Nova Eruptions And Their Consequences

Claus Tappert

Departamento de Física y Astronomía
Universidad de Valparaíso
Valparaíso, Chile
claus.tappert@uv.cl

The deaths of stars and the lives of galaxies
April 8-12, 2013, Santiago

Astro-Necromancy

Contents

- What is a nova?
- Novae and CVs
- Novae and the ISM
- Novae and other galaxies
- Novae and SNe Ia

Nova: modern definition

nova eruption = thermonuclear runaway on the surface of the white-dwarf primary in a cataclysmic variable

Astronomical Society of the Pacific
San Francisco, California
☆ ☆ ☆
Leaflet No. 418 — April, 1964
☆ ☆ ☆
ARE ALL NOVAE BINARY STARS?
By Robert P. Kraft
Mount Wilson and Palomar Observatories

THE CAUSE OF THE NOVA OUTBURST

S. STARRFIELD
Department of Physics, Arizona State University, Tempe, Ariz., U.S.A. and Los Alamos Scientific Laboratory, N.M., U.S.A.

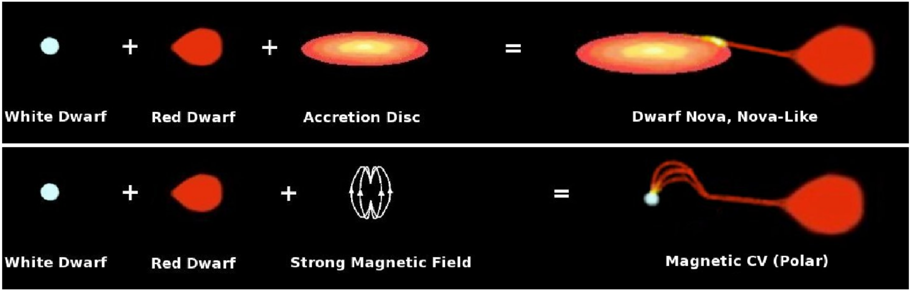
W. M. SPARKS
NASA/Goddard Space Flight Center, Greenbelt, Md., U.S.A.,

and

J. W. TRURAN
University of Illinois Observatory, Urbana, Ill. U.S.A.

P. Eggleton et al. (eds.), Structure and Evolution of Close Binary Systems, 155–172. All Rights Reserved. Copyright © 1976 by the IAU.

CVs - the Legoland version



$P_{\rm orb} \sim 80$ min $-$ 10 h

Novae are recurrent

CV is not destroyed by the nova eruption
$\Rightarrow$ accretion continues

Mon. Not. R. Astron. Soc. **293,** 145–150 (1998)

Nova V1425 Aquilae 1995: the early appearance of accretion processes in an intermediate polar candidate

A. Retter,* E. M. Leibowitz and O. Kovo-Kariti
School of Physics and Astronomy and the Wise Observatory, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel-Aviv University, Tel Aviv, 69978, Israel

(5) These results imply that accretion (probably via an accretion disc) was active in the system already some 15 months after the outburst of the nova.

$\Rightarrow$ next eruption is just a matter of time

Ejected masses

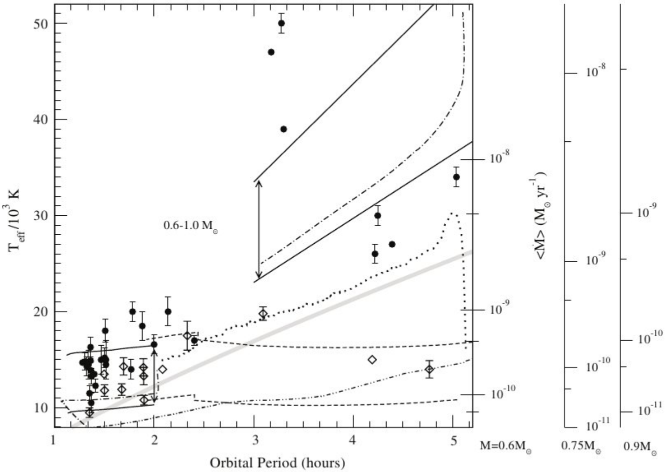
Schwarz, 2013, “Stella Novae”, Cape Town

	QU Vul	V1974 Cyg	V1065 Cen	V382 Vel	V4160 Sgr	V838 Her
t_2 (days)	25	17	11	4	2	2
M_{eject} (1e-5 M_{sun})	>35	19	14-17	18-50	~3.6	0.73

Adapted from Schwarz et al. 2007, ApJ, 657, 453 plus Helton et al. 2010, AJ, 140, 1347

Accretion rates

Townsley & Gänsicke, 2009, ApJ, 693, 1007



Recurrence times

ejected mass $\sim 10^{-4}\ \mathrm{M}_\odot$
highest average mass-transfer rates $\sim 10^{-8}\ \mathrm{M}_\odot/\mathrm{yr}$
$\Rightarrow t_\mathrm{rec} \geq 10^4$ yr

