Cataclysmic variables: Their impact on astroparticle physics

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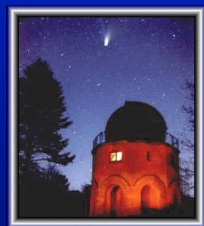


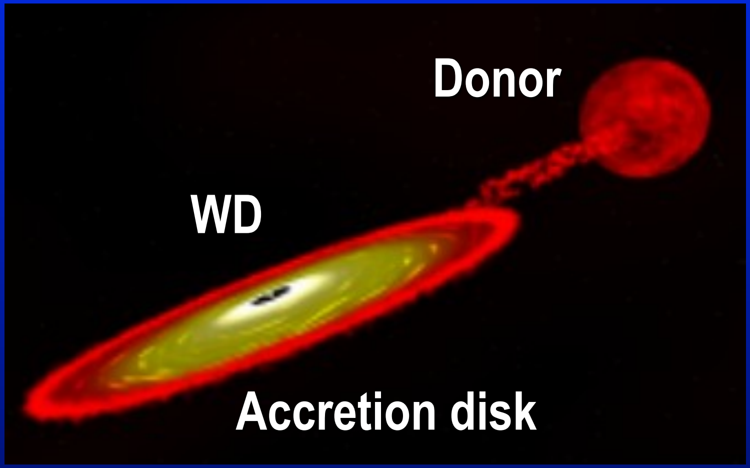
Talk: Frontier Objects in Astrophysics, Vulcano, May 28 - June 2, 2012

Structure of the system & Generation of energy

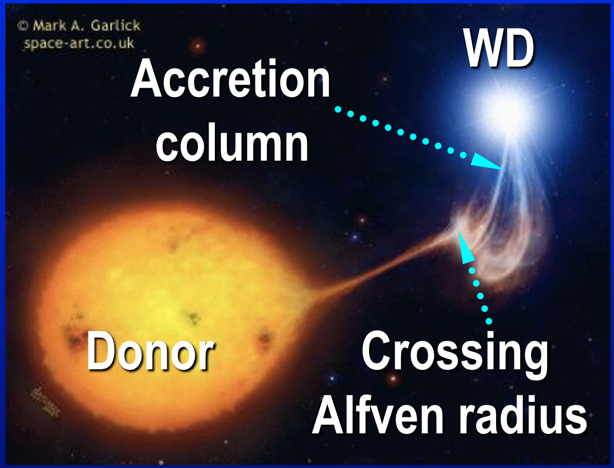
- **Donor** – often low-mass, main-sequence star
  – energy source: - thermonuclear energy in the core, radiative transfer to the outer layers – only thermal emission is observable
  - generation of the magnet. fields in the convective outer layer

- **Accretor** – compact object - white dwarf (WD)
  – energy source: - release of the gravitational energy during accretion of matter from the donor
  - existing magnetic field in some WDs
  - thermonuclear reaction (often episodic) of the accreted matter on the surface of the WD

- CVs with non-magnetized WD:



- CVs with strongly magnetized WD (polars):



Non-thermal emission detected in cataclysmic variables and its importance for the physics

- We review the processes and conditions that lead to the production of non-thermal radiation in cataclysmic variables (CVs).

- Detection of non-thermal radiation suggests the presence of highly energetic particles in these CVs.

- How can this emission be detected and monitored?

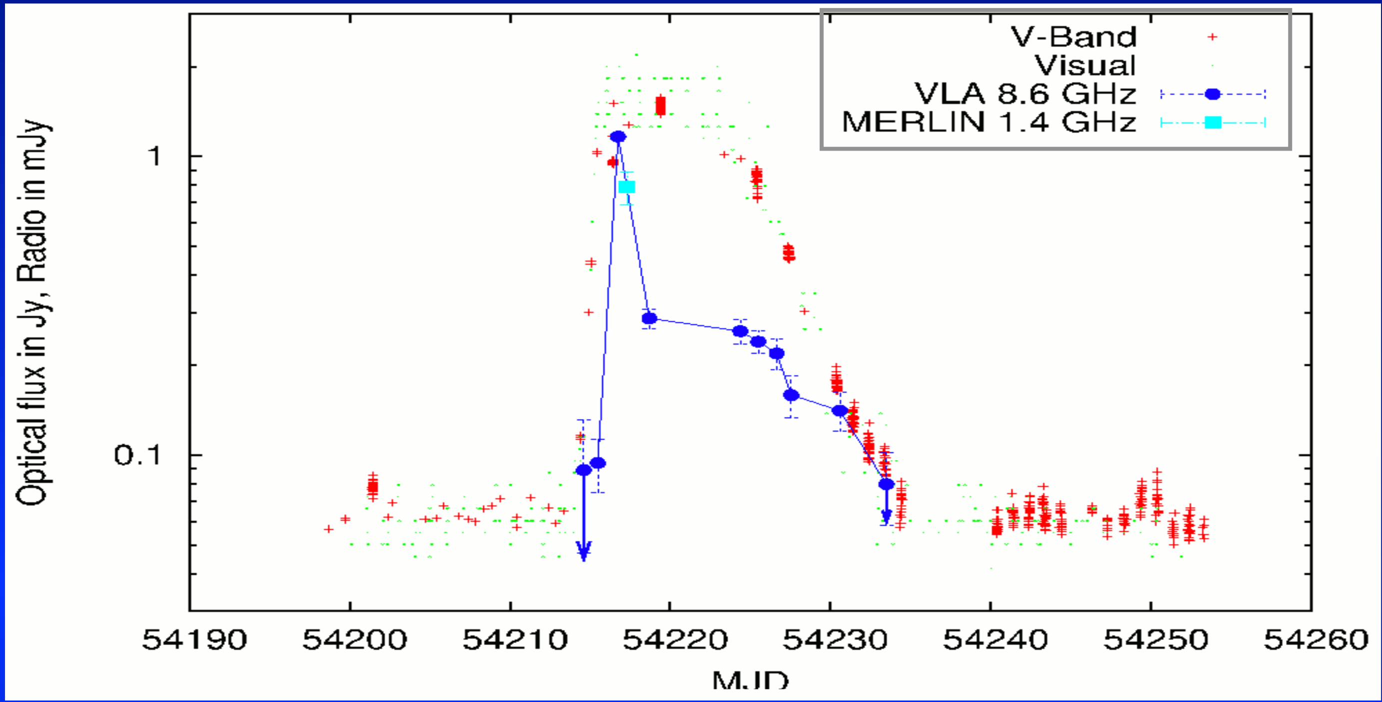
- In which spectral bands and with which techniques?

- We focus on the cases (objects) where such emission was really observed – from gamma rays (including TeV emission) to radio.

CVs with accretion disks

(disks as the sources of non-thermal radiation)

Radio emission from dwarf nova SS Cyg / 3A 2140+433

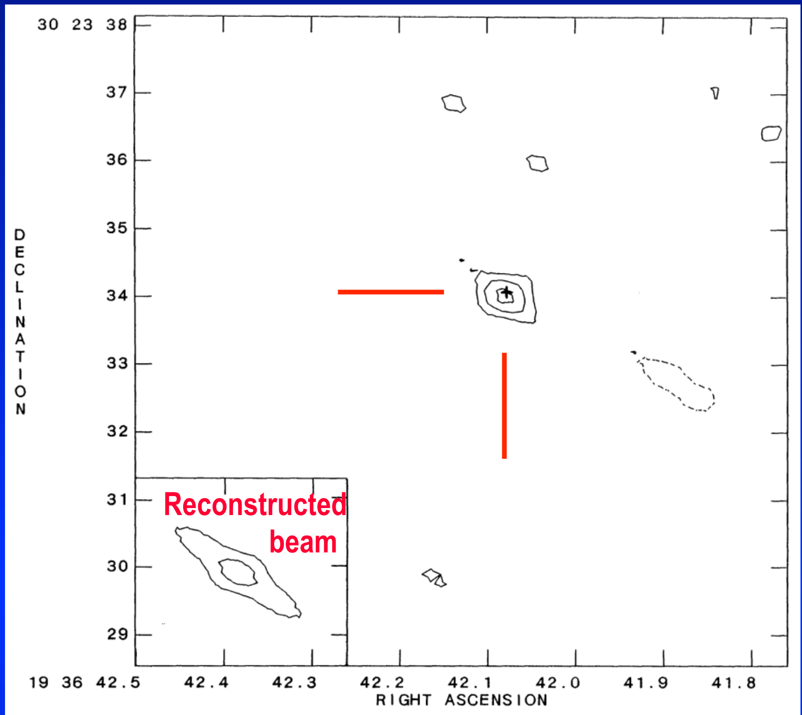


Radio flare during rise to the optical peak of outburst

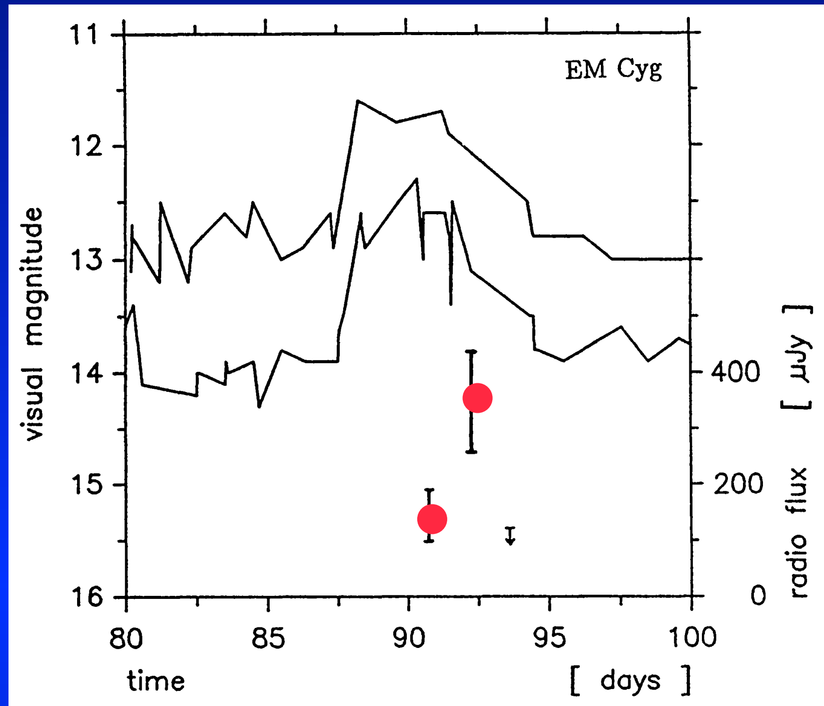
- Radio emission does not directly follow the optical one: the radio-emitting medium is not any detached reprocessing medium – this medium originates from SS Cyg during the outburst
- Radio emission of SS Cyg: **optically thick SYNCHROTRON radiation of a transient jet**
- Size of the radio-emitting medium is much larger than the magnetosphere of the WD
- Symbiosis of the thermal emission of the accretion disk and non-thermal emission of the jet:
  - a single process (thermal-viscous instability of the disk) is the trigger

Kording et al. (2008)

Radio emission from dwarf nova EM Cyg / 1RXS J193840.0+303035



VLA radio map at 6 cm of EM Cyg in outburst



Radio emission only during the optical outburst

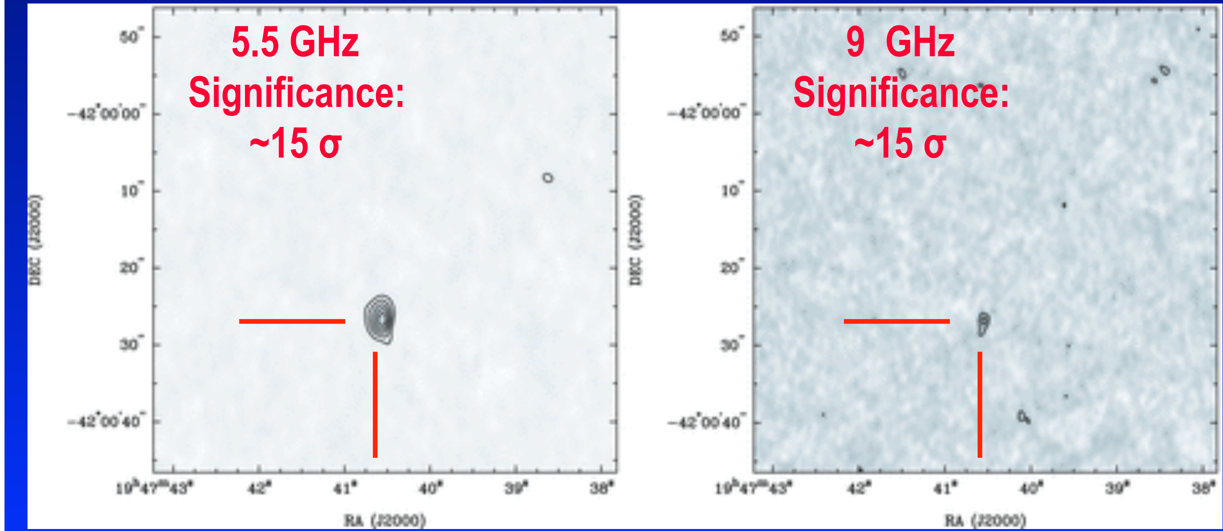
- Radio emission detected only during the optical outburst, not during quiescence.

- Interpretation of the radio emission:

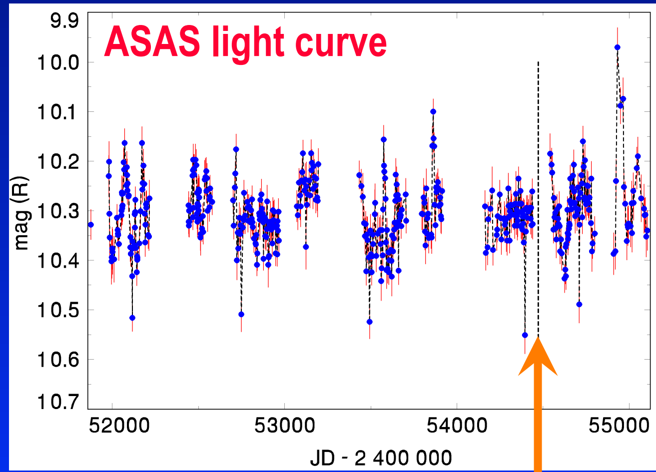
Benz & Guedel (1989), Benz et al. (1996)

- - bremsstrahlung is excluded
- - thermal radiation of the accretion disk is excluded
- - gyrosynchrotron emission of non-thermal electrons is plausible: The radio source is significantly larger than the binary separation – consistent with a transient jet like in SS Cyg – this emission is related to the conditions in the accretion disk

Radio emission from a novalike system – V3885 Sgr



An unresolved point source is detected in the radio bands.



