Probing the Evolution of Cataclysmic Variables: Current Challenges

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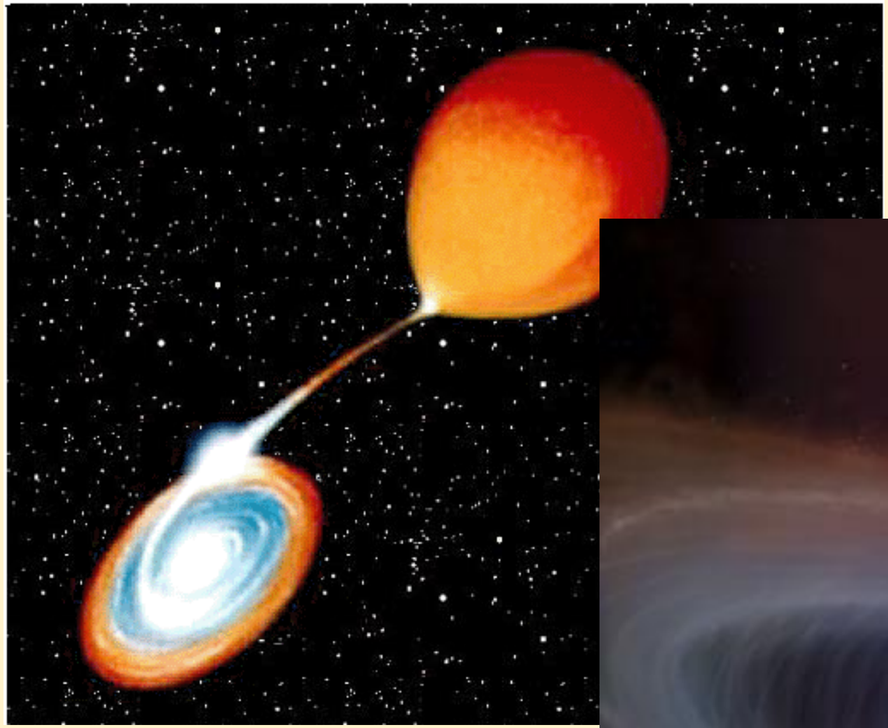
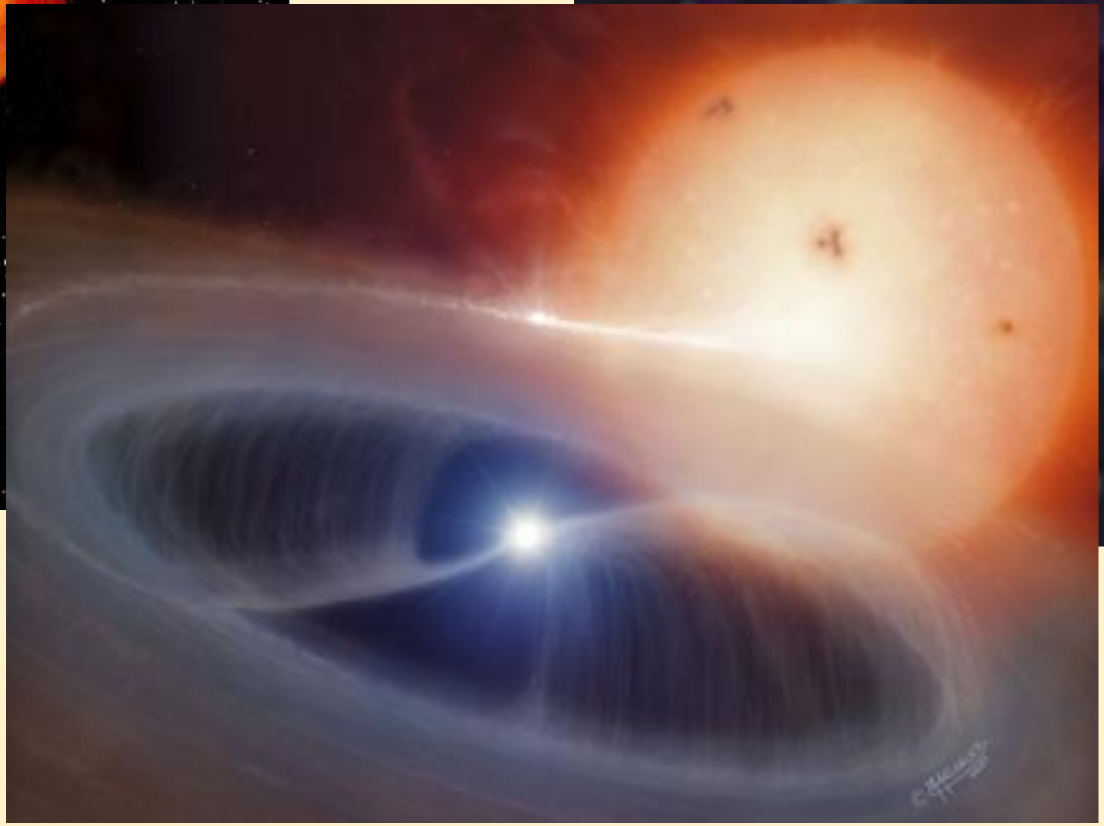
Outline

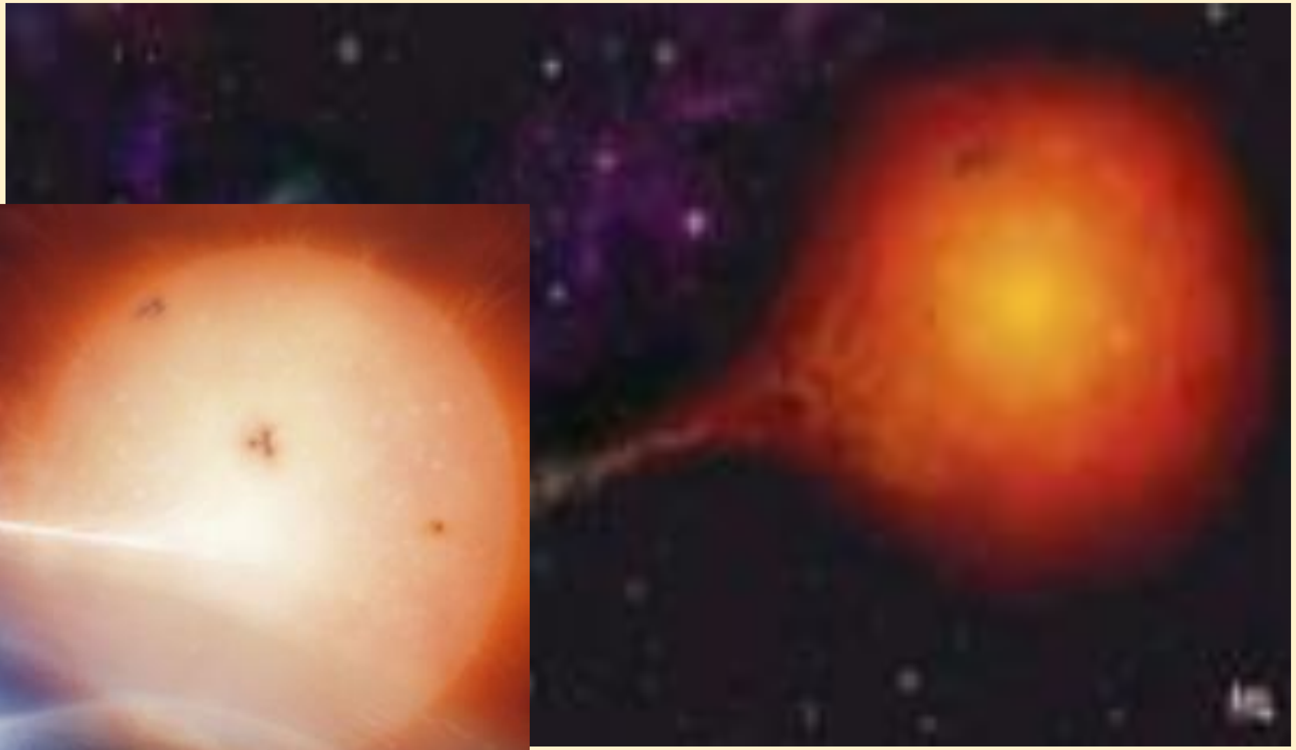
- Overview of Accreting White Dwarfs
- Scientific Objectives (open questions): Non-Magnetic + Magnetic CVs
- Examples of Far UV Multi-Component Synthetic Spectral Analysis
- Observed Properties of Cataclysmic Variable Primaries (white dwarfs)
- Recurrent Novae - T Pyxidis, CI Aquilae, IM Normae
- ER Ursa Majoris Dwarf Novae
- Conclusions and Open Questions

