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Gamma-ray flares from red-giant–jet interactions in AGN

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Summary. — Non-blazar AGN have been recently established as a class of gamma-ray sources. M87, a nearby representative of this class, show fast TeV variability on timescales of a few days. We suggest a scenario of flare gamma-ray emission in non-blazar AGN based on a red giant interacting with the jet at the base. We solve the hydrodynamical equations that describe the evolution of the envelope of a red giant blown by the impact of the jet. If the red giant is at least slightly tidally disrupted by the supermassive black hole, enough stellar material will be blown by the jet, expanding quickly until a significant part of the jet is shocked. This process can render suitable conditions for energy dissipation and proton acceleration, which could explain the detected day-scale TeV flares from M87 via proton-proton collisions. Since the produced radiation would be unbeamed, such an event should be mostly detected from non-blazar AGN. They may be frequent phenomena, detectable in the GeV-TeV range even up to distances of $\sim 1\,\mathrm{Gpc}$ for the most powerful jets. The counterparts at lower energies are expected to be not too bright. M87, and nearby non-blazar AGN in general, can be fast variable sources of gamma rays through red-giant–jet interactions.

PACS `98.54.Cm` – Active and peculiar galaxies and related systems (including BL Lacertae objects, blazars, Seyfert galaxies, Markarian galaxies, and active galactic nuclei).
PACS `98.62.Nx` – Jets and bursts; galactic winds and fountains.
PACS `98.62.Js` – Galactic nuclei (including black holes), circumnuclear matter, and bulges.

1. – Introduction

Active galactic nuclei (AGN) are believed to be powered by an accreting supermassive black hole (SMBH) in the center of a galaxy, a significant fraction of AGN show powerful jets [1]. The emission from the jets is non-thermal and comes from a population of relativistic particles accelerated for instance in strong shocks, although other scenarios are possible as well [2]. This non-thermal emission is thought to be produced through synchrotron and inverse Compton (IC) processes [3], although hadronic models have been also considered in the past [4].

In this work, we study the interaction of a red giant (RG) star with the base of the jet in AGN and their observable consequences in gamma rays [5]. We focus here on the case of M87, a nearby non-blazar AGN that presents very-high-energy recurrent activity with variability timescales of few days [6]. In the framework presented here, the jet impacts the RG envelope, already partially tidaly disrupted by the gravitational field of the central SMBH. The RG envelope is blown up, forming a cloud of gas accelerated and heated by the jet pressure. The jet base is likely strongly magnetized [7, 8]. The jet flow affected by the impact with the RG envelope can be a suitable region for particle acceleration, and a significant fraction of the involved magnetic and kinetic energy of the jet can be transferred to protons and electrons. Although electrons may not be able to reach TeV emitting energies because of the expected large magnetic fields, protons would not suffer from this constraint. These protons could reach the star blown material, and optically thick proton-proton (*pp*) interactions could lead to significant gamma-ray production in the early stages of the cloud expansion. We deal with solar-mass–type stars instead of the more rare high-mass stars, study the RG atmosphere-jet interaction, and follow the hydrodynamical evolution of the cloud. Finally, we do not introduce any beaming factor to the radiation, since in our scenario most of the emission is produced when the cloud has not been significantly accelerated, Doppler boosting being therefore negligible.

2. – The model

Main sequence stars are too compact to be significantly affected by tidal forces from the SMBH, unlike RGs, whose external layers are far less gravitationally bounded to the stellar core. Therefore, in the vicinity of a SMBH, the external layers of an RG will suffer significant tidal disruption [9, 10], which can unbound from the stellar core a cloud with significant mass $\sim 10^{30}$ g. Therefore, if an RG penetrates into the innermost region of the jet, the RG envelope can be already weakly gravitationally attached to the star due to tidal disruption. In this situation, the external layers of the star can be lost due to jet ablation, which is unlikely in the case of undisrupted RGs (except for very powerful jets).

The M87 TeV light curve obtained by [6] shows several peaks, and each of these peaks in our model correspond to different RG-jet events. Note however that some nearby peaks may correspond to a complex disruption process, motivated for instance by a very disrupted and massive envelope, or by jet inhomogeneities. Also, it cannot be discarded that a cluster of several RGs could also enter the jet. We illustrate in fig. 1 (left panel) how the spherical cloud evolves under the effect of the jet pressure as seen in the plane perpendicular to the jet axis.