Shara et al., 2012, ApJ, 756, 107: expansion rate of Z Cam shell
$\Rightarrow t_\mathrm{rec} \geq 10^3$ yr

Recurrent Novae

Darnley, 2013, "Stella Novae", Cape Town

Classical vs. Recurrent Novae

An idealistic viewpoint

Classical Novae

- Only one observed outburst
- Recurrence timescales few thousand – million years
- Secondaries – main sequence stars
- Low mass transfer/accretion rates
- Range of WD masses
- Range of evolution speeds
- Fe II and He/N spectra
- >350 Galactic systems (900 M31)

Recurrent Novae

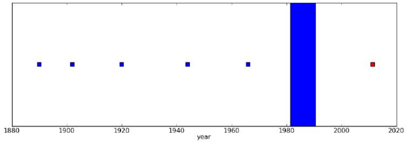
- >1 observed outburst
- Recurrence timescales 10-100 years
- Secondaries – sub-giants (U Sco) or red giants (RS Oph)
- High mass transfer/accretion rates
- High WD Masses
- Fast eruption evolution
- He/N spectra
- 10 Galactic systems (a few confirmed in LMC & M31)

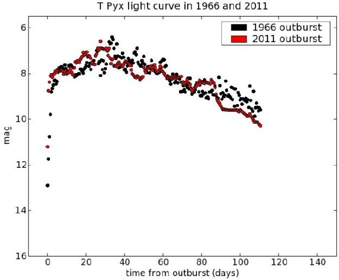
T Pyx

Ederoclite, 2013, “Stella Novae”, Cape Town

$M_{\rm WD} \sim 0.7 \pm 0.2 M_\odot$

Previous explosions: 1890, 1902, 1920, 1944, 1966.



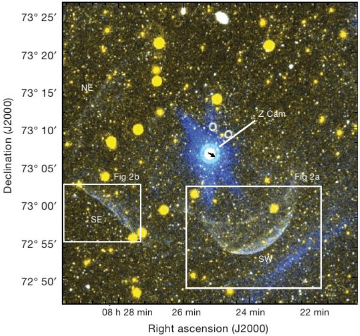


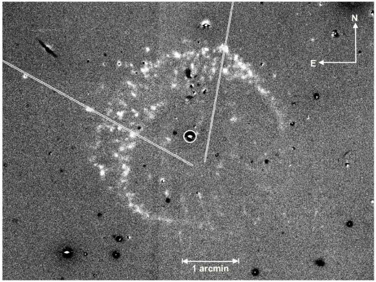
Novae are CVs

- Nova Her 1934 = DQ Her = prototype Intermediate Polar
- Nova Pic 1925 = RR Pic = SW Sex type star
- Nova Cyg 1975 = V1500 Cyg = Polar

CVs are Novae

Shara et al., 2007, Nature, 446, 159; 2012, ApJ, 758, 121





ancient nova shells around dwarf novae Z Cam and AT Cnc

Novae vs CVs

Which parameters influence the recurrence time?

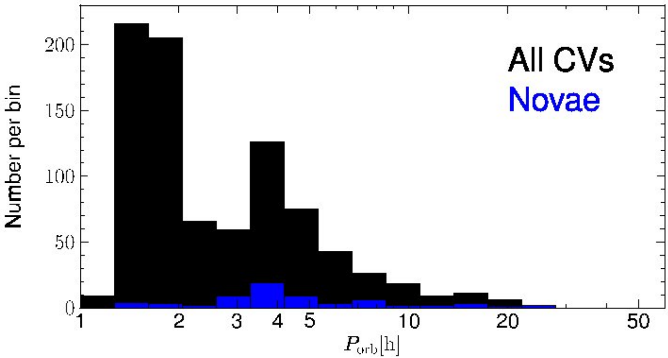
- Mass-transfer rate!
- Magnetic field?
- WD mass
- WD chemical composition (CO vs ONe)
- Chemical composition of the secondary? (Iben & Tutukov, 1984, ApJ, 284, 719)

How does the nova eruption affect CV evolution?

- WD mass?
- Mass-transfer rate (Hibernation)?

Periods

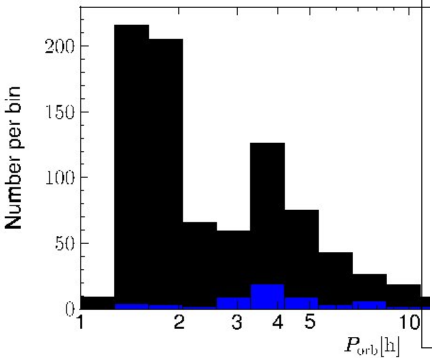
data from Ritter & Kolb, 2003, A&A, 404, 301 (update 7.19, 2013)