Non-Magnetic CVs

Magnetic CVs



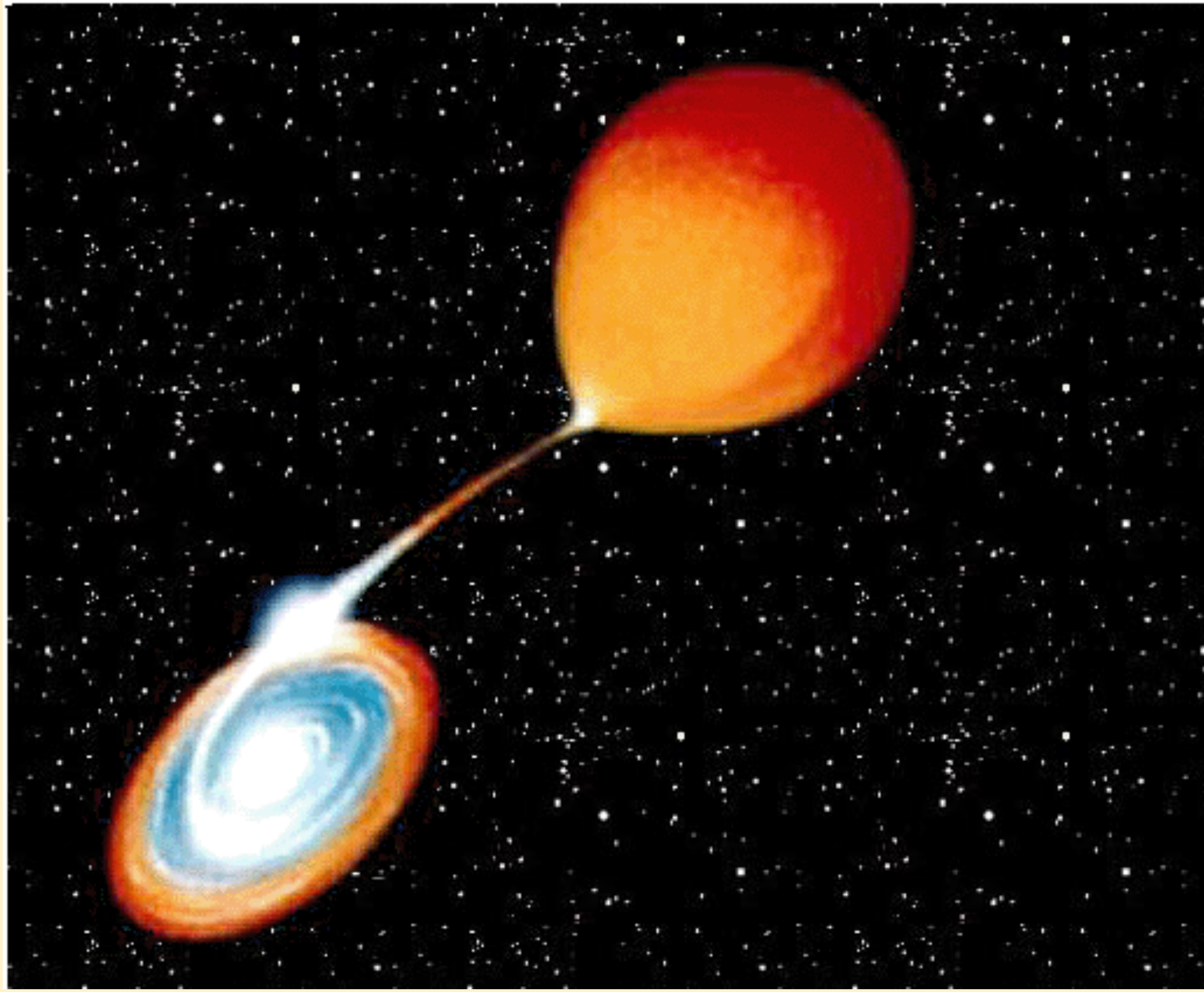




Main open questions:

For Non-magnetics:

1. Fundamental properties of the accreting WD?
2. N/C Abundance Anomaly: Nature or Nurture?
3. Evolution - Which Angular Momentum Braking Law is Correct?
4. SNe Type Ia Progenitors?



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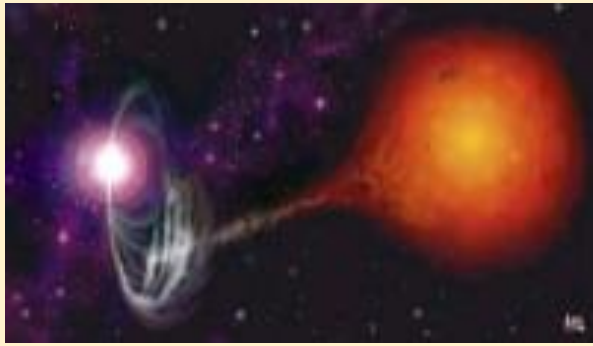

For Non-magnetics:

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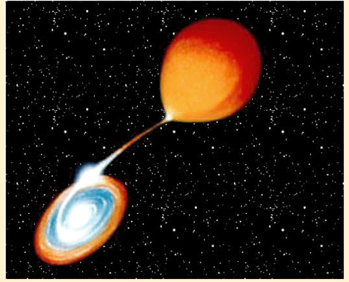
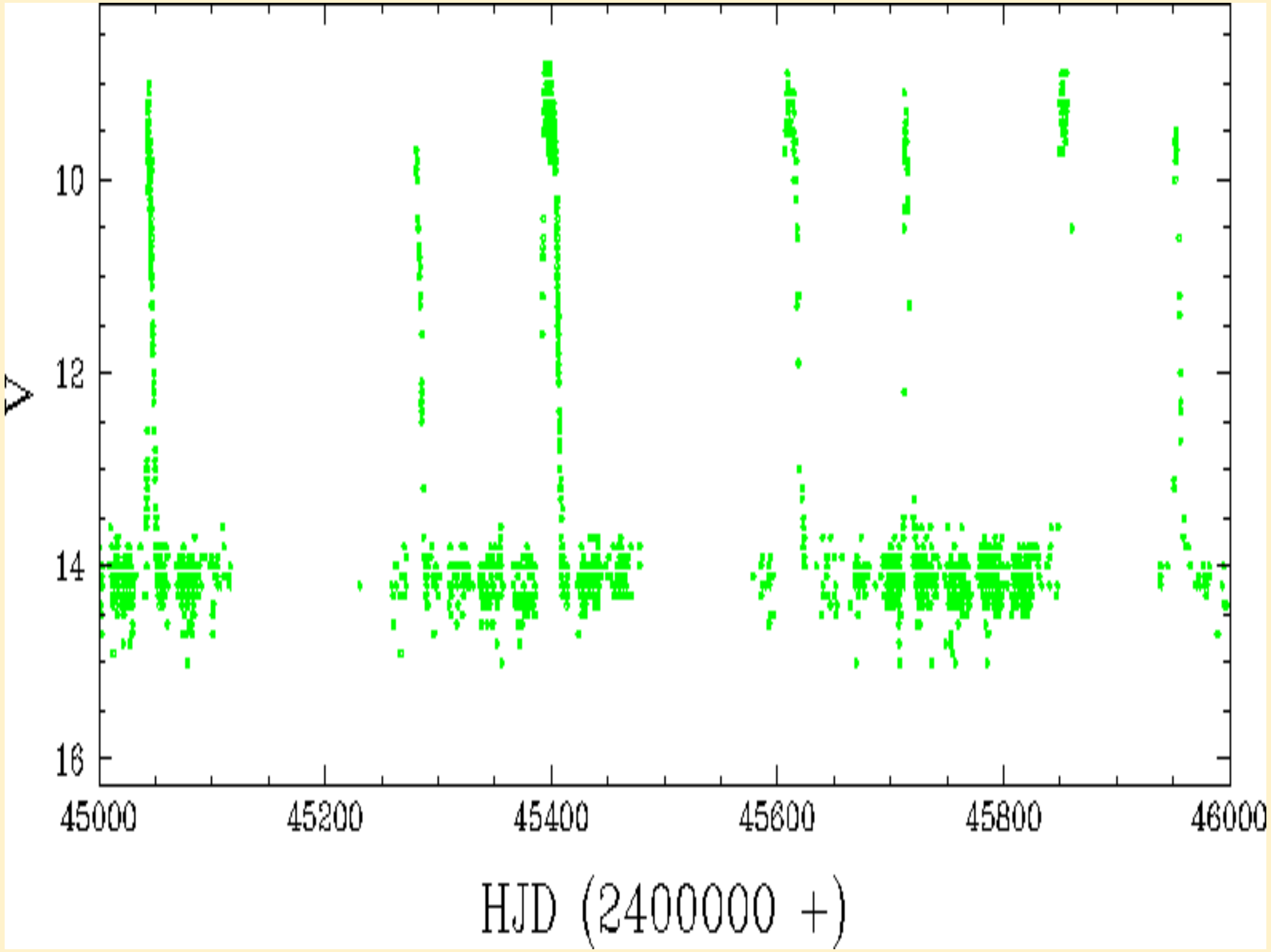
For magnetics:

