The role played by nova explosions in the origin of lithium-7 and cosmic rays

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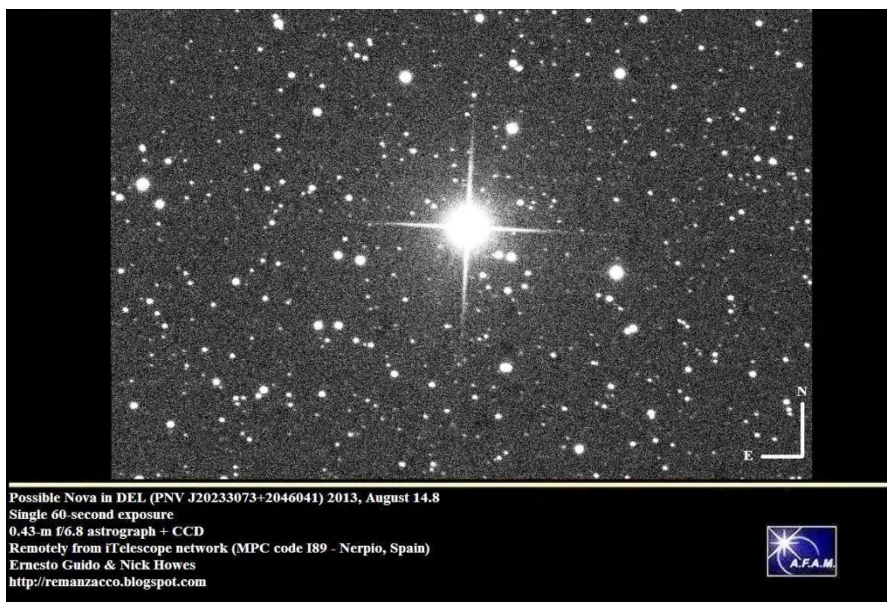


What’s a nova?

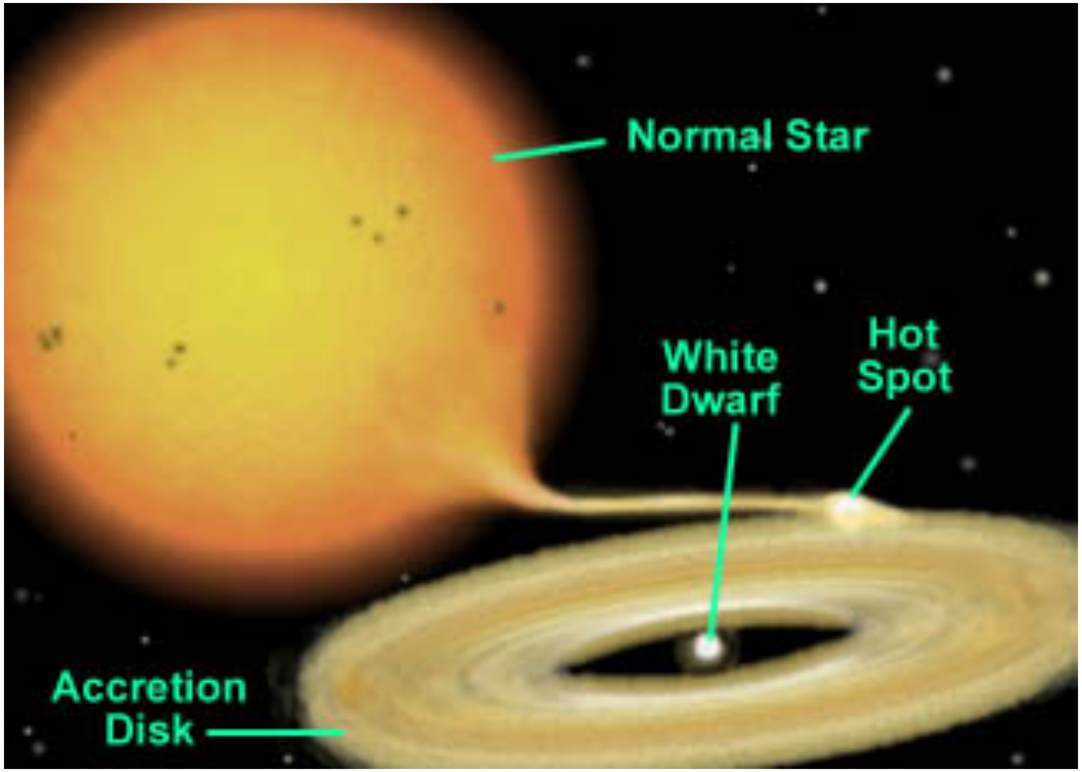
“Nova stella”

Very often discovered by amateur astronomers

Nova Cygni 1975

What's a nova?

A thermonuclear explosion of H on top of an accreting white dwarf in a close binary system



Two recent discoveries about nova explosions

Two recent discoveries about nova explosions

- Observational confirmation of ^{7}Li synthesis during nova explosions: relevance for the origin of lithium in the Universe

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LETTER

doi:10.1038/nature14161

Explosive lithium production in the classical nova V339 Del (Nova Delphini 2013)

Akito Tajitsu[1], Kozo Sadakane[2], Hiroyuki Naito[3,4], Akira Arai[5,6] & Wako Aoki[7]

Tajitsu et al. 2015, Nature

found. Here we report the detection of highly blue-shifted resonance lines of the singly ionized radioactive isotope of beryllium, ^{7}Be, in the near-ultraviolet spectra of the classical nova V339 Del (Nova Delphini 2013) 38 to 48 days after the explosion. ^{7}Be decays to form ^{7}Li within a short time (half-life of 53.22 days[4]). The ^{7}Be was created during the