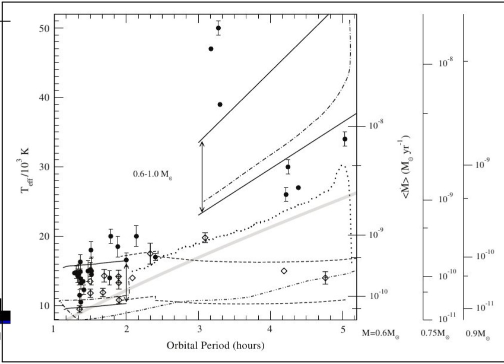


Problem: 200 pre-1980 novae reported, 2/3 still without identification of the post-nova ⇒ Tappert et al., 2012, MNRAS, 423, 2476

Periods

data from Ritter & Kolb, 2003, A&A, 404, 301 (update 7.19, 2013)

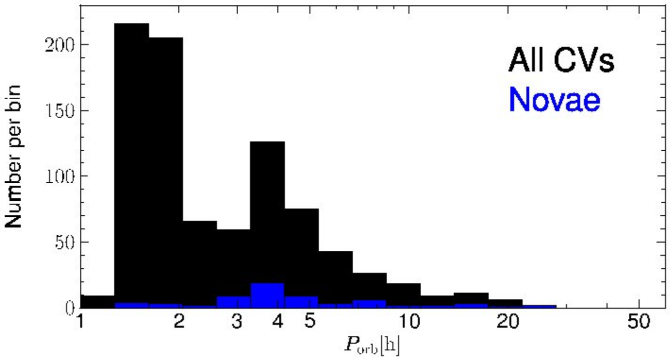




Problem: 200 pre-1980 novae reported, 2/3 still without identification of the post-nova ⇒ Tappert et al., 2012, MNRAS, 423, 2476

Periods

data from Ritter & Kolb, 2003, A&A, 404, 301 (update 7.19, 2013)

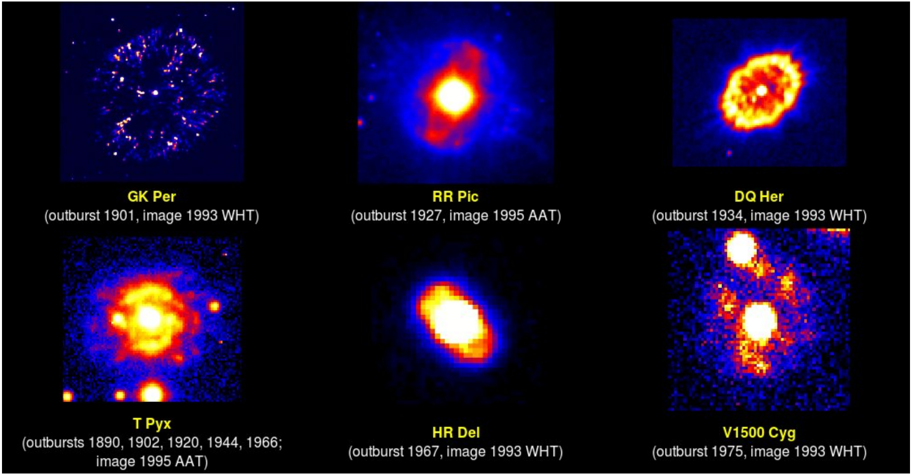


Problem: 200 pre-1980 novae reported, 2/3 still without identification of the post-nova ⇒ Tappert et al., 2012, MNRAS, 423, 2476

Recovering old novae

$\Rightarrow$ work in progress

Ejecta



Jodrell Bank website

TNR

for $\dot{M} \leq 10^{-8} - 10^{-7}\ \mathrm{M}_\odot/\mathrm{yr}$, part of the accreted material is compressed into a degenerate state

Pauli $\Rightarrow$ new e^- have to occupy higher energy levels $\Rightarrow E_{\mathrm{gas}}$ and $T_{\mathrm{gas}} \uparrow$

(non-relativistic) degenerate gas: $P \propto V^{-5/3} \Rightarrow$ independent of T
$\Rightarrow$ when $T_{\mathrm{gas}} > T_{\mathrm{ignition}}$, degeneracy prevents envelope expansion

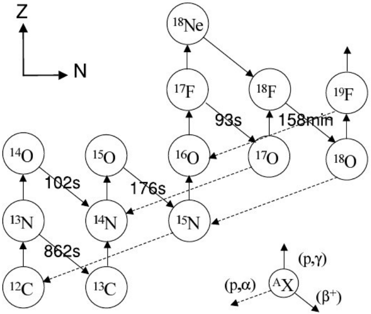
$\Rightarrow$ Thermonuclear Runaway (mainly CNO @ $T \sim 3 \times 10^7$ K)

during TNR T increases further, so in principle at one point $T > T_F$
$\Rightarrow$ degeneracy is lifted, envelope can expand (slowly) and cool down

but: $\tau_{\mathrm{nuc}} \ll \tau_{\mathrm{dyn}} \Rightarrow T$ increases much faster than (controlled) expansion
$+$ convection depositing β^+ unstable nuclei in envelope

cno

Hernanz, 2005, Asp Conf.Ser. 330, p.265



$T_{\mathrm{peak}} \geq 10^8$ K

cycle operates out of equilibrium ($\tau_{\beta^+} \geq \tau_{(p,\gamma)}$)