Relation between the optical and radio activity – long-lasting high state of the optical emission

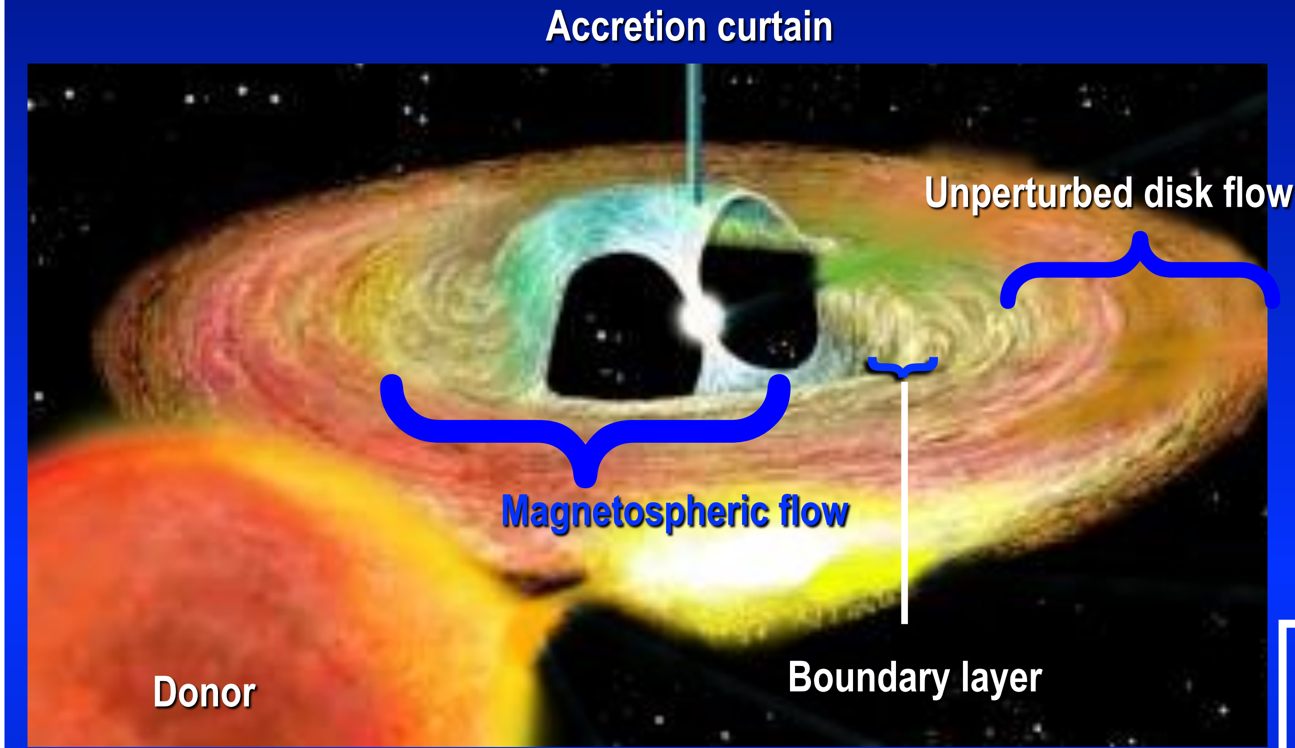
- ATCA radio telescope: flux level 0.16 mJy at 5.5 GHz
- Radio detection during *optical high state* comparable to the peak of the outburst in dwarf novae (e.g. SS Cyg) – dependence on the state of the long-term activity
- The analogies with Z-sources and outbursting dwarf novae suggest **synchrotron** emission of a jet.

Kording et al. (2011)

Intermediate polars

(role of acceleration of particles in the magnetosphere of a rapidly spinning white dwarf)

Structure of the accretion flow in intermediate polar



From Ghosh & Lamb (1978), Warner (1995)

Accretion flow is controlled by the magnetic field of the white dwarf inside the magnetosphere

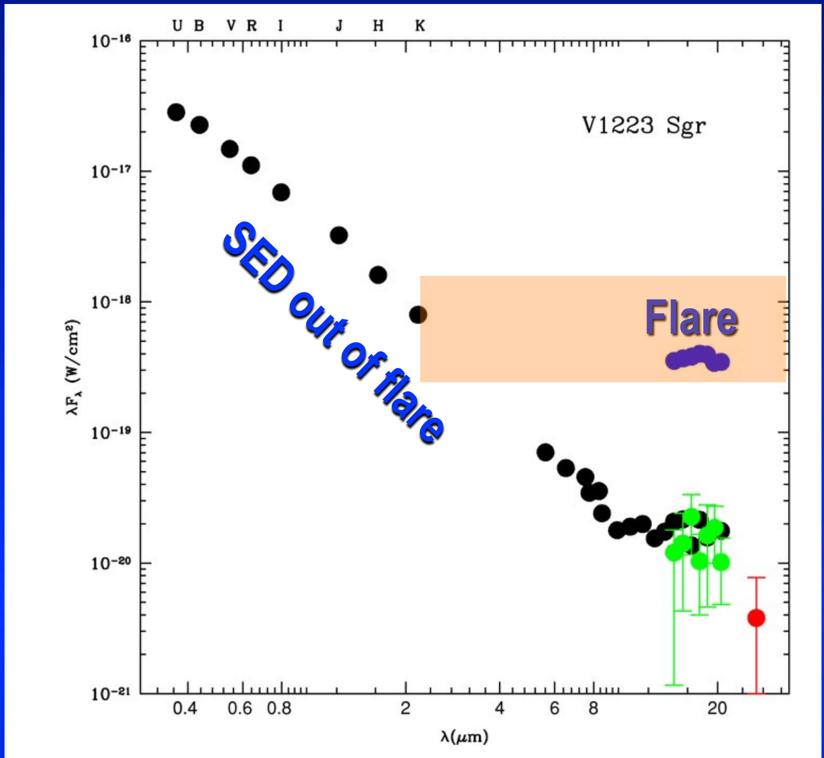
↓

Accretion onto the magnetic poles of the WD

Sources of the accelerated particles:

- strongly magnetized turbulent region at the accretion disk inner radius (Bednarek & Pabich (2010, 2011)
- the propeller mechanism (e.g. Illarionov & Siuniaev 1975)

Flares in intermediate polars – V1223 Sgr / 1H 1853–312

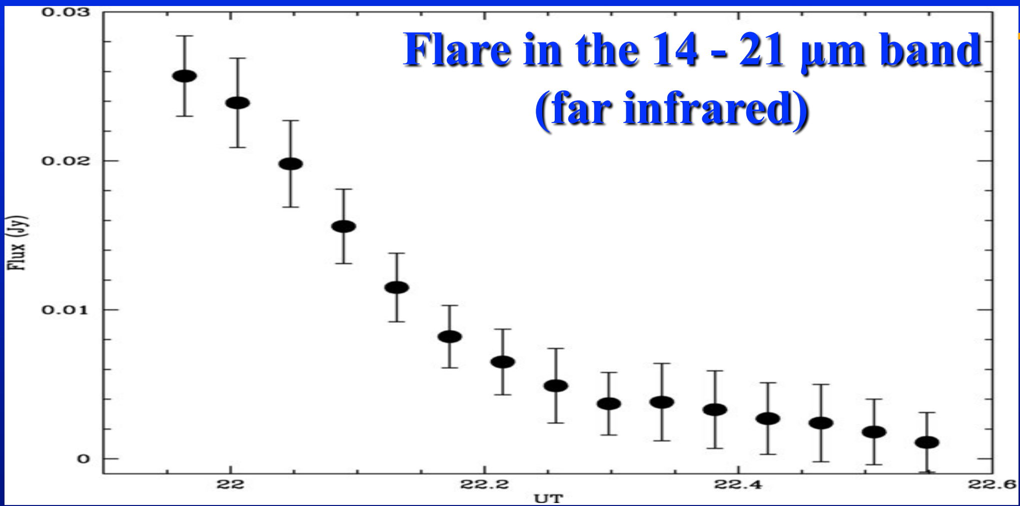


Data in the far-IR band: Spitzer satellite

Extrapolation of the flux of the flare (very flat SYNCHROTRON spectrum) from far IR to the optical band cannot explain the sometimes observed optical flares

Possibilities:

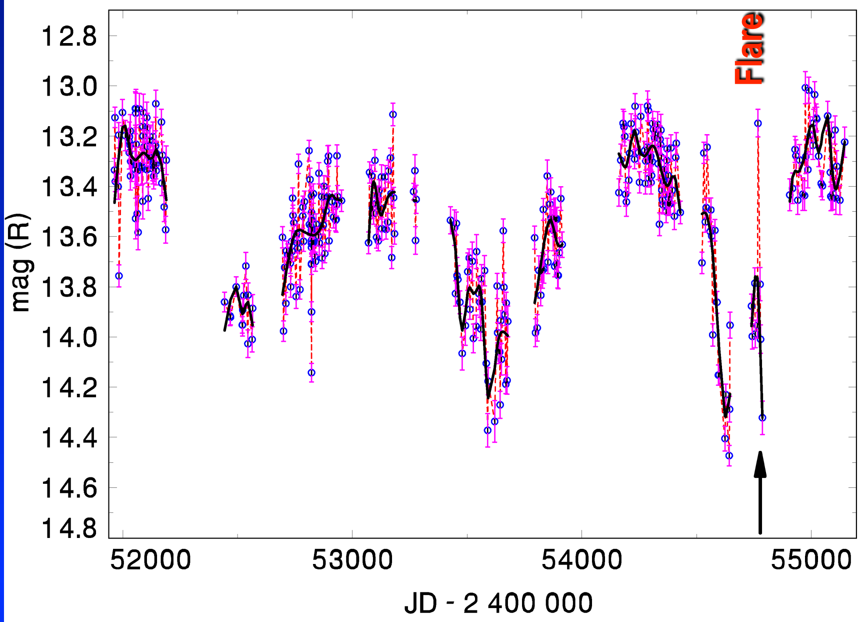
- Interaction of the inner disk region with the synchrotron jet
- Extremely strong synchrotron flares

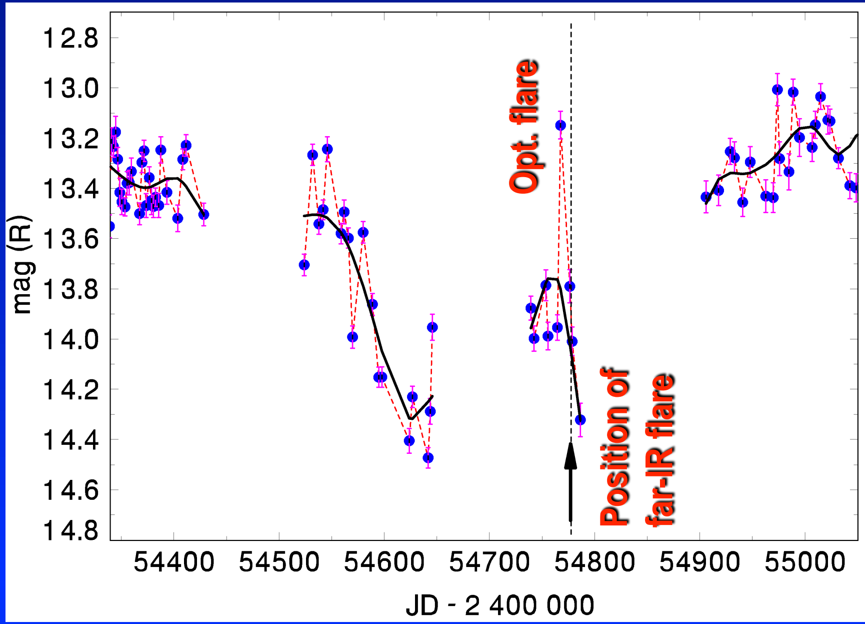


Flux declined by a factor of 13 in 30 minutes.
Transient SYNCHROTRON emission of the flare

Harrison et al. (2010)

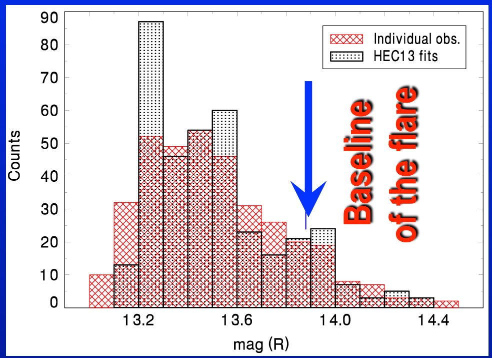
Flares in intermediate polars – V1223 Sgr / 1H 1853–312





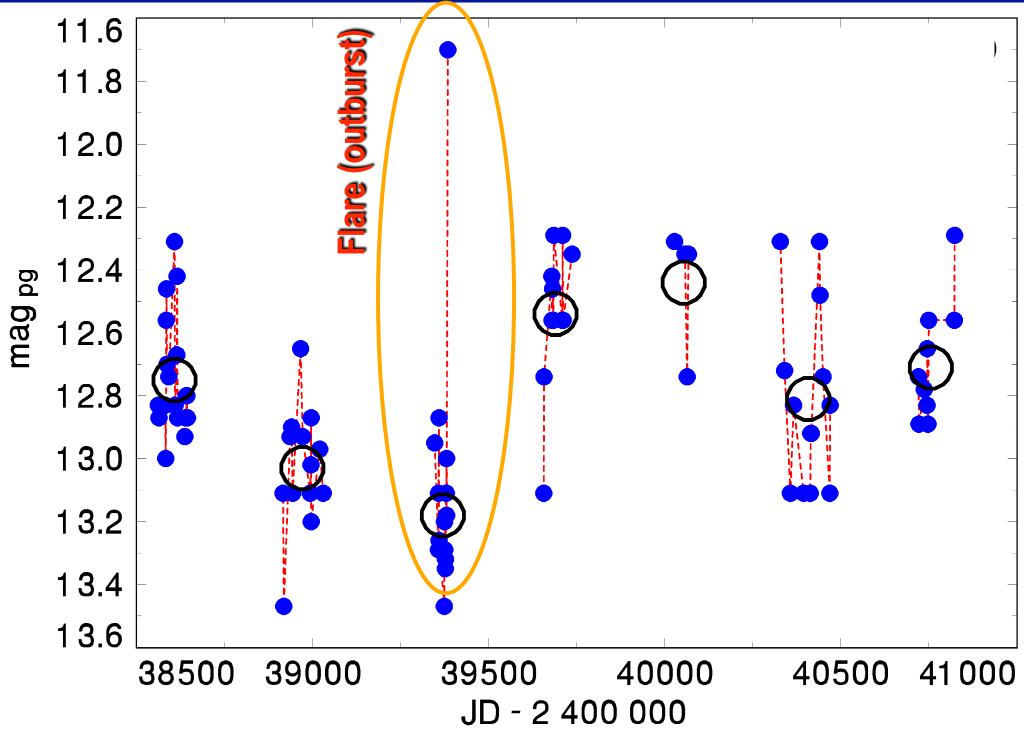
Long-term optical activity. ASAS data (one CCD image per night)

- Position of the synchrotron flare (Spitzer): <u>shallow low state</u>
- Synchrotron flare (Spitzer) close to an optical flare
- A cluster of flares in a given shallow low state is likely (the observed optical and far-IR flares are not quite simultaneous)

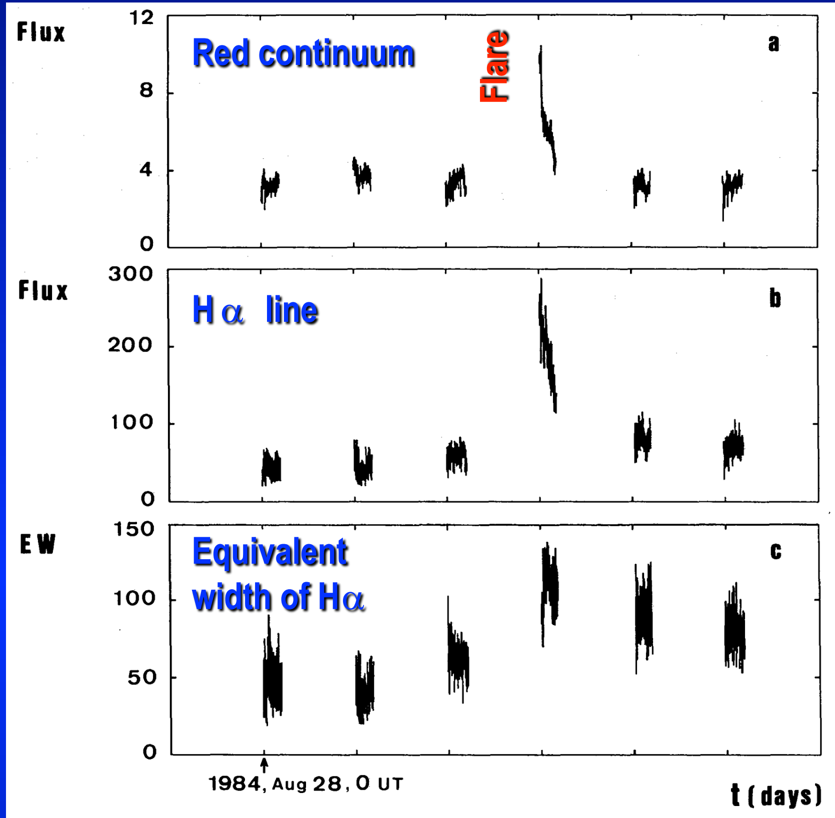


- Shallow low state creates suitable conditions for the flares (increase of the Alfven radius, inner disk region therefore closer to the propeller regime?)