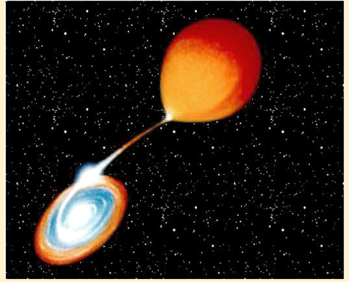
1. Magnetic Field Strengths
2. White Dwarf Temperatures in/outside the accretion caps
3. Accretion Rates onto the magnetic white dwarf
4. Lateral and Radial Diffusion of accreted matter into the magnetic WD?
5. Identity of magnetic CV white dwarf progenitors?

1. Fundamental properties of the accreting WD: The case of Dwarf nova U Gem





The Dwarf nova U Gem – post-OB



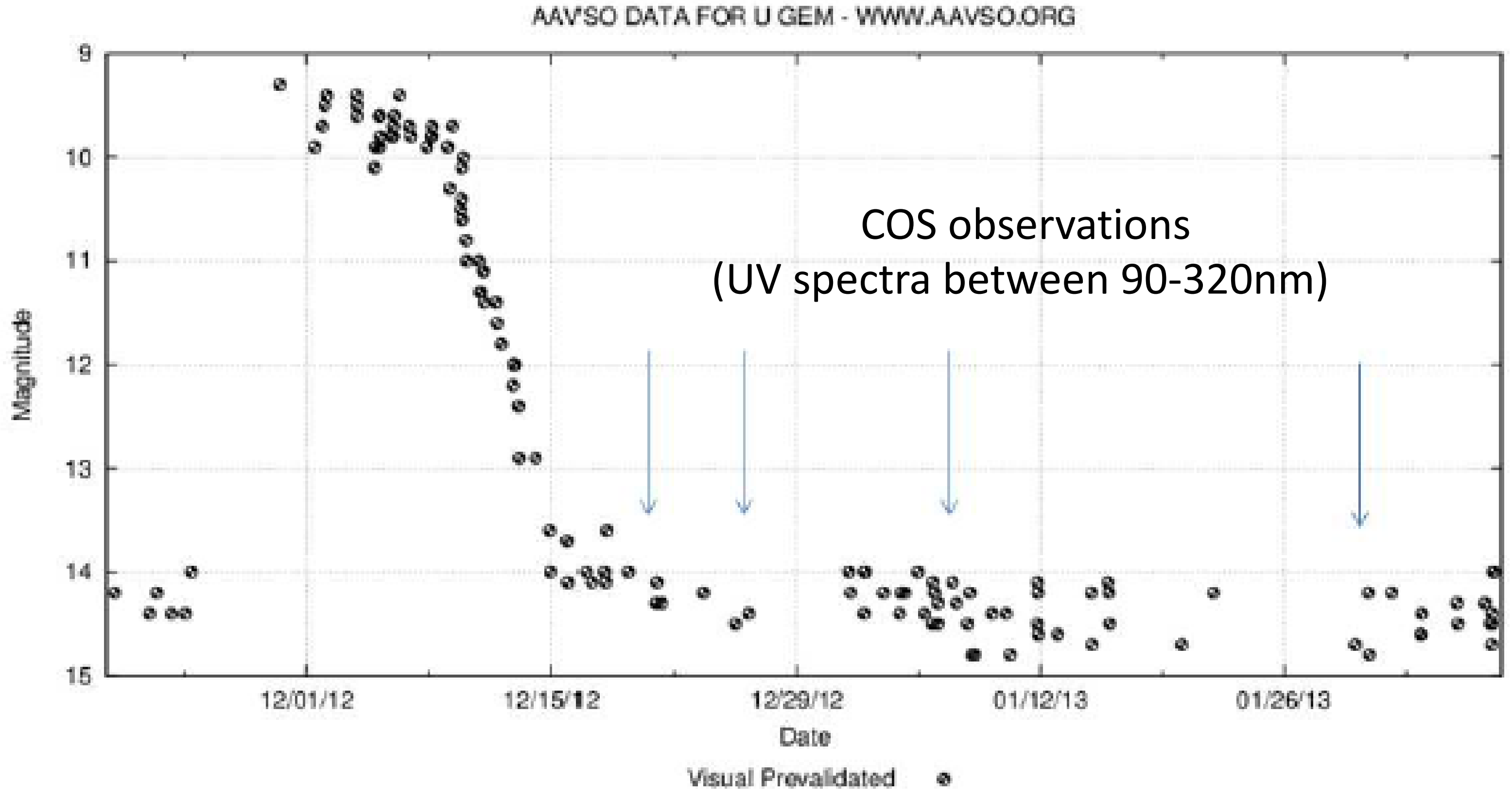
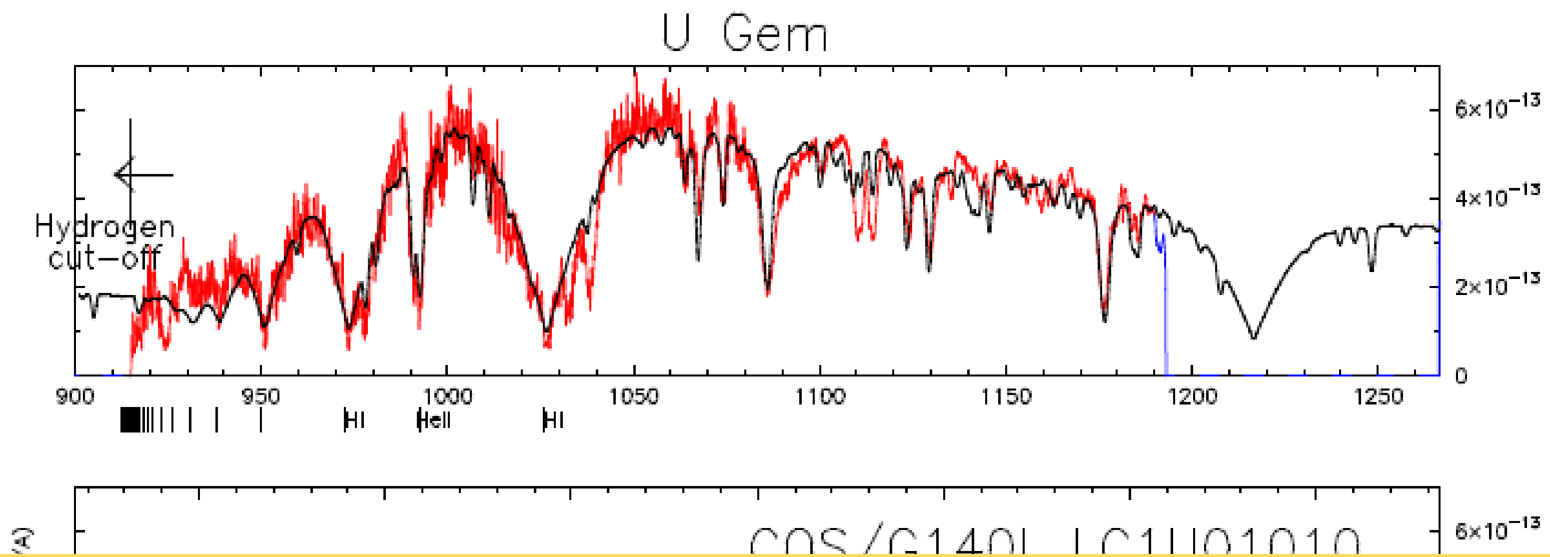
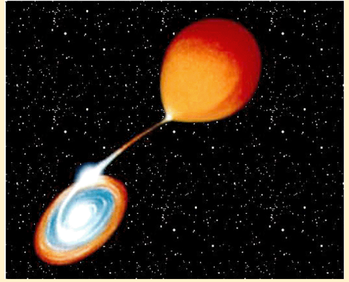


