THE MYSTERIOUS GAMMA-CAS STARS

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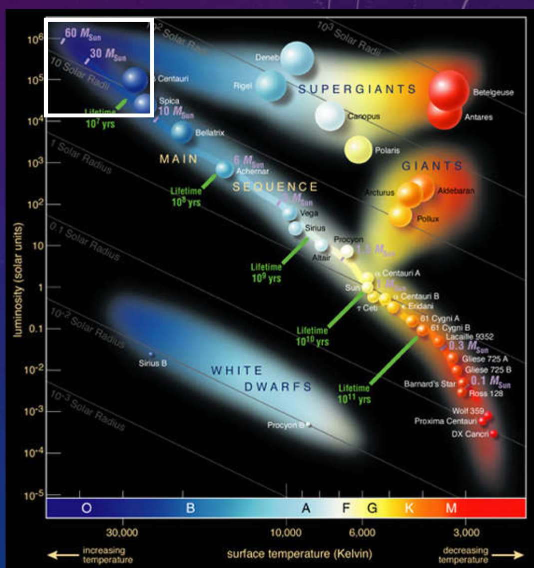
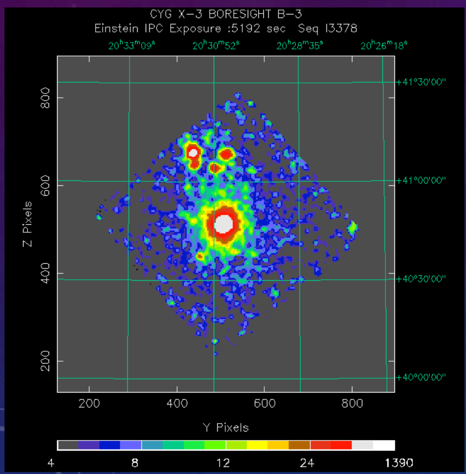
MASSIVE STARS

- the top of the MS (OBAFGKM)
- T > 20kK, M > 15 M_{sol}
  - Blue ⇒ lot of UV
  - Luminous (10^6 L_{sol})
  - Short-lived (<< 1 Gyr)
  - Evolve as LBV/RSG, WR
  - Precursors of SN, NS, BH (+GRB, GW…)
- Rare objects but major contributor to mech. input & chem. enrichment
- Stellar winds !



MASSIVE STARS & X-RAYS



44 years ago…

X-ray emission serendipitously discovered in Dec. 1978 by Einstein ; soon, lot of other cases…

Origin ?

What is a « normal » X-ray emission ?

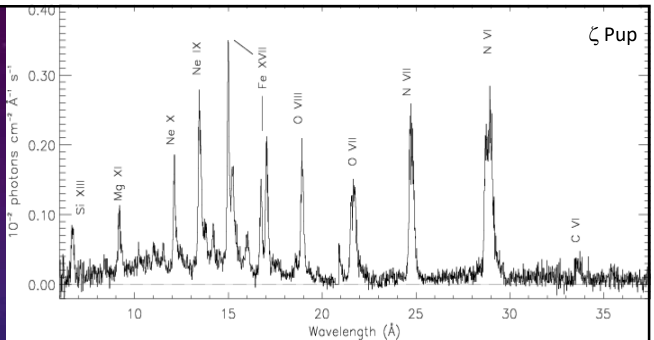
MASSIVE STARS & X-RAYS

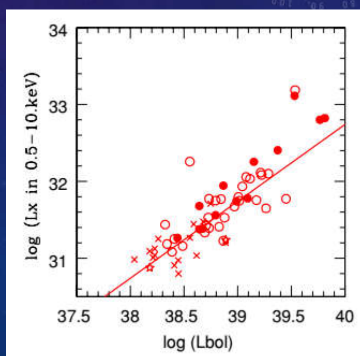
Line-driven winds unstable
⇒ Embedded wind shocks

⇒ X-ray emission

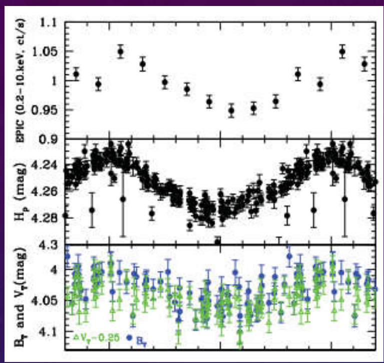
Characteristics :

- Optically-thin thermal plasma (NOT blackbody or power-law)
- Soft (kT~0.6keV), faint (log[Lx/Lbol]~-7), ~constant (→ many clumps) broad lines (wind expansion!)

