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Possible mechanism of quasi-periodic oscillation of x-ray and TeV emissions for Mkn 501*

Yuan Yu-Hai(袁聿海)[a)†] and Yang Jiang-He(杨江和)[b)]

[a)] *Center for Astrophysics, Guangzhou University, Guangzhou 510400, China,*

[b)] *Department of Electronics and Physics, Hunan University of Arts and Science, Changde 415000, China,*

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We propose that the emissions of an advection-dominated accretion flows (ADAF) disc are the seed photons up-scattered to x-ray and TeV γ-rays in Mkn 501 and the instability of an ADAF disc may explain the 23-day quasi-periodic oscillation period observed in the x-rays and TeV lightcurves of Mkn 501. In this model, the ADAF emissions of optical and x-rays go into the jet and are up-scattered to high energies by relativistic electrons. In this process, the instability occurring in ADAF results in the quasi-periodic variation in the seed photons and therefore causes the variation in high energy x- and γ-rays.

Keywords: BL Lacertae objects, black hole mass, gamma-ray source
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1. Introduction

Up to now, 4 BL Lacertae objects have been reported to be possible TeV emitters, namely, Mkn 421, Mkn 501, IES 2344+514 and PKS 2155-304. Two of them (Mkn 421 and Mkn 501) are confirmed as TeV emitters.[1] The common observational properties are their variability, the high energetic gamma-ray emissions are variable and correlate with those at the lower energy bands.[2,3]

The BL Lac Object Mkn 501 was in a state of high activity in the TeV range in 1997. During this time Mkn 501 was observed to show a 23 day periodicity in both the x-ray and TeV γ ray light curves.[4]

There are two general models for the production of TeV γ-rays from AGNs, namely the leptonic and hadronic models. In the leptonic model, high energy γ-rays are produced by the inverse Compton scattering of the high energy electrons in the soft photon field. The soft photons can be emitted from a nearby accretion disc or from disc radiation reprocessed in some region of AGNs (e.g. broad emission line region); or from the synchrotron emission in the jet, or from a differential rotating flux tube near the inner edge of the accreting disc. In the hadronic model protons are accelerated to extremely high energies. These protons initiate a particle cascade through $p\gamma \to \Delta \to \pi's$. The high energy γ-rays are produced by the synchrotron emission from ultrarelativistic electrons and positrons created in a proton-induced cascade (PIC).[5]

The host galaxy of Mkn 501 is an elliptical galaxy. In the core of this kind of galaxy, an advection-dominated accretion flow (ADAF) disc is usually assumed to exist to explain the relatively low luminosity.[6] The estimation of the black hole mass and the very low intrinsic luminosity of Mkn 501 confirms further the correctness of this assumption (see the following text for detail). In this paper, we propose an ADAF model to interpret the observed quasi-periodic oscillation(QPO) in both the x-ray and γ-ray light curves. The ADAF is truncated by a jet within a certain radius. The emission from the ADAF enter into the jet to serve as the seed photon of Compton scattering which is the source of the observed x-ray and TeV γ-ray. The inertial-acoustic instability occurring in ADAF result in the QPO of the seed photon, and further, of the light curve of both x-ray and γ-ray.

The typical emissions of an ADAF range from ra-

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†E-mail: yuanyuhai921@163.com

dio to hard x-ray, with several peaks in the spectrum located in radio, optical or IR, and hard x-ray. These peaks correspond to the self-absorbed synchrotron, the first Compton scattering and the bremsstrahlung radiation, respectively.

2. Model and results

The host galaxy of Mkn 501 is an elliptical galaxy in which an ADAF is generally assumed to exist[6] to interpret the massive black hole and the relatively low luminosity. This assumption can be further confirmed by the following arguments.

Mkn 501 is the second TeV γ-ray emitter locating at a redshift of 0.034. Its TeV γ-ray emission was first detected by Whipple observatory.[7] The energetic TeV γ-rays display very rapid variations on time scales of 5 hours.[8] According to our model, the TeV emission should be due to the Compton up-scattering of the hard x-ray photons from the ADAF. There are two time scales here, the orbital time scale of the disc where the hard x-ray is emitted and the light-passing time scale through the jet where the TeV photon is emitted. The observed minimum time scale should be the smaller of them. Since the hard x-ray is typically emitted from the region of $R \leq 100\ R_{\rm g}$ of ADAF, and assuming the TeV photon is emitted from 10 $R_{\rm g}$ in the jet, we have

$$t \sim \min\left(\frac{100R_{\rm g}}{v_{\rm k}}, 10R_{\rm g}/c\right). \tag{1}$$

So, the time scale of 5 hours will give the mass of the black hole of $\sim 10^8 M_\odot$. On the other hand, the intrinsic luminosity of Mkn 501 is rather low, $L \sim 10^{41}{\rm erg/s}$, which is approximately $10^{-5}L_{\rm Edd}$. Such low luminosity is the typical signal of the existence of an ADAF.