The numerical calculations show that the cloud is destroyed over the time exceeding the cloud-crossing timescale, $r_c/c_{\rm s}$. These simulations also show that the radius of the volume contaning fragments of the destroyed cloud can grow up to an order of magnitude compared to the radius of the original cloud [11]. The fragmented cloud countinues to be suitable for shock formation and particle acceleration. The assumption of a sperical fragmented cloud is, of course, a simplification, but it allows an analytical treatment of such a complicated system, please find more details in the work [5].

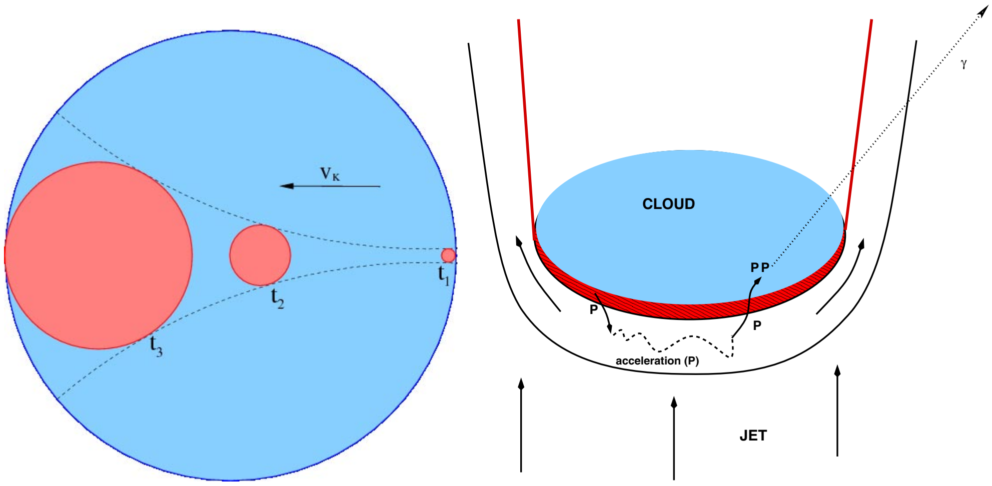

Fig. 1. – On the left panel the sketch of the evolution within the jet of the cloud formed by the disrupted envelope of the RG is shown. The plane of the image is the jet section. On the right panel the sketch of the proton acceleration and gamma-ray production processes is shown. The plane of the image would be normal to the jet section.

3. – Radiation

Particles could be accelerated in the shocked jet region below the cloud. As noted in sect. **1**, the jet is probably magnetically dominated at $z \leq 1\,\mathrm{pc}$. Therefore, one can estimate the magnetic field in the jet as follows: $B_{\rm j} \approx 100\, L_{{\rm j},44}^{1/2} z_{16}^{-1} \theta_{-1}^{-1}\,\mathrm{G}$, where $L_{{\rm j},44} = L_{\rm j}/10^{44}\,\mathrm{erg\,s^{-1}}$. The expected magnetic field in the shocked jet region should be also strong, probably of a similar strength to $B_{\rm j}$. Under such a magnetic field, one can estimate the acceleration timescale: $t_{\rm acc} \approx 0.1\,\xi\,E_2\,B_{{\rm j},2}^{-1}\,\mathrm{s}$, where ξ is the acceleration efficiency parameter, $E_2 = E/10^2\,\mathrm{TeV}$, and $B_{{\rm j},2} = B_{\rm j}/10^2\,\mathrm{G}$, the maximum energy of protons and electrons are $E_{\rm p\ max} \approx 10^7\,B_{{\rm j},2}\,r_{{\rm c},14}\xi^{-1/2}\,\mathrm{TeV}$ and $E_{\rm e\ max} \approx 10\,B_{{\rm j},2}^{-1/2}\,\xi^{-1/2}\,\mathrm{TeV}$, this equation is obtained from limiting the electron acceleration through synchrotron cooling. Even taking a high $\xi \sim 10$ (for mildly relativistic shocks, as those of supernova explosions, $\xi \sim 10^4$), electron energies will be too low to explain the H.E.S.S. spectrum of M87 up to energies of few tens of TeV [6], whereas protons may be accelerated up to ultra-high energies. In addition, the expected $B_{\rm jet}$ values could easily suppress any IC component. On the other hand, the cloud density can be high, making of *pp* interactions the best candidate for gamma-ray production in the RG-jet scenario, the characteristic cooling time for *pp* collisions being: $t_{pp} \approx \frac{10^{15}}{n_{\rm c}} = 10^5\,n_{{\rm c},10}^{-1}\,\mathrm{s}$, where $n_{{\rm c},10} = n_{\rm c}/10^{10}\,\mathrm{cm^{-3}}$ is the cloud density. We note that the high cloud density should not affect significantly the proton acceleration, which would occur in the far less dense jet shocked region. Nevertheless, protons should penetrate in the acceleration process and, in the Blanford-Znajek scenario of jet formation [12, 13] the jet is probably formed only by pairs. Therefore, some cloud material should penetrate into the shocked jet medium, which can occur through Rayleigh-Taylor instabilities [14]. We present in fig. 1 (right panel) a sketch of the mixing, proton acceleration and gamma-ray production processes.