ASTROPHYSICS

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News & Views

A lithium-rich stellar explosion

The contribution of explosions known as novae to the lithium content of the Milky Way is uncertain. Radioactive beryllium, which transforms into lithium, has been detected for the first time in one such explosion. SEE LETTER P.381

MARGARITA HERNANZ

during supernova explosions and their dimmer

Detection of ^{7}Li in Nova Cen 2013

The Astrophysical Journal Letters, 808:L14 (5pp), 2015 July 20 doi:10.1088/2041-8205/808/1/L14

EARLY OPTICAL SPECTRA OF NOVA V1369 CEN SHOW THE PRESENCE OF LITHIUM

Luca Izzo[1,2], Massimo Della Valle[2,3], Elena Mason[4], Francesca Matteucci[5], Donatella Romano[6], Luca Pasquini[7], Leonardo Vanzi[8], Andres Jordan[9], José Miguel Fernandez[10], Paz Bluhm[10], Rafael Brahm[10], Nestor Espinoza[10], and Robert Williams[11]

ABSTRACT

We present early high-resolution spectroscopic observations of the nova V1369 Cen. We have detected an absorption feature at 6695.6 Å that we have identified as blueshifted ^{7}Li I λ6708 Å. The absorption line, moving at $-550\ \mathrm{km\ s^{-1}}$, was observed in five high-resolution spectra of the nova obtained at different epochs. Based on the intensity of this absorption line, we infer that a single nova outburst can inject in the Galaxy $M_{\mathrm{Li}} = 0.3$–4.8×10^{-10} $M_{\odot}$. Given the current estimates of the Galactic nova rate, this amount is sufficient to explain the puzzling origin of the overabundance of lithium observed in young star populations.

Izzo et al. 2015, ApJ

Two recent discoveries about nova explosions

- Observational confirmation of ^{7}Li synthesis during nova explosions: relevance for the origin of lithium in the Universe

- Detection of HE gamma-rays (E > 100 MeV) from a handful of novae: novae as accelerators of particles and thus origin of cosmic rays

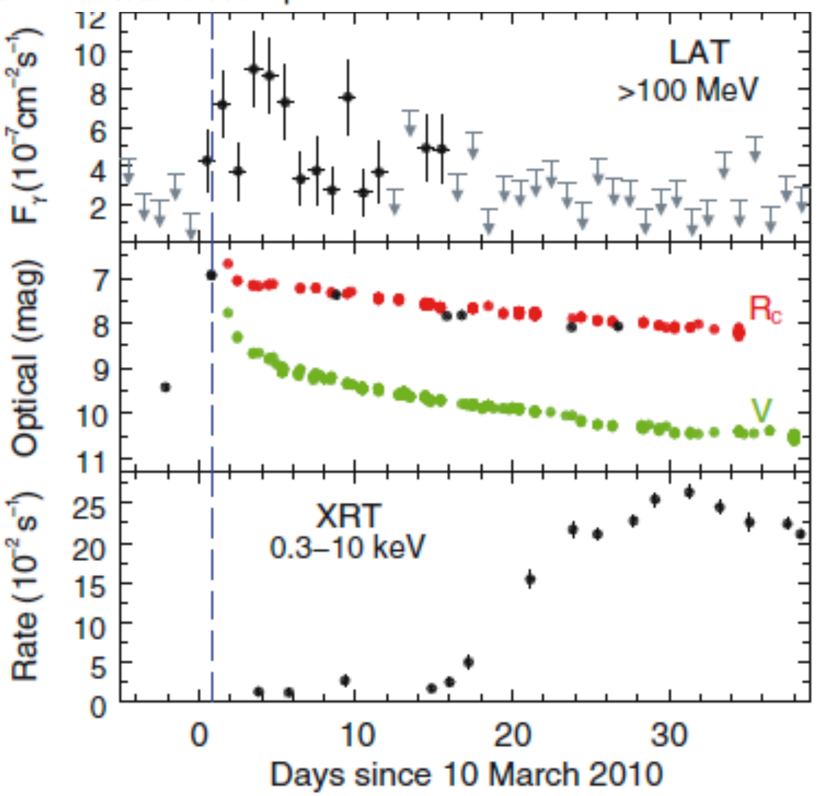
First nova detected in (HE) gamma-rays Fermi/LAT - E>100 MeV

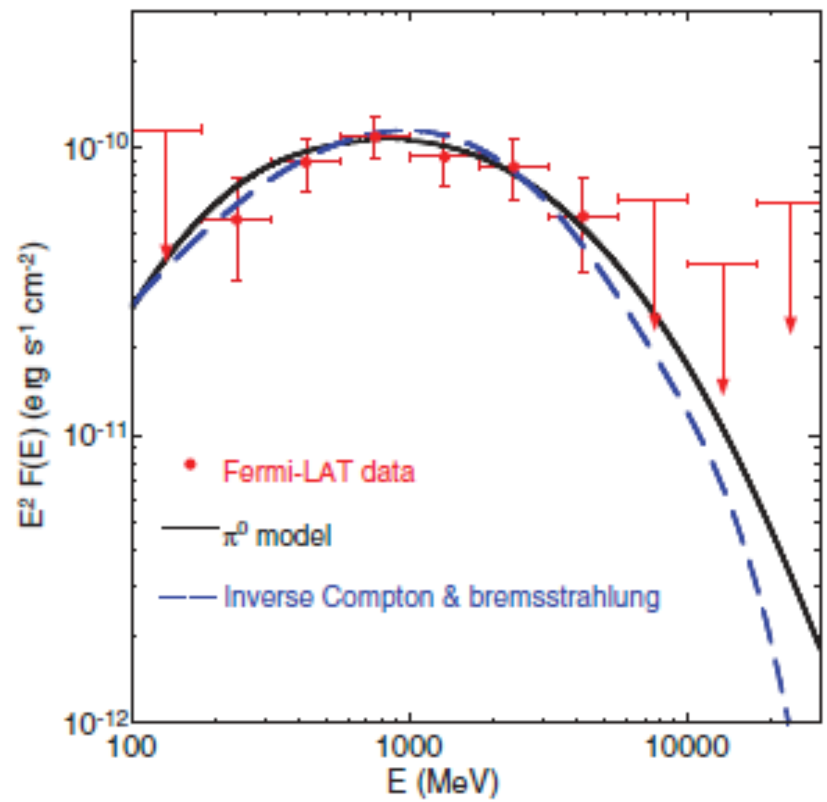
Gamma-Ray Emission Concurrent with the Nova in the Symbiotic Binary V407 Cygni

