POWERSFULL HIGH-ENERGY EMISSION OF THE REMARKABLE BL LAC OBJECT S5 0716+714

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ABSTRACT

BL Lac objects of the intermediate subclass (IBLs) are known to emit a substantial fraction of their power in the energy range 0.1−10 GeV. Detecting γ-ray emission from such sources provides therefore a direct probe of the emission mechanisms and of the underlying powerhouse. The γ-ray satellite, AGILE, detected the remarkable IBL S5 0716+714 (z = 0.3) during a high state in the period from 2007 September–October, marked by two very intense flares reaching peak fluxes of 200 × 10^{-8} photons cm^{-2} s^{-1} above 100 MeV, with simultaneous optical and X-ray observations. We present here a theoretical model for the two major flares and discuss the overall energetics of the source. We conclude that 0716+714 is among the brightest BL Lac’s ever detected at γ-ray energies. Because of its high power and lack of signs for ongoing accretion or surrounding gas, the source is an ideal candidate to test the maximal power extractable from a rotating supermassive black hole via the pure Blandford–Znajek (BZ) mechanism. We find that during the 2007 γ-ray flares 0716+714 approached or just exceeded the upper limit set by BZ for a black hole of mass 10^8 M_⊙.

Key words: BL Lacertae objects: individual (S5 0716+714) – gamma rays: observations

Online-only material: color figures

1. INTRODUCTION

Blazars constitute a class of active galactic nuclei (AGNs) that often show very strong and rapid flux variability over the electromagnetic spectrum. They are widely held to contain a black hole (BH) with mass in the range 10^7–10^9 M_⊙, that launches relativistic jets emitting highly non-thermal radiation. The jet transports energy in electromagnetic form and bulk plus random kinetic energy of charged particles. The source radiation may also show a contribution by the accretion disk (including the big blue bump (BBB)), the broad-line region (BLR), and a dusty torus (see Urry & Padovani 1995); lack of random kinetic energy of charged particles. The source launches relativistic jets emitting highly non-thermal radiation.

The simplest homogeneous synchrotron self-Compton (SSC) model assumes the blazar emissions to be produced in a “blob” of radius R, containing relativistic electrons in a combination of tangled and uniform magnetic fields. The emitters move toward the observer with bulk Lorentz factor Γ (see, e.g., Tavecchio et al. 1998). We assume the emitters to emerge from the injection/acceleration phase with a jet-frame distribution of the random

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energies $\gamma mc^2$ in the form of a standard broken power law

$$n_e(\gamma) = \frac{K \gamma_b^{-1}}{(\gamma/\gamma_b)^{3+\alpha} + (\gamma/\gamma_b)^{3-\alpha}}, \quad (1)$$

where $\xi_1$ and $\xi_2$ are the spectral indices for $\gamma < \gamma_b$ and $\gamma > \gamma_b$, respectively. $\gamma_b$ is the Lorentz factor at the break. These electrons emit a primary synchrotron spectrum; a second contribution is then produced by inverse Compton (IC) as the primary synchrotron photons scatter off the same electron population. The spectral energy distribution (SED) behaves as $\epsilon F(\epsilon) \propto \epsilon^{1-\alpha}$, where $\epsilon$ is the energy of the received photons, and $\alpha = (\xi - 1)/2$.

For electrons in a magnetic field $B$, the synchrotron SED peaks around

$$\epsilon_s = B \frac{3.7 \times 10^6 B \gamma_b^2 \delta}{1 + z}, \quad (2)$$

where $h$ is Planck’s constant, $z$ is the redshift of the source, and $\delta = [\Gamma(1 - \beta \cos \theta)]^{-1}$ is the bulk Doppler factor due to the flow of emitters toward the observer at an angle $\theta$ relative to his/her line of sight; the SED at the synchrotron peak is

$$\epsilon_s F(\epsilon_s) \propto \delta^4 R^2 B^2 K \gamma_b^2. \quad (3)$$

As to the IC component, its SED contribution peaks at

$$\epsilon_c = \frac{4 \gamma_b^2 \epsilon_s}{3}, \quad (4)$$

with a peak value of

$$\epsilon_c F(\epsilon_c) \propto \delta^4 R^4 B^2 K^2 \gamma_b^4 \quad (5)$$

if the scattering takes place in the Thomson regime with the density of target photons scaling as $n_{ph} \propto F_\nu R/c$. The relativistic motion toward the observer amplifies the emitted power by the factor $\delta^4$, and allows it to vary on a timescale

$$t_{\text{car}} \gtrsim \frac{t_{\text{car}}(1 + z)}{\delta}, \quad (6)$$

close to or shorter than the crossing time $t_{\text{car}} = R/c$.