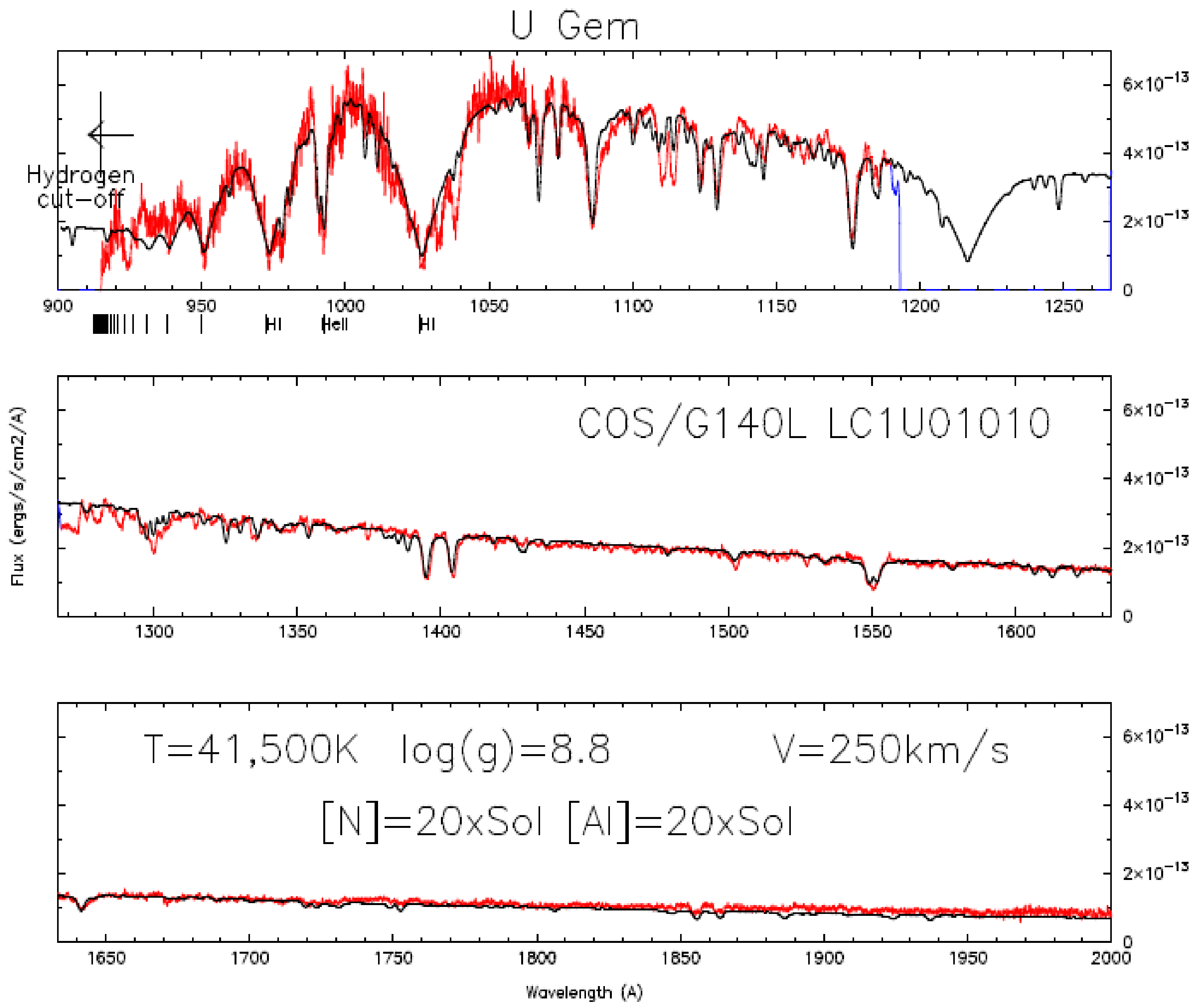
Figure 1. AAVSO optical light curve (visual magnitude vs. time) of U Gem at the time of COS observations. The four HST/COS observations were taken following an outburst lasting 15 days ("wide" outburst), at the dates indicated with vertical arrows.

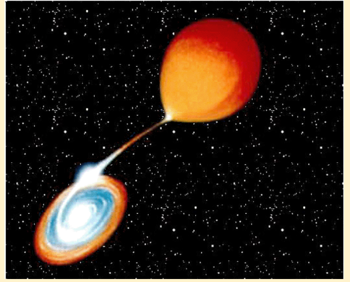




Extracting parameters through synthetic spectra:

- High Gravity LTE and NLTE Model Atmospheres (TLUSTY200, SYNSPEC98)
- Optically Thick, Steady State, Accretion Disk Models (TLUSDISK200)
- Accretion Belt Models
- Accretion Rings
- Accretion Curtain Models

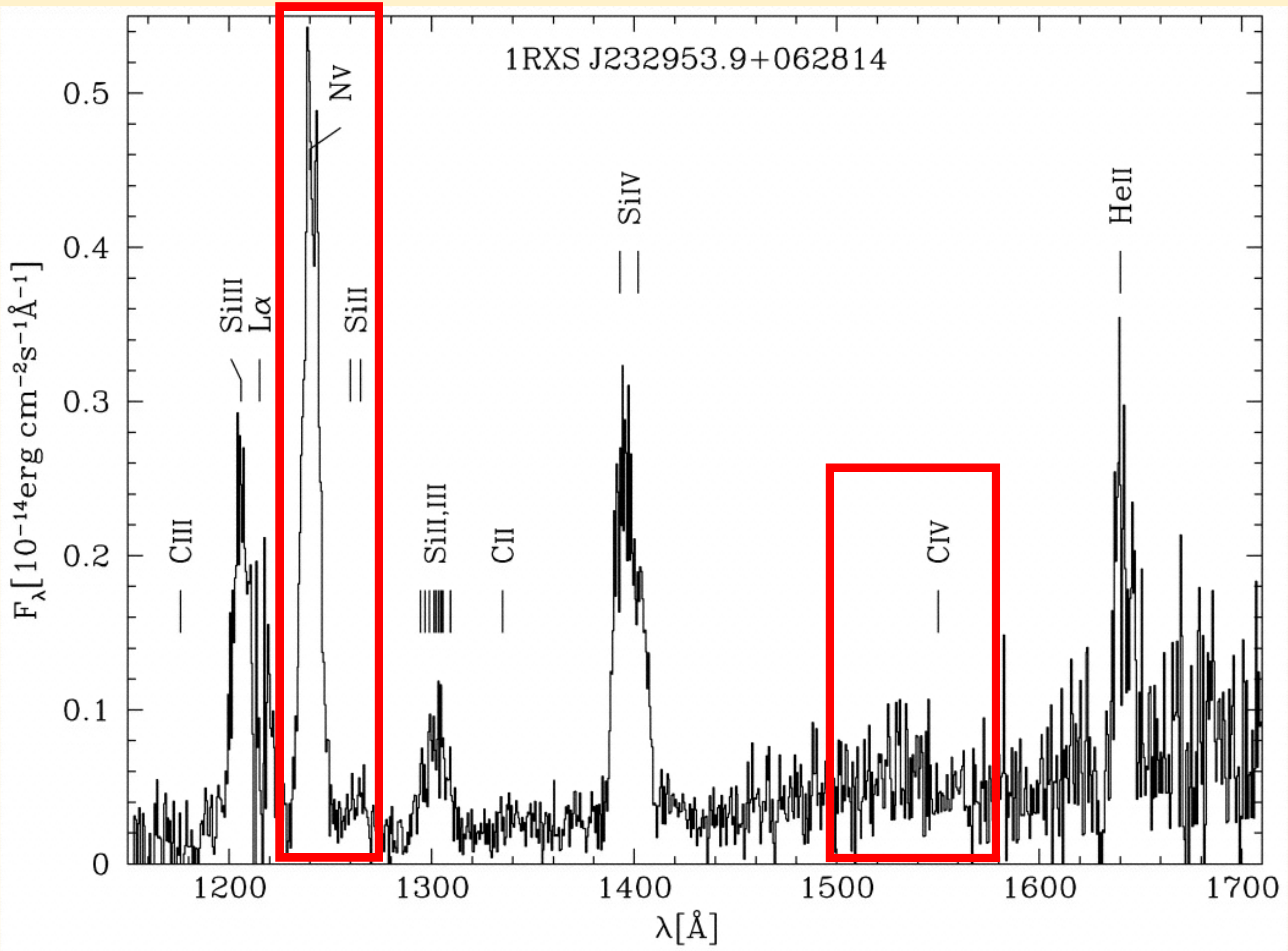




What we learned:

T_WD ~ 41000 K
Type: O-Ne-Mg
M_WD ~1.1M_sun !!!??