Flares in intermediate polars – V1223 Sgr / 1H 1853–312



Bamberg photographic plates (one plate per night) (blue light) (the 1960's)



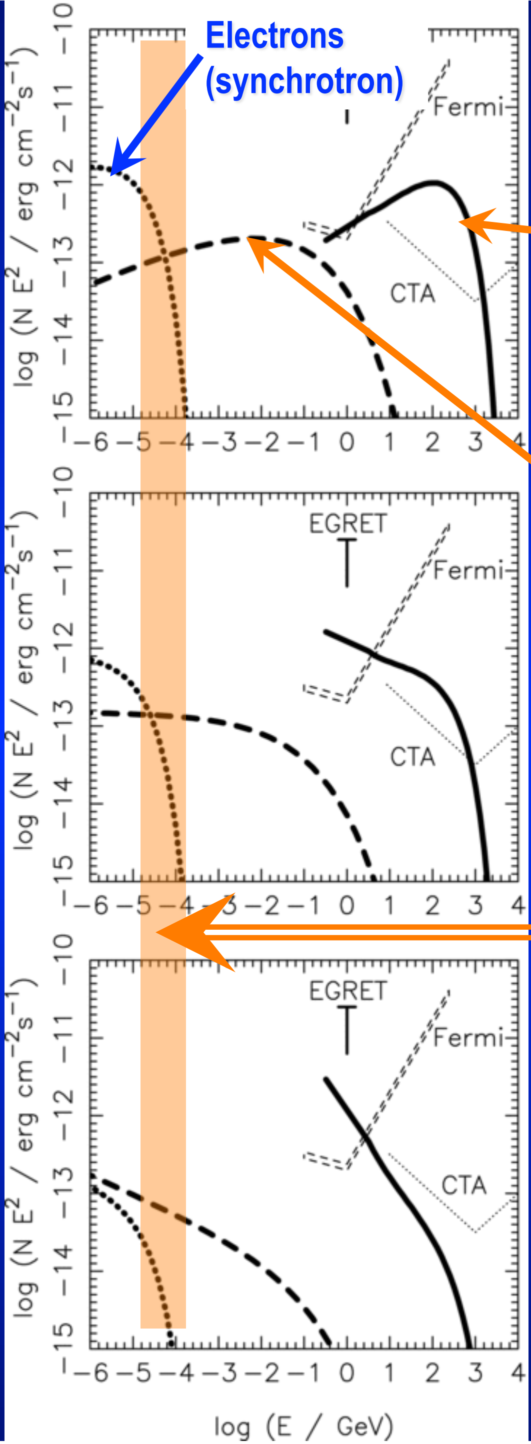
This event occurred during a shallow low state, but still from the level by several magnitudes brighter than the true low states observed in this CV.

Simon (2011)

Flare is longer in the Hα line than in the continuum – also the line emission therefore participated in this event (1984)

Amerongen & van Paradijs (1989)

Predictions of non-thermal emission–V1223 Sgr
* Model *



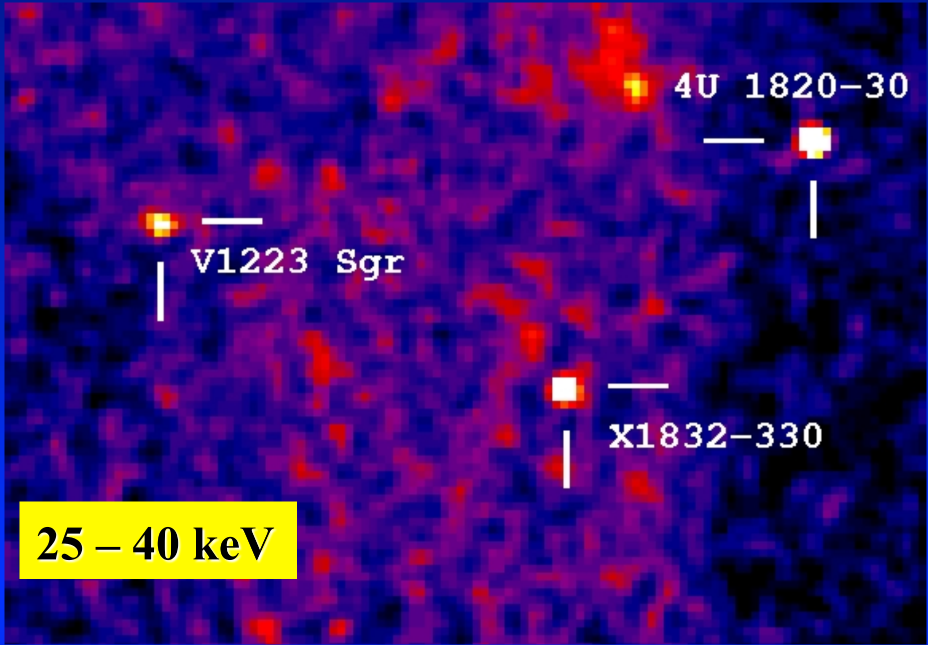
- Spectra of the non-thermal contribution to the X-ray and gamma-ray emission
- Source of the accelerated particles: strongly magnetized turbulent region at the accretion disk inner radius
- Accelerated electrons – source of synchrotron emission
- Accelerated hadrons – convected onto the WD surface and interact with dense matter

– gamma-rays from decay of neutral pions

– secondary leptons from decay of charged pions

Bednarek & Pabich (2010, 2011)

Predictions of non-thermal emission –V1223 Sgr …and observations

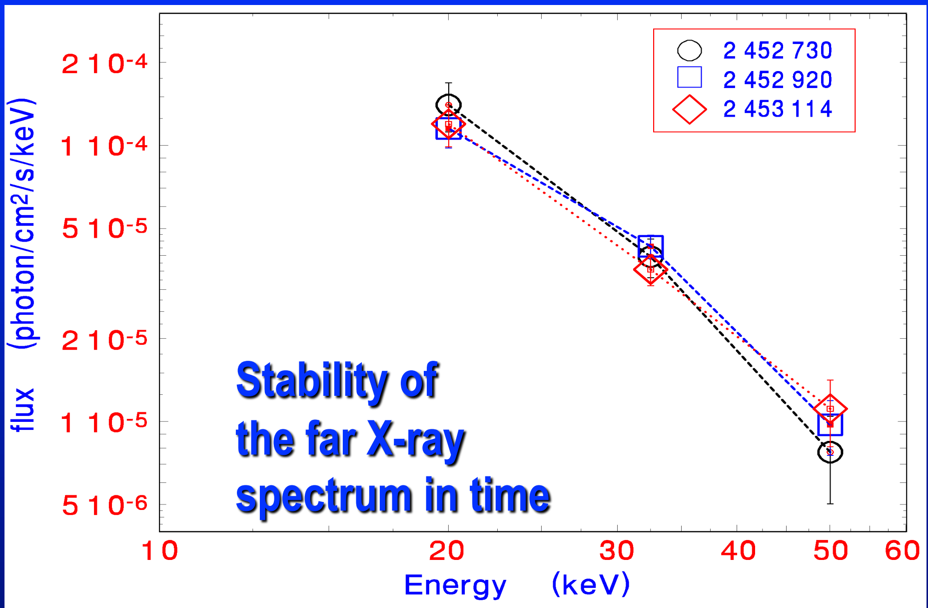


Co-added frames: IBIS/INTEGRAL
Start exp. JD 2452730.17
Exp. time: 66 700 s. Field: 9.1°x7.1°

A very hard X-ray source among CVs – detecting up to *E* ~ 80 keV is possible

Real possibility to search for a contribution of non-thermal emission in hard X-rays:

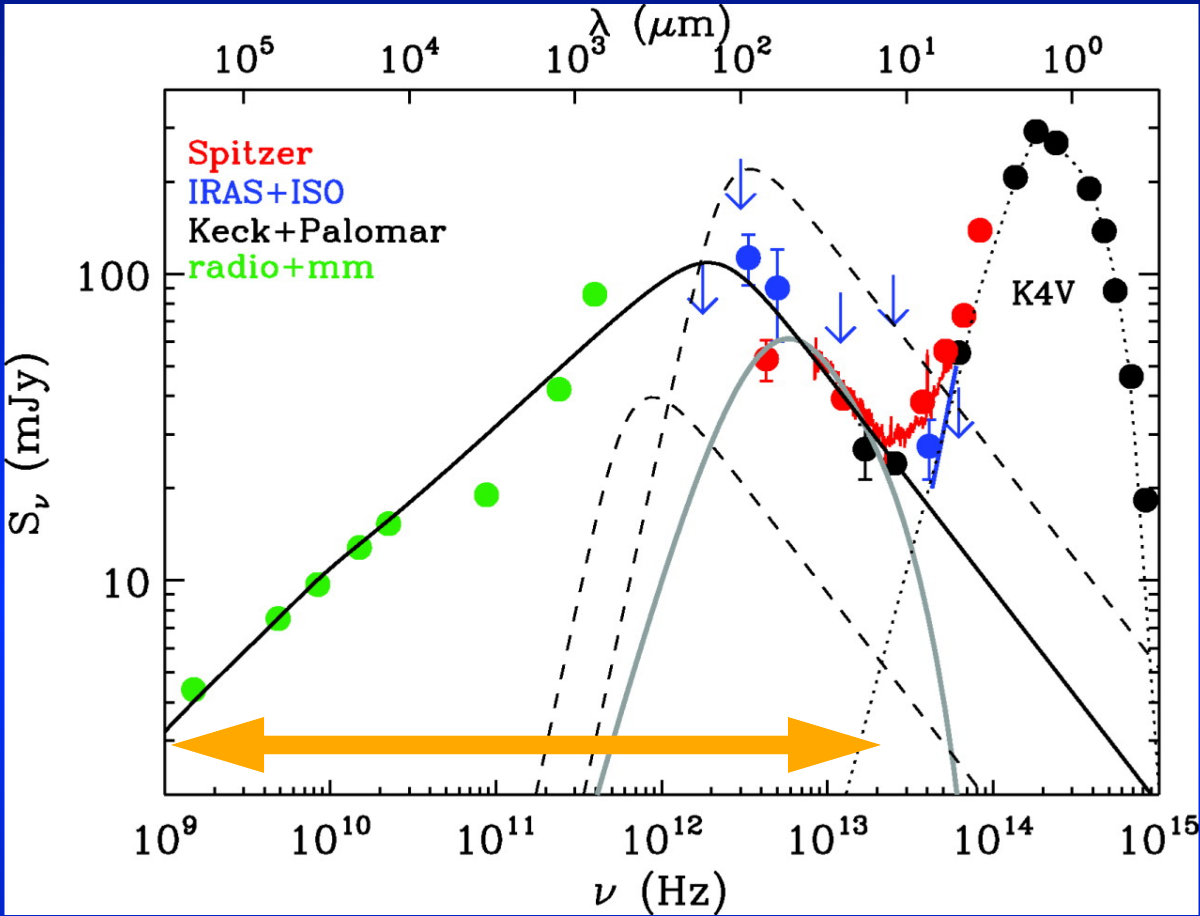
- search for a transient change of the profile (flattening?) of the bremsstrahlung emission

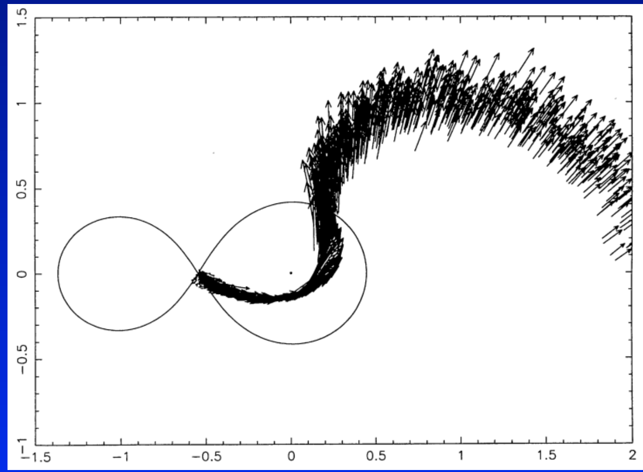


Bremsstrahlung spectrum as a baseline for the search:
Spectral profile in the 15 – 60 keV remains largely unchanged during ~ 400 days.

