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Letter to the Editor

Gamma-ray flaring of 3C 279: a proton-initiated cascade in the jet?

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Summary. The outburst multifrequency spectrum of the quasar 3C279 is interpreted in terms of the proton initiated cascade mechanism (PIC) recently developed investigating the consequences of relativistic baryons in jets. Shock-acceleration generates nonthermal electron and proton distributions. Ambient "soft" synchrotron photons produced by the accelerated electrons cause rapid cooling of protons and subsequent reprocessing of proton secondaries. Hence Doppler-boosted "hard" photons are produced dominating the apparent X- and γ-ray luminosity of the quasar.

Key words: Galaxies: jets of – Radiation mechanisms: synchrotron radiation – Gamma rays: general – X-rays: general

1. Introduction

Previously, high energy emission from knots in jets as a consequence of shock-acceleration of protons and subsequent cascading of secondaries has been studied (Mannheim and Biermann 1989, Mannheim et al. 1991). The effort was motivated by the common opinion that baryonic ultrarelativistic particles are considered as unimportant for the radiative properties of extragalactic radio sources. However, by close inspection this prejudice could not stand against criticism, because it was based upon incomplete account of energy-loss mechanisms acting upon baryons in photon-rich environments. Specifically, the role of hadronic interactions of baryons and photons, although recognised as limiting the energy of cosmic rays (*e.g.,* Greisen 1966), was not further investigated.

However, protons must reach very high energies to satisfy the threshold condition for secondary particle production. *E.g.,* Bethe-Heitler pair production and pion production in a UV-photon field (Sikora et al. 1987, Begelman et al. 1990) require a proton Lorentz factor exceeding $\gamma_p = 10^6$ and $\gamma_p = 10^8$, respectively. Thus the novel approach is closely linked with the question, if such high energies are really reached by particles in jets.

In contrast to other cascade models (*e.g.,* Burns and Lovelace 1982, Zdziarski and Lightman 1985, Svensson 1987) the PIC developes in a plasma, which is constrained by the usual requirements imposed to apply shock-acceleration theory (*e.g.,* Webb et al. 1984) and which has prescribed populations of photons, pairs and protons. Physical parameters can be inferred from observations in the radio to UV range.

Hence the physical picture of emission from knots in jets has evolved, in which proton initiated emission dominates above EUV frequencies, whereas shock-accelerated electrons produce the synchrotron emission below. *Due to relativistic kinematics the emission from a fast moving knot can be highly amplified.* The true energy requirements in the rest frame of the outflowing plasma flow (the comoving frame) are therefore much more relaxed than what is apparently needed to support extremely bright flares.

Moreover, an independent test for the presence of energetic protons in jets is possible by experiments, which are not typically considered as related to the physics of quasars. Biermann (1991) has shown that the fraction of protons escaping from hot spots of FR II galaxies[1] can sustain a cosmic ray flux at the highest observed energies (10^{17} eV–10^{20} eV) consistent with the spectrum and flux level detected at earth by EAS-experiments.

Flat spectrum 3C sources seem to be promising candidates also to find evidence for energetic baryons. A strong radio jet, a blazar-type continuum up to the UV-range showing up in outbursts and rapidly variable X-ray emission are considered as indicative of shock-acceleration in compact knots in a nuclear jet.

In this letter the multifrequency spectrum of 3C279 is interpreted in terms of proton initiated emission and synchrotron emission of shock-accelerated electrons. The emerging physical picture is briefly discussed and its implications for the AGN phenomenon outlined. Emphasis is put upon the implication of considerable γ-ray flare activity of 3C279.

2. The synchrotron blazar component

Variability, high apparent surface brightness, superluminal motion and source counts indicate that the "blazar" component of radio-loud AGN showing up in casual outbursts is generated in a nuclear relativistic jet pointing more or less towards the terrestric observer (*e.g.,* Impey 1989). Diffusive shock-acceleration

[1] Compared to knots in nuclear jets protons in the kpc hot spots of FR II galaxies can reach higher energies and escape directly into the IGM with negligible adiabatic and radiative damping losses, respectively.