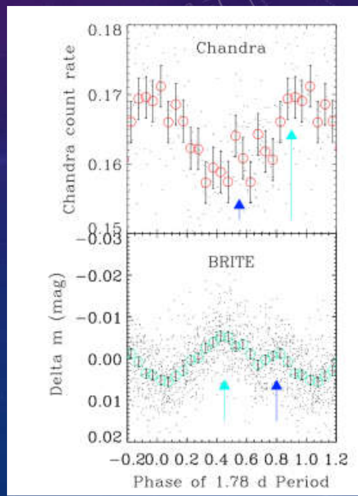




(e.g. Feldmeier 1997, Berghoefer et al. 1996,1997, Waldron & Cassinelli 2007, Zhekov & Palla 2007, Nazé et al. 2011)



MASSIVE STARS & X-RAYS



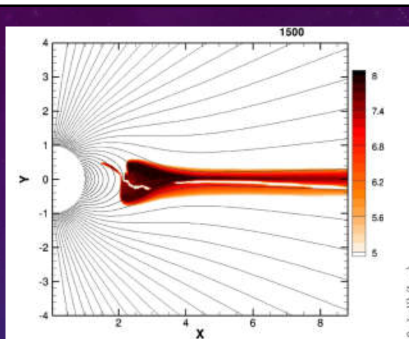
X-rays linked to wind features

- Pulsations : ξ^1CMa & β CMa
- CIRs : ζ Pup, λ Cep, ζ Oph, ξ Per

$\Rightarrow$ Soft X-ray range, limited modulation

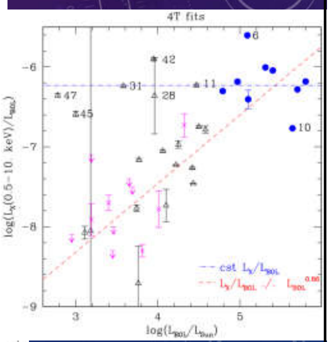
(Oskinova et al. 2014, Cazorla & Nazé 2017 ; Rauw et al. 2015, Massa et al. 2019, Nichols et al. 2021)

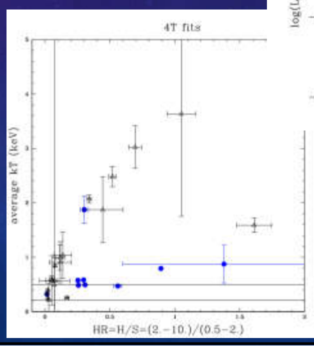
MASSIVE STARS & X-RAYS



Magnetically confined winds

- Strong B-field channels winds
  $\Rightarrow$ collision at equator
- Stationary plasma: narrow X-ray lines
- Additional X-rays : Lx somewhat $\uparrow$
- Face-on collision : kT somewhat $\uparrow$
- in several cases, modulation with rotational phase in magnetic oblique rotators (modulated flux – absorption only for NGC1624-2)



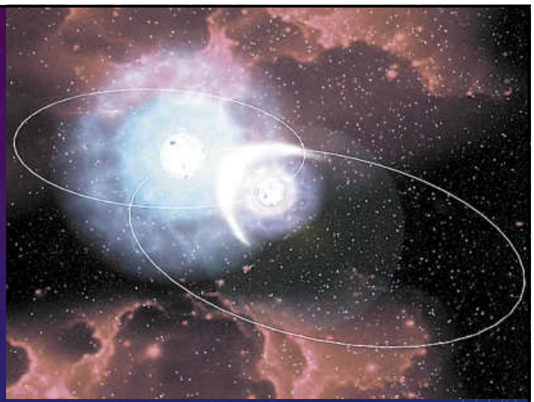


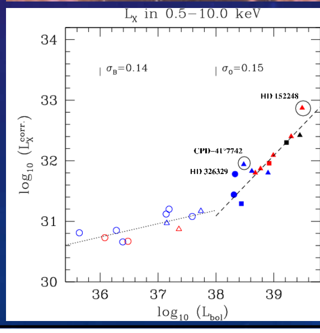
(for a review, ud-Doula & Nazé 2016)

MASSIVE STARS & X-RAYS

Binaries:

- Two massive stars = two supersonic winds $\Rightarrow$ collision
- Shocked plasma seen from radio to γ-rays
  - X-rays : since first obs. of massive stars but NOT all binaries are X-ray bright
  - As in MCWS, kT and Lx somewhat ↑
  - Extended emission far from the stars
  - Phase-locked variations (intrinsic flux and/or absorption)





(for a review, Rauw & Nazé 2016)

