$-ray correlation studies and the VLBA maps of OJ 287.
The results presented in this work do not include the observational uncertainties. However, our conclusions on the emission processes remain unchanged even if we deviate the observed fluxes and the other quantities within the allowed ranges.

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