β^+ unstable nuclei release energy in the envelope

Observed Abundances

Livio & Truran, 1994, ApJ, 425, 797

Heavy Element Abundances in Novae

			Mass Fractions										
Object	Year	Ref.	H	He	C	N	O	Ne	Na-Fe	Z	$(Z/Z_\odot)$	$(Ne/Ne_\odot)$	(Ne/Z)
T Aur	1891	4	0.47	0.40		0.079	0.051			0.13	6.8		
RR Pic	1925	13	0.53	0.43	0.0039	0.022	0.0058	0.011		0.043	2.3	6.3	13.5
DQ Her	1934	15	0.34	0.095	0.045	0.23	0.29			0.57	30.		
DQ Her	1934	7	0.27	0.16	0.058	0.29	0.22			0.57	30.		
HR Del	1967	12	0.45	0.48		0.027	0.047	0.0030		0.077	4.1	1.7	2.0
V1500 Cyg	1975	3	0.49	0.21	0.070	0.075	0.13	0.023		0.30	16.	13.	4.0
V1500 Cyg	1975	6	0.57	0.27	0.058	0.041	0.050	0.0099		0.16	8.4	5.6	3.3
V1688 Cyg	1978	11	0.45	0.23	0.047	0.14	0.13	0.0068		0.32	17	3.9	1.1
V1688 Cyg	1978	1	0.45	0.22	0.070	0.14	0.12			0.33	17.		
V693 CrA	1981	14	0.29	0.32	0.0046	0.080	0.12	0.17	0.016	0.39	21.	97.	23.
V693 CrA	1981	1	0.16	0.18	0.0078	0.14	0.21	0.26	0.030	0.66	35.	148.	21.
V1370 Aql	1982	10	0.053	0.088	0.035	0.14	0.051	0.52	0.11	0.86	45.	296.	32.
V1370 Aql	1982	1	0.044	0.10	0.050	0.19	0.037	0.56	0.017	0.86	45.		34.
GQ Mus	1983	5	0.27	0.32	0.016	0.19	0.19	0.0034	0.0068	0.41	22.	1.9	0.073
PW Vul	1984	8	0.69	0.25	0.0033	0.049	0.014	0.00066		0.067	3.5	.38	0.52
PW Vul	1984	5	0.54	0.28	0.032	0.11	0.038			0.18	9.5		
PW Vul	1984	1	0.47	0.23	0.073	0.14	0.083	0.0040	0.0048	0.30	16.	2.3	0.70
QU Vul	1984	9	0.30	0.60	0.0013	0.018	0.039	0.040	0.0049	0.10	5.3	23.	21.
QU Vul	1984	1	0.33	0.26	0.0095	0.074	0.17	0.086	0.063	0.40	21.	49.	11.
V842 Cen	1986	1	0.41	0.23	0.12	0.21	0.030	0.00090	0.0038	0.36	19.	.51	0.13
V827 Her	1987	1	0.36	0.29	0.087	0.24	0.016	0.00066	0.0021	0.35	18.	.38	0.099
QV Vul	1987	1	0.68	0.27		0.010	0.041	0.00099	0.00096	0.053	2.8	.56	0.98
V2214 Oph	1988	1	0.34	0.26		0.31	0.060	0.017	0.015	0.40	21.	9.7	2.2
V977 Sco	1989	1	0.51	0.39		0.042	0.030	0.026	0.0027	0.10	5.3	15.	14.
V443 Sct	1989	1	0.49	0.45		0.053	0.0070	0.00014	0.0017	0.062	3.3	.80	0.12
LMC	1990A	2	0.37	0.59	0.00058	0.0072	0.0059	0.013	0.012	0.039	2.1	7.4	18.

References.—(1) Andrea 1992; (2) Dopita et al. 1992; (3) Ferland & Shields 1978; (4) Gallagher et al. 1980; (5) Hassall et al. 1990; (6) Lance et al. 1988; (7) Petitjean et al. 1990; (8) Saizar et al. 1991; (9) Saizar et al. 1992; (10) Snijders et al. 1987; (11) Strickland et al. 1981; (12) Tylenda 1978; (13) Williams & Gallagher 1979; (14) Williams et al. 1985; (15) Williams et al. 1978.

Some Mixing Required

theory of the eruption + observation of the shell
⇒ processed material hast to be mixed into the accreted envelope

but how?