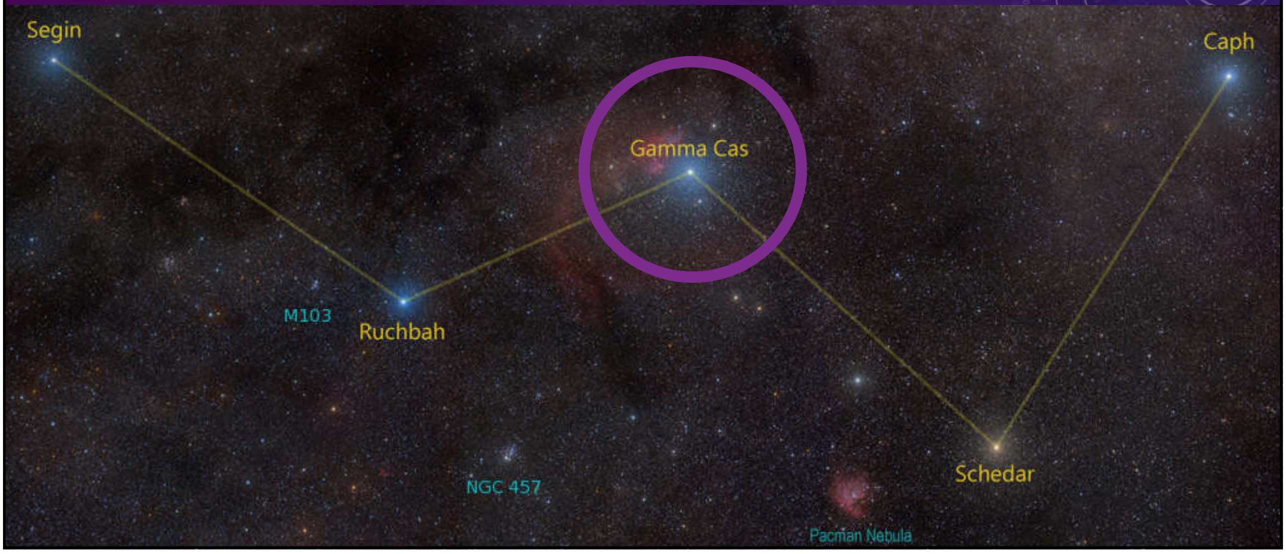
MASSIVE STARS & X-RAYS

What about B-stars?

- As O-stars for earliest ones
  - Embedded wind shocks, pulsations
  - MCWS (but usually less bright and less hot)
  - CIRs, CWBs : not detected
- Nothing if late-type (but PMS companion may emit)

Except…

MASSIVE STARS & X-RAYS



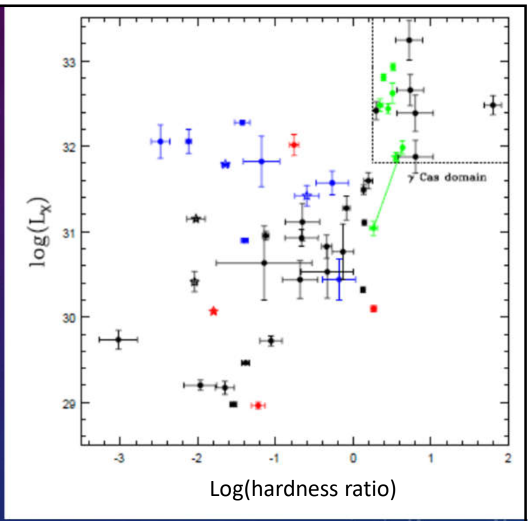
THE γ-CAS PHENOMENON

γ Cas (B0.5IVe)

- Be star : decretion disk ∃
- *Bright* X-rays :
  Lx and Lx/Lbol
  intermediate between
  OB-stars and HMXBs
- *Hard* X-rays : kT = 13 keV
- *Variable* X-rays : « flares »
  (short so high density!)
- Fluorescent Fe/Si lines
- fir triplets require high density and/or close UV source

γ CAS ANALOGS

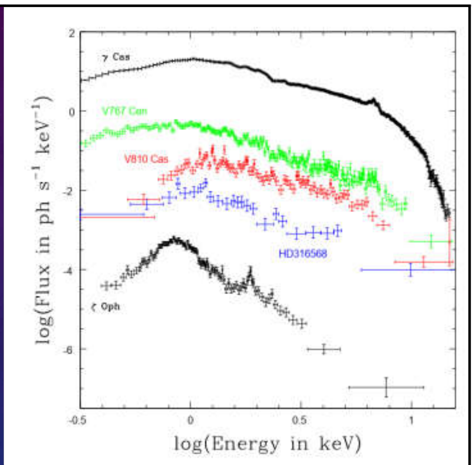
- γ Cas served as prototype of Be stars
  but peculiar X-rays discovered in 1976
- Lone bird ? No !
  - Serendipitous discoveries
  - Dedicated searches (Be survey, X-ray emitting Be, counterparts of unidentified X-ray sources)
  - ⇒ Currently 25 γ Cas analogs
    /!\ incidence rate = ?

