\textbf{\textit{\textcolor{red}{\gamma} Cas: the magnetic star-disk interaction hypothesis}}

(and the observations behind it).

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Main Collaborators

- Raimundo Lopes de Oliveira (present today)
- Christian Motch (present)
- Greg Henry (for 20 yrs!)
- Gregor Rauw, Yael Nazé
- R. Robinson (original collaborator)
- Ph. Stee (present)
- Steve Cranmer
PART 1: γ Cas: X-ray/UV rapid variations.
Campaign of 14-15 March 1996 simultaneous RXTE and far-UV/GHRS

27 hrs. (3-10 keV) 21+ hrs. (1382—1417Å)
4s/16sec cadence 1s → 1 min. cadence

PART 2: XR response to 2010 Be outburst.

(An awfully lucky break!)
PART 3: Correlated XR/optical variations.

- Rotation signature in light curve
- Interlude: UV light curve features.
- And “long cycles”
  (Suggestion of a disk dynamo).

PART 4: Magnetic star-disk interactions

(Time permitting:) cartoon on UV and XR “dips.”
Attributes of hard X-ray light curves

- Variations on many timescales;
- Rapid “flares” (secs-min) - same rise & decay times - 1/3 of total flux;
- Basal flux is 2/3 of total, slow variations;
- Both basal and flare fluxes track together; have $kT = 12-14$ keV.

RXTE: 4 light curve segments: 1996 March 14

Examine implications from the flare EM and expansion-decay time of typical flare on pre-flare density, volume.
Using standard arguments for plasma overheating, expansion vs cooling:

\[ t_{rad} = \frac{3kT^{3/4}}{\Lambda N_e} \]

\[ \Phi_{rad} = \Lambda T^{1/4} N_e^2 \text{ Vol.} \]

Results:

• Pre-flare density \( \geq 10^{14} \text{ cm}^{-3} \)
  (this is a photospheric density),

• Pre-flare parcel diameter: a few \( 10^3 \text{ km} \).

Overall the March 1996 RXTE curve looked like this
(dashed line shows smoothed curve)

Two maxima

Our GHRS program centered on the 1394, 1403 Å Si IV resonance lines.

Note: we can bin over “Continuum” wavelengths.

Use summed values to form a “UVC” light curve (Smith et al. 1998).

UVC time series grayscale shows many rapid variations.

Superimposed on weak line profiles, “migrating subfeatures,” probably due to small absorbing low density clouds locked in corotation over star’s surface. *(also origin of basal flux?)*

(Smith, Lopes de Oliveira, Motch 2016 AdvSpRes, 58, 782)
From time series GHRS/UVC fluxes we create a high-quality light curve (1996 March 14-15):

Curve shows two weak UVC absorption dips ~10 hrs apart.


The short dip durations tell us: these absorptions arise in corotating structures.
Now, with a trick: plot the two $\gamma$ Cas light curves together.
Meanwhile, XR-UV correlation extends to UV lines! (formed in Be star atmosphere)

And that’s not all...
Important S IV doublet matched with XR curve:

There’s also a correlation between 21 hrs of RXTE flux and fluxes of a pair of nearly optically thin S IV features, (1404.8,1406.0Å). [Ionization structure of Sulfur is like Silicon.]
There’s also a correlation between 21 hrs of RXTE flux and fluxes of a pair of nearly optically thin S IV features. AND: Wiggles can be ID’ed with specific migr. subfeatures in grayscale.
PART 2: X-ray response to Be outburst in 2010.

During disk outburst, a hardening of XR spectrum due to increased column density \( n_H \) to emission sources.

\[
\text{Ergo, XRs are emitted beyond column, near Be star.}
\]
PART 3: Optical correlations (with APT)

Over 1st 15 yrs APT in the γ Cas B, V-filter light curves disclosed:

- Moderate amplitude long-cycles (55-91 days),
  (skip for the moment)

- Faint rotational signature, \( P_{\text{rot}} = 1.21581 \) days (29 hr)

Periodogram:

Which we hoped for a while was perfectly stable over many years.···
But rotational waveform, amplitude will change on short term:

Average: 1997-2003, slow rise to max

2003 Nov. 19-24, quick rise to max

And, alas, a secular trend to zero!

(Henry & Smith 2012)
INTERLUDE: meanwhile the rotation signal for $\gamma$ Cas is alive & well in aligning UV light curves: the two dip features in the March 1996 curve are also replicated in the only two other available IUE curves.
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OVERALL:

UV & optical signals are +/- stable but also variable.

END OF SEGUE ON UV DIPs & ROTATION
PART 2: (end of rotation segue)

In the γ Cas B, V-filter light curves, APT also found:

- Large amplitude long cycles (0.02-0.03 mag, 55-91 dy)
- $\Delta V \approx 1.5 \Delta B$. Thus variations are reddish (i.e. from disk).

Nothing is repetitive: ~70 day cycles are unstable.
Here was the surprise:

During a 2000-2001 campaign, the XR fluxes followed the ~80d optical cycles!

(Set the $\Delta XR/\Delta V$ scaling to $130 \times$.)

Many APT obsns, 2000-1

Six RXTE 27 hr.-long visits:

(Robinson, Smith & Henry 2002)
Motch et al. 2015 (ApJ, 806, 177) found a similar correlation between RXTE/ASM and APT fluxes (same scaling).

Exemplars, time history: 2000-2006
(XR/ASM & optical/APT)

Conclusions of APT/ASM Comparison:

- Optical/XR variations up to ≈1 year still (imperfectly) correlate! (Be disk *is* implicated in hard XR variations.)

- No time lag of XR behind optical signal (<1 mo. @ 3σ) (contra binary accretion).
PART 4: suggested star-disk interactions

The foregoing leads us to a scenario of interacting magnetic fields. Envisioned geometry:

- small-scale stellar field,
- toroidal disk field.
PART 4: Consider the two magnetic field geometries:

STAR: *local* fields emerge from Cantiello’s FeCV subsurface circulation cells.

(Cantiello & Braithwaite 2011, AA, 540, A1400)
MEANWHILE:

THE DISK:
Seed fields are amplified by MRI-generated turbulence.

3D-simulated, evolved magnetic fields in MRI-disk. Red & yellow are enhanced bundles.
(Mignone 2016)

Chaotic evolution over time of magnetic stresses in a Keplerian disk dynamo.
Cartoon: geometry of star-disk interaction:

Entanglement of field systems, breaking and “X-point” reconnections, slingshot-rebouncing:

View of interaction within disk plane:

View of interaction from the pole:


Observed parameters for recent solar Type IV/CME eruption:

$\overline{B} = 4.4 \text{ G}, \text{ height } = 1.3 R_\odot, \ E_o \geq 1 \text{ MeV}, \ V_{\text{eject}} \geq 2000 \text{ km/s}$

High-energy e-beam (200 keV) impacts the cell’s emerging field; explosive thermalization results: a “flare”* \( (kT \approx 10 \text{ keV}, \quad @ \quad N_e = 10^{-14} \text{ atoms cm}^{-3} ) \).

*X-ray flares produced only in response to impact of a beam.

Thus any one cell exhibits a surface flare only when impacted; the distribution of XR-active cells can change at any time.

We have leveraged the concept of cells. We have no idea of their lifetimes.
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MY CARTOON:

If a solid-body proto-wind column emerges from star’s surface, regulated by cell’s magnetic field, we will have a “directed” absorption of UV & often soft-XR flux, i.e. sudden dip in a UV, and often, XR color curve.

End of present speculation... ...

(but not end of story!)