V407 Cyg: WD + red giant

The Fermi-LAT Collaboration*†

Abdo et al. 2010, Science





Other Novae detected in (HE) gamma-rays
Fermi/LAT - E>100 MeV

Fermi establishes classical novae as a distinct class of gamma-ray sources

The Fermi-LAT Collaboration*†

Science **345**, 554 (2014)

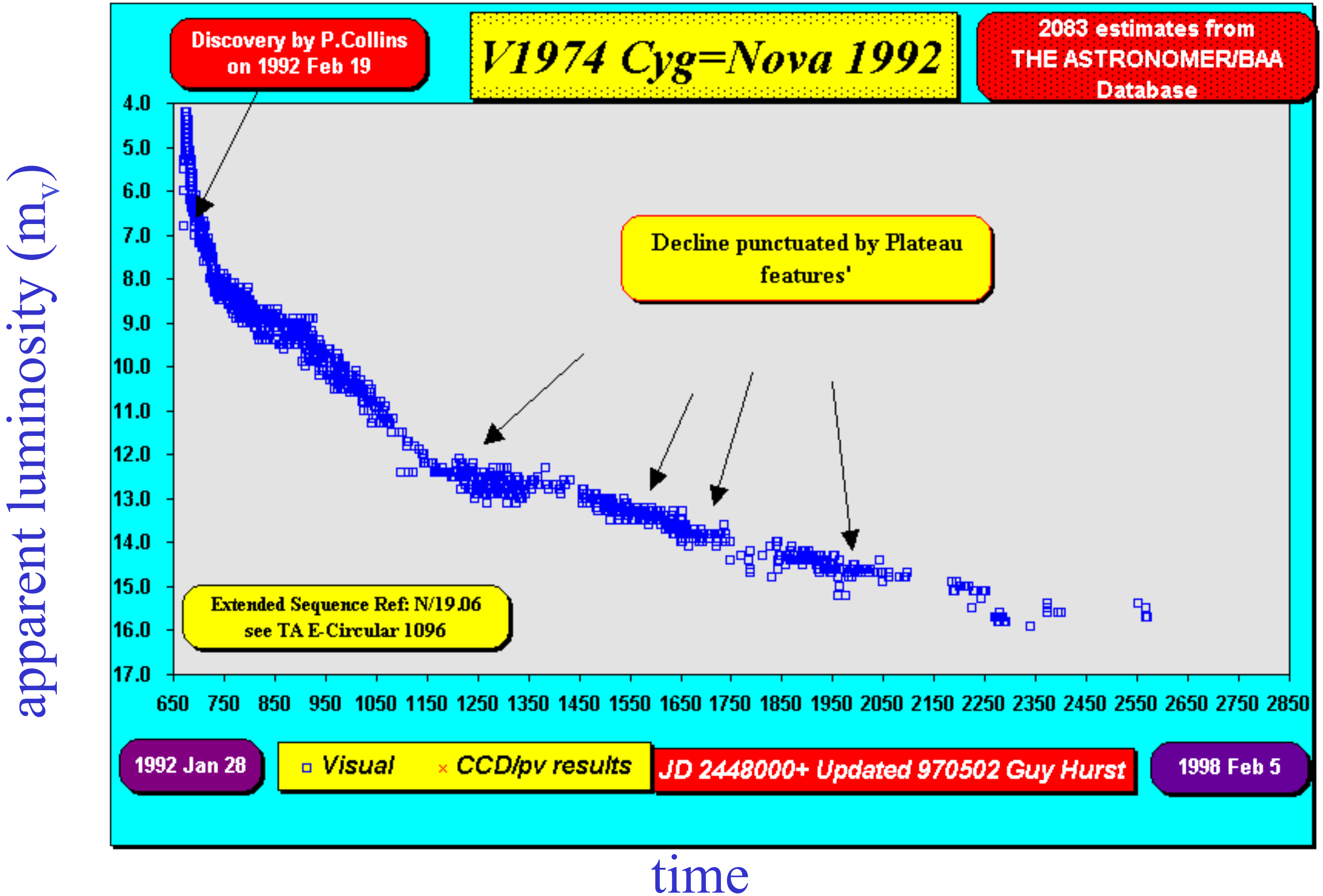
A classical nova results from runaway thermonuclear explosions on the surface of a white dwarf that accretes matter from a low-mass main-sequence stellar companion. In 2012 and 2013, three novae were detected in γ rays and stood in contrast to the first γ-ray–detected nova V407 Cygni 2010, which belongs to a rare class of symbiotic binary systems. Despite likely differences in the compositions and masses of their white dwarf progenitors, the three classical novae are similarly characterized as soft-spectrum transient γ-ray sources detected over 2- to 3-week durations. The γ-ray detections point to unexpected high-energy particle acceleration processes linked to the mass ejection from thermonuclear explosions in an unanticipated class of Galactic γ-ray sources.