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is commonly assumed to operate producing power-law distributions of particles. In an ordinary hydrogen plasma, electrons and protons will be accelerated. Protons may be favoured, because a) they "see" a thinner shock front due to their greater radius of gyration, b) they can more likely satisfy threshold energies for resonant interaction with plasma waves, so that they can be injected into the acceleration mechanism directly from the thermal plasma and c) they suffer fewer energy losses at low energies compared to electrons. Therefore protons are expected to have a higher energy density than electrons, *i.e.* $\eta = u_{\rm p}/u_{\rm e} \gg 1$, as observed in the solar wind, the earth's bow shock, the galactic cosmic ray population and perhaps also in the intracluster medium of clusters of galaxies (Kim et al. 1990).

If the particles spend sufficient time in the acceleration region, the maximum energy is determined by the balance of energy losses and gains. Biermann and Strittmatter (1987) obtained cooling time scales in the comoving frame

$$t_{\rm e}^{-1} = \frac{\sigma_T \gamma_{\rm e} B^2}{6\pi m_{\rm e} c}(1+a) \qquad (1)$$

$$t_{\rm p}^{-1} = \frac{\sigma_T m_{\rm e}^2 \gamma_{\rm p} B^2}{6\pi m_{\rm p}^3 c}(1+240a) \qquad (2)$$

considering synchrotron, inverse Compton and proton-photon energy losses in a soft target photon field with $\alpha = 1$ and magnetic field of strength B (cgs units). The symbol $a = u_\gamma/u_B$ denotes the ratio of the energy densities of synchrotron photons produced by accelerated electrons and magnetic field, respectively. Balancing with shock-acceleration in a plasma with fully developed Kolmógorov turbulence yields the maximum electronic synchrotron frequency

$$\nu_{\rm c} \simeq 9 \times 10^{14} \beta_{\rm s}^2 f(a) \ {\rm Hz} \qquad (3)$$

where $\beta_{\rm s}$ denotes the dimensionless (nonrelativistic) shock speed and $f(a)$ a function with a very weak dependence upon the photon/magnetic ratio, which can be neglected for $a < 1$, so that $f(a) \approx 1$. The proton Lorentz factor obtained likewise is given by

$$\gamma_{\rm p,max} \simeq 2 \times 10^{10} B^{-1/2}(1+240a)^{-1/2} \qquad (4)$$

and the differential particle distributions are power-laws with index 2.

The extremely high energy possible for protons is entirely consistent with the "traditional picture" of shock-acceleration in jets. The radius of gyration of a proton of dimensionless energy $\gamma_{\rm p,max}$, which gives a measure of a typical interaction length for the acceleration, is only

$$R_{\rm gyr} = (B/1\,{\rm G})^{-1}(\gamma_{\rm p,max}/10^9) \quad {\rm milliparsec} \qquad (5)$$

i.e. much smaller than the compact knots presumably causing BL Lac emission (Bregman et al. 1990).

From equations (1) to (4) one obtains the ratio of proton and electron initiated luminosity, respectively

$$\frac{L_{\rm p}}{L_{\rm e}} = \frac{u_{\rm p}}{t_{\rm p}(\gamma_{\rm p,max})} \Big/ \frac{u_{\rm e}}{t_{\rm e}(\gamma_{\rm e,max})} \simeq \eta \frac{m_{\rm e}}{m_{\rm p}} g(a) := \eta_o g(a) \qquad (6)$$

with another weak-dependence function $g(a) \approx 1$ for $a < 1$, so that for $\eta_o \simeq 1$ we have $L_{\rm p} \approx L_{\rm e}$. The minimum energy magnetic field strength $B \propto (1+\eta)^{2/7}$ is then increased by a factor of 9 compared to the case $\eta < 1$.

The Lorentz-invariant (IR to UV) luminosity generated by the accelerated electrons seems amplified in the direction of the relativistic bulk flow with speed $\beta_{\rm jet}$ according to

$$L^{\rm (obs)} = \delta^3 L \qquad (7)$$

where $\delta = 1/\left[\gamma_{\rm jet}(1-\beta_{\rm jet}\cos\theta)\right]$ denotes the Doppler-parameter and θ the angle to the line of sight (Urry and Shafer 1984).