Simon et al. (2006)

AE Aqr / 1RXS J204009.4–005216 (int. polar in a propeller regime)





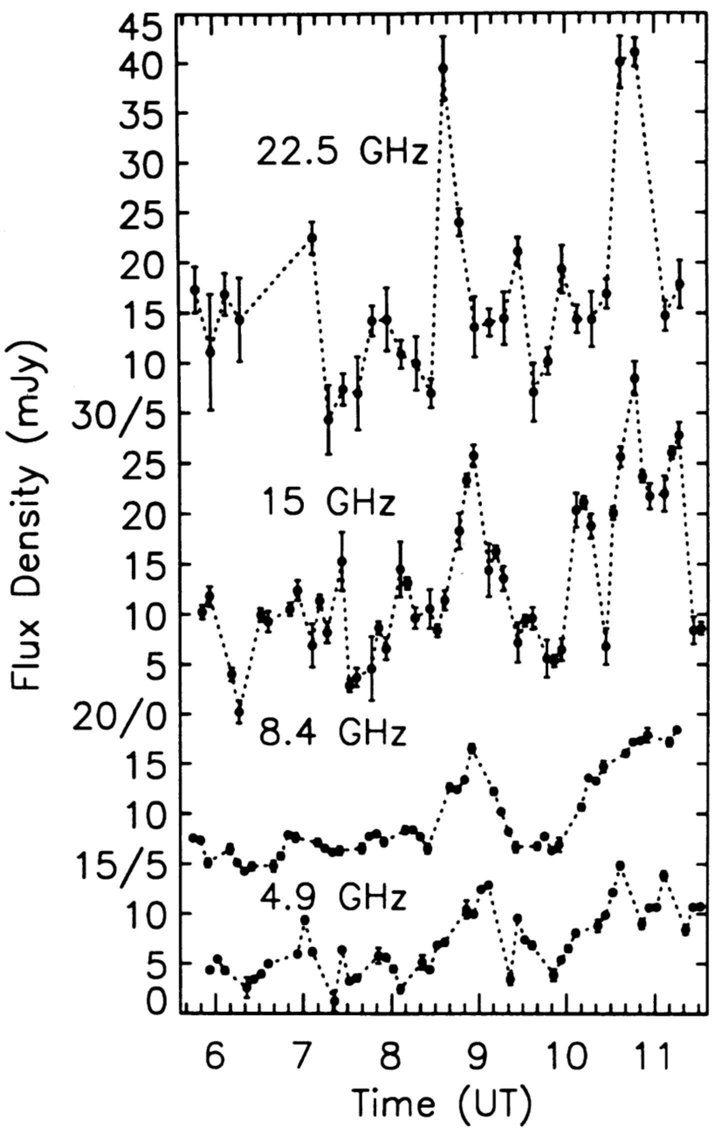
AE Aqr in a propeller regime. Most of the transferring matter is ejected by the rapidly spinning (33 s) magnetized WD (but some accretion onto it remains).

Wynn et al. (1997)

- A significant excess emission above the K4 V spectrum of the donor
- Far-infrared band (λ > 12.5 μm) – **synchrotron emission** from electrons in expanding clouds (initial evolutionary timescale of seconds)
- Contribution of thermal emission from cold circumbinary material possible for a specific disk temperature profile.

Dubus et al. (2007)

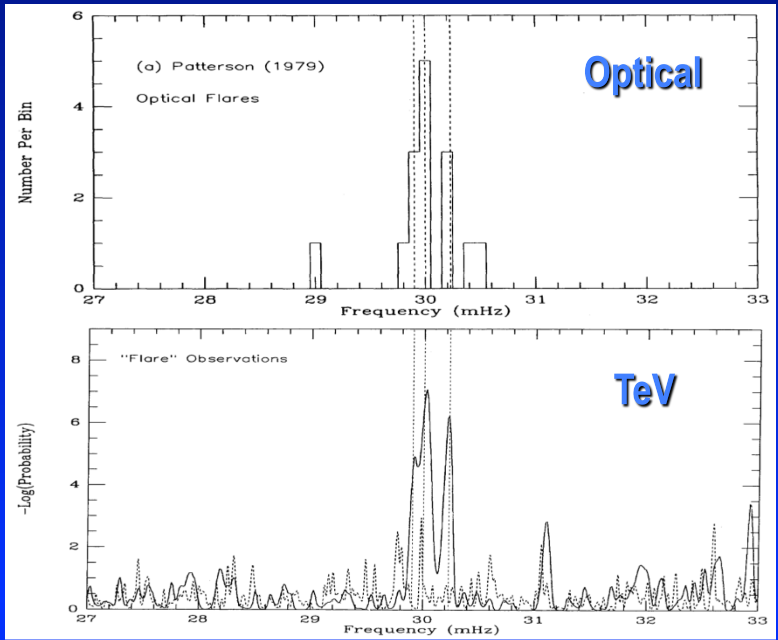
AE Aqr / 1RXS J204009.4–005216 – radio emission



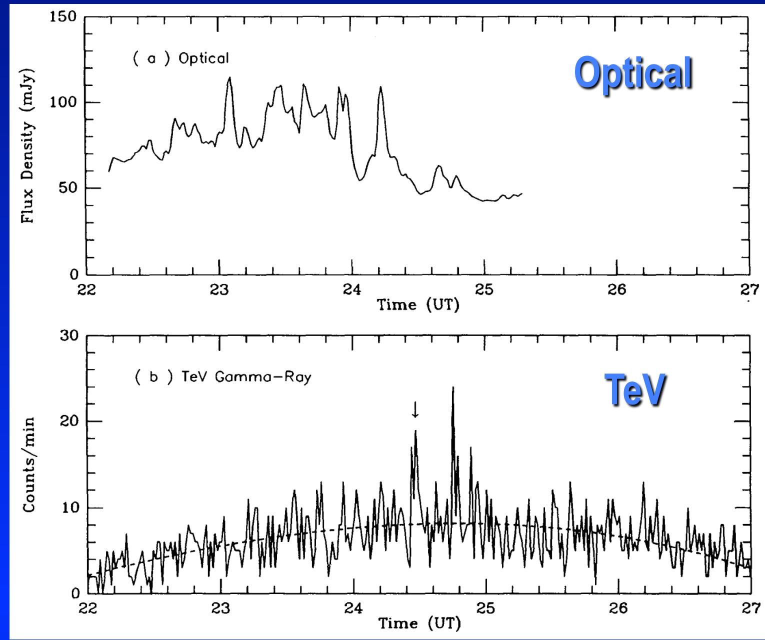
Bastian et al. (1988)
Kuijpers et al. (1997)
Abada-Simon et al. (1993, 1995)

- Superposition of discrete, synchrotron emitting flares from the vicinity of the WD (the strongest variability at the shortest λ)
- Flare – expanding plasmoid; spherical cloud of relativistic electrons which expands adiabatically
- Optical and radio flares are not strongly directed toward any preferred direction in the frame of the binary.
- Relation between the optical (thermal) and radio (synchrotron) emission:
  Part of matter of the blobs is trapped in the WD magnetosphere and these particles are accelerated – generation of the synchrotron emission (delayed) is a consequence of the blobs of transferring matter.

AE Aqr / 1RXS J204009.4–005216 – TeV emission



Optical and TeV flares occur at the same frequency (33 s spin period of the WD)



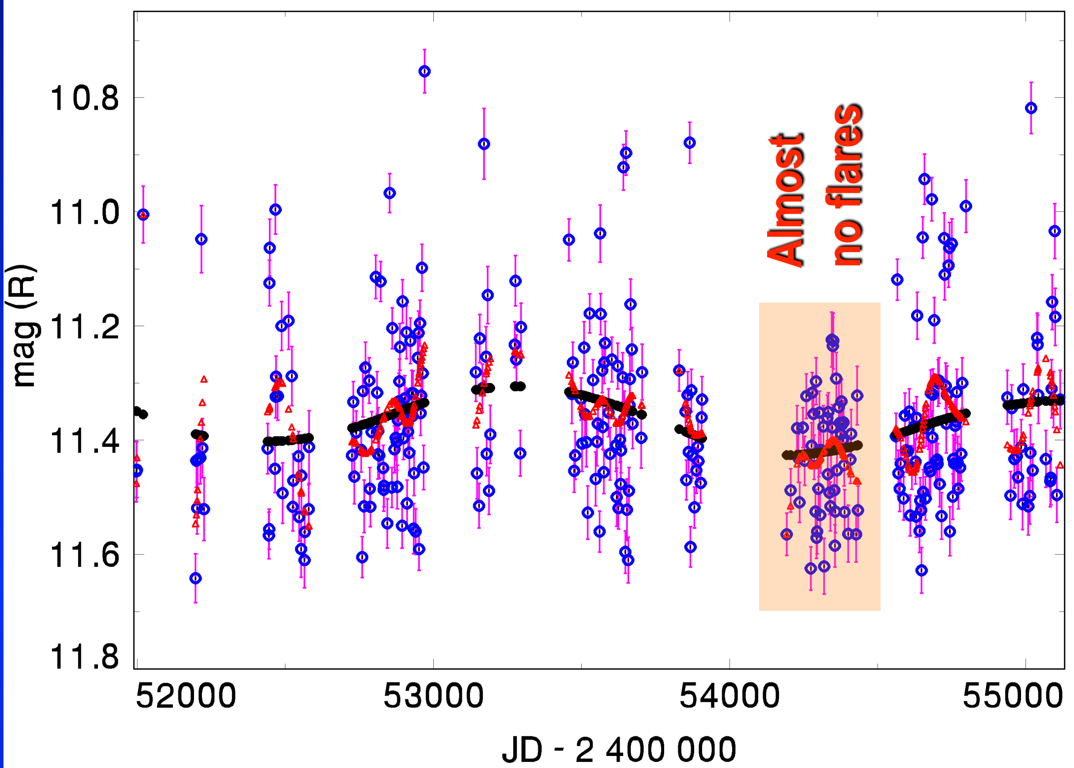
Relation between the state of the optical activity and TeV flare:
TeV emission occurs when the optical brightness is low

- Highly transient – TeV flares for only ~0.2 % of time
- Acceleration of particles by the rotating magnetic field of the WD in intermediate polars in the propeller regime – detected by ground-based Cherenkov telescopes in the TeV band
- TeV emission during a low optical brightness: the accretion luminosity must be low to allow the disk inner edge radius to be outside the co-rotation radius

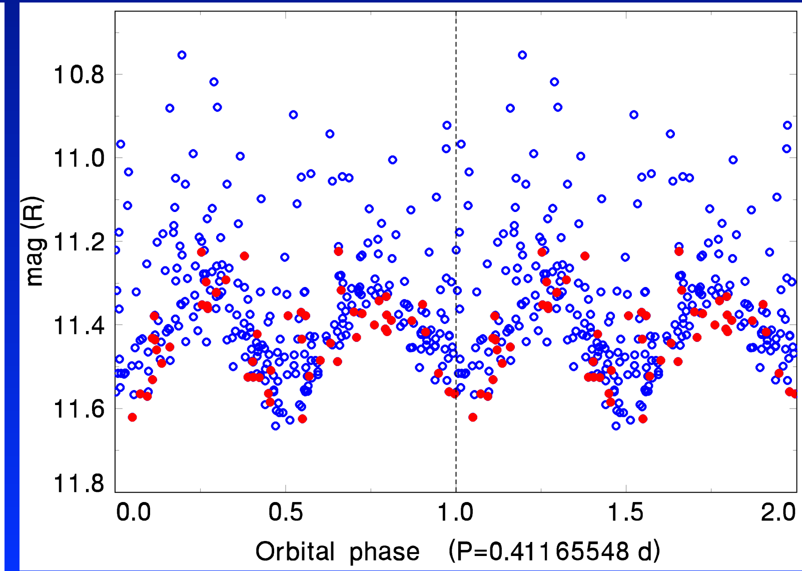
Meintjes et al. (1992, 1994)
Meintjes & de Jager (2000)

- Electrons are accelerated to E~10^{13} eV and converted to γ-rays via π^o decay in the blobs

AE Aqr / 1RXS J204009.4–005216 – long-term activity



Evolution of the mean level of the optical brightness



Orbital modulation:

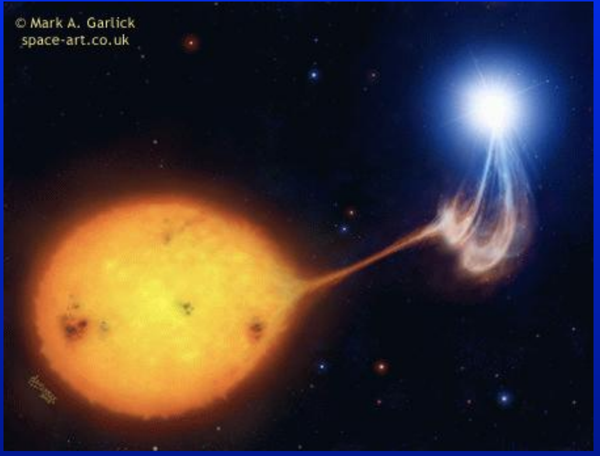
(a) Lower envelope – tidal deformation of the donor

(b) Flares – duration of minutes

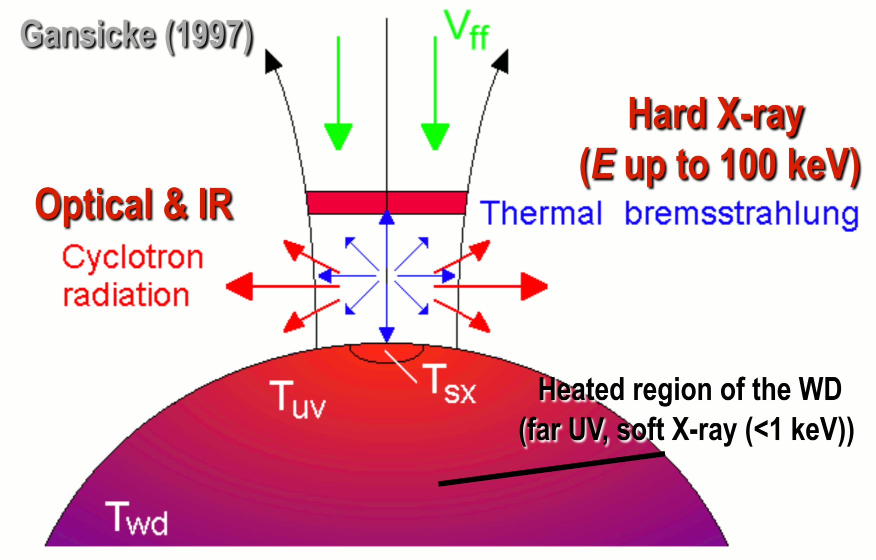
- The mean level of the optical brightness varies on the timescale of years.
- More numerous flares lead to a higher optical brightness of the system.
- This evolution suggests a variable amount (and size?) of the blobs on this timescale – variable conditions for the generation of accelerated particles

Discless magnetic cataclysmics – polars

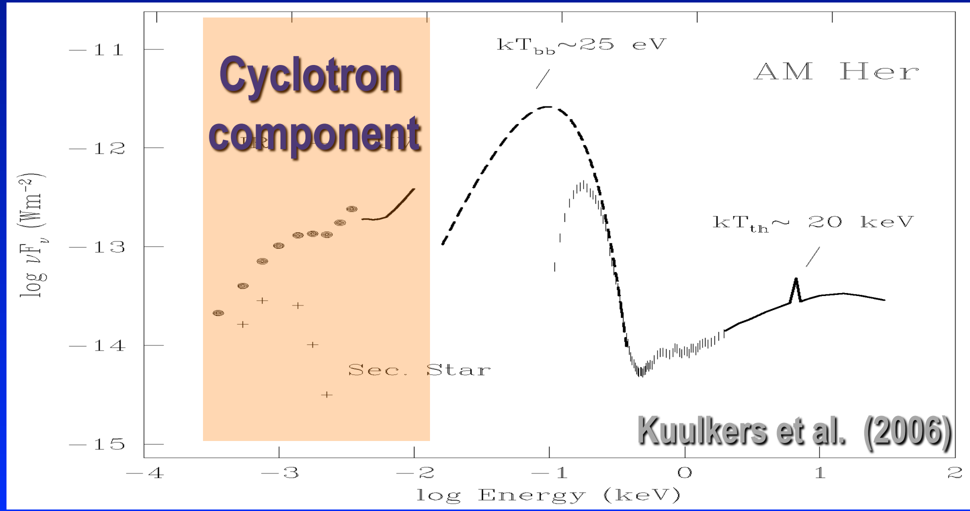
- Strongly magnetized white dwarf ($B \sim 10^9$ Gauss)
- Accretion of matter directly onto the region(s) of the magnetic pole(s)