2. The N/C anomaly: Nature or Nurture?:



The N/C anomaly: Nature or Nurture?:

Possible explanations:

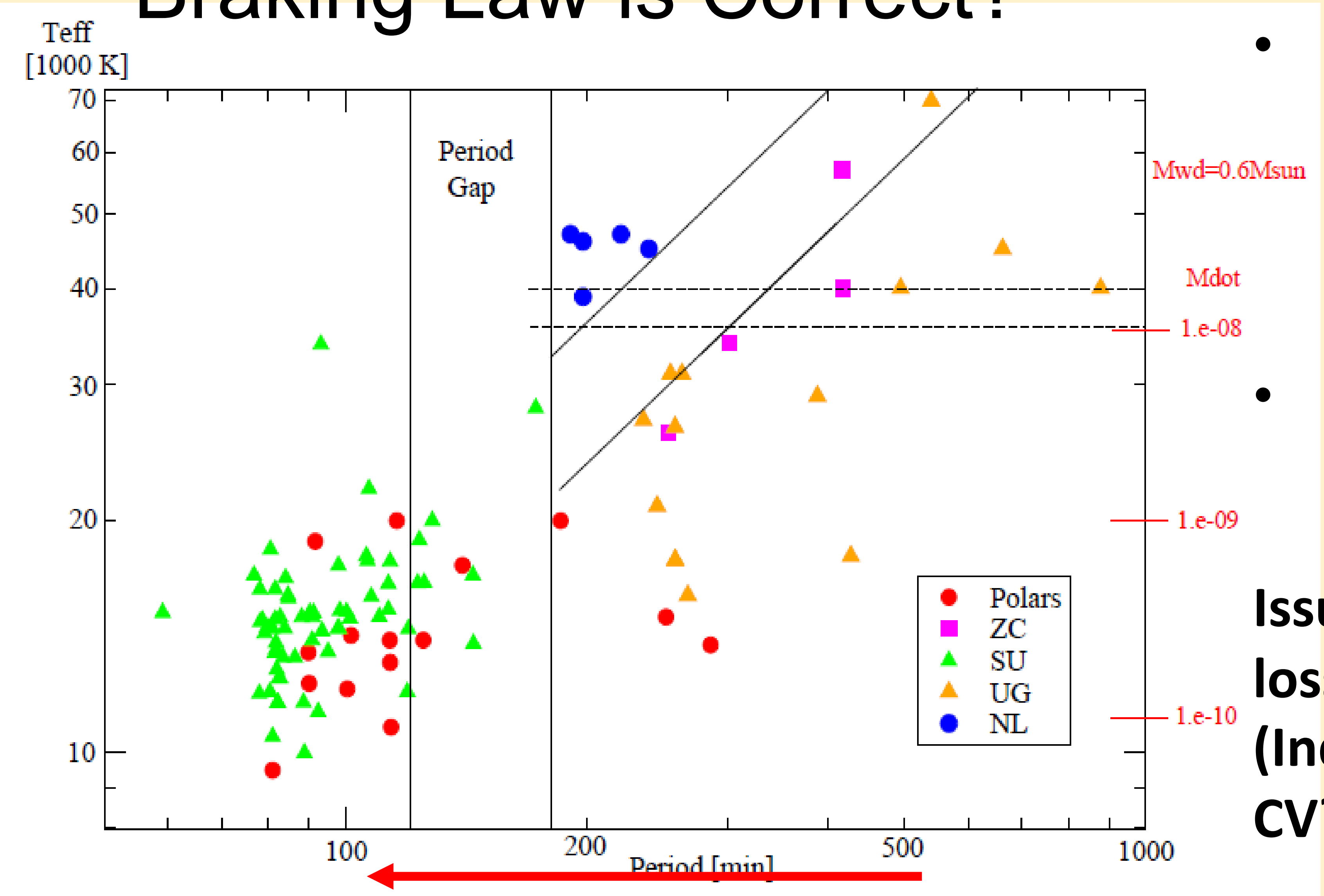
- Does the large N/C in the mass transferring donor originate from peeling down by mass transfer into the CNO processed core of a formerly more massive secondary?

- A nova explosion involves the dynamical ejection of the accreted layers and a “common envelope” phase consisting of remaining gas that did not achieve escape and either envelops the entire binary or remains as an extended atmosphere supported by the continued stable H-burning on the plateau branch near L_edd.

Accretion of CNO-processed material by the secondary during the dynamical nova shell ejection is probably minimal. However, during the “common envelope” stage, the accretion of CNO-processed material may be appreciable.
(Sion \& Sparks 2014, ApJL, 796, L10)

λ[Å]

3. Evolution - Which Angular Momentum Braking Law is Correct?



- CVs "migrate" from high to low periods as a result of angular momentum loss from binary
- There is a "gap" in period distribution

Issues: angular momentum loss mechanism?? (Independent of nature of CV? Mass evolution?)

Mass determination: eclipsing binaries

Table 1: Reliable CV White Dwarf Masses

Object	Period	M_{wd} ($M_\odot$)	σ (($M_\odot$))	Type	Method
SDSS1507+5230	66.6	0.892	0.008	-	E
PHL1445	76.29	0.73	0.03	DN	E
SDSS1433+1011	78.1	0.865	0.005	-	E
WZ Sge	81.6	0.85	0.04	DN	S
SDSS1501+5501	81.9	0.767	-		E
SDSS1035+0551	82.1	0.835,0.84	-	DN	E
SDSS1502+3334	84.8	0.709	0.004	-	E
SDSS0903+3300	85.1	0.872.	0.011	-	E
ASASSN-14ag	86.8	0.63	0.04	DN	E
XZ Eri	88.1	0.769	0.017	-	E
V4140 Sgr	88.46	0.73	0.03	DN	E
V2051 Oph	89.9	0.78	0.06	DN	E
SDSS1057+2759	90.42	0.800	0.015	DN	E
SDSS1227+5139	90.7	0.796	0.018	-	E
OYCar	90.9	0.84	0.04	DN	E
CTCV2354-4700	94.4	0.935	0.031	-	E
SDSS1152+4049	97.5	0.560	0.028	-	E
EX Hya	98.26	0.78	0.03	IP	S
V1500 Cyg	-	>0.9	-	Polar, Nova	S
OU Vir	104.7	0.703	0.012	DN	E
HT Cas	106.1	0.61		NL	E
IYUMa	106.4	0.79	0.04		E

Mass determination: eclipsing binaries

- Zorotovic, M., Schreiber, M.R., Gaensicke, B.2011, A\&A, 536, 4232; 32 CV WD masses from Eclipsing CVs

$\langle M_{wd} \rangle = 0.83 \pm 0.23\ M_{\odot}$ → No difference in $\langle M_{wd} \rangle$ above and below the period gap

- McAllister, M., Littlefair, S.P., Parsons, S.G. et al. 2019,MNRAS, 485, 5535; 47 CV WD masses from Eclipsing CVs

$\langle M_{wd} \rangle = 0.81 \pm 0.02\ M_{\odot}$

$\langle M_{wd} \rangle$(Below Gap) = $0.81 \pm 0.02\ M_{\odot}$
$\langle M_{wd} \rangle$(Above Gap) = $0.82 \pm 0.02\ M_{\odot}$

No WD Mass Growth

4. SNe Ia Progenitors – the case of Recurrent Novae

- >1 observed eruption
- Recurrence timescales 10 – 100 years
- Donor stars – sub-giants (U Sco), red giants (RS Oph) or MS stars
- High mass transfer/accretion rates; high WD Masses
- Rapid eruption evolution (light curves)
- High ejection velocities
- He/N spectra
- 10 Galactic systems (16 M31, 3 LMC)

- ***WD mass increasing to reach SN Ia (?)***

SNe Ia progenitors – The case of T Pyx, IM Nor, CI Aql

- They have main sequence (MS) donor companions.
- Slow optical decline timescales compared to other recurrent novae.
- **CI Aql** shows eclipses on an orbital period of 14.8 hr (Lederle & Kimeswenger (2003) Mennickent & Honeycutt (1995)).
- **IM Nor** shows “wide” eclipses with an orbital period of 2.46 hours, presumably of an accretion disk (Warner and Woudt 2003).
- **T Pyx** shows no eclipses.

