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NON-THERMAL EMISSION FROM CATACLYSMIC VARIABLES: IMPLICATIONS ON ASTROPARTICLE PHYSICS

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Abstract. We review the lines of evidence that some cataclysmic variables (CVs) are the sources of non-thermal radiation. It was really observed in some dwarf novae in outburst, a novalike CV in the high state, an intermediate polar, polars, and classical novae (CNe) during outburst. The detection of this radiation suggests the presence of highly energetic particles in these CVs. The conditions for the observability of this emission depend on the state of activity, and the system parameters. We review the processes and conditions that lead to the production of this radiation in various spectral bands, from gamma-rays including TeV emission to radio. Synchrotron and cyclotron emissions suggest the presence of strong magnetic fields in CV. In some CVs, e.g. during some dwarf nova outbursts, the magnetic field generated in the accretion disk leads to the synchrotron jets radiating in radio. The propeller effect or a shock in the case of the magnetized white dwarf (WD) can lead to a strong acceleration of the particles that produce gamma-ray emission via π^0 decay; even Cherenkov radiation is possible. In addition, a gamma-ray production via π^0 decay was observed in the ejecta of an outburst of a symbiotic CN. Nuclear reactions during thermonuclear runaway in the outer layer of the WD undergoing CN outburst lead to the production of radioactive isotopes; their decay is the source of gamma-ray emission. The production of accelerated particles in CVs often has episodic character with a very small duty cycle; this makes their detection and establishing the relation of the behavior in various bands difficult.

Keywords: acceleration of particles, astroparticle physics, nuclear reactions, nucleosynthesis, abundances, elementary particles, magnetic fields, radiation mechanisms: non-thermal, circumstellar matter, accretion, accretion disks, Novae, cataclysmic variables, X-rays: binaries.

1. Introduction

In cataclysmic variable (CV), matter flows from a companion star, the so-called donor (often a low-mass, main-sequence star), onto the white dwarf (WD) accretor. This mass-transferring binary is a complicated and very active system with various emission regions. Release of the gravitational energy during accretion of matter from the donor onto the WD is the dominant energy source of the CV system. This accretion usually occurs via accretion disk embedding the WD. However, if the WD has a strong magnetic field, this field largely influences the accretion flow – such systems are called polars. Thermonuclear reaction of the accreted matter on the surface of the WD is another, often episodic source of energy. Review can be found in [40].

CVs have been shown to radiate in various spectral regions via various emission mechanisms. The complicated structure of the emission regions and the operation of the individual emission mechanisms largely vary with the state of their activity. CVs are therefore very important laboratories for a study of the physical processes, including a search for the highly energetic particles.

We discuss the processes and conditions that lead to the production of non-thermal radiation in CVs. The detection of such a radiation suggests the presence of highly energetic particles in these CVs. How can this emission be detected and monitored? In which spectral bands and with which techniques? We also show the importance of non-thermal radiation of CVs for the physics of these systems. We focus on the cases where such emission was really observed – from gamma-rays (including TeV emission) to radio.

2. Non-thermal radiation in various types of CVs

We review the types of CVs and their states of activity in which non-thermal radiation was observed in various spectral regions.

2.1. CVs with accretion disks and “non-magnetized” WDs

In some CVs, the accretion disk suffers from a thermal-viscous instability if the mass transfer rate $\dot{m}$ lies between certain limits. It gives rise to the large-amplitude optical outbursts in the so-called dwarf novae (e.g. [17]). The accretion disk is a source of intense thermal emission during the outburst (or during the high state in novalike CVs) (e.g. [40]). Nevertheless, we will show several CVs which are also the sources of non-thermal radiation.

The dwarf nova SS Cyg/3A 2140+433 is a very good example. Its non-thermal radio emission was generated during its outburst [25]. This radio emission does not directly follow the optical one; the radio-emitting medium is therefore not any detached reprocessing medium. It originates from SS Cyg itself during the outburst. Radio emission of SS Cyg is optically thick synchrotron radiation of a transient jet because the size of the radio-emitting medium is much larger than the magnetosphere of the WD. A similar behavior, that is radio emission only during the optical outburst, was observed in the dwarf nova EM Cyg/1RXS J193840.0+303035. Gyrosynchrotron emission of non-thermal electrons is a plausible explanation. The radio source is significantly larger than the binary separation. This is consistent with a transient jet like in SS Cyg. This radio emission, related to the conditions in the accretion disk [6, 7], suggests a symbiosis of the thermal emission of the accretion disk and the non-thermal radiation of the jet. A single process (thermal-viscous instability of the disk) is the trigger of both types of emission.