Structure of the accretion region in polar



Schematic view of the accretion region at the magnetic pole of the WD



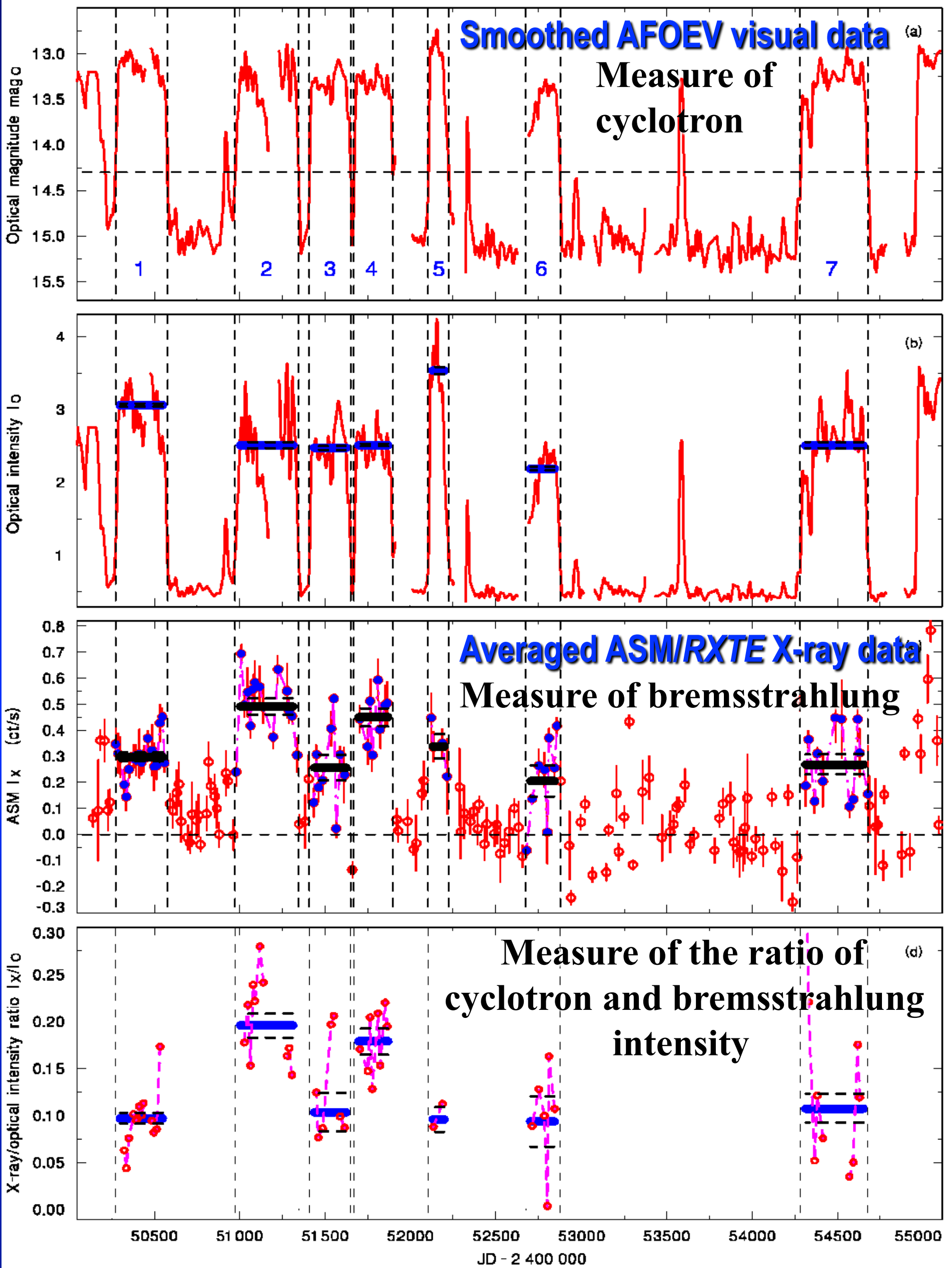
Spectral energy distribution – the result of several processes operating in the accretion region

A small region (~0.1 WD radius) near the magnetic pole of the white dwarf – source of radiation via several processes:

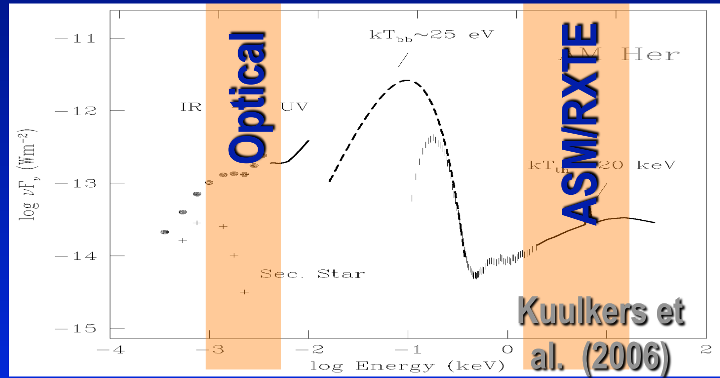
- cyclotron (mainly optical and IR emission)
- thermal (heated surface of the WD)
- bremsstrahlung

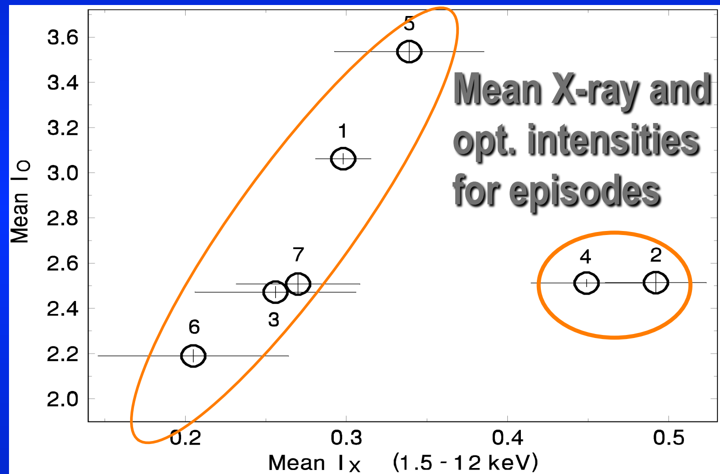
The total flux emitted by this region is the sum of the emissions generated by all these three processes – the conditions in this region and the mass accretion rate play the key role

AM Her / 3A 1815+498 (polar)



Relation between the optical and X-ray light curves in the individual high-state episodes. Only the HEC13 fits are shown for the optical data. Simon (2011)



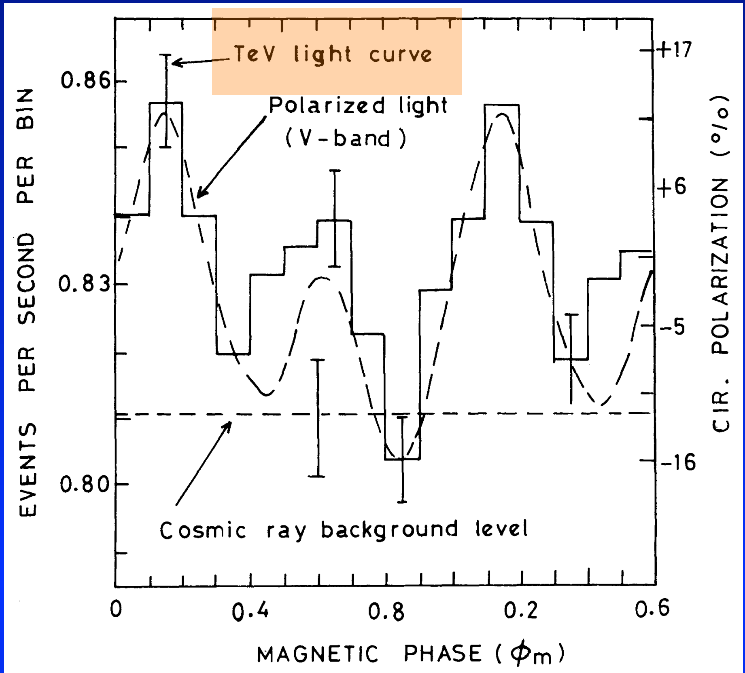


- Relation between the intensity of emission of two different processes operating in the accretion region(s) on the white dwarf in a given episode:
  - Optical – dominant cyclotron emission
  - Hard X-ray – bremsstrahlung emission

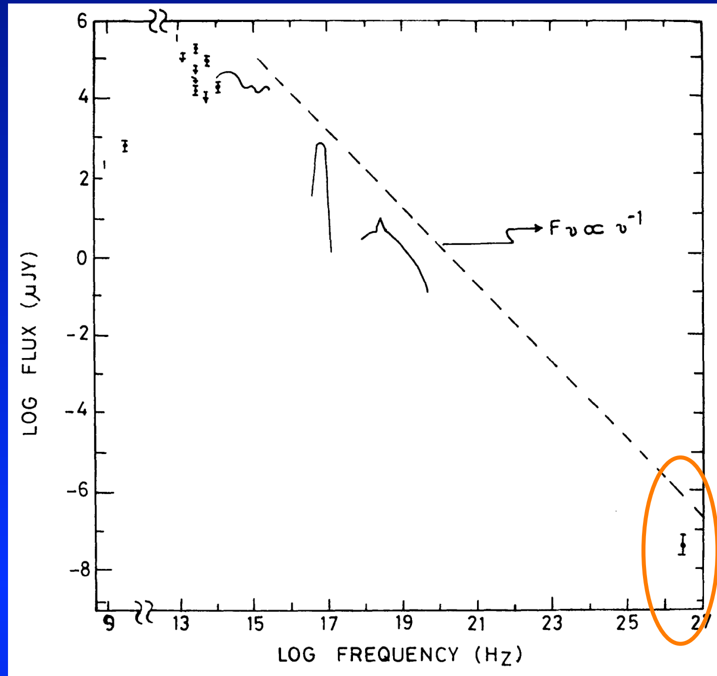
- Properties of the emitting region(s) on the WD are established in the start of the high-state episode.

AM Her / 3A 1815+498 – TeV emission

Bhat et al. (1991)



Comparison of the TeV light curve with the time evolution of the polarized optical light (folded with the orbital period).



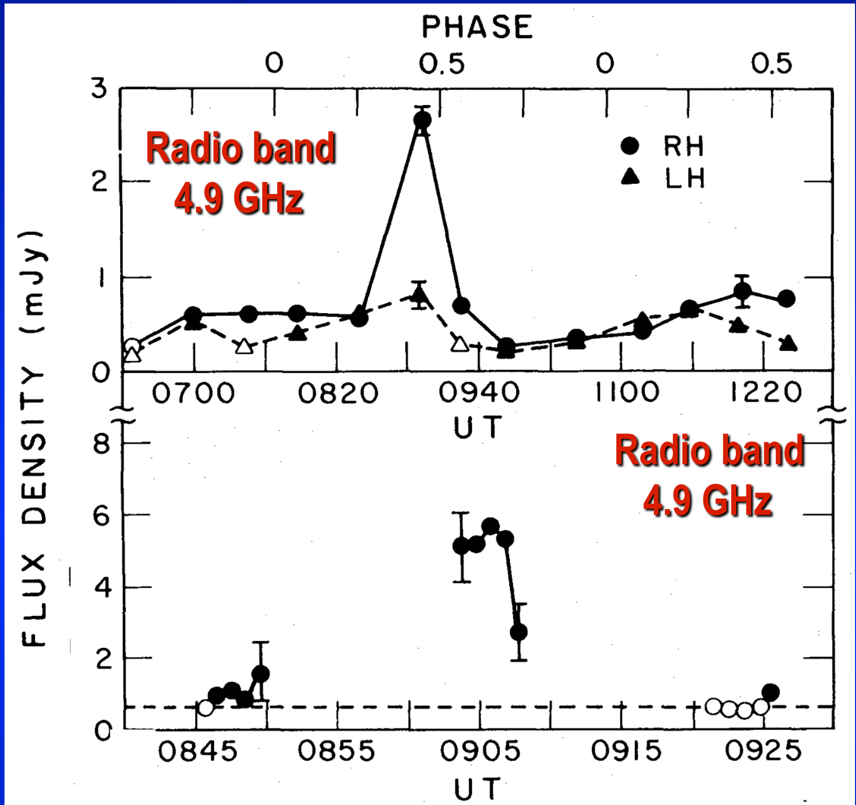
Spectral energy distribution from infrared to TeV. High state of the long-term activity.