SNe Ia progenitors – The case of T Pyx, IM Nor, CI Aql

- Recurrent Novae require a massive white dwarf accreting at a high rate.
- Do their white dwarf masses increase, decrease, or stay constant?
- Do their white dwarfs reach the Chandrasekhar Limit →Type Ia SNe?

T Pyx	6.4	15.5	62	19	0.076	1890, 1902, 1920, 1944, 1966, 2011
CI Aql	9.0	16.7	32	42	0.6184	1917, 1941, 2000
IM Nor	8.5	18.3	80	82	0.1026	1920, 2002

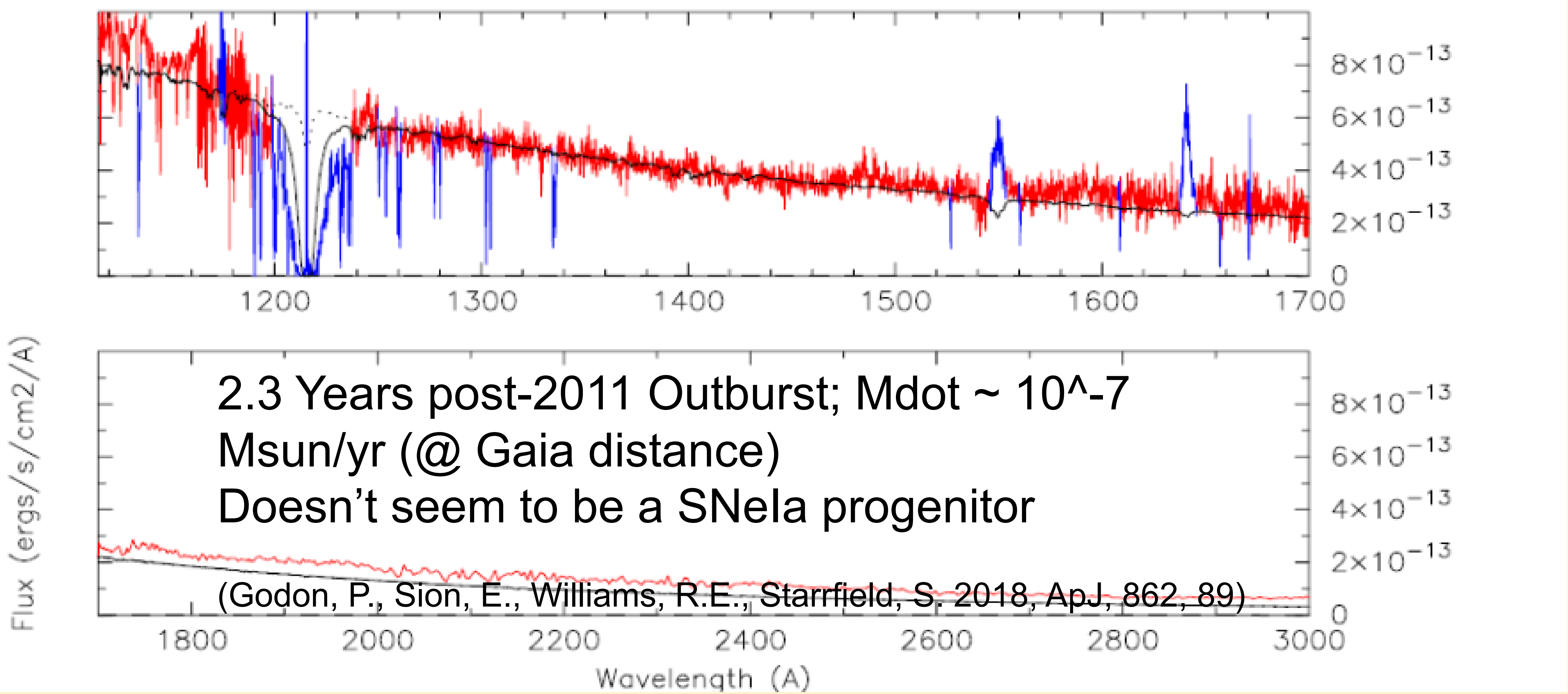
T Pyx – to SNe or not?

If the distance to T Pyx is 3.3 +0.5 / −0.4 kpc (Gaia DR2), then its accretion rate is 10^-7 Msun/yr and the WD is losing mass over time, never to become a Type Ia Supernova (Godon et al. 2018; Patterson et al. 2017)

If the light echo distance of 4.8 kpc is correct (Sokoloski et al. 2014), then its accretion rate is ~ 10^-6 Msun/yr and the WD is gaining more mass than it loses in nova explosions and will reach the Chandrasekhar Limit as a Type Ia Supernova (Godon et al. 2014).

So… WD gaining or losing mass?

T Pyx – to SNe or not?



2.3 Years post-2011 Outburst; Mdot ~ 10^-7 Msun/yr (@ Gaia distance)

Doesn't seem to be a SNeIa progenitor

(Godon, P., Sion, E., Williams, R.E., Starrfield, S. 2018, ApJ, 862, 89)

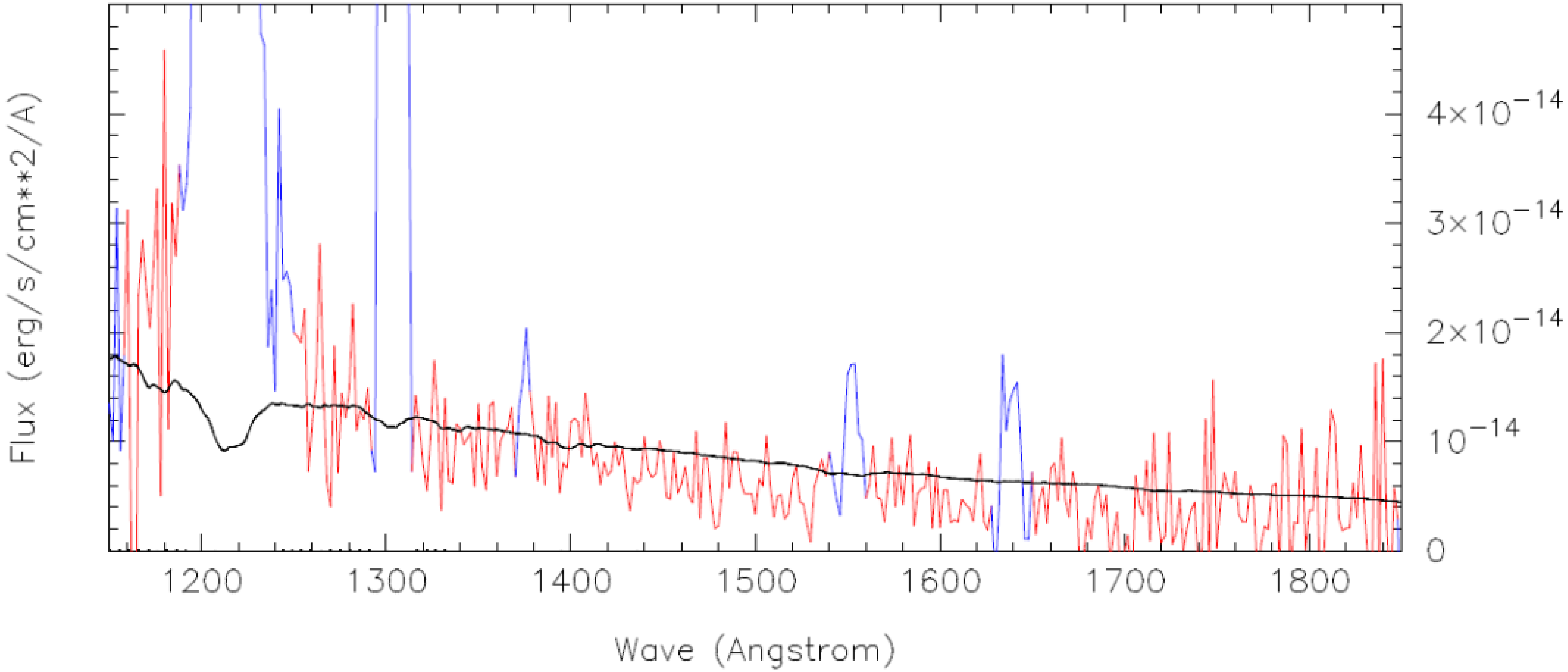
IM Nor – the distance challenge

- Known Outbursts: 1920, 2002
- The 2002 outburst of the RN IM Nor was followed visually and spectroscopically.
- It was detected as a hard X-ray source 6 months after the 2002 outburst (Orio et al. 2005).
- Woudt and Warner (2003) found its Porb to be 2.46h which places IM Nor in the middle of the CV period gap.
- Patterson et al.(2015) calls it a twin of T Pyxidis, with P/Pdot = 3 x 10^6 years

IM Nor – the distance challenge

- The Gaia distance is 1 kpc. With a 1.2 $M_\odot$ white dwarf, a model best fit WD photosphere yields a photospheric temperature Teff = 150,000 to 170,000 K, while our accretion disk models give an accretion rates a factor of 50-100 *too low* to account for the short (82 yr) recurrence time of IM Nor !!!???