- ***V407 Cyg: WD + red giant (wind) system (symbiotic recurrent nova)***
- ***Classical Novae: WD + MS***

Outline

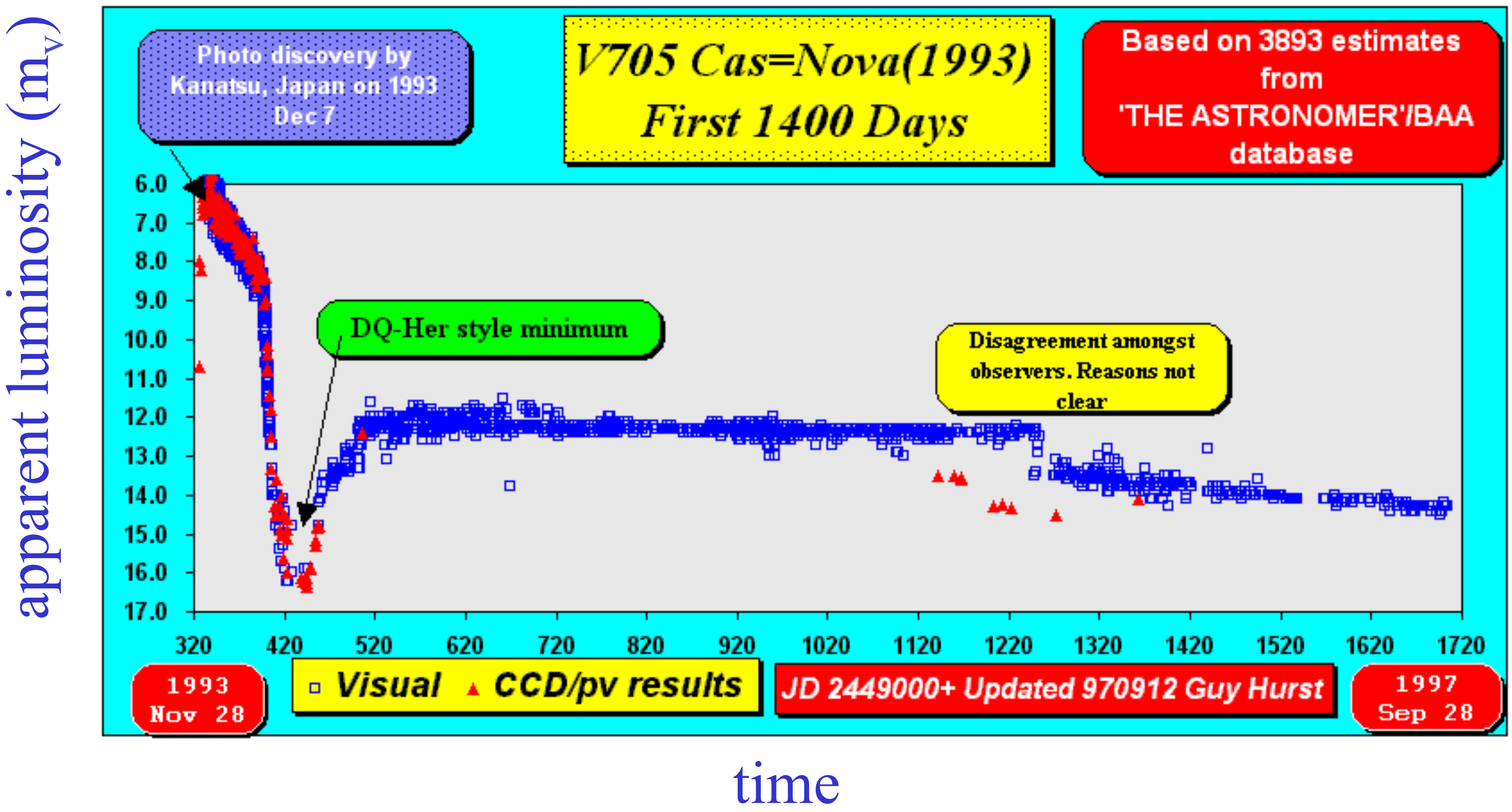
- Introduction on novae
- Origin of ^{7}Li (galactic, cosmic)
  - Role played by novae
  - Models
  - First detections in novae: ^{7}Be-^{7}Li (UV) and ^{7}Li (optical)
  - Implications. Gamma-rays from novae in the MeV range: relationship with synthesis and ejection of radioactive isotopes - ^{7}Be → ^{7}Li
- HE gamma-rays: discoveries by Fermi/LAT
  - Symbiotic recurrent novae vs. classical novae
  - Prediction for RS Oph (pre-Fermi launch). Relevance for cosmic rays origin
- Summary

Novae observations: optical light curves



L increases very fast by factors greater than 10⁴ - absolute L_{max}: $\sim 10^{4\text{-}5} L_{\odot}$