Method of confirmation that TeV emission really comes from the observed object (i.e. argument against spurious detection):
– correlate the time variations of its intensity with some period specific for this object

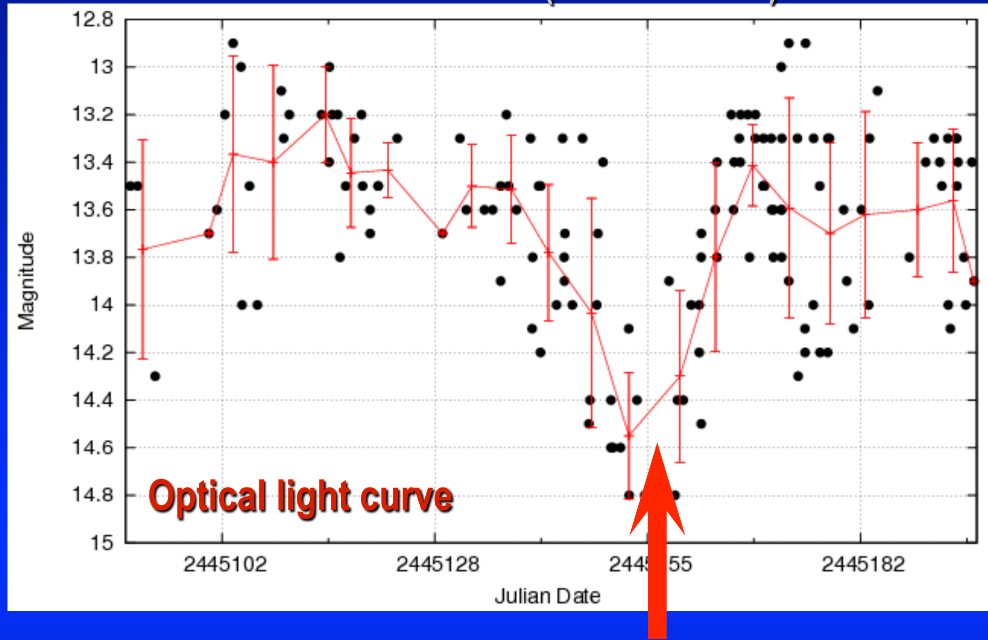
- Intensity of TeV emission is strongly modulated with the orbital period of AM Her – strong evidence that this gamma-ray emission really comes from this object

Radio emission from AM Her (polar)

Dulk et al. (1983)



AAVSO database (Henden 2011)



Position of the radio flare
in the optical low state

- **Several sites of radio emission existed in the same time:**

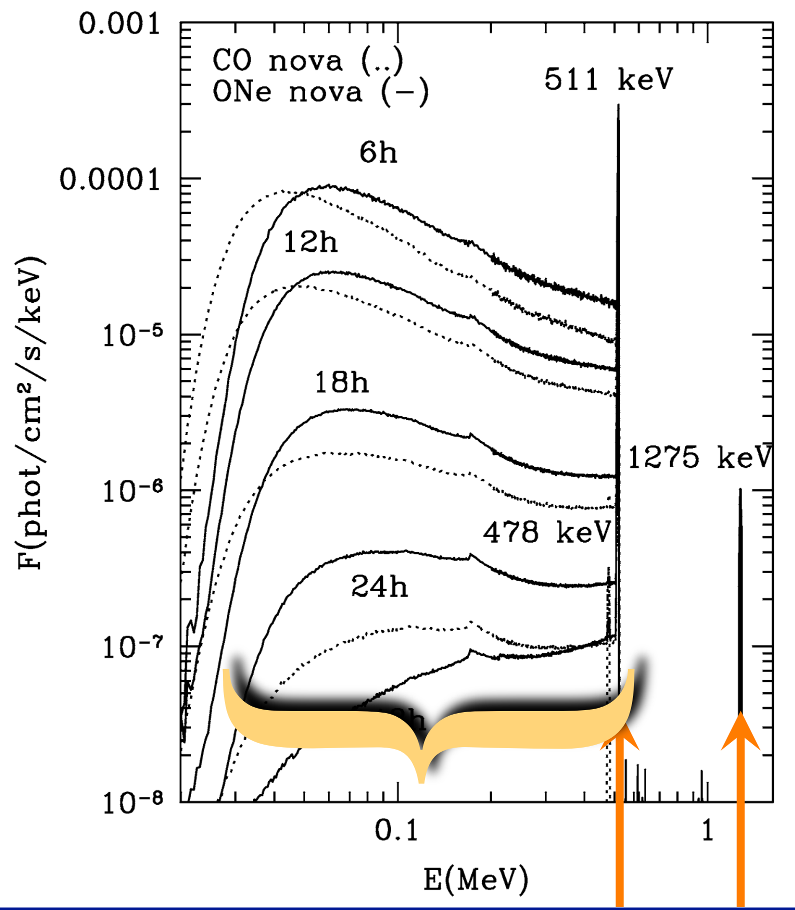
- Quiescent radio emission: Energetic electrons trapped in the magnetosphere of the WD

- Radio outburst (flare): Electron-cyclotron maser near the surface of the late-type donor (corona and the magnetic field (~1000 gauss) of the donor)

Outbursts of classical novae

Nucleosynthesis during nova outburst

Outburst of classical nova – thermonuclear runaway in the accreted matter on the surface of the white dwarf



Early temporal evolution of gamma-ray spectrum during nova outburst

Isotope	Lifetime	Emission	Process
^{13}N	862 s	511 keV & cont.	β^+-decay
^{18}F	158 min	511 keV & cont.	β^+-decay
^{7}Be	77 days	478 keV	e^--capture
^{22}Na	3.75 years	1275 & 511 keV	β^+-decay
^{26}Al	10^6 years	1809 & 511 keV	β^+-decay

- Radioactive isotopes are synthetised during the thermonuclear runaway

⇓

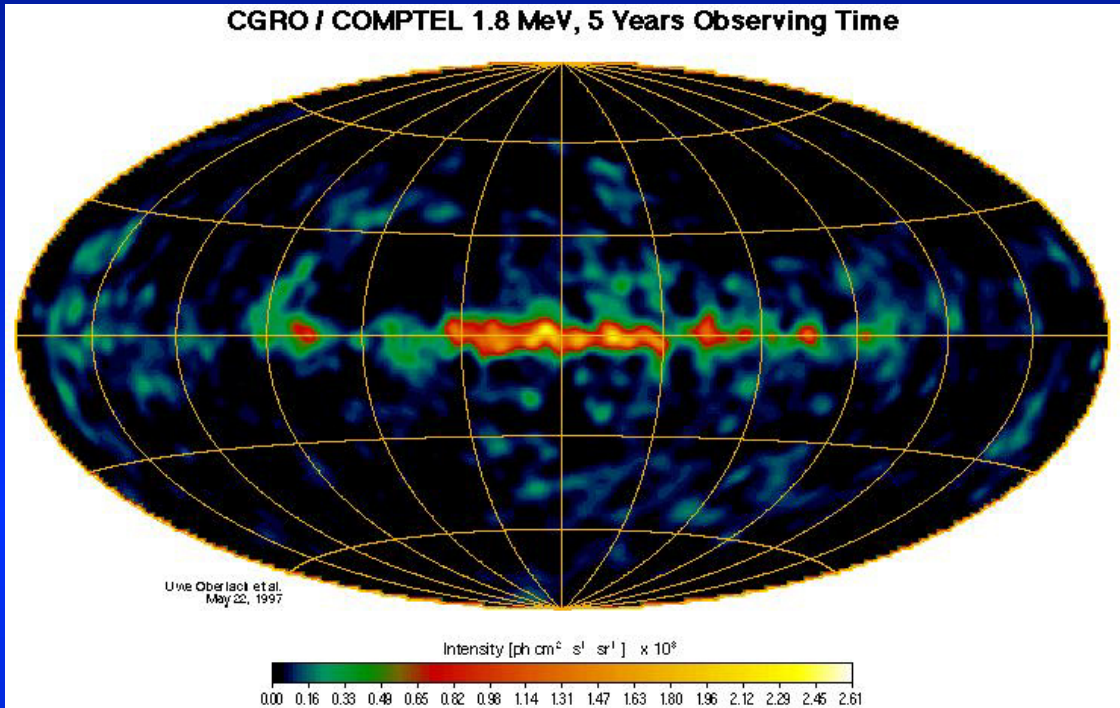
Gamma-ray emission during their decay

- Detection of gamma-rays strongly depends on the isotope's lifetime and on the optical depth in the ejecta

Hernanz & Jose (2005)

Products of nucleosynthesis in the Galaxy (I)

Gamma-ray line emission of ^{26}Al E = 1.809 MeV

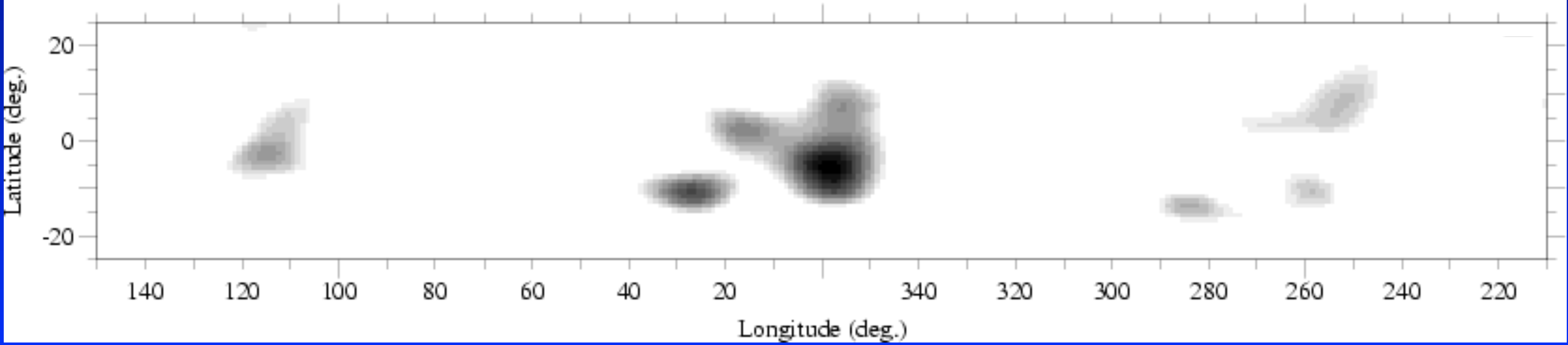


HEASARC

- Cumulative effect of the production of ^{26}Al in various types of sources and its ejection into the space (i.e. it does NOT come from a single source)
- ^{26}Al is concentrated toward the Galactic plane – it was produced by the objects located in our Galaxy
- Explosions of classical novae contribute about 15 percent (Jose et al. 2006)

Products of nucleosynthesis in the Galaxy (II)

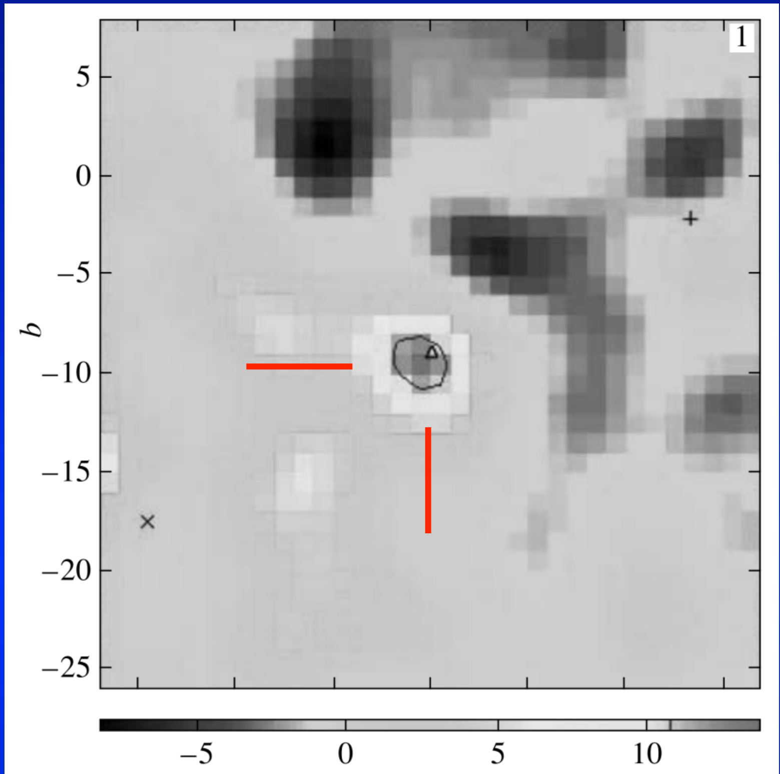
Distribution of the gamma-ray line emission of ^{22}Na E = 1.272 MeV in the Galaxy



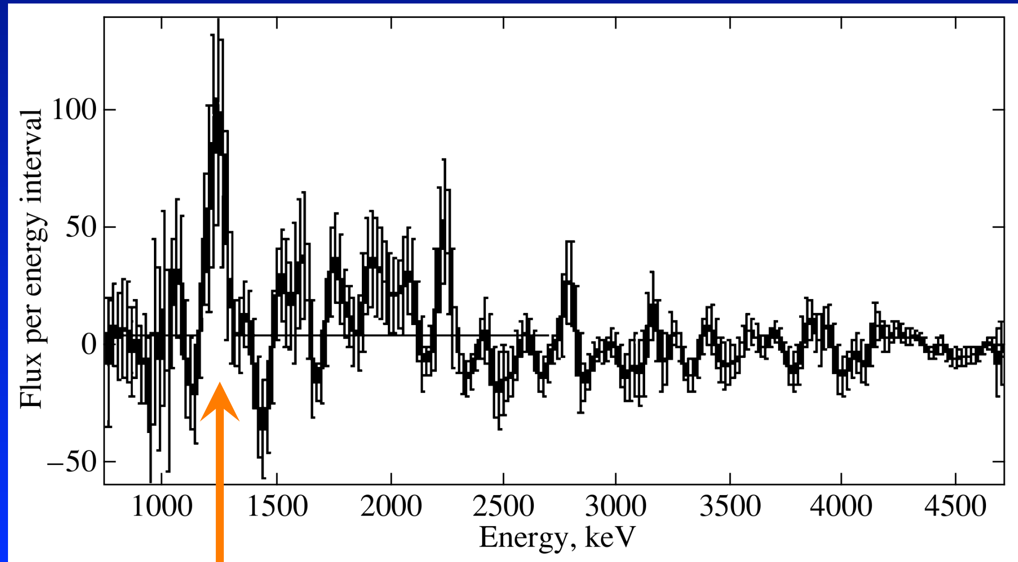
- Radioactive ^{22}Na: decay time scale 3.75 years
- Cumulative effect of the production of ^{22}Na in various types of sources and processes (COMPTEL / CGRO data)
- ^{22}Na is concentrated toward the Galactic bulge
- Outbursts of classical novae (Neon-type) contribute only partly – excitation of ^{22}Ne-nuclei, e.g. through the low-energy cosmic ray interactions with the nuclei of the interstellar matter, can dominate

Iyudin et al. (2005)

Nucleosynthesis during outburst – V723 Cas (Nova Cas 1995)



COMPTEL/CGRO field of Nova Cas 1995 (total integration time: ~4.5 years)

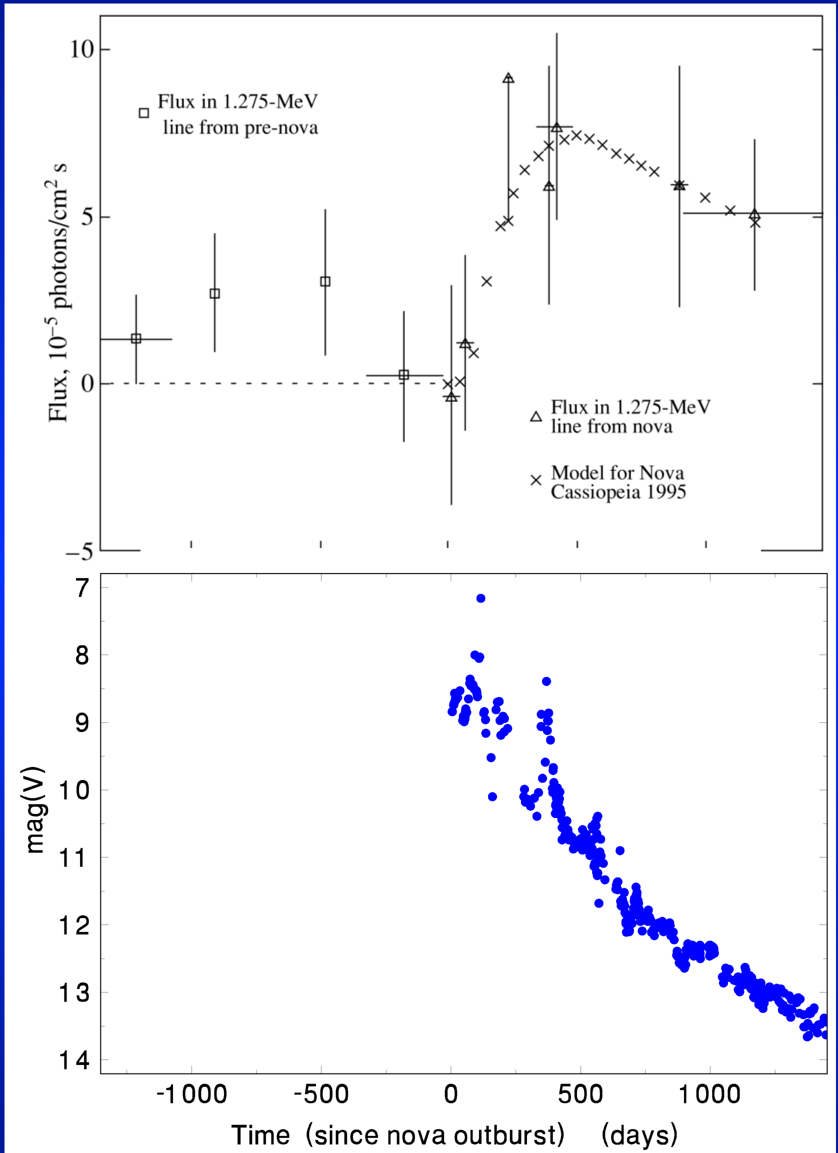


COMPTEL/CGRO spectrum from the position of Nova Cas 1995 and the fit. The ^{22}Na line (1.275 MeV) was detected at the ~4σ level.