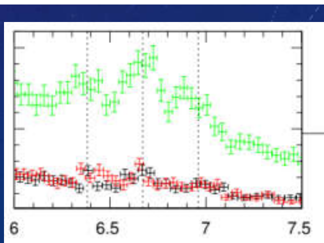


(Jernigan et al. 1976 – Nebot-Gomez et al. 2013,2015, Nazé & Motch 2018, Nazé et al. 2020c)

γ CAS ANALOGS

- Criteria :
  - BRIGHT : -6.2 < log(Lx/Lbol) < -4
    or log(Lx in 0.5-10keV) in 31.6-33.2
  - HARD : Optically thin thermal plasma but with kT>5keV (or HR>1.6 or Lx[2-10keV]> 10^{31}erg/s)
  - If enough SNR :
    - presence of Fe complex with fluorescence line
    - short-term variations (flaring)



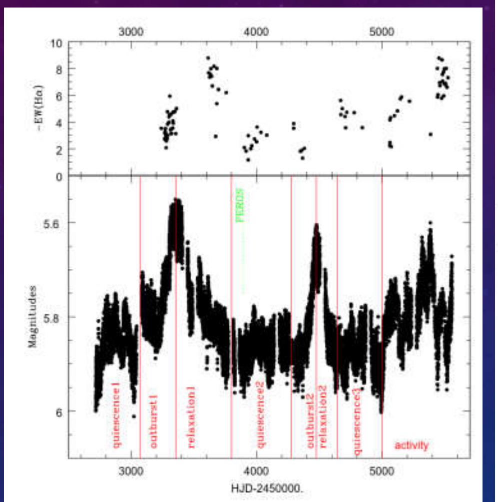


THE γ-CAS PHENOMENON

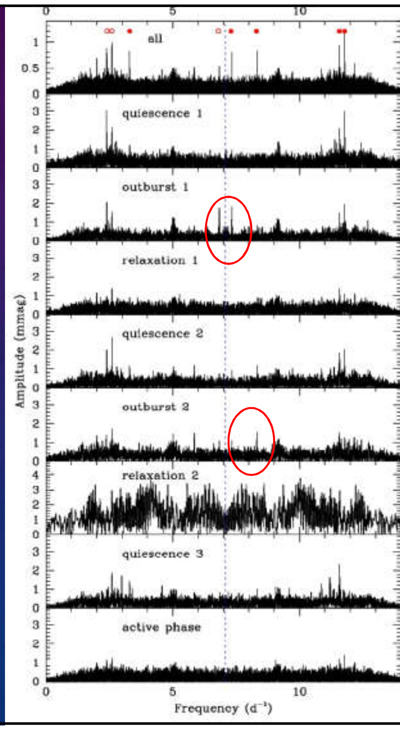
γ Cas are Be stars but not all Be stars are γ Cas : why ?
Do they have something special ?

Where does the X-ray emission come from ?
What is the link with the disk ?

PHOTOMETRIC VARIABILITY : π AQR



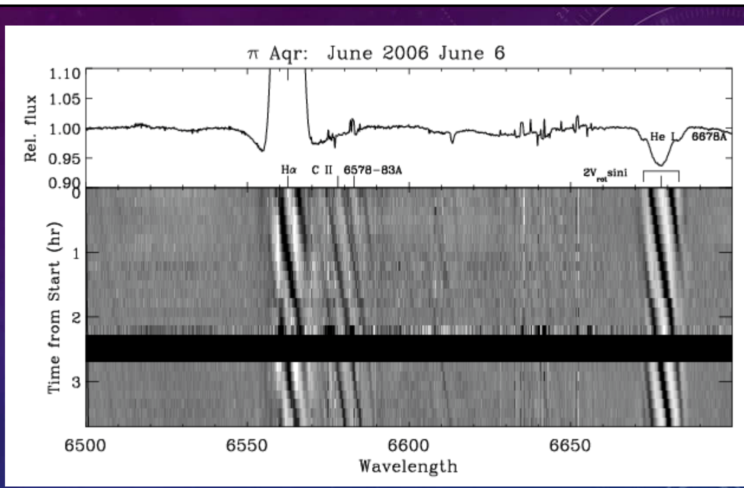
(Nazé et al. 2020a)

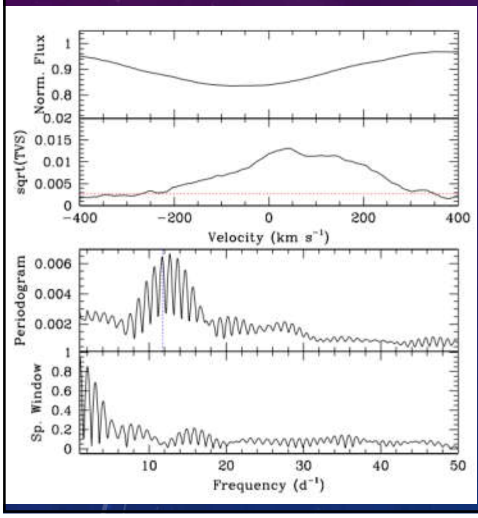


Short-term optical variations

- Photometry : SMEI (7yrs) – pmodes @ high f, varying

PHOTOMETRIC VARIABILITY : π AQR





Short-term optical variations

- Spectroscopy : FEROS in 2006 + Aurélie in 2019

⇒Same f as in photometry (12/d)