Novae observations: optical light curves



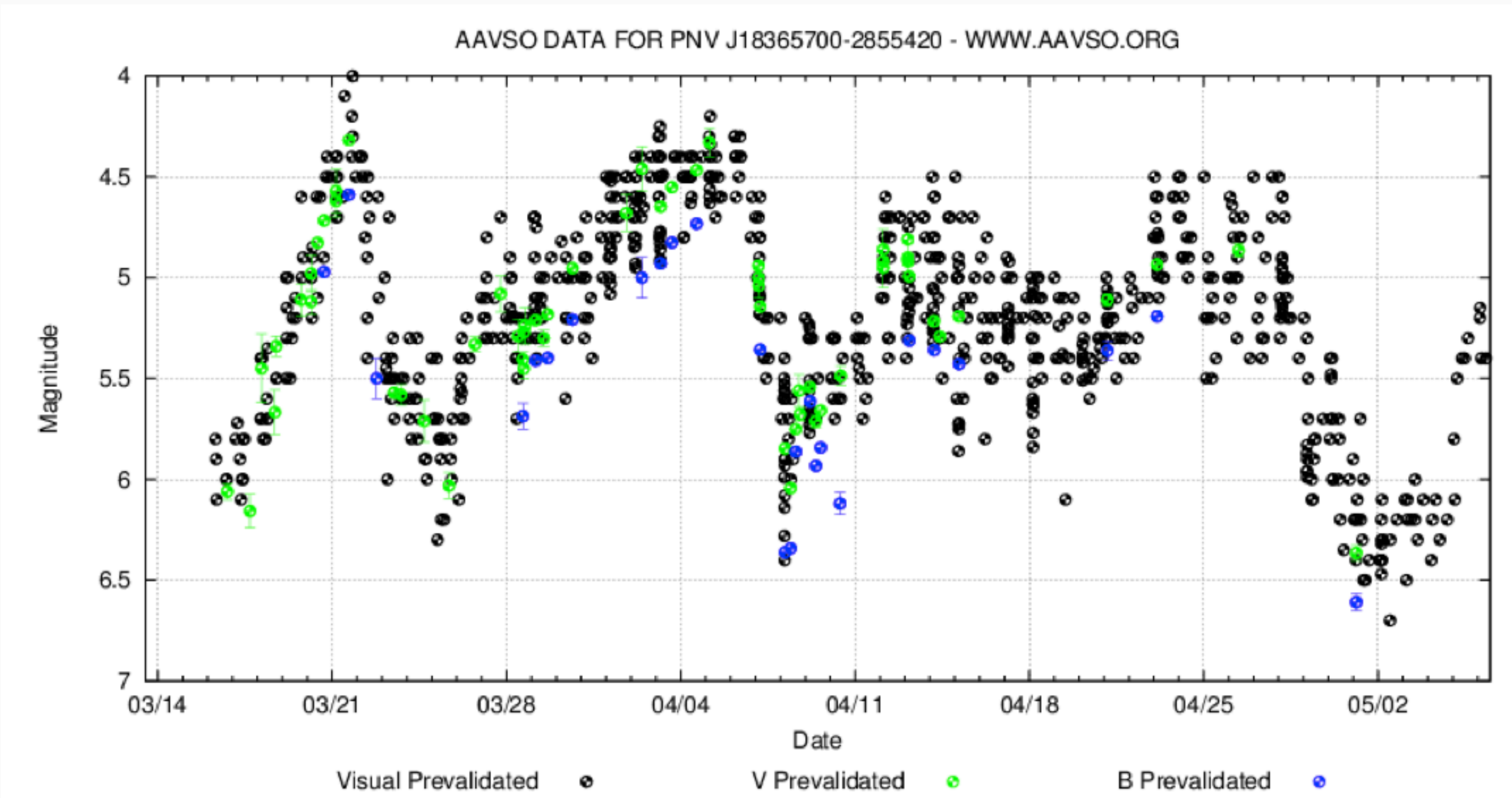
Dip in the LC related to dust formation

Novae observations: light curve of **Nova Sgr 2015 No.2**

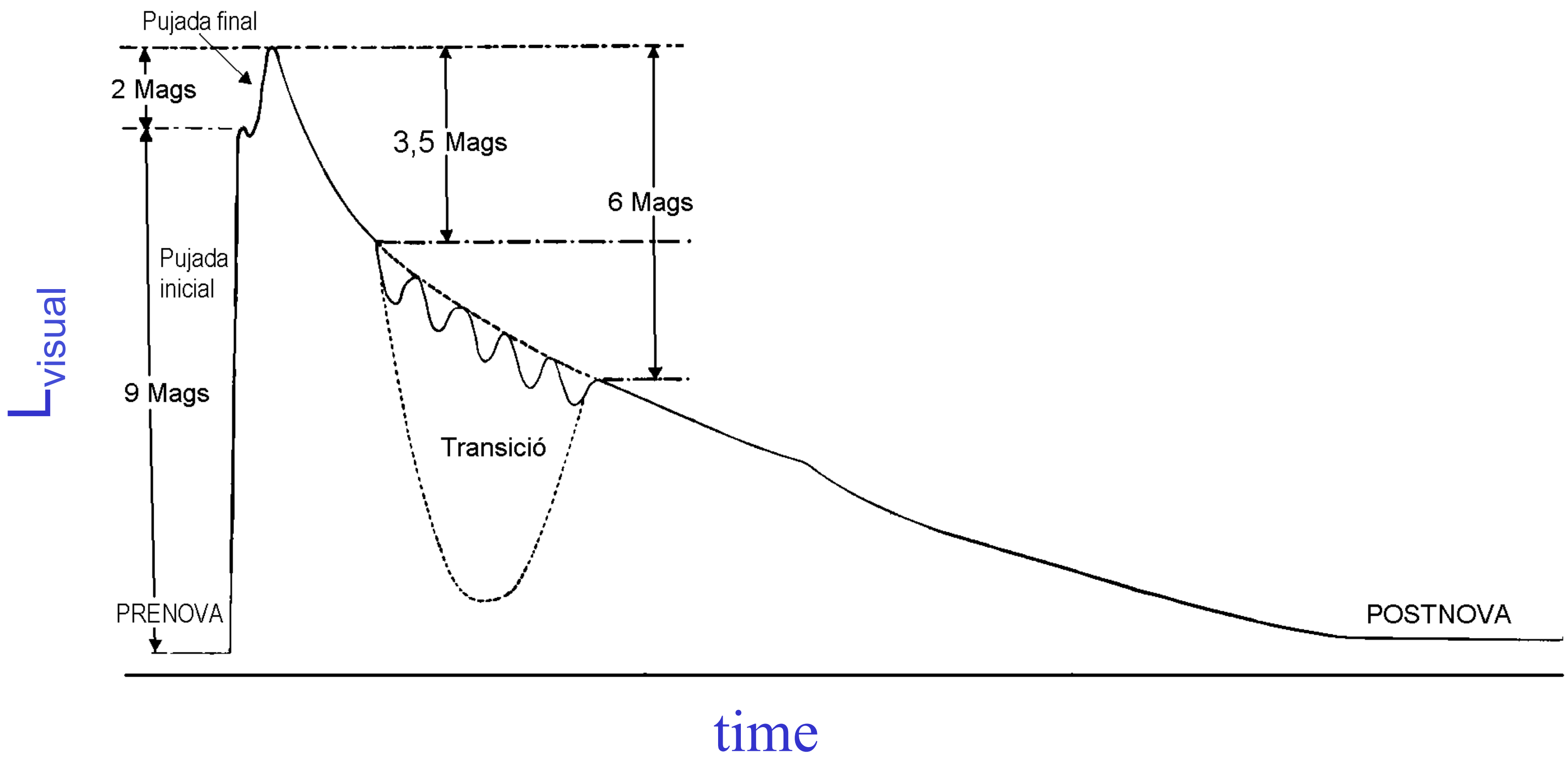
Light Curve Generator (LCG)