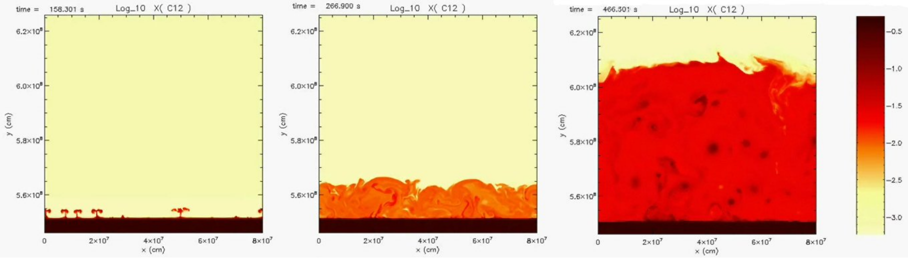
José, 2013, "Stella Novae", Cape Town

The mixing mechanism: the *Holy Grail* of nova modeling

* **Diffusion Induced Convection** [Prialnik & Kovetz 1984; Kovetz & Prialnik 1985; Iben, Fujimoto & MacDonald 1991, 1992; Fujimoto & Iben 1992]
* **Shear mixing** [Durisen 1977; Kippenhahn & Thomas 1978; MacDonald 1983; Livio & Truran 1987; Kutter & Sparks 1987; Sparks & Kutter 1987]
* **Convective Oveshoot Induced Flame Propagation** [Woosley 1986]
* **Convection Induced Shear Mixing** [Kutter & Sparks 1989]
* **Multidimensional processes** [Glasner & Livne 1995; Glasner, Livne & Truran 1997, 2005, 2007, 2012; Rosner et al. 2002; Alexakis et al. 2004, Casanova et al. 2010, 2011a,b]

Kelvin-Helmholtz

Casanova et al., 2011, Nature, 478, 490; A&A, 527, 5



2D simulations

mostly independent of specifics of the initial perturbation, grid resolution, size of computational domain

3D simulation in progress

Chemical enrichment

$\sim$35 nova eruptions per year in the Galaxy
(Shafter, 1997, ApJ, 487, 226)

observed shell mass $\sim 2 \times 10^{-4}\ \mathrm{M_\odot/yr}$

$\Rightarrow$ contributed mass rate $\sim 7 \times 10^{-3}\ \mathrm{M_\odot/yr}$

in comparison, SNe: $\sim 6 \times 10^{-2}\ \mathrm{M_\odot/yr}$

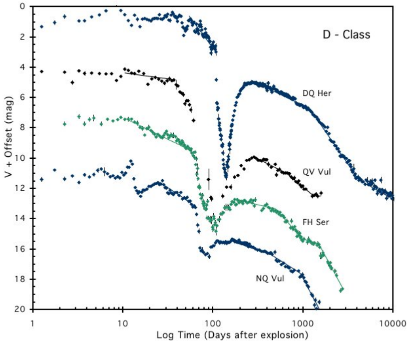
$\Rightarrow$ much less important than SNe
(if not $\sim$10 times more elements are produced)

but: M_{ejected} could actually be higher (Gehrz et al., 1998, PASP, 110, 3; Gehrz, 2013, "Stella Novae", Cape Town)

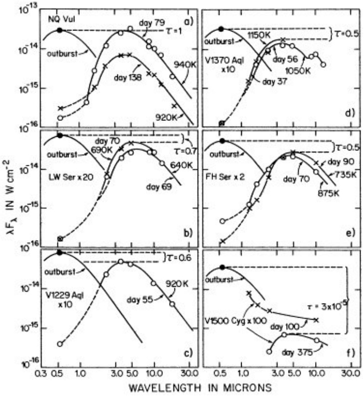
important contributers of particular isotopes,
mainly ^{13}C, ^{15}N, ^{17}O; also ^{7}Li(!) and ^{26}Al