In addition, radio emission (frequencies of 5.5 GHz and 9 GHz; ATCA radio telescope) was also detected from the novalike system V3885 Sgr. The ASAS [33] light curve shows a relation between the optical and radio activity. This radio emission falls into a long-lasting high state of the optical emission, with the luminosity comparable to the peak of the outburst in dwarf novae (e.g. SS Cyg). The analogies with Z-sources and outbursting dwarf novae suggest synchrotron emission of a jet [26].

2.2. Intermediate polars

Accretion flow of intermediate polar is controlled by the magnetic field of the WD inside the magnetosphere of this accretor. Accretion of matter therefore occurs onto the magnetic poles of this WD [16, 40]. Non-thermal radiation can be produced by electrons and protons which are accelerated in the transition region between the rotating WD magnetosphere and the accreting matter. Gamma-ray emission from the decay of neutral pions is predicted to be produced in hadronic collisions [5].

V1223 Sgr/1H 1853−312 was observed to display brief brightenings that cannot be explained by a thermal-viscous instability of its accretion disk. Part of a flare observed in far infrared (IR) (λ of 14÷21 μm) by *Spitzer* satellite, with the flux declining by a factor of 13 in 30 minutes, suggests a transient synchrotron emission [18]. Another two brightenings were observed in the optical band. One of them, with an amplitude of more than 1 mag in the red continuum, lasted only for several hours. It was accompanied by an increase of the Hα line flux, which was longer than in the continuum. This suggests that also the line emission participated in this event [39]. Another flare (a brightening by > 1 mag) was found on an archival photographic plate (the Bamberg Observatory) in blue

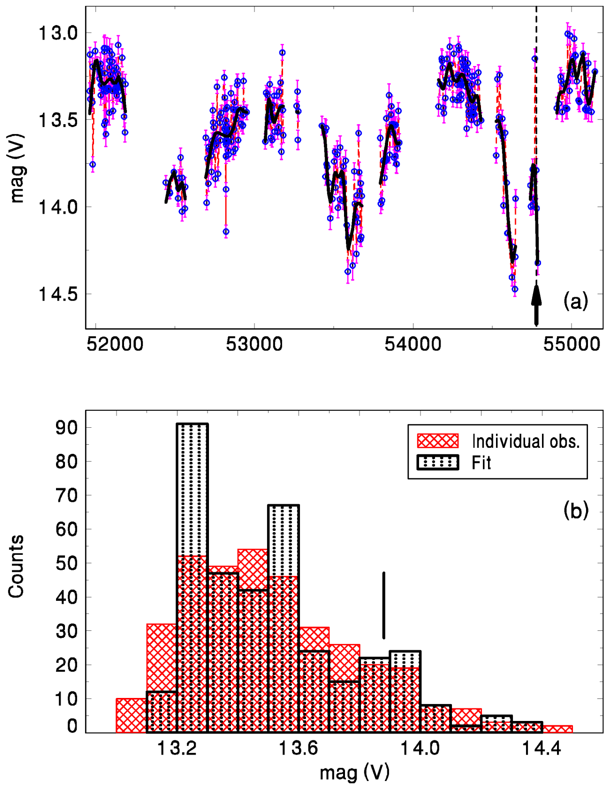

Figure 1. (a) Position of the synchrotron flare observed by [18] (arrow) in the optical (the V band) light curve of V1223 Sgr (ASAS data [33], one CCD image per night). The smooth line represents the HEC13 fit. (b) Statistical distribution of the brightness from panel 'a'. The baseline level of the synchrotron flare is marked by the vertical line. Notice that the flare occurred from a shallow low state of the optical brightness. See Sect. 2.2 for details.

light [34]. One photographic plate of the field was obtained per night during this monitoring.