- Plot another light curve
- Search observations for PNV J18365700-2855420
- Create star chart for PNV J18365700-2855420
- Search VSX for PNV J18365700-2855420

AAVSO

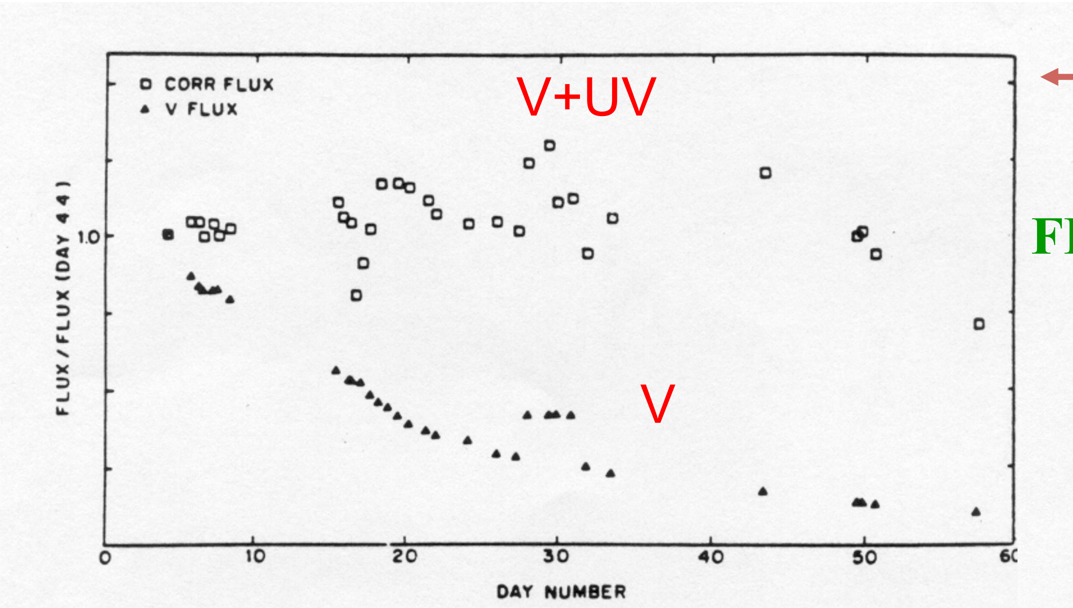


Novae observations: optical light curves



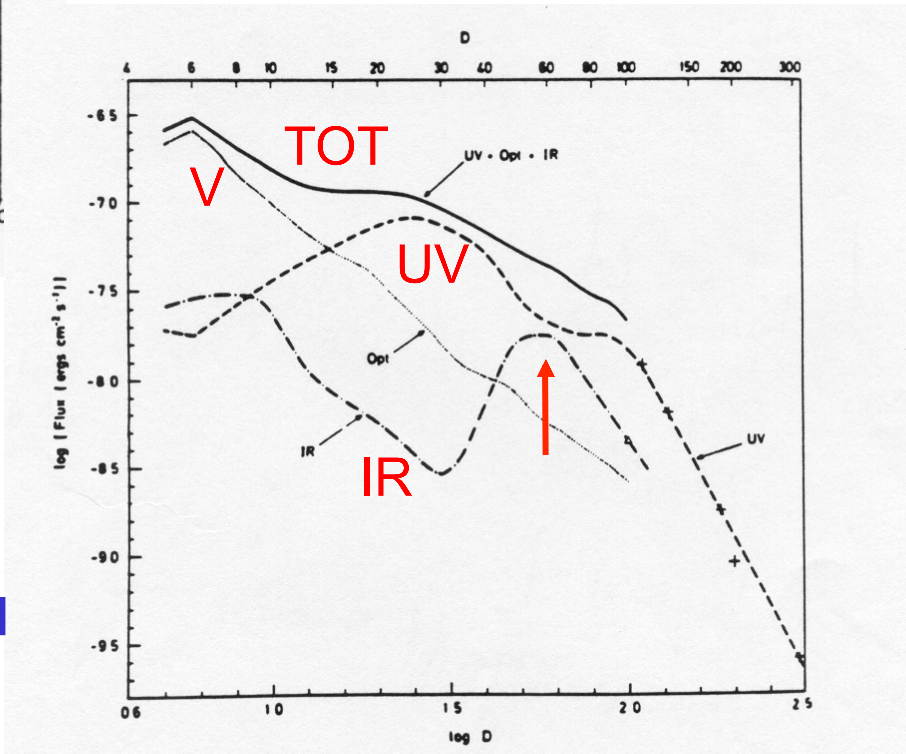
L increases very fast by factors ≥ 10⁴

Novae observations: light curves



UV satellites: $L_{bol}(L_V + L_{UV})$=ct.