Due to the synchrotron and IC losses, the electrons cool with timescale

$$\tau_{\text{cool}}(\gamma) = \frac{3mc}{4\beta^2 \sigma_T \gamma(U_b + U_i)},$$

where $\sigma_T$ is the Thomson cross section, $U_b = B^2/8\pi$, and $U_i$ is the energy density of radiation before scattering. This sets a typical cooling break at $\gamma_{\text{cool}} = 3mc^2/4\sigma_T R B^3(U_b + U_i)$ beyond which the electrons cool rapidly. In the following, we take into account this constraint on the particle distributions.

Simultaneous multi-frequency observations can provide the five quantities $R$, $\delta$, $B$, $K_e$, and $\gamma_b$ with the five Equations (2)–(6).

For BL Lacs with high-frequency peaks (HBLs) requiring electrons of higher energies ($\gamma_b > 10^4$), the scattering approaches the Klein–Nishina (KN) regime with a blob-frame photon energy $> m_e c^2/\gamma_b$. In the extreme KN regime the IC SED peaks at $\epsilon_c \sim \gamma_b m_e c^2 \delta (1 + z)$; the dependence on $B$ and $\gamma_b$ progressively weakens as the two latter parameters grow.

### 2.2. An Addition to the Model, External Seed Photons

Additional target photon can be provided by a source external to the jet (see Dermer et al. 2009). In this case, the high-energy component of the spectra is due to the electrons that Compton-scatter the external photons (EC); the SED now peaks at energies

$$\epsilon_e = \frac{4 \gamma_b^2 \epsilon_{\text{ext}} \delta}{3(1 + z)}, \quad (7)$$

and the corresponding SED value is

$$\epsilon_e F(\epsilon_e) \propto \delta^4 R^3 K \gamma_b^2 N'_{\text{ext}} \epsilon_{\text{ext}}'. \quad (8)$$

In this EC process two new ingredients enter: $\epsilon_{\text{ext}}'$ and $N'_{\text{ext}}$, respectively, the energy and the density at peak of the EC as seen by the moving blob. This has two main consequences.

1. The model contains two further degrees of freedom and the parameter evaluation may be degenerate.
2. These new quantities are related to $N_{\text{ext}}$ and $\epsilon_{\text{ext}}$ in the observer frame by means of the bulk Lorentz factor $\Gamma$ in a manner that depends on the geometry of the system (Dermer & Schlickeiser 2002), causing an additional dependence on $\Gamma$ in the external photon spectra. Dermer & Schlickeiser (1993) discuss SED dependences on $\Gamma$ varying from $\propto \Gamma^3$ to $\propto \Gamma^6$, for photons entering into the blob from behind or head-on, respectively.

#### 2.3. Flux Variation Patterns

Equations (2)–(8) show that, in the synchrotron–IC framework, variabilities of the first and second peaks are correlated, possibly with a lag $t_{\text{lag}} \sim t_{\text{car}}(1 + z)/\delta$.

When the energy fluxes around these peaks $\phi \propto \epsilon F(\epsilon)$ are simultaneously monitored, we can compare the corresponding light curves $\phi(t)$ in the respective band energy $\epsilon_s$ and $\epsilon_c$, possibly with a time lag $t_{\text{lag}}$. Then given two times $t_1$ and $t_2$, the ratio $r_{\epsilon} \equiv \phi_{\epsilon}(t_2 + t_{\text{lag}})/\phi_{\epsilon}(t_1 + t_{\text{lag}})$ shows a dependence on $r_{\epsilon} \equiv \phi_{s}(t_2)/\phi_{s}(t_1)$ that is related to the emission mechanism. Here, we consider some relevant cases.