An ADAF is thermally and viscously stable. However, it is inertial-acoustically unstable.[9] The inertial-acoustic mode, in its simplest form, is a sound wave modified by rotation. The existence of this instability relies on the increase of the coefficient of viscosity upon compression in comparison with that of the expanded phase. The oscillation timescale of the inertial-acoustic mode is comparable to the dynamical time scale which is[10]

$$p = 2\pi/\Omega(R), \tag{2}$$

where $\Omega(R)$ is the angular velocity of the accretion flow at radius R. According to the self-similar solution,[11] we have typically $\Omega \sim 0.3\Omega_{\rm Kep}$ depending on the value of the viscous parameter α and the adiabatic index γ,

$$p = 1.2 \times 10^{-1}({\rm days})M_8 {r_*}^{3/2}, \tag{3}$$

where r_*, in units of $\dfrac{GM}{c^2}$, is the radius at which the instability occurs. So for a black hole with mass $M = 10^8 M_\odot$, the instability should occur at $\sim 33R_{\rm g}$ to produce the 23 day periodicity observed in the light curve of Mkn 501.

Observation told us that in the high activity epoch of Mkn 501, two peaks exist in the spectrum, with one at $\sim$ 100keV and the other at a certain frequency between GeV and TeV ranges. [12] If we interpret that the QPO of the hard x-ray and TeV γ-ray is caused by the instability of the accretion disc, then we must interpret the two peaks as well. Since for Mkn 501 the luminosity is $\sim 10^{-5}L_{\rm Edd}$, the mass accretion rate should be relatively low. In this case, as mentioned above the typical ADAF emission spectrum has three peaks, located in the radio, optical and hard x-ray, respectively. They are due to synchrotron radiation, the first-generation Compton up-scattering of the synchrotron photon, and the bremsstrahlung emissions.[13] Therefore, there should exist three peaks in the Compton up-scattered spectrum emitted from the jet, if a typical ADAF emission spectrum serves as the seed photon of Compton scattering. This is in conflict with the observation.[14] This difficulty can be eliminated if we take into account the existence of the jet in Mkn 501. The ADAF will be truncated by the formation of the jet within a certain radius. Using this scenario, Yuan[15] successfully calculated the spectrum of the radio source located at the centre of the Galaxy and nearby elliptical galaxies NGC 4649, M87 and NGC 4636, which are hard to explain by a canonical ADAF model. Due to the truncation of the disc, the peak flux in the optical band is significantly reduced (see, e.g. Figs.1 and 5 in Yuan[15]). Thus only two main peaks are emitted from the ADAF and enter into the jet to serve as the seed photon for up-scattering. This is the reason why we only observed two peaks in the spectrum of Mkn 501.[14] In addition, the frequency of the radio peak will become lower due to the truncation of the ADAF of Yuan.[15] The value of the frequency of the radio peak will be $\sim 10^{11}$Hz, and the ratio between the frequencies of the radio and the x-ray peaks is about 9 orders of magnitude. If we set the Lorentz factor of the electron in the jet γ as $\gamma^2 \sim 10^8$, the up-scattered peak of this radio peak should be present at $\sim$100keV, while the up-scattered

peak of the x-ray peak of the disc should be present at $\sim 10^{11}$eV due to the effect of the Klein–Nishina limit.

3. Discussion

Quasi-periodic variation with time scale of years is common in blazar.[16−20] The variation over scales of months was only reported in 3C 66A[21] and Mkn 501. During the Mkn 501 1997 flare, Mkn 501 was observed by the BeppoSAX on April 7 and 16. The x-rays show some particular properties not observed before in other sources. The x-ray luminosity increases by a factor ≥ 20 with the peak of the power output being shifted in energy by a factor ≥ 100.[14] The corresponding TeV emissions brightened by a factor of more than 5 during the same observation period as the x-ray observations. On April 16, the TeV flux was a factor ~ 100 more than in the quiescent state.[22] For a TeV gamma-ray source, the energy distribution spectrum is explained by the simple synchrotron self-Compton (SSC) model, but the hadronic model cannot be ruled out unambiguously on the basis of arguments concerning the time variability of the TeV-flux of Mkn 501.[22]

In the hadronic model, the π^0's decay to produce the TeV γ-rays while the $\pi^{\pm}$'s decay to pairs and produce the synchrotron emission in the x-rays. In this sense, one can expect that the x-ray and the high energy TeV γ-rays vary simultaneously and no delay can be found between them as the observations indicated in the paper by Aharonian *et al*[22] who claimed that the time delay between the x-ray and the TeV γ-rays is one day or less. Such time delay is also reported recently by Krawczynski *et al*[23] who claimed that their analysis indicates that the 25keV variations happen rather simultaneously with the TeV variations, or even lead them by several hours. But Fig.7 of Krawczynski *et al*[23] cannot let one draw a definite conclusion on the time lag. It is possible that the emissions in the optical bands are not from the synchrotron emissions of the pairs produced from the $\pi^{\pm}$'s and therefore, there is no expected correlation between the optical and the x-ray/TeV-γ-rays. The observations show that there is no correlation between the optical and the high energy emissions[24] or only weak correlation between them. In this sense, the correlated x-ray and TeV γ-ray variations cannot distinguish the SSC model from the hadronic one.