FH Ser 1970 - Gallagher & Code 1974

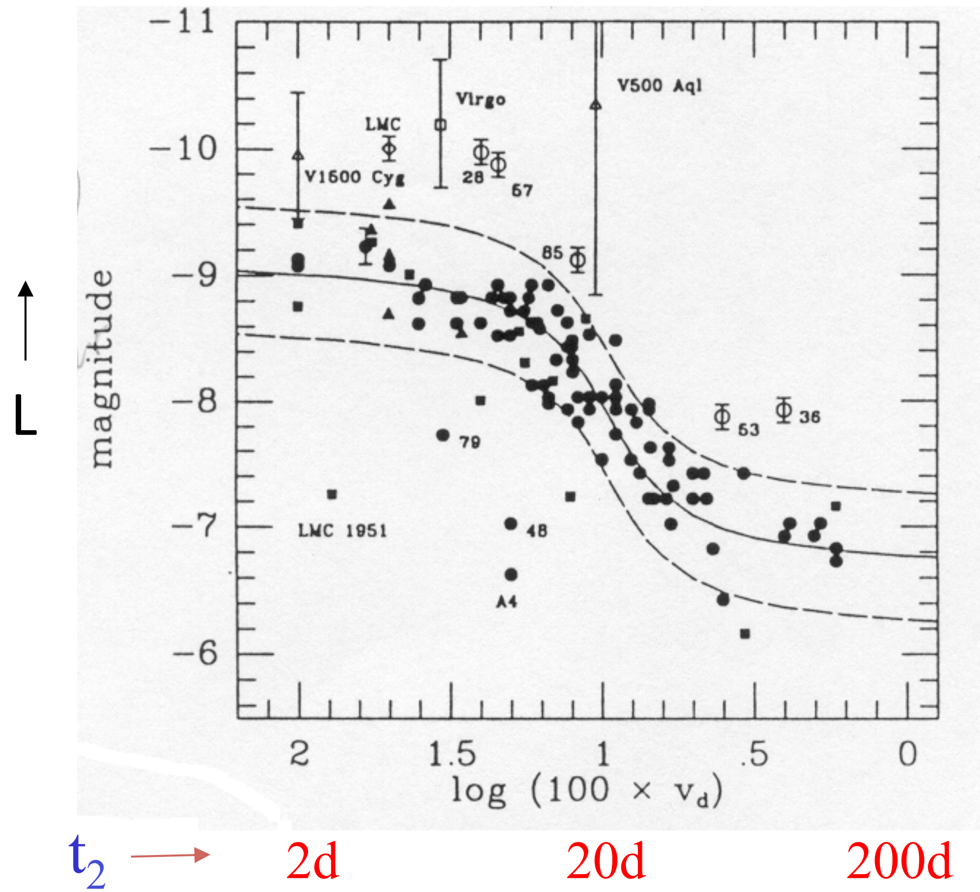


$L_{bol}(L_V+L_{UV}+ L_{IR})$ =ct.

Nova Cyg 1978 – Stickland et al. 1981

IR emission → dust formation

Novae observations: optical light curve. Rate of decline-luminosity relationship (MMRD)



t_2 : time needed to $\Delta m=2$

v_d: speed class $2/t_2$

$t_2<10$ days: very fast nova

$t_2>150$ days: very slow nova

→ *Distance determination*

Della Valle and Livio 1995

Abundances in novae ejecta from optical and UV spectra

Object	Year	Reference	H	He	C	N	O	Ne	Na-Fe	Z	$(Z/Z_\odot)$	$(Ne/Ne_\odot)$	CNO/Ne-Fe
Solar	...	1	0.71	0.27	0.0031	0.001	0.0097	0.0018	0.0034	0.019	1.0	1.0	2.7
T Aur	1891	2	0.47	0.40	...	0.079	0.051	...	...	0.13	6.8	...	...
RR Pic ...	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.9
DQ Her ..	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	..
DQ Her	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	...	...	[illegible]	[illegible]	...	...
HR Del	1967	6	0.45	0.48	...	0.027	0.047	0.0030	...	0.077	4.1	1.7	25.
V1500 Cyg	1975	7	0.49	0.21	0.070	0.075	0.13	0.023	...	0.30	16.	13.	12.
V1500 Cyg	1975	8	0.57	0.27	0.058	0.041	0.050	0.0099	...	0.16	8.4	5.6	15.
V1668 Cyg	1978	9	0.45	0.23	0.047	0.14	0.13	0.0068	...	0.32	17.	3.9	47.
V1668 Cyg	1978	10	0.45	0.22	0.070	0.14	0.12	...	...	0.33	17.	...	...
V693 CrA	1981	11	0.40	0.21	0.004	0.069	0.067	0.023	...	0.39	21.	128.	...
V693 CrA	1981	12	0.29	0.32	0.046	0.080	0.12	0.17	0.016	0.39	21.	97.	1.3
V693 CrA	1981	10	0.16	0.18	0.0078	0.14	0.21	0.26	0.030	0.66	35.	148.	1.2
V1370 Aql	1982	13	0.053	0.088	0.035	0.14	0.051	0.52	0.11	0.86	45.	296.	0.36
V1370 Aql	1982	10	0.044	0.10	0.050	0.19	0.037	0.56	0.017	0.86	45.	296.	0.48
GQ Mus	1983	14	0.37	0.39	0.0081	0.13	0.095	0.0023	0.0039	0.2 4	13.	1.2	38.
PW Vul	1984	15	0.69	0.25	0.0033	0.049	0.014	0.00066	...	0.067	3.5	0.38	100.
PW Vul	1984	10	0.47	0.23	0.073	0.14	0.083	0.0040	0.0048	0.30	16.	2.3	34.
PW Vul	1984	16	0.617	0.247	0.018	0.069	0.0443	0.001	0.0027	0.14	7.7	1.	31.
QU Vul	1984	17	0.30	0.60	0.0013	0.018	0.039	0.040	0.0049	0.10	5.3	23.	1.3
QU Vul	1984	10	0.33	0.26	0.0095	0.074	0.17	0.086	0.063	0.40	21.	49.	1.7
QU Vul	1984	18	0.36	0.19	...	0.071	0.19	0.18	0.0014	0.44	23.	100.	1.4
V842 Cen	1986	10	0.41	0.23	0.12	0.21	0.030	0.00090	0.0038	0.36	19.	0.51	77.
V827 Her	1987	10	0.36	0.29	0.087	0.24	0.016	0.00066	0.0021	0.35	18.	0.38	124.
QV Vul	1987	10	0.68	0.27	...	0.010	0.041	0.00099	0.00096	0.053	2.8	0.56	26.
V2214 Oph	1988	10	0.34	0.26	...	0.31	0.060	0.017	0.015	0.40	21.	9.7	12.
V977 Sco	1989	10	0.51	0.39	[illegible]	0.042	0.030	0.026	0.0027	0.10	5.3	15.	2.5
V433 Sct	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]3.
V351 Pup	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.4
V1974 Cyg	1992	18	0.19	0.32	...	0.085	0.29	0.11	0.0051	0.49	27.	68.	3.2
V1974 Cyg	1992	20	0.30	0.52	0.015	0.023	0.10	0.037	0.075	0.18	9.7	21.	3.1
V838 Her	1991	11	0.60	0.31	0.012	0.012	0.004	0.056	...	0.09	0.11	31.	...