(Some) Novae are dusty

Strope et al., 2010, AJ, 140, 34



Gehrz, 1988, Ann. Rev. A&A, 26, 377



∼20% of classical novae produce dust

Dust from novae

Gehrz et al., 1998, PASP, 110, 3

SUMMARY OF THE PHYSICAL CHARACTERISTICS OF 25 RECENT CLASSICAL NOVAE FROM INFRARED MEASUREMENTa

Nova	Year	V_o (km s^{-1})	Dust Optical Depth $\tau_d = (L_{IR})_{max}/(L_o)_{max}$	t_d; $t_{(IRmax)}$ (days)	Shell Density at R_c (g cm^{-2})	Types of Dust Formed[b]	t_3[c] (days)	M_{gas} ($M_\odot$)	M_{dust} ($M_\odot$)	Gas-to-Dust Ratio M_{gas}/M_{dust}	References
FH Ser	1970	560	0.5	?; 60	...	C	62	...	...	...	1, 2
V1229 Aql	1970	575	0.55	...	...	C	37	...	...	...	1, 2
V1301 Aql	1975	...	...	...	...	C	35	...	...	...	1, 2
V1500 Cyg[a]	1975	1180	?	100; 100	3×10^{-17}	...	3.6	$0.05–8 \times 10^{-4}$	...	...	1, 2
NQ Vul	1976	750	1.00	32; 80	2.3×10^{-15}	C	65	10^{-4}	2×10^{-7}	520	1, 2
V4021 Sgr	1977	...	≤0.60	...	...	C	70	...	...	...	1, 2
LW Ser	1978	1250	0.70	23; 75	3×10^{-16}	C	50	2×10^{-5}	3.6×10^{-7}	56	1, 2
V1668 Cyg	1978	1300	0.08	33; 57	7.6×10^{-17}	C	23	2×10^{-5}	2×10^{-8}	800	1, 2
V1370 Aql[d]	1982	2800	0.50	≤16; ≤37	...	C; SiC; SiO_2	?	...	...	...	1, 2
GQ Mus	1983	600	No dust	...	$\leq 10^{-17}$	No dust	45	$\leq 2.6 \times 10^{-6}$	...	...	1, 2
PW Vul	1984 #1	285	3×10^{-3}	152; ≤ 280	2.0×10^{-17}	C	97	$\leq 3.2 \times 10^{-6}$	5.1×10^{-10}	6.3×10^{-3}	1, 2
QU Vul[a]	1984 #2	1–5000	3×10^{-3}	40–200; 240	...	SiO_2	40	3×10^{-4}	10^{-8}	3×10^{4}	1, 2
OS And[a,e]	1986	900	Dust	?; ?	1.1×10^{-17}	C?	22	...	...	...	2, 3, 10
V1819 Cyg[a]	1986	1000	No dust	...	...	No dust	87–104	...	...	...	2, 3
V842 Cen	1986	1200	1.00	36; 87	...	C; SiC; HC	48	...	...	...	2, 3
V827 Her[a]	1987	1000	0.10	43; 83	...	C	55	...	...	...	1, 2
V4135 Sgr	1987	500	...	...	...	...	30	...	...	...	2, 3
QV Vul	1987	700	1.00	56; 115	2.0×10^{-16}	C; SiO_2; HC; SiC	?	3×10^{-5}	3.4×10^{-8}	890	2, 3
LMC 1988 #1	1988 #1	800	0.06	59; 57	...	C?	43	...	...	...	2, 3
LMC 1988 #2	1988 #2	1500	...	...	...	...	15	...	...	...	2, 3
V2214 Oph	1988	500	...	...	...	...	73	...	...	...	2, 3
V838 Her	1991	3500	0.05	18; 25	...	C	5	$0.9–6.4 \times 10^{-4}$	3×10^{-5}	3–21	4
V1974 Cyg[a]	1992	2250	...	...	...	No dust	47	$2–5 \times 10^{-4}$	...	...	5, 6
V705 Cas	1993	840	0.52	70; 106	...	C; HC; SiO_2	90	$1–1.3 \times 10^{-5}$	2×10^{-6}	5	7, 8
Aql 1995[a]	1995	1510	0.05	...	...	C	30	...	...	...	9

⇒ C, SiC, SiO_2, hydrocarbons

Pre-solar grains?

José & Hernanz, 2007, M&P Science, 42, 1135

Table 1. Presolar grains with an inferred nova origin.

Grain	Composition	$^{12}C/^{13}C$	$^{14}N/^{15}N$	$\delta^{29}Si/^{28}Si$	$\delta^{30}Si/^{28}Si$	$^{26}Al/^{27}Al$	$^{20}Ne/^{22}Ne$
AF15bB-429-3	SiC	9.4 ± 0.2	–	28 ± 30	1118 ± 44	–	–
AF15bC-126-3	SiC	6.8 ± 0.2	5.22 ± 0.11	-105 ± 17	237 ± 20	–	–
KJGM4C-100-3	SiC	5.1 ± 0.1	19.7 ± 0.3	55 ± 5	119 ± 6	0.0114	–
KJGM4C-311-6	SiC	8.4 ± 0.1	13.7 ± 0.1	-4 ± 5	149 ± 6	>0.08	–
KJC-112	SiC	4.0 ± 0.2	6.7 ± 0.3	–	–	–	–
KFC1a-551	C	8.5 ± 0.1	273 ± 8	84 ± 54	761 ± 72	–	–
KFB1a-161	C	3.8 ± 0.1	312 ± 43	-133 ± 81	37 ± 87	–	<0.01
Solar		89	272	0	0	0	14
Nova models		0.2–3	0.1–1900	−950 to1800	−1000 to 47,000	0.01–0.9	0.1–2900

The solar N ratio in the table is that from terrestrial air. Grains AF are from the Acfer 094 meteorite, whereas grains KJ and KF are from the Murchison meteorite (see Amari et al. 2001c and Amari 2002 for details). Errors are 1σ.

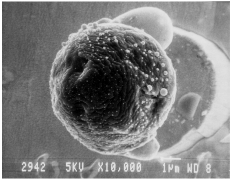


image from S.Armani

⇒ mixed with solar metallicity material

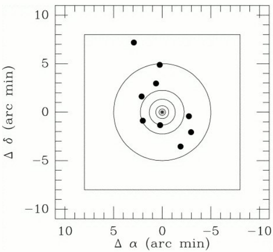
Nittler & Hoppe, 2005, ApJL, 631, L89: SN origin?