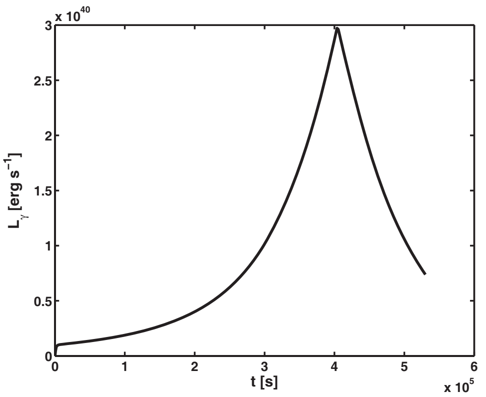

Fig. 2. – Gamma-ray *pp* light curve for the weak tidal disruption case. The parameter values are characteristic of M87: $L_\mathrm{j} = 2 \times 10^{44}\,\mathrm{erg\,s^{-1}}$, $M_\mathrm{BH} = 6.4 \times 10^9\,M_\odot$, $\theta_{-1} = 0.5$, $M_\mathrm{RG} = 1\,M_\odot$, $z_\mathrm{jc} \approx 2.5 \times 10^{16}\,\mathrm{cm}$, and $M_\mathrm{c} \approx 1.3 \times 10^{28}\,\mathrm{g}$.

The gamma-ray *pp* light curve for M87 is presented in fig. 2, in which the maximum is reached at $t_\mathrm{peak} \approx 4 \times 10^5\,\mathrm{s}$, with a width of $\sim$ 1–2 days. A value for η of 0.1 has been adopted.

4. – Discussion and conclusions

We remark that, if a detectable gamma-ray flare with a duration of few days were to be produced in M87, in particular through *pp* interactions, the cloud should have a mass of $\sim 10^{28}$ g. Such a massive cloud cannot acquire a large speed in the jet direction at the times when *pp* collisions are an efficient gamma-ray–emitting mechanism, and therefore the emission will not suffer significant Doppler boosting. In the case of a lighter cloud, large Lorentz factors can be achieved, but then *pp* interactions will be inefficient in producing gamma rays, the probability to detect a flare will be lower due to beaming, and the duration of the event will be shorter than observed because of faster expansion and beaming [15].

At farther distances, the strong jet luminosity dependence $L_\gamma \propto L_\mathrm{j}^{1.6}$ implies that FR II sources with say $L_\mathrm{j} \sim 10^{46}\,\mathrm{erg\,s^{-1}}$ may be still detectable up to distances of $\sim 0.5\,\mathrm{Gpc}$. For the most powerful jets, L_γ would be limited by the jet size becoming $L_\gamma = \chi\eta L_\mathrm{j}$, where η is the fraction of the obscured jet energy converted to the energy of relativistic particles. Taking for instance $L_\mathrm{j} \sim 10^{47}\,\mathrm{erg\,s^{-1}}$, L_γ could be as high as $\approx 2 \times 10^{45}\,\eta_{-1}\,\mathrm{erg\,s^{-1}}$. An improvement of a factor of several orders of magnitude in the VHE sensitivity (*e.g.*, through the forthcoming Cherenkov Telescope Array (CTA)) would test our gamma-ray predictions for the whole RG-jet interaction process.

The luminosity in the range 0.1–100 GeV would also be significant unless there is a strong low-energy cutoff in the proton spectrum. Therefore, Fermi may detect day-long GeV flares originated due to RG-jet interactions from FR II galaxies up to distances of few hundreds of Mpc. Summarizing, GeV and TeV instrumentation can potentially detect a number of RG-jet interactions per year taking place in nearby FR II and very nearby FR I galaxies, with the most powerful events being detectable up to 1 Gpc.

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