If the variability is mainly due to electron injection/acceleration, $K$ and/or $\gamma_b$ changes; then, $r_{\epsilon} = r_s$ results if SSC dominates the IC emission. If instead EC dominates then $r_{\epsilon} = r_c$ applies (compare Equation (3) with Equations (5) and (8)). If variations are mainly due to changes in $B$, then $r_{\epsilon} = r_b$ holds for SSC, and $r_{\epsilon} = 1$ applies for EC. If instead $\Gamma$ varies, we have $r_{\epsilon} = r_c$ in the SSC; in the EC framework we have different behaviors depending on the geometry of the jet relative to the external radiation: $r_{\epsilon} = r_s$ with $x$ ranging from $3/4$ for seed photons entering from behind, to $3/2$ for photons entering head-on the flow.

In Table 1, we report the relations for the Thomson and the extreme KN regimes (see also Paggi et al. 2009). The cooling of electrons acts as a variation of $K$ and $\gamma_b$. Hence, in a flare due to electron injection/acceleration, the trajectories $t_{\epsilon}$ versus $r_s$ remain unchanged by pure radiative cooling.

#### 2.4. Modeling the $\gamma$-ray Flaring States

A 1 day time lag between the emission in optical and $\gamma$-ray bands during the two flares is apparent form Figures 1 and 3 of Chen et al. (2008). This constrains the emitting region radius and the Doppler factor to $R \leq 5 \times 10^{18}(\delta/20)$ cm; the duration of both flares is 1 day or less, which argues for cooling times $\tau_{\text{cool}}(\gamma_b) \sim R/c$. 


Table 1

| Model   | $\Gamma$ Changes | $B$ Changes | $K$ Changes | $\gamma_b$ Changes |
|---------|------------------|-------------|-------------|---------------------|
| SSC Th. | $r_e = r_s^2$    | $r_e = r_s$ | $r_e = r_s$ | $r_e = r_s^2$       |
| EC Th.  | $r_e = r_s$      | $r_e = 1$   | $r_e = r_s$ | $r_e = r_s^2$       |
| SSC KN  | $r_e = r_s$      | $r_e = r_s^2$ | $r_e = r_s$ | $r_e = r_s^2$       |
| EC KN   | $r_e = r_s$      | $r_e = 1$   | $r_e = r_s$ | $r_e = r_s^2$       |

Moreover, optical and gamma light curves around the two flare dates show evidence that $r_e = r_s^2$ applies (see Figure 2 and its caption): this argues for a SSC process in the Thomson regime, and concurs with the lack of sign of external gas to rule out EC process (see also Table 1).

Previous radio monitoring by the Very Long Baseline Array (VLBA) telescope of 0716+714 showed the presence of more superluminal components relative to the active state of 2003–2004 (Rastorgueva et al. 2009). Moreover, the absence of the signatures of IC catastrophe provided a lower limit $\delta \gtrsim 14$ for the Doppler factor (Ostorero et al. 2006; Fuhrmann et al. 2008; see also Wagner et al. 1996); Bach et al. (2005) also argue for high Doppler factors in these fast variable components and for a viewing angle $\theta \lesssim 4^\circ$.

We note that modeling the SED of 0716+714 with a standard one-zone SSC model would fail to reproduce the simultaneous radio, optical, X-ray, and $\gamma$-ray data for the October flare. In particular, the crossover in the X-ray band would not be well reproduced, and the hard X-ray flux would be overestimated by a factor $\sim 3$; furthermore, it would be difficult to model the hardness of the $\gamma$-ray spectrum during the September flare (Figure 1, red dashed lines). A one-component model also hardly explain together the slow trends of the radio, optical, and hard X-ray bands and the faster variability observed in the optical, soft X-ray, and $\gamma$-ray bands (see Villata et al. 2008; Giommi et al. 2008; Chen et al. 2008). Hence, we adopt a two-component model: the first produces the slowly variable radio and hard X-ray bands, whereas the second is responsible for the faster variability in optical-UV, soft X-, and $\gamma$-ray bands. Despite these problems, the possibility to fully constrain by observations the parameters stimulate us to also show for comparison a one-component model.

The SEDs of all these models are shown in Figure 1 and the parameters are listed in Table 2; a viewing angle $\theta \approx 2^\circ$ is adopted according to Bach et al. (2005).