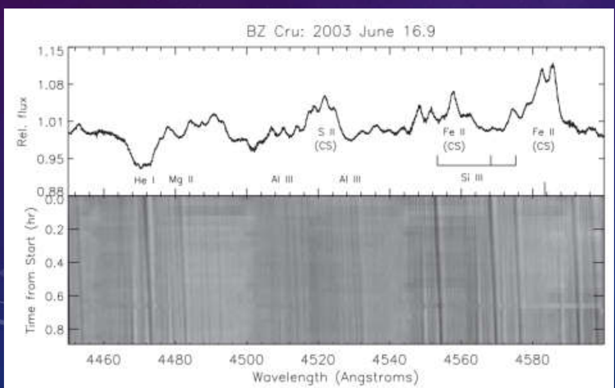
⇒Amplitude similar despite very different disk states

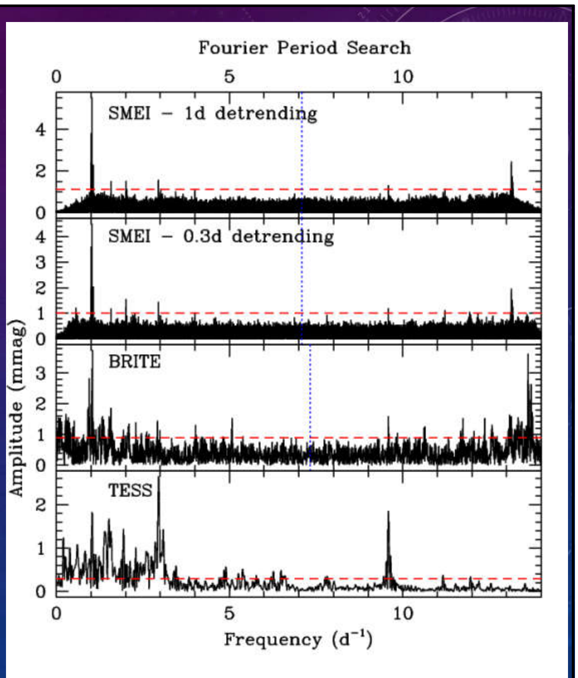
(Nazé et al. 2020a)

PHOTOMETRIC VARIABILITY : BZ CRU

Short-term optical variations

- Photometry : SMEI (for 7yrs), BRITE (80d), TESS (a month)
- Spectroscopy : only small-scale changes, no P detected



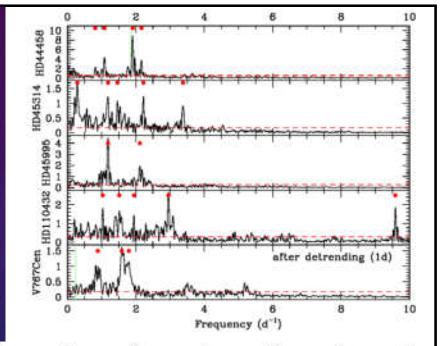


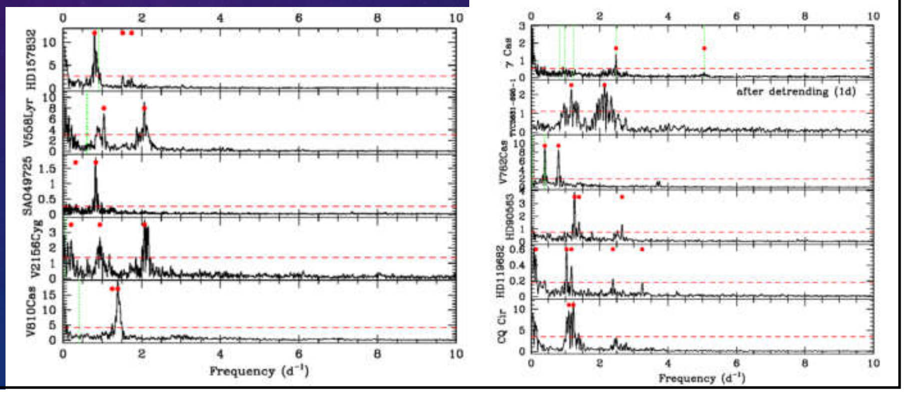
(Nazé et al. 2020a)

PHOTOMETRIC VARIABILITY : OTHER γ-CAS STARS

TESS photometry for 15 γ Cas stars

- Long-term (~month) variations
- Red noise
- Freq groups
- Coherent signals
  - Dominant
  - High-f