To up-scatter the x-ray to the 1 TeV region, the required electron energy is $\gamma = \dfrac{1\,\mathrm{TeV}}{m_\mathrm{e}c^2} \approx 2\times 10^6$, which is in the extreme Klein–Nishina regime. For the inverse Compton process, we can estimate the optical depth, $\tau_{\mathrm{KN}} = n_{\mathrm{X}}\sigma_{\mathrm{KN}}l$, where $\sigma_{\mathrm{KN}} = \dfrac{3}{8}\sigma_{\mathrm{T}}\dfrac{1}{X}\left(\ln X + \dfrac{1}{2}\right)$ is the cross section in the extreme Klein–Nishina regime, $X = \dfrac{\gamma\hbar\omega}{m_\mathrm{e}c^2}$, n_{X} is the x-ray photon density which can be estimated from the observed x-ray flux and l is the distance.

For Mkn501, BeppoSAX observations indicate that over the whole 0.1–200keV range, the spectrum was exceptionally hard.[14] TeV observations show that the TeV spectrum gradually steepens with energy starting at 3TeV.[25] Considered the 0.5keV disc photons to be up-scattered to 3TeV, then the electron should have an energy of $\gamma = 6\times 10^6$. During the flare episode, the x-ray flux[14] gives an x-ray photon density of $n_{\mathrm{X}} = 2.4\times 10^{12}\mathrm{cm}^{-3}$ (here we choose $l = 33r_{\mathrm{g}}$), therefore we can obtain a corresponding optical depth $\tau_{\mathrm{KN}} \sim 1.0$ for the episode. But in the quiescent state, the x-ray flux is about ten times smaller than that during the flare episodes (see Section 2.2), implying an optical depth of $\tau_{\mathrm{KN}} \approx 0.1$. The optical depth suggests that the TeV flux produced by the disc x-rays in the quiescent state is much less than that during the flare state.

In our proposal, the emissions in the x-ray and the TeV γ-rays come from the up-scattered radio and x-rays produced by the ADAF disc. In this sense, the emissions of x-rays and the TeV γ-rays are different from those of radio to lower-than-x-ray regions. Therefore, correlated variation can be expected for the x-rays and the high energy TeV γ-rays but no similar result for optical and x-rays/TeV-γ-rays. The observational results are consistent with the expectation.

The observations in the x-rays and the TeV γ-rays indicate that there is the same quasi-periodicity of 23 days in the light curves, which is perhaps caused by the orbital motion of the relativistic jet emerging from the less massive black hole of the binary black hole system[26] and by the interaction of the shock wave and the helical structure of the jet.[27,28] But if their periodicity is caused by the motion of the jet, then one can expect that the same value of period should show up in the optical and the radio bands, and the high energy bands should be correlated with the lower energy optical band. But the observations do not support the expected correlation strongly.

In our argument, the observed emissions are mainly from the jet, but the synchrotron process is re-

sponsible for the lower energy emissions such as radio through optical bands while in the range from x-ray to TeV γ-rays bands at least two processes are responsible: namely, the relatively stable SSC process and the inverse Compton process with the soft photons being the optical to x-ray photons from the ADAF, which enter the jet and are up-scattered to the x-ray and TeV γ-rays. The instability occurring in the ADAF disc will result in the variation of the disc optical and x-ray emissions and therefore cause the variations in x-ray and TeV γ-rays. In this sense, if the optical emissions are variable, then the x-ray to TeV γ-rays emission are also variable, and vice versa, it is possibly not the case, and the correlated x-rays and TeV emissions do not correlate with x-ray/TeV and optical emissions. One should bear in mind that optical observations were scarce during the 1997 x-ray/TeV burst period. If one can get a similar value of period in the optical bands, then the result will favour the jet motion model, otherwise our model should be responsible for the periodicity phenomenon in Mkn 501. Continuous optical observations are strongly encouraged for this source.

So, there is an ADAF around a black hole of mass $\sim 10^8 M_\odot$ at the centre of Mkn 501, and the soft photons from the ADAF are scattered up to TeV. Therefore, a similar periodicity is observed in the x-ray and TeV gamma-ray regions.

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