IM Nor – the distance challenge



TELC 9/7-11/2019

Fig. 5.— An accretion disk model fit to the HST COS spectrum of IM Nor. The WD mass is 1.2 $M_\odot$, the inclination $i = 80°$, and the accretion rate is $3.5 \times 10^{-8} M_\odot$/yr giving a distance of 3.9 kpc (model #9 in Table 2).

Sion, E., Godon, P., Darnley, M., Starrfield, S., Williams, R.E. 2019, submitted to ApJ

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- For a distance of 3.90 kpc, a 1.2$M_\odot$ white dwarf accreting at the rate of 3.5 times $10^{-8} M_\odot$/yr (possibly driven by nova irradiation of the donor star) gives the recurrence time (82 years) of IM Nor.

CI Aql – a likely SNeIa candidate?

- FUV spectral analysis +Gaia distance → reveal CI Aql's FUV light is dominated by an optically thick accretion disk with an accretion rate of the order of 4×10^{-8} $M_\odot$/yr.

CI Aql – a likely SNeIa candidate?

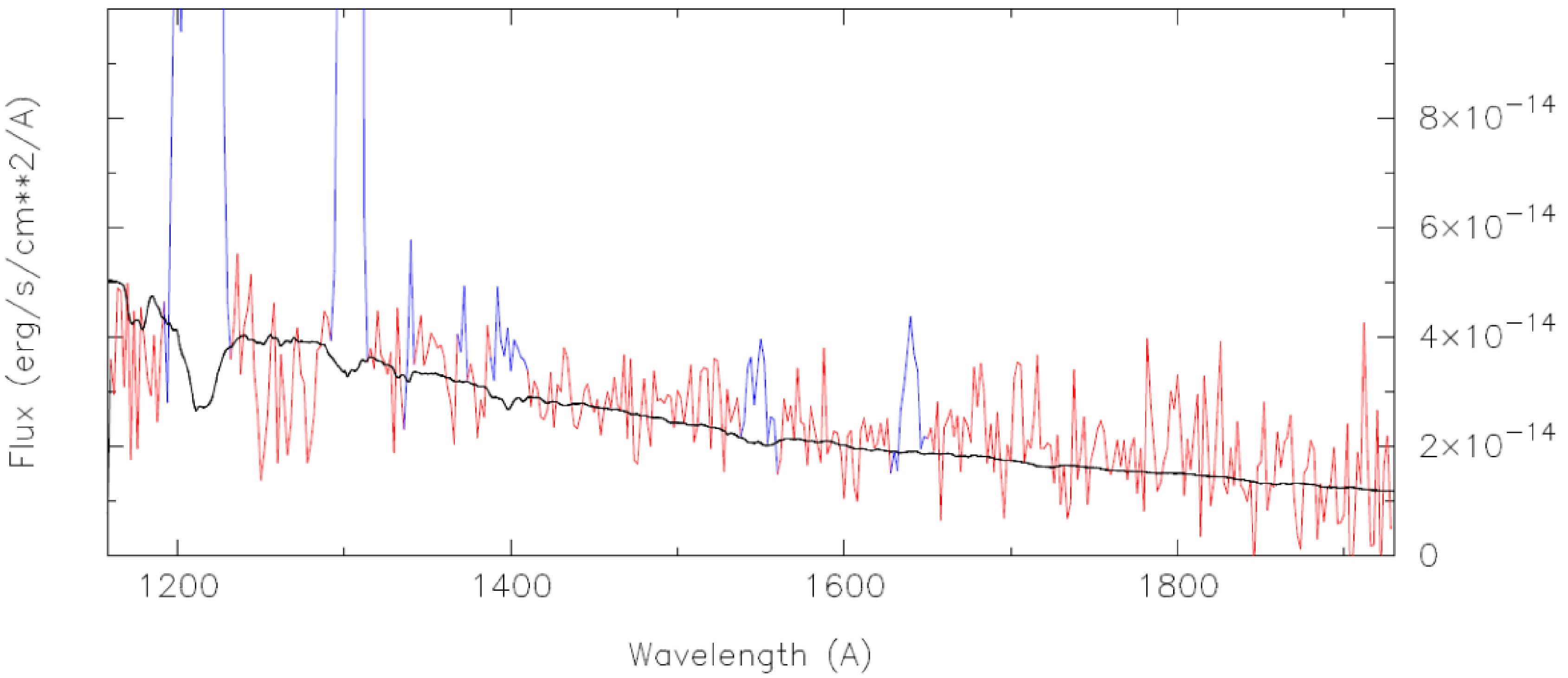


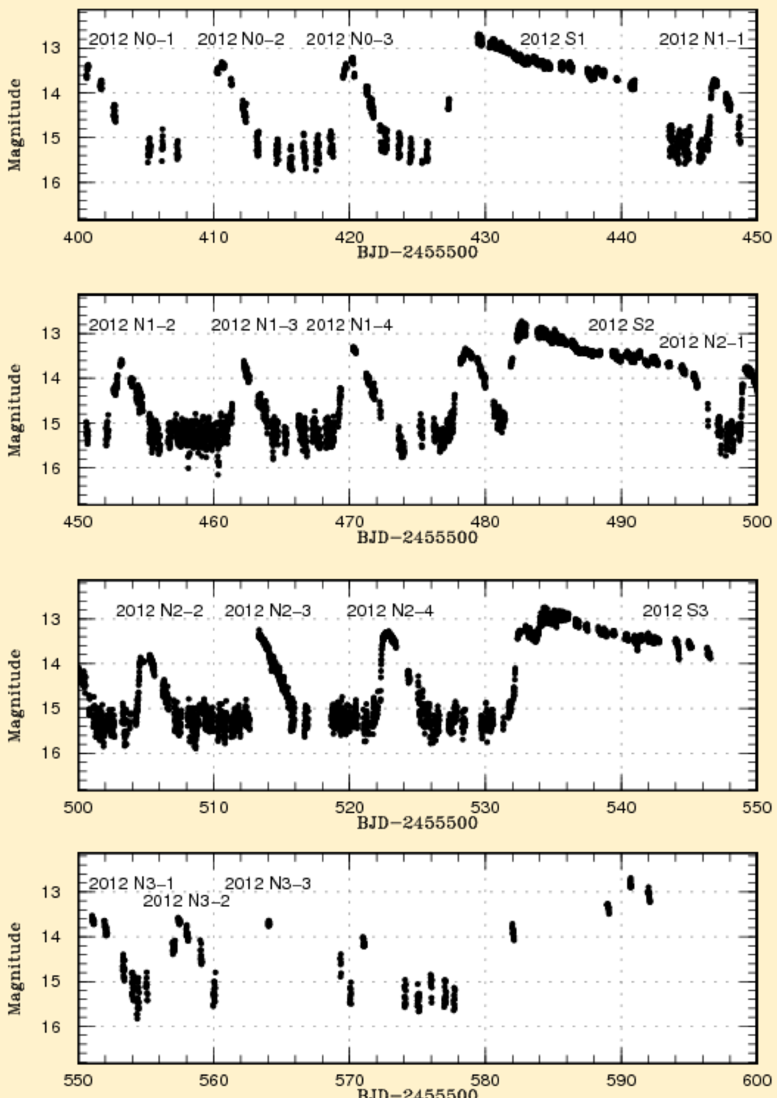
Fig. 2.— An accretion disk model fit to CI Aql with inner truncation. The inner disk radius was taken to be 5200 km. The outer disk radius, Rd, was chosen such that the outer disk's surface temperature reaches only 5,000 K so its contribution to the FUV is insignificant. This best fit truncated disk has an accretion rate of $dM/dt = 4 \times 10^{-8} M_{\odot}/yr$