Extrapolation of the flux of the flare with a very flat synchrotron spectrum, observed by [18], from far IR to the optical band can hardly explain the observed bright optical flares in V1223 Sgr. It is possible that some interaction of the inner disk region with the synchrotron jet occurred to produce the optical brightening; this scenario is supported by an increase of the Hα emission during the flare.

Placing the flares in the long-term optical light curve can give us important information about the conditions suitable for generating these events in V1223 Sgr (Fig. 1a). In the last years, this system was in the so-called high state of its activity, but it displayed several recurring decreases to the so-called shallow low state. Nevertheless, even during this shallow low state it was always much brighter that in the true low state reported by [15].

In the statistical distribution (Fig. 1b), the upper (brighter) limit of the brightness is significantly better defined than its lower (fainter) limit. Also the time fraction spent in the high state is considerably larger than in the shallow low state. The synchrotron flare in *Spitzer* data occurred from a shallow low state (Fig. 1b). It is close to an optical flare, but it is not precisely coinciding with it (Fig. 1a). A cluster of flares in a given shallow low state can explain it.

A similar situation is as regards the flare on the Bamberg plate [34]. It therefore appears that the episodes of shallow low state create suitable conditions for the flares in V1223 Sgr (increase of the Alfvén radius, inner disk region therefore being closer to the propeller regime, but still with a high $\dot{m}$?).

AE Aqr/1RXS J204009.4−005216 is a unique system because it is an intermediate polar in a propeller regime. Most of the transferring matter is therefore ejected by the rapidly spinning (33 s) magnetized WD [41]. An interaction of these blobs with the magnetosphere of the WD leads to the flares of the optical (thermal) emission. A typical duration of a single flare is several minutes but these events can be clustered [32]. Part of matter of these blobs is trapped in the WD magnetosphere and these particles are accelerated according to the model by [27]. Synchrotron emission from electrons in expanding clouds then dominates in far IR and radio bands. This radio emission is a superposition of discrete, synchrotron emitting flares from the vicinity of the WD [10]. The flare is an expanding plasmoid – a spherical cloud of relativistic electrons which expands adiabatically [4]. Generation of the synchrotron emission is therefore a consequence of the blobs [27], although the occurrence of the individual spikes of the radio emission is not directly correlated with the optical spikes [1].

AE Aqr is a transient TeV source detected by ground-based Cherenkov telescopes [29, 30]. A method of confirmation that TeV emission really comes from the observed object (i.e. an argument against a spurious detection) is to correlate the time variations of its TeV intensity with some period already known to be specific for this object. Indeed, the optical and TeV flares display the same frequency (a 33 s spin period of the WD detected in the optical band). TeV flares are highly transient, with quite a small duty cycle (0.2 percent). These TeV flares were interpreted as due to acceleration of particles by the rotating magnetic field of the WD in intermediate polar in the propeller regime. TeV flares occur only during a low optical brightness; the accretion luminosity must be low to allow the inner edge of the disk to be outside the co-rotation radius. Electrons are accelerated to $E \approx 10^{13}$ eV and converted to gamma-rays via π^0 decay in the blobs.

All this production of non-thermal radiation of AE Aqr depends on the state of its long-term activity which can be measured in the optical band. The mean level of this brightness largely varies on the timescale of years (Fig. 2a). This activity is mainly caused by a variable amount and brightness of the flares. The more numerous flares lead to a higher optical brightness of the system because they emit optical radiation. Even a season with almost absent flares was observed (Fig. 2a). This behavior can be explained by a transient decrease or even a cessation of the mass inflow from the donor. Such an evolution suggests a variable amount of the blobs on this timescale. This implies variable conditions for the generation of the accelerated particles.