3. THE EXTREME ENERGETICS OF 0716+714

Under the assumption of isotropic emission, the observed power radiated from a source with luminosity distance $D_L(z)$ is

$$L_{\text{obs}} = 4\pi D_L(z)^2 \int d\epsilon F(\epsilon).$$

The jet transports a total power $P_{\text{tot,flare}} = L_r + L_{\text{kin}} + L_B$ contributed by intrinsic radiated power, kinetic energy flow of the electrons and of the cold protons (with one proton per emitting electron), and Poynting flux, respectively:

$$L_r = L_{\text{obs}} \varepsilon_r / \delta^4 = 2 \times 10^{-3} (8/15)^{-4} \Gamma_1^2 L_{\text{obs}},$$

$$L_e = 0.8 \times 10^{43} R_{16}^2 \Gamma_1^2 (n_e c')_4 \text{erg s}^{-1},$$

$$L_p = 1.4 \times 10^{45} R_{16}^2 \Gamma_1^2 (n_p)_1 \text{erg s}^{-1},$$

$$L_B = 3.8 \times 10^{42} R_{16}^2 \Gamma_1^2 B^2 \text{erg s}^{-1},$$

see also Celotti & Ghisellini (2008). The latter authors show that in BL Lacs $L_r$ tends to match the sum of the other contributions. In fact, for the two flares of 0716+714 at redshift $z = 0.31$ we find $L_r \approx 2 \times 10^{45} \text{erg s}^{-1}$, and from our two-component SSC model (with the parameters listed in Table 2) we obtain a total jet power

$$P_{\text{tot,flare}} = (3.5 \pm 1) \times 10^{45} \text{erg s}^{-1}$$

with $L_r \gtrsim (L_e + L_p + L_B)$. Under this condition, the total jet power is minimized and the details of cooling does not affect materially the global energetics, being the radiated luminosity $L_r$ mainly contributed by peaks emission. Moreover, the uncertainty in $P_{\text{tot,flare}}$ is mainly due to the observed $\gamma$-ray flux error.

For the one-component model, we obtain $P_{\text{tot,flare}} = (1 \pm 0.5) \times 10^{46} \text{erg s}^{-1}$ and $L_r \lesssim (L_e + L_p + L_B)$ holds. In this case, the total jet power is not dominated by the radiated one, but the parameters now are well constrained by the observation and the uncertainty is still due to the flux error.

3.1. Testing the Blandford–Znajek Mechanism

Here, we compare the jet powers provided by our models with the BZ mechanism; this set a limit on the power extractable from a rotating BH

$$P_{\text{BZ}} \simeq 2 \times 10^{15} M_9 \text{erg s}^{-1}$$

under conservative values of $B$, as discussed in Cavaliere & D’Elia (2002, and references therein; see also our discussion).
Estimating the redshift and the BH mass of 0716+714 is not trivial because of the lack of emission lines. Recently, however, Nilsson et al. (2008) pinpointed the host galaxy of this source and reported a determination of its redshift at \( z = 0.31 \pm 0.08 \). Then, for this host, a BH of mass \( M \approx 5 \times 10^8 M_\odot \) should accord with the fundamental plane of BL Lacs (Falomo et al. 2003).

On the other hand, some authors using micro-variability of the optical flux estimate the mass of the central BH for 0716+714 by

\[
M < \frac{c^3 \delta \tau}{6G(1+z)} \approx 3 \times 10^8 M_\odot \left[ \frac{\delta \tau}{20 \times 600} \right].
\]

Considering \( \tau \approx 450 \text{s} \) as the shortest variability time found by Sasada et al. (2008) one obtains \( M < 2 \times 10^8 \delta(\tau/20) M_\odot \). Gupta et al. (2009) obtained the more stringent constraint \( M < 5 \times 10^7 M_\odot \) for the case of a Kerr BH. However, these authors discuss that the micro-variability in 0716+714 may be due to a small region in the jet or due to internal disk modes, so that the BH mass would be higher.

We note that a BH of mass \( M < 10^8 M_\odot \) in 0716+714 would imply in Equation (13) a power limit \( P_{\text{BZ}} \ll L_\nu \) inconsistent with the power \( L_\nu \) emitted during the flares.