Sion, E., Wilson, R.E., Godon, P.,Starrfield, S., Williams, R.E., Darnley,M. 2019, ApJ, 872, 68

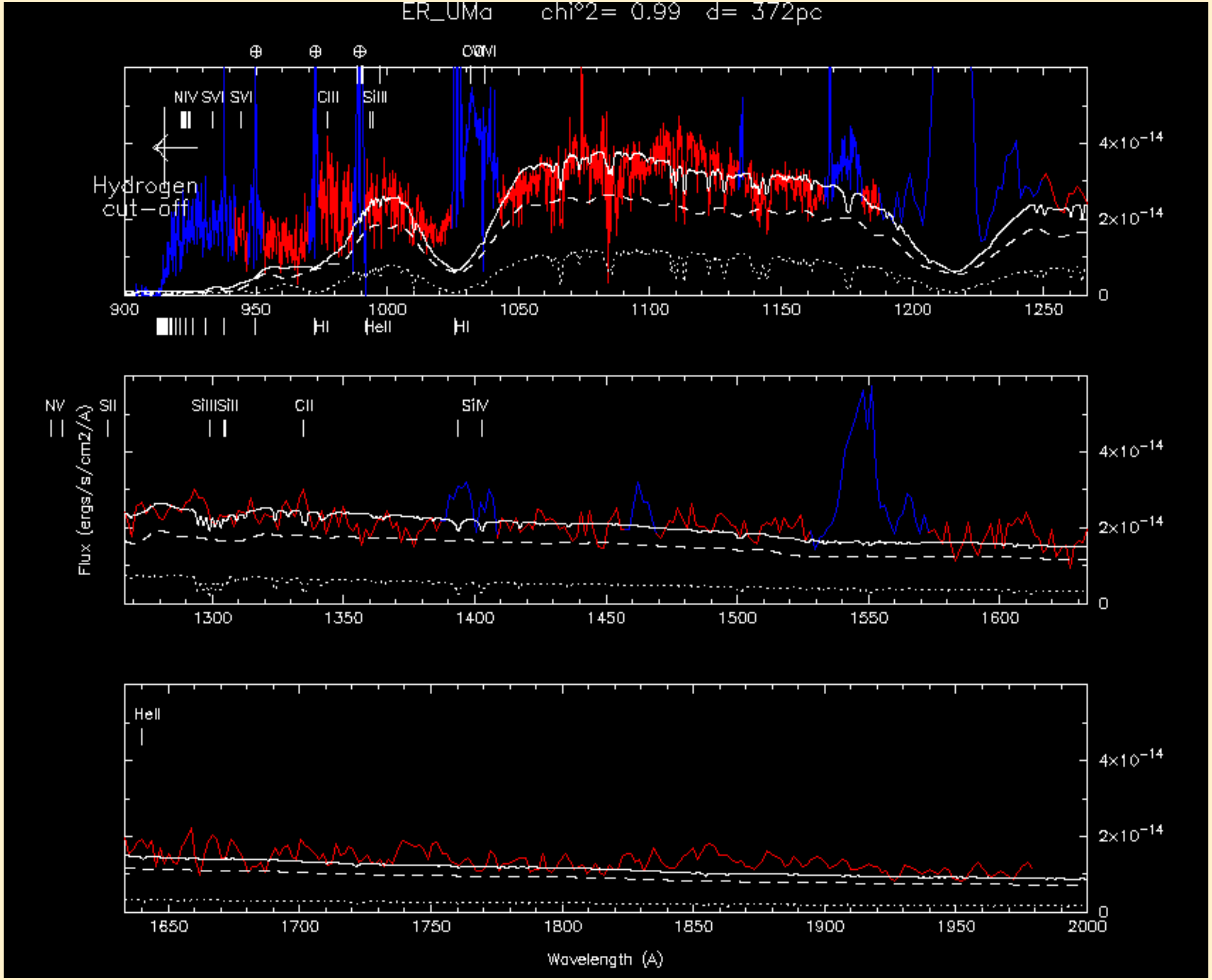
CI Aql – a likely SNeIa candidate?

- FUV spectral analysis +Gaia distance → reveal CI Aql's FUV light is dominated by an optically thick accretion disk with an accretion rate of the order of 4×10^{-8} M⊙/yr.
- dP/dt translates to a white dwarf mass change rate, dM1/dt, within the modest range of $+4.8\times10^{-8}$ to $+7.8\times10^{-8}$ M⊙/yr.
- The estimated white dwarf mass change through outburst for CI Aql, based on simple differencing of its pre- and post outburst orbit period, is unchanged from the previously published $+5.3\times10^{-6}$ M⊙.
- **At the WD's estimated mass increase rate, it will terminate as a Type Ia supernova within 10 million years.**

5. Final case: ER UMa – link between Novae and DNe?



- Subclass of SU Ursa Majoris Dwarf Novae
- They Have Normal Outbursts and Superoutbursts
- They have Very Short Cycle (days!) and Super Cycle Times
- They Exhibit Negative and Positive Super Humps
- Do They Have Higher Accretion Rates than Other Dwarf Novae below the CV Period Gap between 2 hrs and 3 hrs (where few CVs are found)?
- Does their peculiar behavior bear any relation to recent Classical Novae?



Guzman, G., Sion, E.M, Godon, P.2019, AJ, 158, 99

- With the Gaia parallax distance and the orbital inclination of 50◦ : we find that during the brief quiescence of only four days, the accretion rate is 7.3 × 10^−11 M⨀/yr ... For higher inclinations of 60 to 75 degrees, the accretion rate is 1 – 3 x 10^-10 Msun/yr.

- ER UMa's white dwarf contributes 55% of the FUV flux and the accretion disk contributes the remaining 45% of the flux.

- The white dwarf in ER UMa is markedly hotter (32,000 K) than the other white dwarfs in dwarf novae below the CV period gap which have typical temperatures ∼15,000 K.

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Do the ER UMa Systems have higher than average mass transfer rates than other DNe below the period gap? Missing evolutionary link?

Broad Questions Answered or Remaining Open

- Do CVs really evolve across the period gap or are there two distinct populations of CVs, one above the period gap and one below the period gap? → **YES!** CVs do indeed evolve across the period gap (Zorotovic et al. 2016 and subsequent papers)
- Do CVs undergo hibernation? Is hibernation theory correct? Shara versus Schaefer → It depends on how you determine hibernation

  NO! (Schaefer, B. et a. 2019, MNRAS, 487, 1120 references)

  YES! (Shara et al. 1986, ApJ, 311, 163, Schmidtbroeck et al. 2018)

Broad Questions Answered or Remaining Open (cont)

- Do CV white dwarf masses increase with time above and below the period gap (as a result of evolution) ? **NO!** (Zorotovic et al. 2011, ApJ, ; M. McAllister et al. 2019, MNRAS, 486, 5094)
- Are H-rich CVs with near-Chandrasekhar mass WDs the single degenerate pathway to Type Ia supernovae? → **YES!** (Shara et al.2018)
- What is the evolutionary status of the Nova-like Variables? open question (e.g.) Sahman 2019, Compact WD Binaries Conf. abstract, Yerevan, Armenia)

Broad Questions Answered or Remaining Open (cont)

- What is the correct angular momentum braking law for CVs above the period gap? → open question
- Are the CNO-processed abundances due to core material from the donor or contamination of the donor star due to TNR burning on the white dwarf → Open question

Conclusions

--The surface temperatures, chemical abundances, rotation rates and accretion rates onto the hot accreting WD components are being secured in a wide variety of interacting binaries spanning the range of orbital periods from hundreds of days (Symbiotic Novae & RNe) down to orbital periods of minutes (AM CVn Systems).

--CV White Dwarfs above the period gap are hotter than the ones below the period gap.

--Magnetic CV White Dwarfs are cooler than Non-Magnetic CV White Dwarfs at a given orbital period.

Conclusions

--CV White Dwarfs rotate much faster than single white dwarfs but not as fast as expected from the accreted angular momentum during the lifetime of the CV.

--~10% or more of CVs reveal the N/C abundance anomaly. For at least some of the CVs, the C/N anomaly and suprasolar abundances of A > 20 nuclides (e.g. Al, P, A) imply their origin from Explosive Thermonuclear Burning, then contamination of the donor star during the common envelope phase of the nova, followed by re-accretion by the White Dwarf (Sion and Sparks, 2014, ApJL).

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Thank you!

Questions: Ed Sion edward.sion@villanova.edu