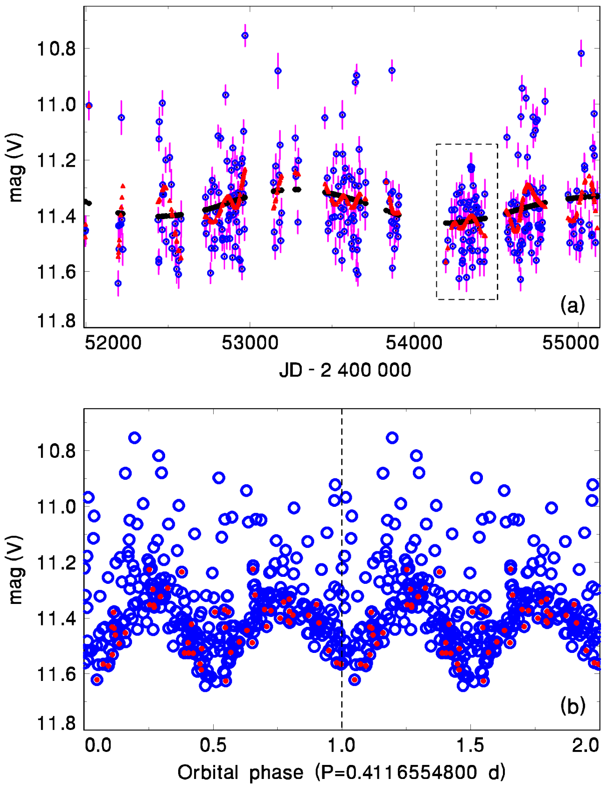

Figure 2. (a) Long-term activity of AE Aqr in the optical band (ASAS data [33], one CCD image per night). The smooth lines represent the HEC13 fits. The segment with almost absent flares is marked by the box. (b) The light curve folded with the orbital period according to the ephemeris of [12]. Open circles represent all the data points from panel 'a'. Closed circles denote the data from the box in panel 'a'. See Sect. 2.2 for details.

The light curve of AE Aqr folded with the orbital period according to the ephemeris of [12] displays a large scatter caused by the real variations, not by a noise (Fig. 2b). The flares can occur at any orbital phase (see also [32]), and the detection of a higher intensity of the flares is less frequent. The profile of the lower envelope of the folded light curve (remaining all the time, even when the flares are missing) is caused by the tidal deformation of the donor [32].

2.3. Polars

Polars are CVs with a strongly magnetized WD (typically $B > 10^7$ G (e.g. [40]). No disk is formed and the accreting matter flows directly onto the accretion region(s) in the vicinity of the magnetic pole(s) of the WD. This falling matter forms an accretion column above the surface of the accretor (less than 0.1 of the radius of the WD). This column is a source of radiation via several mechanisms. It radiates via cyclotron mechanism in the optical and near IR bands, while the accretion shock emits bremsstrahlung in hard X-rays (e.g. [13, 28]). Intensity of the cyclotron emission largely varies with the orbital phase of the polar, which reflects the changing aspect of the emission region with respect to the observer [14].

AM Her/3A 1815+498 displays a significantly variable ratio of the intensities of the cyclotron and bremsstrahlung components for the individual high-state episodes [35]. This suggests large changes of the properties of the emission region(s) on the WD. These properties are established already in the early phase (several days long) of the high-state episode but they are not reproduced for every individual episode. An increase of $\dot{m}$ from the donor that switches the polar from the low to the high state of its long-term activity also establishes a division of the emission released during the accretion process into various spectral regions, hence into the individual emission mechanisms operating in the accretion region. This division is valid only for a given episode. Each high-state episode is thus characterized by the specific configuration of the accreting matter [35]. This is also supported by the change of the profile of the optical orbital modulation, as observed by [24]. The observed behavior can be reconciled if the bremsstrahlung emission is confined to a smaller region than the cyclotron emission. Also the role of several modes of accretion, e.g. a single-pole and two-poles accretion [19], is worth considering. These findings show that both the positions of these emission regions and their contributions to the total intensity varied with time. The emission region caused by the accretion of matter and its conditions are therefore proved to be highly unstable in time.

Several sites of non-thermalradio emission (frequency of 4.9 GHz) existed in AM Her [11] in the same time, specifically in the optical low state of its long-term activity [20]. Quiescent radio emission was ascribed to the energetic electrons trapped in the magnetosphere of the WD. A radio outburst (flare) was explained as an electron-cyclotron maser near the surface of the late-type donor, in its corona with the magnetic field ($B \approx 1000$ G).