Therefore, the true photon density in the outlowing plasma and hence the synchrotron-self-Compton flux is much lower than would be deduced by assuming isotropic emission.

The main species of secondary particles produced by the extremely energetic protons (with respect to luminosity) are pions. Their decay products, γ-rays and pairs then initiate an electromagnetic cascade by causing the production of further pairs and γ-rays etc. in the photon atmosphere generated by the accelerated electrons.

The type of the resulting electromagnetic spectrum depends upon the radiation compactness

$$l = \frac{\sigma_T}{4\pi m_{\rm e}^3}\frac{L}{R} \simeq 2 \times 10^{-30}\frac{\delta^{-3} L^{\rm (obs)}}{R} \qquad (8)$$

which measures the optical depth with respect to pair creation.

For a small compactness $l \ll 1$ the electromagnetic cascade terminates after very few generations (little reprocessing), so that most of the escaping photon luminosity is concentrated at high energies leading to a X-ray flux-density spectrum $S_\nu \propto \nu^{-\alpha_X}$ with $\alpha_X \approx 0.5 - 0.7$ (Mannheim et al. 1991). On the other hand, as l increases, more and more generations shift power towards lower energies (much reprocessing), leading to $\alpha \approx 1$ below the energy, where the pair creation opacity equals one.

To summarise we can state that *the cosmic ray ratio η governs the ratio $L(>UV)/L(<UV)$ and the radiation compactness governs the X-ray spectral index and the amount of γ-rays.*

Figure 1. depicts a PIC fit to the multifrequency spectrum of 3C279 (Makino et al. 1989). The outburst observed in 1988 March-July is assumed to be a knot in the nuclear jet which may be either freshly created or just twisted into the observer's direction. Physical parameters indicate a "proton-blazar" event: $\eta_o = 1$, Doppler-parameter $\delta = 10$ and source size of one parsec (corresponding to a compactness $l \simeq 3\times10^{-5}$, cf. Equation 8). This leads to a minimum energy m.f. strength of $B = 1$ G corresponding to a low ratio of photon to magnetic energy density, so that synchrotron-self-Compton emission is unimportant.

The high value of the Doppler-parameter is consistent with the apparent speed of VLBI radio components, which has been observed in the wide range $v/c \approx 2 - 10$ (*e.g.*, Unwin 1987, Browne 1987)

The (comoving frame) cutoff frequency of $\approx 10^{14}$ Hz and the power-law emission below with $\alpha = \alpha_{\rm thin} + 0.5 \simeq 1$ down to a break at $\approx 10^{12}$ Hz is consistent with synchrotron emission from the shock-accelerated electrons (Biermann and Strittmatter 1987). The cascade emission initiated by the shock-accelerated protons roughly fits the $\alpha_X^{\rm (obs)} \simeq 0.6$ power-law extending almost up to 10^{19} Hz. Considering that the model can describe the entire nonthermal continuum rather well, the fact that the PIC X-ray spectral index $\langle\alpha_X^{(pic)}\rangle \approx 0.7$ is somewhat to steep certainly does not rule the model out. In fact, the fit suggests steepening towards high energies consistent with the highest energy GINGA data indicated by the large error bars. Moreover, adding a weak Compton reflected X-ray component (possibly due to clouds surrounding the nuclear jet) would lead to a flatter X-ray spectrum at least up to some 10 keV, where the Klein-Nishina turnover of the scattering cross section becomes important (*e.g.*, Lightman and White 1988).

Remarkably, PIC also predicts an enormous apparent γ-ray luminosity of a few times 10^{47} erg/s ($H_0 = 100$ km/s/Mpc and $q_0 = 1/2$) in outbursts as observed in 1988.5. The energy spectral index is roughly 1.95 turning over in the 10-100 GeV region, cf. Figure 1. In fact, flare activity, which may be connected to the birth of a fast moving knot in the jet, has been reported by the GRO/EGRET-team (Bertsch et al. 1991) during June 15-28 1991. An outburst at 37 GHz in February 1991 is probably related to this high frequency event (Valtaoja 1991), although most of the radio emission is coming from different parts of the knot or a different time during its evolution than the infrared to UV continuum. The flux at 37 GHz was about 22 Jy in 1991.1 having decayed to 16 Jy until 1991.5, which is comparable to the peak flux of the 1988 outburst. Therefore our spectrum fitted to the 1988.5 data should also be a good representation of the 1991.5 spectrum relevant for the observed γ-ray flux.