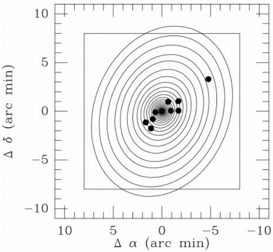
Extragalactic Novae

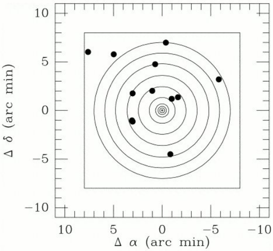
M 51

M 87

M 101







Shafter et al., 2000, ApJ, 530, 193

Nova populations

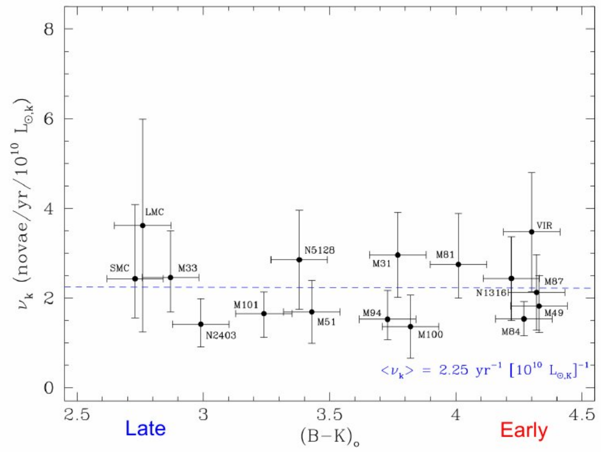
disc	bulge
fast	slow
bright	faint
young	old
high M_1	low M_1
hot WD	cool WD
He/N	Fe II
short t_{rec}	long t_{rec}

- Duerbeck, 1990, Lec.Notes Phys., 369, 34
- Williams, 1992, AJ, 104, 725
- della Valle et al., 1992, A&A, 266, 232
- della Valle & Livio, 1998, ApJ, 506, 818
- Nelson et al., 2004, ApJ, 602, 938

$\Rightarrow$ luminosity-specific nova rate is expected to vary with Hubble type (Yungelson et al., 1997, ApJ, 481, 127)

Nova rate vs Hubble type

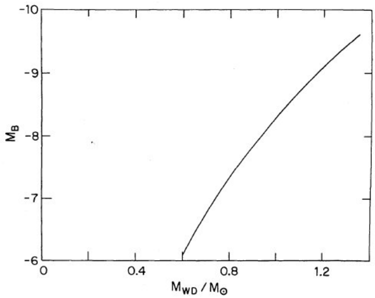
Shafter, 2013, “Stella Novae”, Cape Town

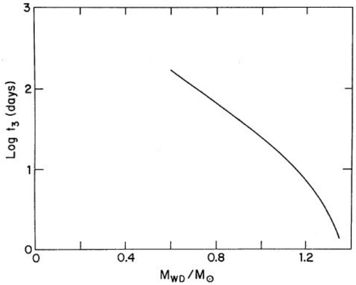


⇒ LSNR roughly constant, but large uncertainties

Standard candles? Theory

Livio, 1992, ApJ, 393, 516





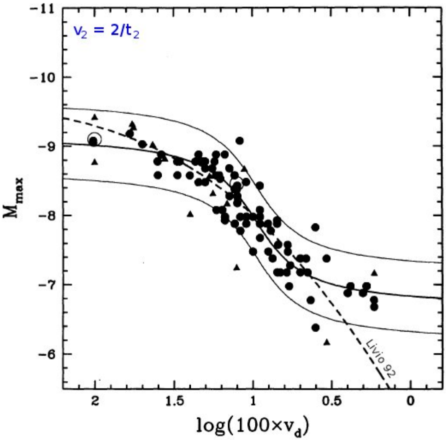
$M_B^{\max} \approx -8.3 - 10.0 \log(M_1/M_\odot)$

$t_3 = 51.3(M_1/M_{\rm Ch})^{-1}[((M_1/M_{\rm Ch})^{-2/3} - (M_1/M_{\rm Ch})^{2/3})]^{3/2}$

$\Rightarrow$ maximum magnitude vs rate of decline (MMRD): $t_3 = t_3(M_B^{\max})$

Standard candles? Observations

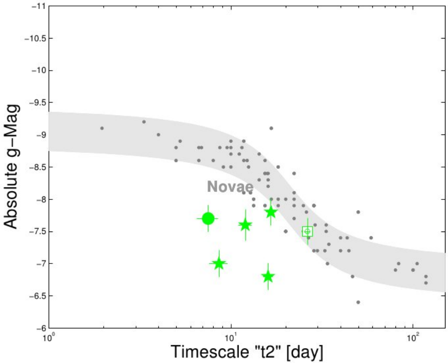
della Valle & Livio, 1995, ApJ, 452, 704:
M31 and LMC + V1974 Cyg and V838 Her



scatter theoretically expected:
$M^{\rm max}$ also depends on $\dot{M}$, $T_{\rm WD}$, B