Iyudin (2010)

- Direct detection of the gamma-ray line emission during outburst of the individual classical nova (evidence that classical novae contribute to the gamma-ray flux of ^{22}Na in the Galaxy)
- ^{22}Na was synthetized during thermonuclear reactions on the surface of the WD

Nucleosynthesis during outburst – V723 Cas (Nova Cas 1995)



Time evolution of the ^{22}Na gamma-ray line (1.275 MeV) flux and the optical magnitude.

Time evolution of the ^{22}Na gamma-ray flux is a combination of:

- the decreasing absorption of the gamma-ray flux in the ejecta
- time dependence of the undecayed ^{22}Na nuclei

Important properties needed for the detection of the ^{22}Na γ-ray flux:

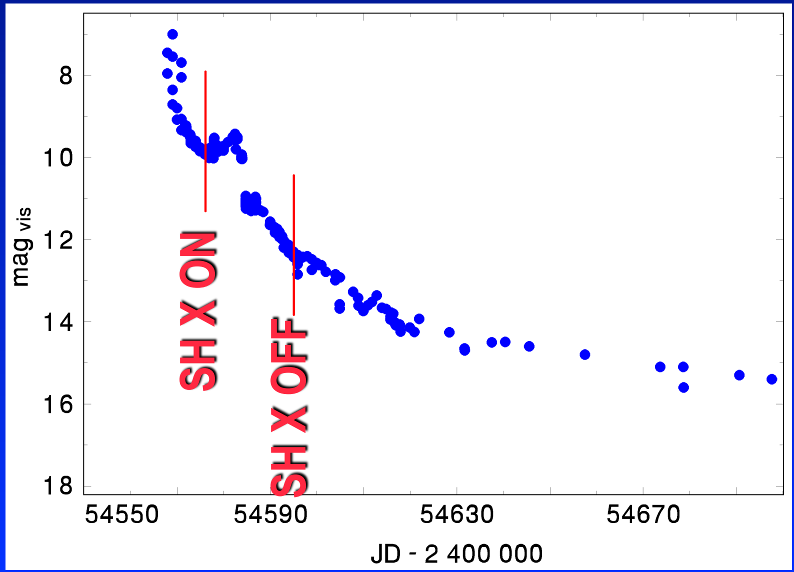
- Type of nova (slow nova)
- Massive ejected envelope
- Low mass of the WD (only 0.66 M_{sun})

↓

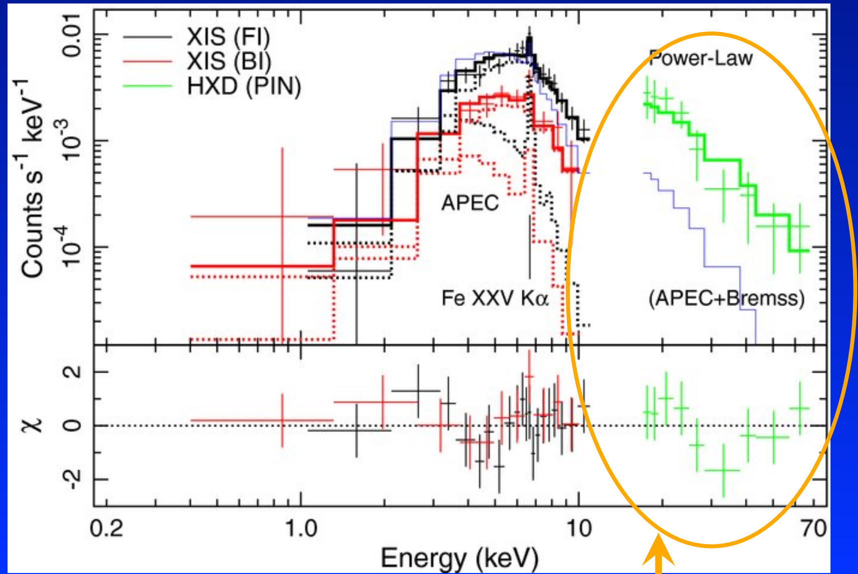
Necessary for the formation and preservation of ^{22}Na

Iyudin (2010)

Sign of accelerated electrons during outburst – V2491 Cyg



Time evolution of emission during outburst.
Superhard X-ray component: SH X



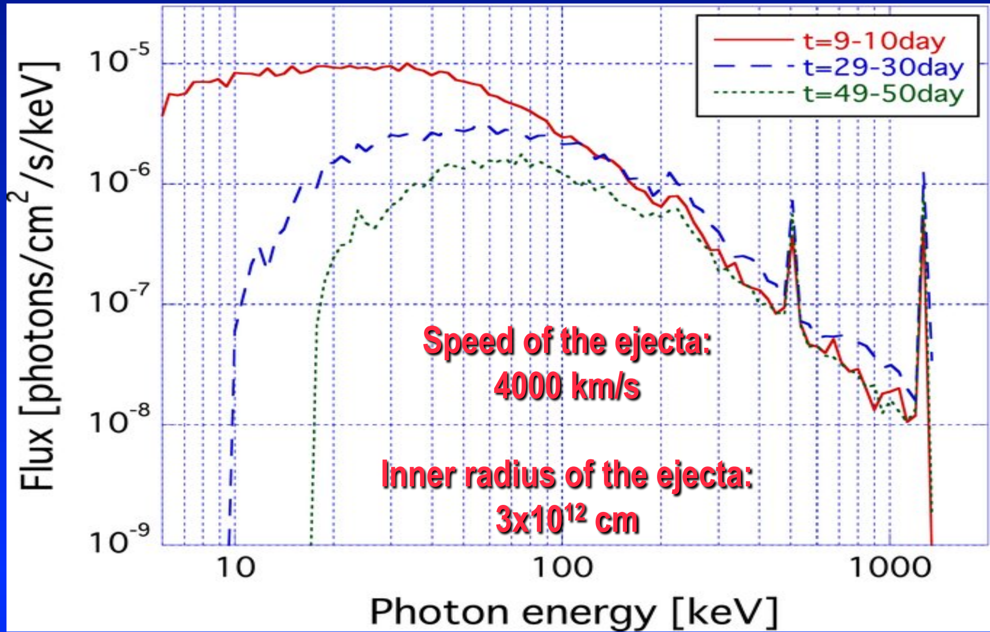
X-ray spectrum

Superhard component (SH X)

- **Detection of superhard (>10 keV) X-ray emission up to 70 keV (*Suzaku* satellite)**
- **9 days after the start of the outburst: power-law emission attenuated by a heavy extinction of 1.4×10^{23} cm^{-2} contributed**
- **The superhard emission decayed during outburst (it was not present on day 29)**
- **Nonthermal origin for the emission – the presence of accelerated population of electrons with a nonthermal energy distribution in the nova explosion.**

Takei et al. (2009)

Nucleosynthesis during outburst – Compton degradation



- **Explanation of the absence of the 1.275 MeV line of ^{22}Na and the extremely hard X-ray spectrum of V2491 Cyg in outburst:**

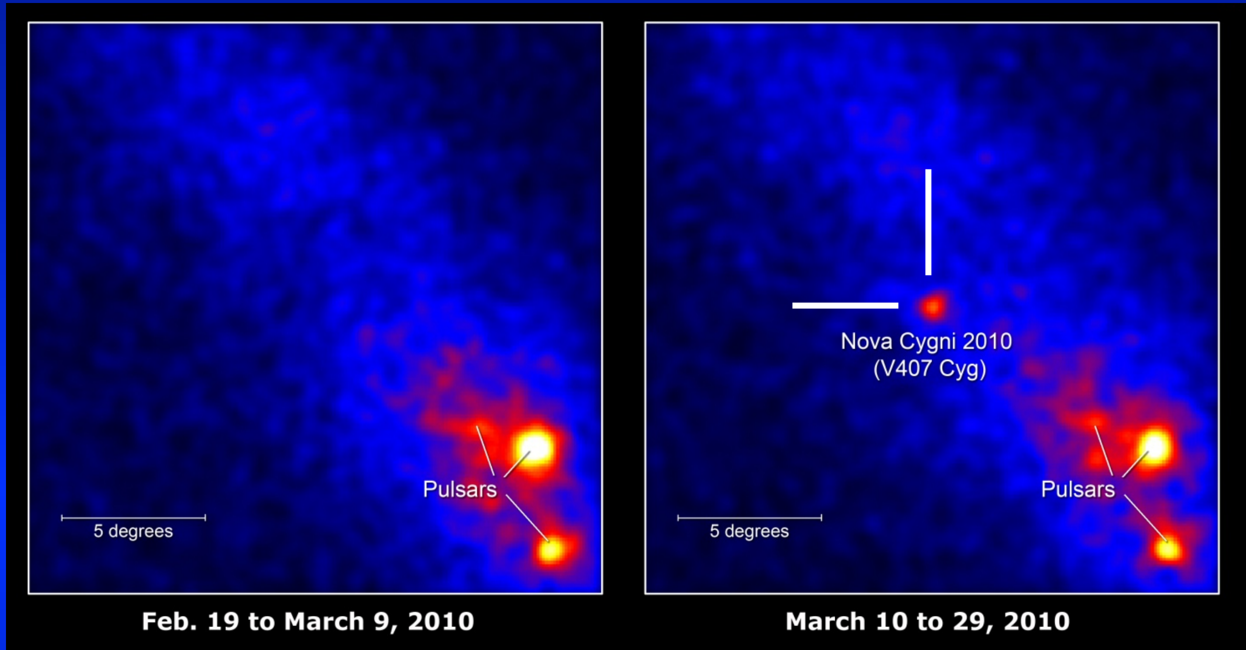
➤ Radiative transfer: repeated scattering of the gamma-ray photons by electrons in the matter (wind) ejected from a white dwarf

➤ The result of this Compton degradation: flat spectrum in the hard X-ray range

➤ The ejecta become transparent to the γ-ray photons within several tens days.

Suzuki & Shigeyama (2010)

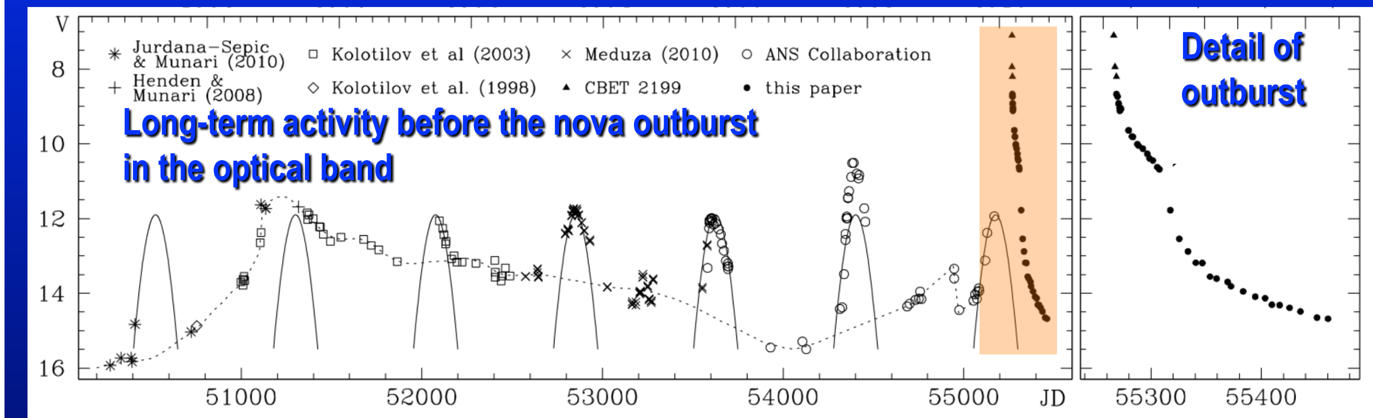
Gamma rays from the shock in classical nova outburst – the unique case of V407 Cyg (Nova Cyg 2010)



NASA Press Release

NASA/DOE/ Fermi LAT Collaboration

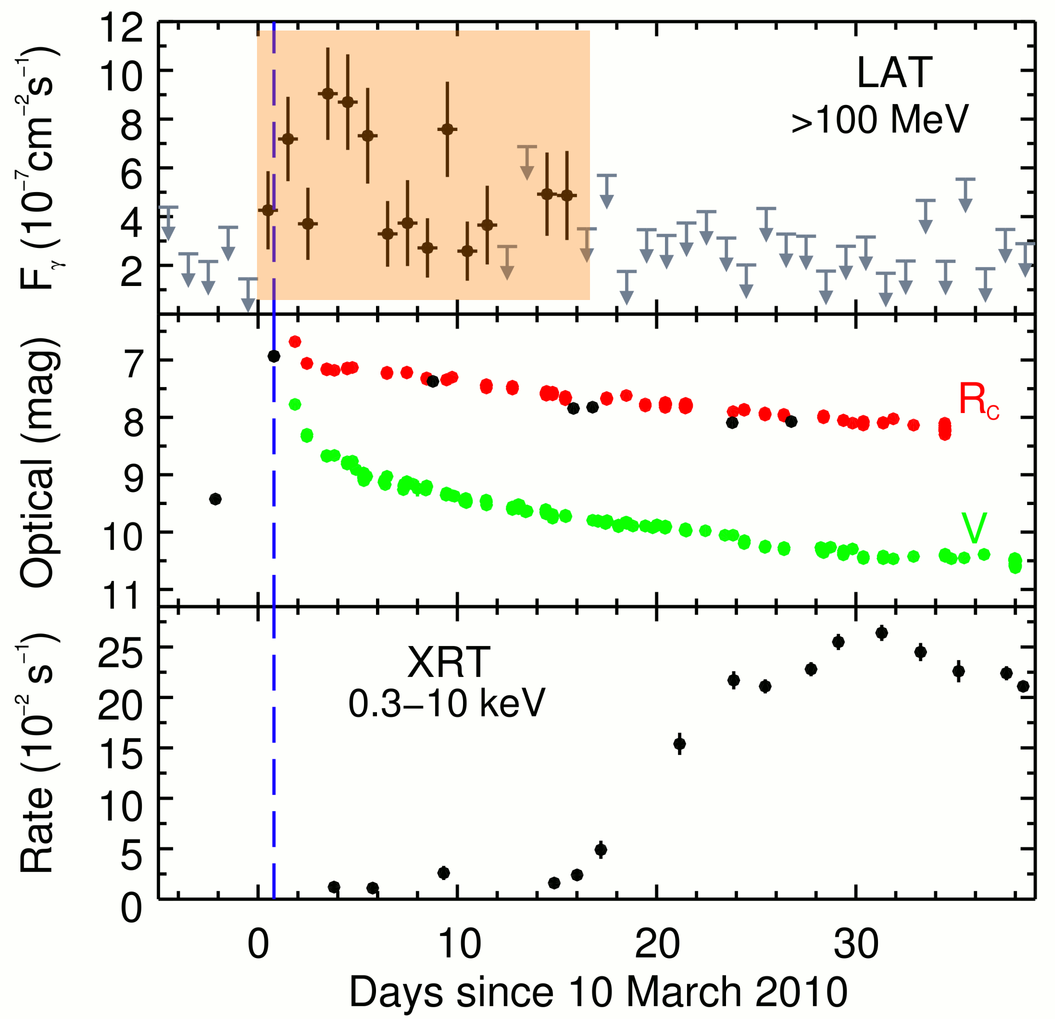
A new gamma-ray source – classical nova in outburst – detected by Fermi/LAT