In the high state of the long-term optical activity, AM Her is sometimes able to accelerate particles that produce TeV emission [8]. Its intensity is strongly modulated with the already known orbital period seen in the polarized optical light of AM Her. This is strong evidence that this gamma-ray emission really comes from this object [8]. Protons can be accelerated to very high energies (GeV to TeV) at the shock front on the top of the accretion column [38], with the subsequent gamma-ray production via π^0 decay [3].

2.4. Outbursts of classical novae

Radioactive isotopes are synthesized during outburst of classical nova (CN). Gamma-ray emission is then produced during their decay. Detection of these gamma-rays strongly depends on the isotope's lifetime and on the optical depth in the ejecta of the nova.

Only cumulative effect of the production of ^{26}Al (lifetime of 10^6 years) emitting the gamma-ray line with $E = 1.809$ MeV in various types of sources, concentrated toward the Galactic plane, and its ejection into the space has been observed by COMPTEL/*CGRO* [9]. This emission therefore does not come from a single source. Outbursts of CNe contribute about 15 percent [23]. The situation of ^{22}Na with a lifetime of 3.75 years ($E = 1.272$ MeV) is similar. Outbursts of the Neon-type CNe contribute only partly; excitation of ^{22}Ne-nuclei, e.g. through the low-energy cosmic ray interactions with the nuclei of the interstellar matter, can dominate [21].

It is very important that in V723 Cas (Nova Cas 1995), the nucleosynthesis during its outburst was really observed in the gamma-ray band [22] (Fig. 3). Both the COMPTEL/*CGRO* field of Nova Cas 1995 (total integration time of ∼4.5 years) and a spectrum from the position of this nova revealed a new source emitting the ^{22}Na line ($E = 1.275$ MeV). This is direct evidence that CNe contribute to the gamma-ray flux of ^{22}Na in the Galaxy. This ^{22}Na was synthesized during thermonuclear reactions on the surface of the WD [22]. Time evolution of the ^{22}Na gamma-ray flux of V723 Cas is a combination of a decreasing absorption of the gamma-ray flux in the ejecta and the time dependence of the undecayed ^{22}Na nuclei. The case of V723 Cas also enabled to identify the important properties needed for the formation and preservation of ^{22}Na, hence for the detection of the ^{22}Na gamma-ray flux: type of CN (slow nova), massive ejected envelope, low mass of the WD (only $0.66\,M_\odot$) [22].

Strongly accelerated population of electrons with a nonthermal energy distribution during an outburst of the classical nova V2491 Cyg was proved by the detection of superhard ($E > 10$ keV) X-ray emission with a power-law spectral profile up to E of 70 keV, attenuated by a heavy extinction of 1.4×10^{23} cm^{-2} (*Suzaku* satellite) [37]. According to the model by [36], Compton degradation, i.e. repeated scattering of the gamma-ray photons by electrons in the matter ejected from a WD, can explain the extremely hard X-ray spectrum and the absence of the 1.275 MeV line of ^{22}Na. The ejecta become transparent to the gamma--ray photons within several tens days.

Gamma-rays from the shock in the very fast CN in the symbiotic binary V407 Cyg (Nova Cyg 2010), detected by LAT/*Fermi*, represent a unique case of the CN activity [2]. The environment of the erupting WD was very specific. This object was deeply embedded in the dense wind of its cool giant companion [31]. According to [2], a variable gamma-ray emission started with the rise of the optical luminosity of the outburst and lasted for about 18 days. Continuum emission with no lines was detected in the spectral region between 0.2 and 5 GeV. No spectral