(Nazé et al. 2020b)

PHOTOMETRIC VARIABILITY

Comparison with other stars

/!\ small # stat

- Long-term variations : not only low-f signals appearing at outbursts !
- Red noise : γ Cas * ~ OB *
- Freq groups : 1/3 in Be, ¼ in γ Cas *
- Coherent signals
  - Dominant : 20 to 30% in Be, 30% in γ Cas *
  - Strong high-f signals (>5/d) : rare (~ 10% of Be and γ Cas *)

(Nazé et al. 2020b)

THE γ-CAS PHENOMENON

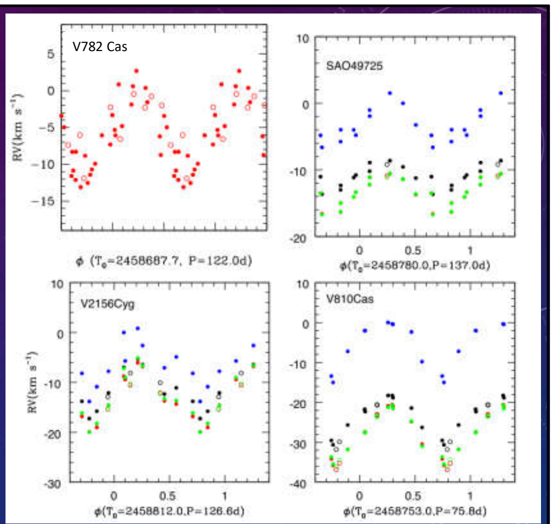
Origin of X-rays ?

- Companion
  - Accretion onto compact companion (WD, NS in propeller stage) *(Murakami et al. 1986, Postnov et al. 2017*
  - Collision between disk and wind of hot companion *Langer et al. 2020*
- Be: star-disk interactions through small-scale mag fields *Smith et al. 1999)*

MULTIPLICITY OF γ-CAS STARS

Are they binaries ?

- γ Cas & π Aqr : known binaries
  (e.g. Bjorkman et al. 2002, Nemravova et al. 2012, Smith et al. 2012)
- Spectroscopic monitoring of 16 other γ Cas stars
  - Six with full orbital solutions : long P, low K (one quadruple system : V782 Cas !)
  - Five with RV shifts but no period yet



(Nazé et al. 2022)

MULTIPLICITY OF γ-CAS STARS

(Nazé et al. 2022)

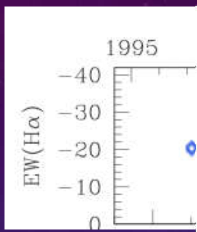
Name	P (d)	e	Be Sp.type	M(Be) ($M_\odot$)	M_{comp} ($M_\odot$)	i (°)	Reference
γ Casstars							
γ Cas	203.6	0	B0IV	13	0.98*	45	Nemravová et al. (2012)
V782 Cas	122.0	0	B2.5III	9	0.6–0.7*	60–90	this work
HD 45995	103.1	0	B2V	10	1.0 ± 0.1*	46.8	this work
V558 Lyr	83.3	0	B3V	8	0.7–0.8*	60–90	this work
SAO 49725	26.11	0	B0.5III	13	0.2–0.5*	30–90	this work
	137.0	0			0.4–0.7*	30–90	this work
V2156 Cyg	126.6	0	B1.5V	11	0.7–0.8*	60–90	this work
π Aqr	84.1	0	B1V	15	2.4 ± 0.5	70	Bjorkman et al. (2002)
V810 Cas	75.8	0	B1	12.5	0.7–0.8*	60–90	this work
Other Be stars							
ϕ Per	126.7	0	B1.5V	9.6	1.2 ± 0.2	77.6	Mourard et al. (2015)
ζ Tau	133.0	0	B1IV	11	0.9–1.0*	60–90	Ruždjak et al. (2009)
HR 2142	80.9	0	B1.5IV-V	10.5	0.7*	85	Peters et al. (2016)
LB-1	78.8	0	B3V	7 ± 2	1.5 ± 0.4*	39	Shenar et al. (2020)
HD 55606	93.8	0	B2.5-3V	6.0–6.6	0.83–0.9	75–85	Chojnowski et al. (2018)
FY CMa	37.3	0	B0.5IV	10–13	1.1–1.5	>66	Peters et al. (2008)
o Pup	28.9	0	B1IV	11–15	0.7–1.0$^+$		Koubský et al. (2012)
MX Pup	5.15	0.46	B1.5III	15	0.6–6.6	5–50	Carrier, Burki & Burnet (2002)
χ Oph	138.8	0.44	B2V	10	1.7–2*	60–90	Abt & Levy (1978)
HD 161306	99.9	0	B0	15	0.9$^+$		Koubský et al. (2014)
HR 6819	40.3	0.04	B2.5V	6	0.4–0.8*	35	Gies & Wang (2020)
59 Cyg	28.2	0.14	B1.5V	6.3–9.4	0.6–0.9	60–80	Peters et al. (2013)
60 Cyg	146.6	0	B1V	11.8	1.5–3.4	>29	Koubský et al. (2000)