- A very fast nova in the symbiotic binary
- The erupting WD deeply embedded in the dense wind of its cool giant companion

Munari et al. (2011)

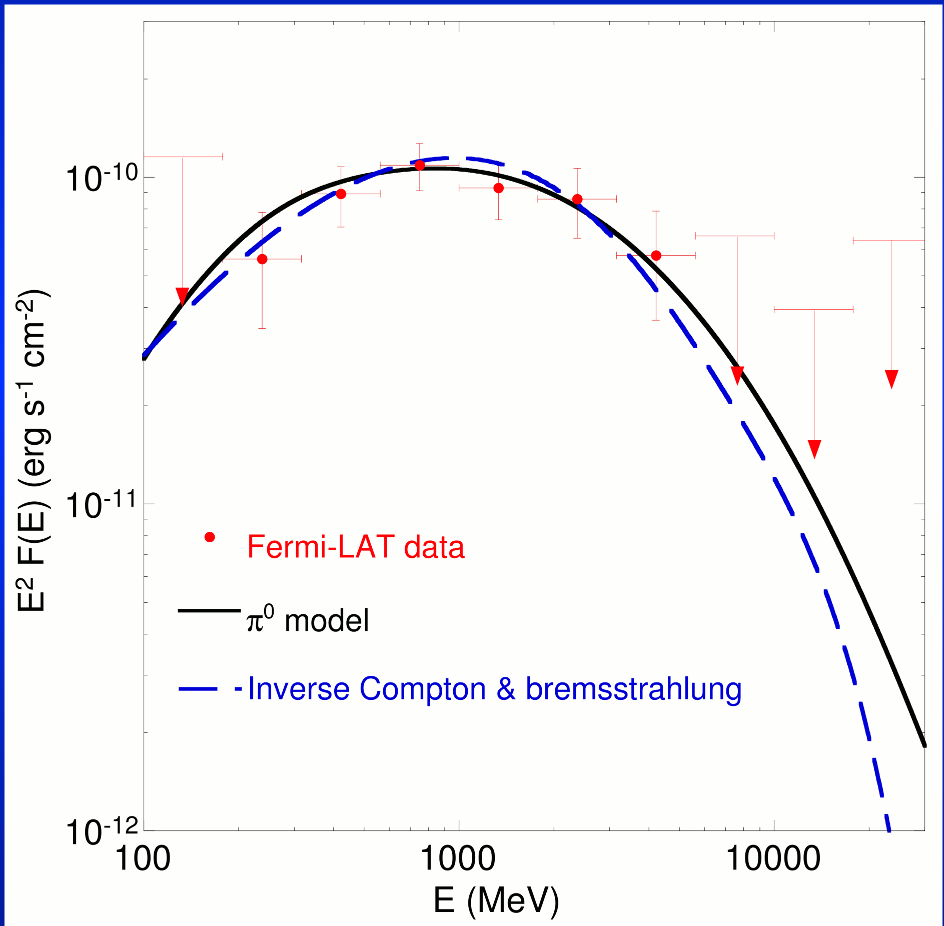
Gamma rays from the shock in classical nova outburst – the unique case of V407 Cyg



Abdo et al. (2010)

- Variable γ-ray emission (0.1-10 GeV) started with the rise of the optical luminosity of the outburst
- Material of the nova shell interacts with the dense ambient medium of the red giant donor
- Particles are accelerated by this interaction of the shell to produce π^0 decay γ-rays from proton-proton interactions
- Geometrical effect of the nova shell evolution in a dense environment of the symbiotic binary and its interaction with the wind of the donor (red giant)

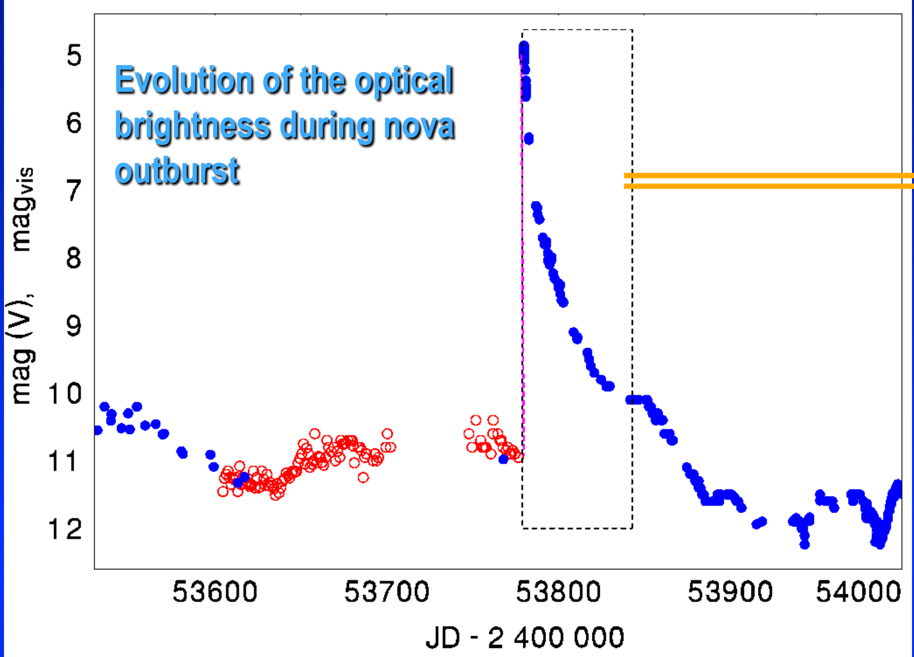
Gamma rays from the shock in classical nova outburst – the unique case of V407 Cyg

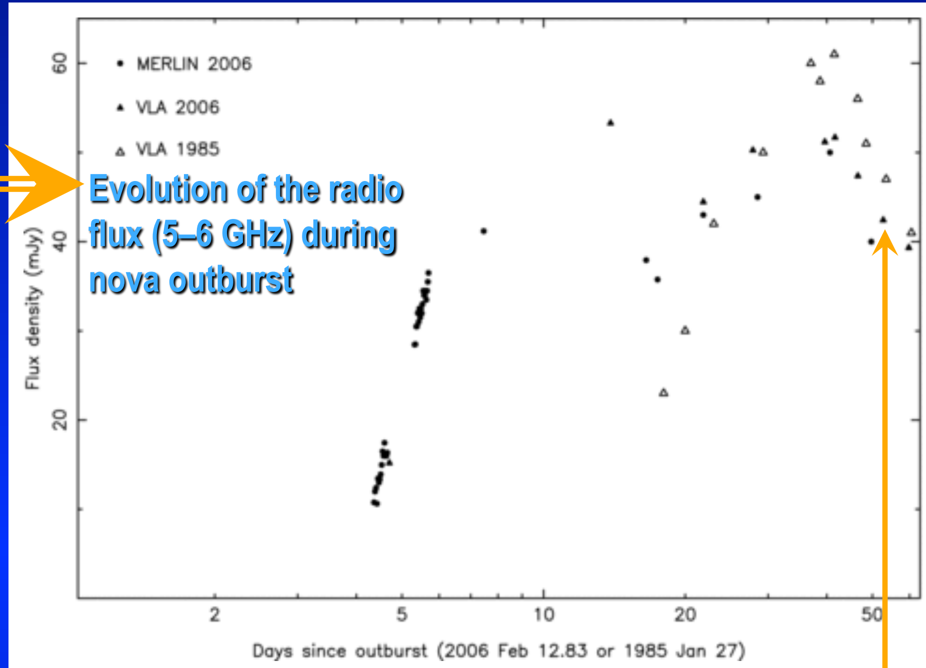


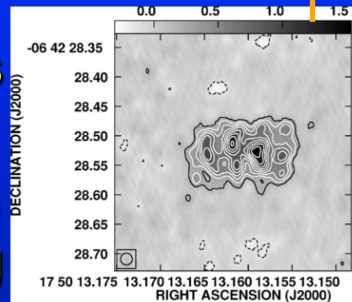
- **Spectral energy distribution over the period of 18 days**
- **Implications for the observability of such emission:**
  - ***Continuum emission (no lines)***
  - ***Duration of the event: several days***
- **No spectral variability over the duration of the active gamma-ray period**
- **Most gamma-rays come from the part of the nova shell approaching the red giant donor star**

Abdo et al. (2010)

Radio emission during nova outburst – RS Oph



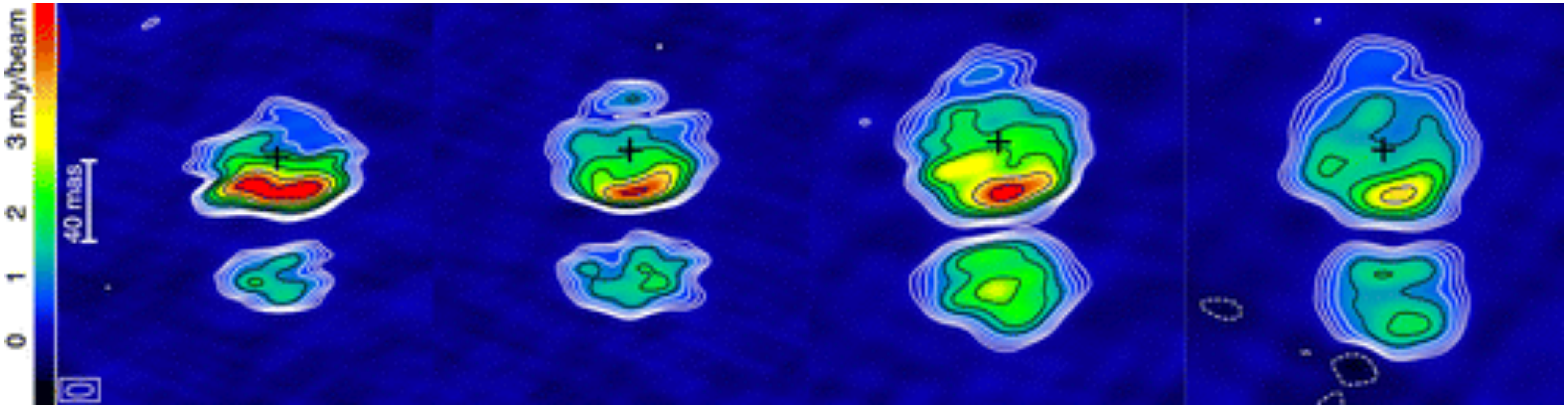




- Continuous radio spectrum, duration of the radio event – tens of days
- Two radio components – an expanding, decelerating shell seen in both non-thermal and thermal emission + bipolar ejecta generating non-thermal emission
- Non-thermal nature of the most extended components – Day 63: east and west structures are non-thermal (decelerating expansion)

Eyres et al. (2009)

Radio emission during nova outburst – RS Oph



Expansion and outward motion of the lobes. 1.7 GHz VLBA – from 5 to 8 weeks after the start of the outburst. The binary system is unresolved (the black plus sign). North is to the left

- The first system with the white dwarf to clearly show narrow, bipolar outflows leading to **SYNCHROTRON lobes**

- Sources of collimation and power for the *highly collimated outflows (HCO)* (since the duration of HCOs is much longer than that of the thermonuclear runaway (TNR)):
  - TNR triggered the jets, but some other process was involved in powering them
  - quasi-steady nuclear burning on the surface of the WD powered (Retter 2004) or illuminated the jets
  - jets were powered by accretion of matter onto the white dwarf from the donor

Sokoloski et al. (2008)

General conclusions (I)

- Cataclysmic variables (CVs) are proved to be the sources of non-thermal emission – implications:
  - presence of highly energetic particles in these systems
  - processes for creation and/or acceleration of these particles must operate here
  - presence of strong magnetic fields (for synchrotron and cyclotron emissions)

- Types of CVs with the observed non-thermal emission:

– dwarf novae in outburst
– novalike CV in the high state
– intermediate polar (during flares)
– polars
– classical novae during outburst

- Processes and spectral bands of the observed non-thermal emission:
  - Synchrotron: – jets (launched during outburst of DNe) (radio)
    – flares in intermediate polar (far IR, optical?)
    – clouds launched from the system by the propeller effect (AE Aqr) (radio)

General conclusions (II)

- Cyclotron: – emitting regions in polars: (1) accretion region on the WD (optical, IR)
  (2) the donor's magnetosphere (radio)

- Creation of π^0 particles:
  – propeller effect
  – shock on a strongly magnetized WD
  – ejecta of outburst of a symbiotic classical nova
  gamma-ray production via π^0 decay – Cherenkov radiation (ground-based detectors)
  – gamma-ray obs. by FERMI satellite
  (predicted: hard X-rays – secondary leptons from decay of charged pions (synchrotron))

- Nuclear reactions: thermonuclear runaway in the outer layer of the WD during outburst of classical nova:
  – production of radioactive isotopes
  – decay of these isotopes is the source of gamma-ray emission

General conclusions (III)

- Evaluation of the conditions suitable for the generation or acceleration of particles in cataclysmic variables: usage of the long-term activity in the optical – data coverage in other bands is often fragmentary (or absent).

- Solution and further prospects: use the optical activity as a guiding line and correlate the observations obtained in other bands with the state of the optical activity.

- Phenomena related to the generation of the highly energetic particles often have episodic character with low duty cycle: e.g. ultra-high energy flares in the propeller systems (AE Aqr), radio flares in polars (AM Her) – this makes their detection and establishing a relation between various emission processes very difficult.

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