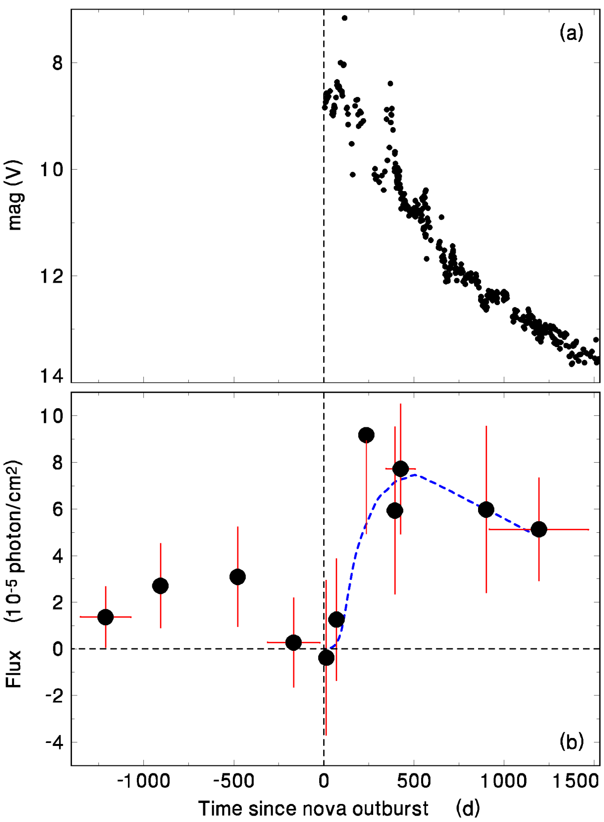

Figure 3. (a) Outburst of the classical nova V723 Cas (Nova Cas 1995) in the optical band (AAVSO data [20]). The vertical line denotes the time of the discovery of the optical outburst. The outburst started at most several days before the discovery. (b) Time evolution of the flux of the line (E = 1.275 MeV) of the radioactive isotope ^{22}Na of V723 Cas (adapted from [22]). See Sect. 2.4 for details.

variability was observed over the duration of the active gamma-ray period. Most gamma-rays come from the part of the nova shell approaching the red giant donor [2]. This gamma-ray emission was interpreted as an interaction of the material of the nova shell with the dense medium of the red giant donor. Particles were accelerated by this interaction of the shell to produce π^0 decay gamma-rays from proton-proton interactions [2].

3. General conclusions

Non-thermal radiation was definitely observed in the following types of CVs: dwarf nova in outburst, novalike CV in the high state, intermediate polar, CN during outburst. This brings evidence that the processes for the creation and/or acceleration of highly energetic particles must operate in such CVs. The conditions for generating the non-thermal radiation depend on the state of the system's activity and its parameters. These processes, states of the activity, and the spectral bands in which non-thermal radiation can be observed can be summarized in the following way.

Synchrotron emission provides us with evidence of generation of the magnetic fields influencing the transferring matter. This emission, which can be studied in the radio band, can come from the jets launched during the outbursts of dwarf novae and even during the high state of some novalike systems. However, the structure of this medium is uncertain in some systems (e.g. the flare radiating in far IR, observed in the intermediate polar V1223 Sgr). Also in the case of AE Aqr, the synchrotron emission in radio is produced by the clouds launched from the system by the propeller effect rather than in a jet.

Also cyclotron emission carries information about strong magnetic field existing in some CVs, namely polars. It emerges that even a single polar can possess several simultaneously existing cyclotron-emitting regions: accretion region on the WD (emitting in the optical and IR bands), and the donor's magnetosphere, radiating in radio.

Gamma-ray production via π^0 decay suggests operation of mechanisms that lead to acceleration of protons in various types of CVs. π^0 particles can be created in the transition region between the rotating WD magnetosphere and the accreting matter, by the propeller effect, by a shock on a strongly magnetized WD, or in ejecta of outburst of a symbiotic CN.

Production of radioactive isotopes occurs during the nuclear reactions in the outer layer of the WD during a CN outburst. Only some isotopes lead to the production of the observable gamma-rays. Only cumulative effect of many CNe can be expected from the gamma emission of ^{26}Al. The situation is more optimistic as regards ^{22}Na, which was detected from a single CN.

We offer the following solution and further prospects in search for the suitable states of activity of CVs in which the highly energetic particles are produced. The long-term activity of these objects in the optical band appears to be a plausible indicator of suitable conditions for the generation of these particles. The reason is that the data coverage in other spectral bands is fragmentary or even absent. The phenomena related to the generation of the highly energetic particles often have episodic character with a low duty cycle: e.g. ultra-high energy flares in the propeller systems (AE Aqr), radio flares in polars (AM Her). This property makes the detection of these phenomena and establishing a relation between various emission processes difficult.

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