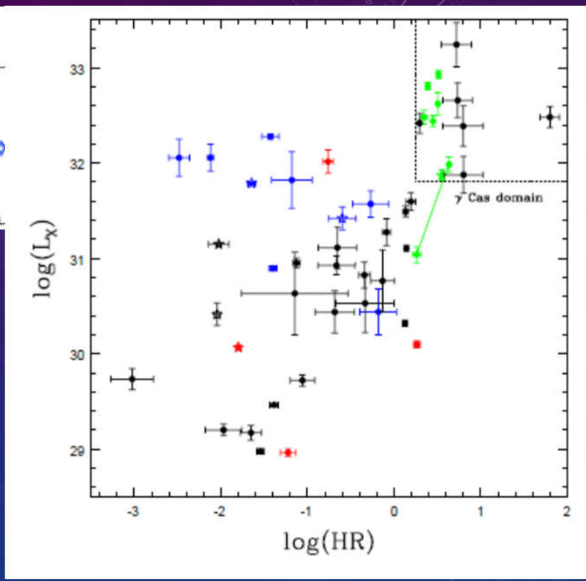
THE γ-CAS PHENOMENON

Origin of X-rays ? Role of the disk !?

$\Rightarrow$ monitoring needed !

MONITORING: HD45314



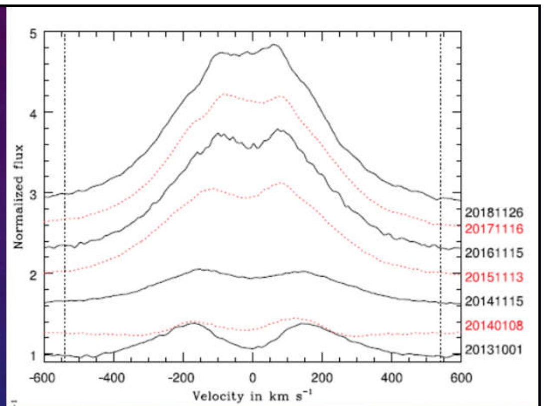


Long term changes

- From EW & V-mag variations
- X-ray data at 3 times:
  Dense disk, shell phase, limited disk
- Near disappearance of disk
  = near disappearance of γ Cas characteristics !

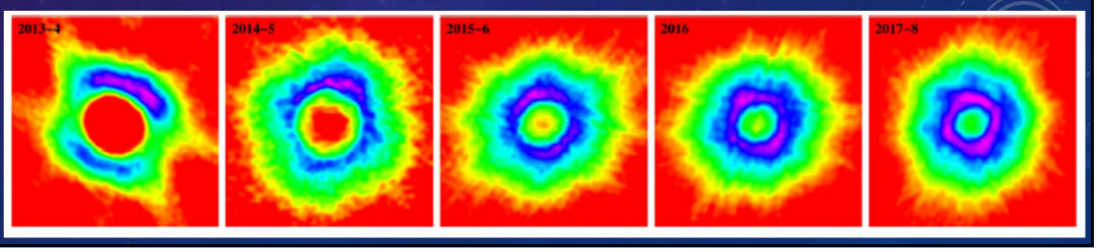
(Rauw et al. 2018)

MONITORING: π AQR



Long term changes, from amateur data :

- End of 2013 (disappearance)
  -> 2018 (strong emission)
- V/R modulation disappears : disk more symmetric
- Peak separation : R(disk) changes from 2 to 13R*

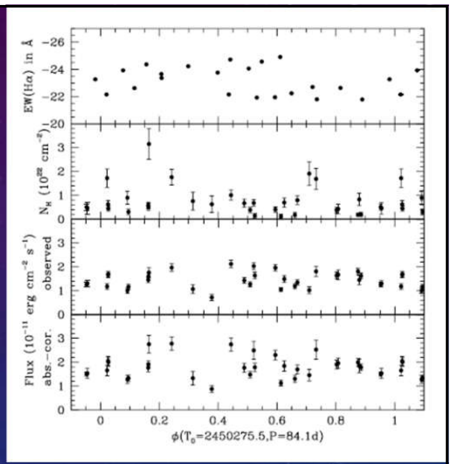


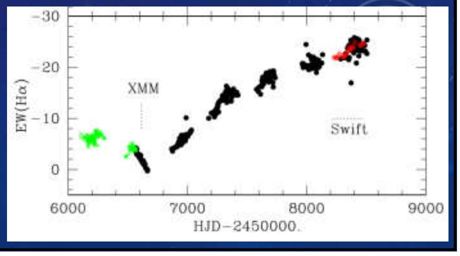
(Nazé et al. 2019a,b)

MONITORING: π AQR

X-ray vs optical

- 3-orbit monitoring :
  - both EW and Fx vary but no direct correlation between them
  - No correlation with orbital phase either
- Long-term : @ EW >>, V-mag <
  + slight (50%) increase in average X-ray flux,
  Nh somewhat larger, HR larger, flux range similar
  to XMM (large short-term variations around the mean !)
  NO disappearance of γ Cas character !