4. DISCUSSION AND CONCLUSIONS

We modeled the 0716+714 flares of 2007 September 11 and October 23 with a two-component SSC model, similarly to Tavecchio & Ghisellini (2009). Despite the larger number of model parameters, we believe that our two-component modeling reproduces the complex variability and the hard \( \gamma \)-ray spectra of 0716+714 better than a one-component model.

Our Figure 2 indicates a quadratic dependence between the synchrotron and IC fluxes. This concurs with the lack of emission lines and BBB to rule out models involving external sources of seed photons that produce a linear dependence, and to strongly support electrons radiating in the Thomson regime within the SSC framework as the most likely radiation process. We refer to our Figures 2 and 1 in Chen et al. (2008) to show that the 2007 September data lie around the maximum; in time, the trajectory starts from the lower \( r_e \) value, attains a maximum and then falls down. In 2007 October, the trajectory describes the decline of a flare starting from the higher \( r_e \) value. Rises and falls both occur on one-day timescale, and the trajectories are quadratic. This suggests the electron acceleration and cooling to occur on similar timescales.

The crossover between the synchrotron and IC branches of the SED is located in X-rays (see also Foschini et al. 2006; Ferrero et al. 2006), and is contributed by both the slowly variable component (I) and the faster component (II).

As to the faster components (II) adopted for the two flares, they are marked by high electron energies \( \gamma_b \sim 7 \times 10^3 \) with a sharp low energy cutoff \( \gamma_{\text{min}} \sim 2 \times 10^3 \) (see also Tsang &

### Table 2

| Date   | Comp. | \( \Gamma \) | \( B \) (G) | \( R \) (cm) | \( K \)(cm\(^{-3}\)) | \( \gamma_b \) | \( \gamma_{\text{lim}} \) | \( \zeta_1 \) | \( \zeta_2 \) | \( \tau_{\text{cool}}(\gamma_b)/\zeta_2 \) |
|--------|-------|-------------|-------------|-------------|----------------|-------------|----------------|---------|---------|----------------|
| Sept 11 | c I   | 10          | 0.4         | \( 3 \times 10^6 \) | 3.5            | 3800        | 100            | 2       | 4.5     | 1.3             |
|        | e II  | 15          | 0.3         | \( 3.5 \times 10^6 \) | 1.4            | 7000        | 3500           | 2       | 5       | 1.0             |
|        | Single | 15         | 0.3         | \( 3.5 \times 10^6 \) | 1.8            | 7000        | 60             | 1.8     | 5       | 1.0             |
| Oct 23  | c I   | 10          | 0.4         | \( 3 \times 10^6 \) | 2.5            | 4000        | 40             | 2       | 4.5     | 1.2             |
|        | e II  | 15          | 0.3         | \( 3.5 \times 10^6 \) | 1.5            | 6500        | 1300           | 2       | 5       | 1.1             |
|        | Single | 15         | 0.3         | \( 3.5 \times 10^6 \) | 1.8            | 6500        | 30             | 1.8     | 5       | 1.1             |

### Figure 2

Variability plane with the trajectories of 0716+714 based on simultaneous optical and \( \gamma \)-ray observations. Open circles are for 2007 September, and filled triangles for 2007 October data. The thick solid line represents the quadratic trend, expected from electrons injected or accelerating in the SSC framework; for comparison, the linear behavior expected from EC is represented by the thin dotted line.

Kirk 2007). Moreover, high bulk Lorentz factor \( \Gamma = 15 \) (that is \( \delta \approx 23 \)) is used in accord with Wagner et al. (1996). In Table 2, it is shown that our choice of parameters implies \( \tau_{\text{cool}}(\gamma_b) \approx \tau_{\text{cool}} \) for the fast components II; those quench very rapidly causing strong variability in the optical–UV, soft X- and \( \gamma \)-ray bands. Little or no variability results in radio and hard-X ray bands produced by the rising part of the slow components I. This behavior is in agreement with the complex multi-band variability reported by Chen et al. (2008), Giommi et al. (2008), and Villata et al. (2008).