Standard candles??? The Fast and not so Furious

Kasliwal et al., 2011, ApJ, 735, 94

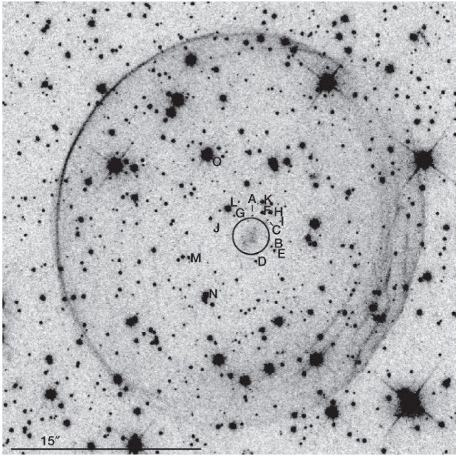


inconsistent with the MMRD!

also: most Faint and Fast Novae are FeII class ⇒ supposed to be slow!

SN Ia progenitors?

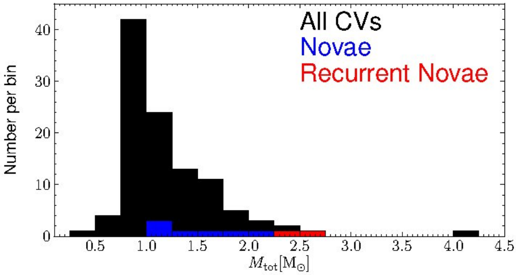
Schaefer & Pagnotta, 2012, Nature, 481, 164



no remnant $< M_V = 8.4$!

$\Rightarrow$ double-degenerate (or CV?)

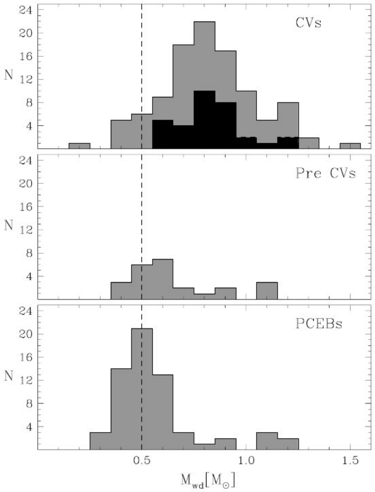
CV Masses



data from Ritter & Kolb, 2003, A&A, 404, 301 (update 7.19, 2013)

Mass growth in CV WDs?

Zorotovic et al., 2011, A&A, 536, 42



$\Rightarrow M_{\text{ejected}} < M_{\text{accreted}}$

but

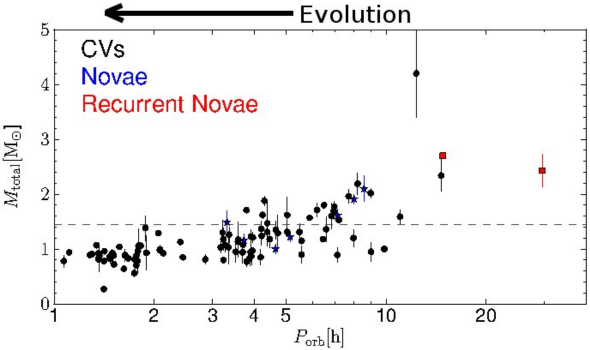
- mixing
- observed M_{shell} thought to be a lower limit

Mass evolution

Nova eruptions are the primary mechanism for mass loss in CVs

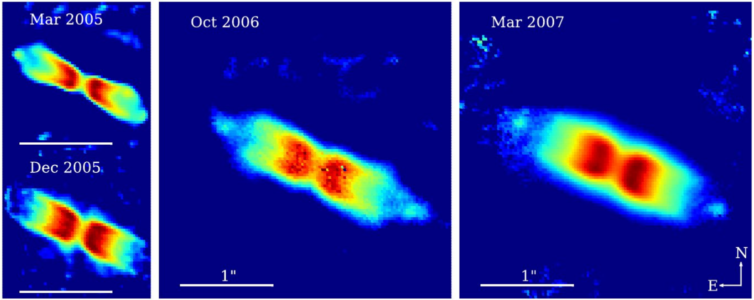
$\Rightarrow$ they prevent SNe Ia

and they're doing a pretty good job, too:



The one and (still) only He nova: V445 Pup

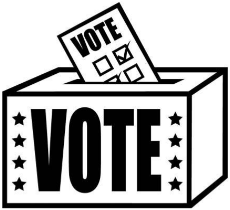
Woudt et al., 2009, ApJ, 706, 738



luminosities & velocities $\Rightarrow$ massive WD + He star

SN Ia progenitor?

The ultimate answer



The Big South African SNe Ia Progenitors Vote

	Yes	No
CNe	5	25
RNe	25	5

many thanks to Helena Uthas who kept the record!

Summary

- CNe = TNR @ CV-WDs
- All novae are recurrent but less so than Recurrent Novae
- Don’t ignore old novae: CV parameters $\longleftrightarrow$ Nova eruptions
- Nova WDs like to mix before they erupt
- Novae might shine even less standardly than previously assumed
- Novae prevent CVs from becoming SNe, though they might fail to do so in isolated cases