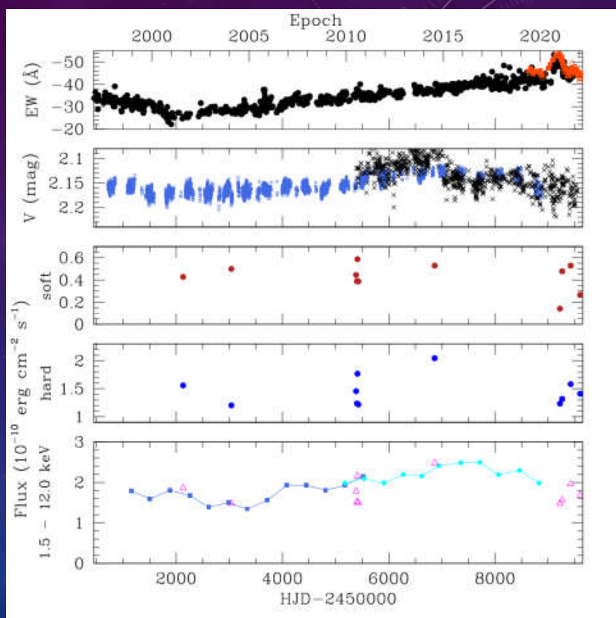


(Nazé et al. 2019b & in press)

MONITORING: γ CAS

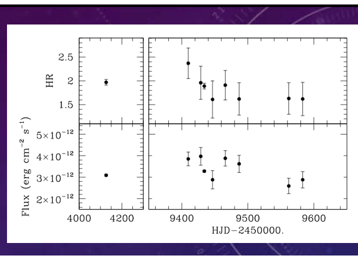
X-ray vs optical

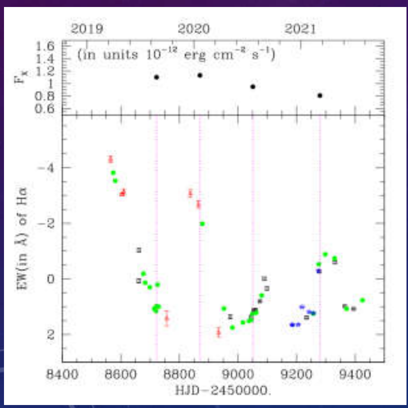
- No trace of variations with orbital period
- RXTE/MAXI & V-mag : direct correlation
- Recent increase in EW (-45 to -55 angstr) :
  - No significant change in V-mag
  - Average Fx vary by ~2,
    HR constant when no absorbing event
  - No obvious EW-Fx correlation



(Rauw et al., in prep)

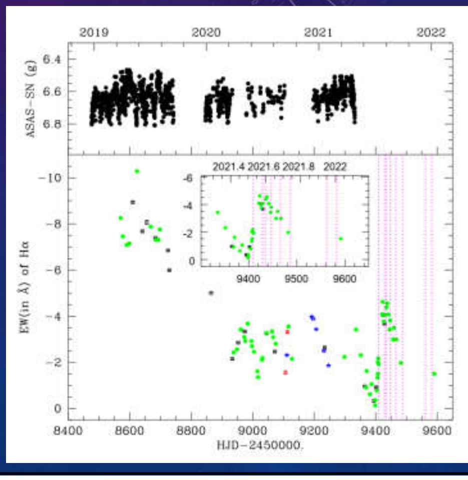
MONITORING: V767 CEN AND HD119682





Triggered X-ray observations as emission decreased :

- HD119682
  - γ Cas character still present
  - HR constant, Fx changes
- V767 Cen
  - γ Cas character still present
  - Fx and HR always similar
    No obvious reaction to decrease/flaring



(Nazé et al., in press)

IN SUMMARY...

- Some Be stars display bright, hard, and flaring X-ray emission : the γ Cas stars
- Photometry : variable on several timescales, similarly to other Be stars
- Multiplicity : orbit for 8 of 25 γ Cas stars, 5 more are candidate binaries
  long P, Mcomp << as in other Be binaries
- X-ray/optical monitorings :
  - Long-term variations exist, but no clear link with EW(Hα) or orbital period
  - γ Cas character remain even when EW(Hα) ↓↓
- The future : « clean » X-ray statistics, iron line at high-res