Considering the redshift \( z = 0.31 \) of 0716+714, we find that its intrinsic radiative luminosity is of order \( L_r \approx 2 \times 10^{45} \text{ erg s}^{-1} \). On adding the other jet components in Equations (10)–(12), the total power becomes \( P_{\text{tot, flare}} \approx 4 \times 10^{45} \text{ erg s}^{-1} \) for the two-component model, and \( P_{\text{tot, flare}} \approx 2 \times 10^{46} \text{ erg s}^{-1} \) for the one-component model: the source exceeds the BZ limit \( P_{\text{BZ}} \approx 2 \times 10^{45} M_{\odot}/M_2 \text{ erg s}^{-1} \) (see Figure 3). This obtains for a maximally rotating BH of \( 10^9 M_\odot \) (spun by past accretion) via interaction with a disk magnetic field \( B \approx 10^4 \text{ G} \) sustained by gas or radiation pressure, in the absence of ongoing accretion (see discussion by Cavaliere & D’Elia 2002). The simultaneous nature of our multi-frequency data during the 2007 \( \gamma \)-ray flares of 0716+714 is a crucial ingredient of our result. Other BL Lacs with weak or negligible accretion disk or BLR contributions have been reported to attain (model dependent) high total luminosities, e.g., \( 2302+107 \) with an inferred \( P \approx 10^{46} \text{ erg s}^{-1} \) (see Celotti & Ghisellini 2008). Corbel & Reves (2008, ATel 1744) report the high \( \gamma \)-ray peak flux recently attained by 0235+164 at \( z \approx 0.94 \) for which, however, EC contributions cannot be ruled out. However, to our knowledge, only the simultaneous data obtained by our group.
Figure 3. Observed high-energy peak fluxes (top panel) and the corresponding intrinsic peak luminosities (bottom panel) for a number of BL Lac objects during their flaring states, ordered with their $z$: Mrk 421 (open symbols, here shown for reference), BL Lac, W Comae, and 0716+714. For the first three objects, data are respectively from Donnarumma et al. (2009), Ravasio et al. (2002), and Böttcher et al. (2002). The shaded area represents the BZ limiting luminosity range for a BH mass in the range $3 \times 10^8$–$10^{10} M_\odot$. The arrow points at the total jet power by also adding the components of Equations (10)–(12).

(A color version of this figure is available in the online journal.)

for 0716+714 provide a model-independent evaluation of the total jet power from a BL Lac being close or just above the BZ limit.

We also show in Figure 3 the intrinsic radiated power for other BL Lacs with intense $\gamma$-ray and TeV emissions, as for the 1997 flare of BL Lacertae with peak flux around $500 \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$ but with lower redshift $z = 0.069$ (Bloom et al. 1997; see also Ravasio et al. 2002) and intermittent evidence of lines and thermal emissions. We also report W Comae with redshift $z = 0.102$ but $\gamma$-ray flux at levels of $50 \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$ (Böttcher et al. 2002).

The increasing trend of $L_\gamma$ with $z$ is likely to arise from the Malmquist bias, while the decrease at low $z$ may result from sampling a limited cosmological volume. Nevertheless, we stress that up to now no BL Lac source has sharply exceeded the BZ limiting power. It will be worthwhile to keep under close watch the most distant BL Lacs (despite the obvious monitoring difficulties) to catch powerful emissions. If violations will be found, these may be possibly discussed in terms of the Blandford–Payne mechanism (Blandford & Payne 1982) that, however, requires ongoing accretion not supported in the case of 0716+714. Alternatively, higher powers may be attained with higher magnetic fields up to $B^2/4\pi \lesssim \rho c^2$ related to the plunging orbits (see Meier 1999), which however imply short source lifetimes in the absence of accretion.

In conclusion, we find the total power transported in the jet of 0716+714 to be $P_{\text{tot,flare}} \sim 4 \times 10^{45}$ erg s$^{-1}$, and so to approach the limit of the BZ mechanism for a BH up to $10^9 M_\odot$ with conservative values of $B$. Such high powers in 0716+714 constitute an unescapable consequence of two observed facts.

1. The $\gamma$-ray flux attains high levels in the SED during the two flares, with an emitted power comparable with the optical one as shown by simultaneous observations (see Figure 1).

2. The lack of external sources of seed photons related to emission lines or BBB concurs with the observed quadratic dependence $r_c \sim r_+^2$ to rule out EC contributions to the high energy hump (see Figure 2) and considerable ongoing accretion.

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