The "jump" of the X-ray flux by 20% in 45 min reported by Makino et al., if it is really caused intrinsically, seems to contradict the derived source size, which basically reflects the fact, that PIC can produce X-ray spectra harder than $\alpha = 1$ only in extended components with low photon compactness[2]. However, the outbursts in total flux have rise times of a few months matching to almost parsec sized VLBI knots with a Doppler factor of 10. Shock-in-jet models (Qian et al. 1991, Aller et al. 1985) may also alleviate the problem. Moreover, one must bear in mind that the X-ray photons are produced in a coherent fashion, since very few particles injected at highest energy coherently multiply during the cascade development thereby weakening causality restrictions for incoherent emission.

3. Conclusions

Having demonstrated the simplicity of the PIC mechanism as an explanation of the high energy emission from extragalactic jets one is left with a new parameter, *viz.* the "cosmic ray ratio" η. However, including protons (and other baryons) into the shock-acceleration picture of jets may alleviate problems, *e.g.* a) extremely powerful high energy emission is possible without distorting the physical picture to artificial electron distributions, b) the so-far arbitrariness of the parameter η is abandoned leading to new physical insight. Moreover, new questions are stimulated, *e.g.*: Can independent phenomena induced by neutrons and neutrinos (MacDonald et al. 1991, Begelman and de Kool 1991, Stecker et al. 1991) improve our knowledge about relativistic baryons? In fact, we point out that the model implies a remarkable neutrino flare at extremely high energies corresponding to the 0-th order cascade generation: photons are further reprocessed, neutrinos are not.

Since the cosmic ray ratio η is not predictable at the present stage of theoretical investigation, the diffuse γ-ray background contribution of jet-sources is not known. However, due to the small solid angle into which the γ-rays are emitted and a possibly low duty cycle of events one can guess that the contribution is only marginal.

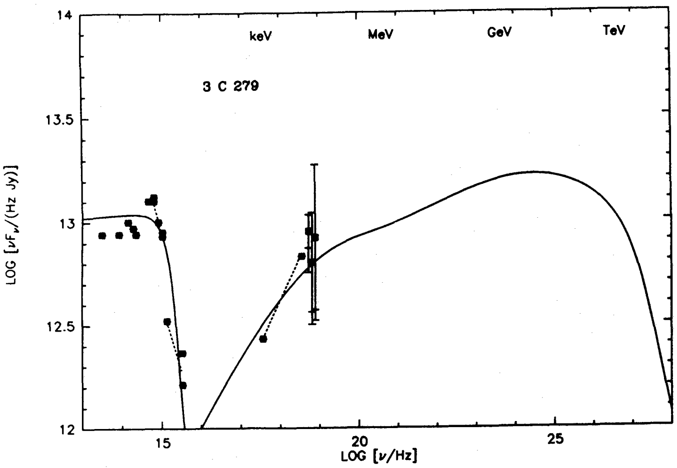

Fig. 1. The multifrequency spectrum of the quasar 3C279 (Makino et al. 1989 and references therein) during the outburst in 1988.5 (similar to 1991.5) fitted with the PIC single component model ($\nu F_\nu = 10^{13}$ Hz Jy corresponds to $dL/d\log E \simeq 3\times 10^{46}$ erg/s). The proton to electron energy density ratio used for the fit is $\eta = m_p/m_e$ and the compactness in the comoving frame is $l = 3\times 10^{-5}$. Cascading of photoproduced secondary particles yields synchrotron radiating pairs dominating the emission above 10^{16} Hz, whereas shock-accelerated electrons dominate the radio to UV range.

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[2] One could also increase δ to decrease R for constant l (same spectrum), cf. Equation (8).

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