V1370 Aql 1982 $Z=0.86=45\ Z_\odot$; $Ne=0.56=296\ Ne_\odot$

QU Vul 1984 $Z=0.44=23\ Z_\odot$; $Ne=0.18=100\ Ne_\odot$

Gehrz et al 1998, PASP

Abundance determinations from IR observations

Nova	X	Y	$\frac{(n_X/n_Y)_{nova}}{(n_X/n_Y)_\odot}$
QU Vul/1984 #2	Ne	H	≥1.2
QU Vul/1984 #2	Al	Si	70
QU Vul/1984 #2	Mg	Si	4.7
QU Vul/1984 #2	Ne	Si	≥6.4
V1974 Cyg/1992	Ne	H	≥4
V1974 Cyg/1992	Ne	H	≥10
V1974 Cyg/1992	Ne	Si	≈35
V1974 Cyg/1992	Al	Si	≈5
V1974 Cyg/1992	Mg	Si	≥3
V1974 Cyg/1992	C	H	≈12
V1974 Cyg/1992	N	H	≈50
V1974 Cyg/1992	O	H	≈25
V1974 Cyg/1992	Ne	H	≈50
V1974 Cyg/1992	Mg	H	≈5
V1974 Cyg/1992	Al	H	≈5
V1974 Cyg/1992	Si	H	≈6
V1974 Cyg/1992	S	H	≈5
V1974 Cyg/1992	Ar	H	≈5
V1974 Cyg/1992	Fe	H	≈4
V1974 Cyg/1992	Ne	O	≈4
V705 Cas/1993	Silicates	H	≈15
V705 Cas/1993	C	H	≈45
Nova Aql/1995	C	H	≤0.6

Gehrz et al 1998, PASP

Novae observations: summary of properties

- Expansion velocities of the ejecta ~ 10^2-10^3 km/s
- Ejected masses ~ 10^{-5} - 10^{-4} $M_\odot$
- Energetics and luminosity: K.E.~10^{45} erg

  $L = 10^5 L_\odot$ close to $L_{Eddington}$
- ***Ejecta enhanced in C, N, O, Ne w.r.t. solar***
- Nova rate in the Milky Way: ~ 35 ± 11 per yr (Shafter 1997), but only a few discovered optically

What's a nova?

Reminder: A thermonuclear explosion of H on top of an accreting white dwarf in a close binary system

White dwarfs

- Endpoints of stellar evolution ($M < 10 M_\odot$): no E_{nuc} available; compression until electrons become degenerate
- Chemical composition: He, CO, ONe; masses: typical $0.6\ M_\odot$, maximum: $M_{Chandrasekhar}$ ($\sim 1.4 M_\odot$)
- When isolated, they cool down to very low L ($\sim 10^{-4.5} L_\odot$):

  "fossils" allowing to do "stellar archeology" (age of the Galaxy, star formation rate)
- When in interacting binary systems, they can be "rejuvenated" and eventually explode

Rejuvenation of white dwarfs in close binary systems

Effect of accretion: depends on L and M of the WD, accretion rate and chemical comp. of accreted matter → properties of the binary system: M_1, M_2, P_{orb}-A, $(dM/dt)_{acc}$

➡ "central" explosive C burning → total disruption of the star, thermonuclear Supernova (SNIa): KE~10^{51} erg, $M_{ejected}$ ~ M_{WD} ($1M_{\odot}$~10^{33}g) , v_{ejec} ~ 10^4 km/s, *≤1/100 yr* in the Galaxy

➡ explosive H-nuclear burning on top of the WD → envelope ejection, nova explosion: KE~10^{45} erg, $M_{ejected}$ ~ 10^{-4-5} $M_{\odot}$, v_{ejec} ~ 10^{2-3} km/s - No disruption of the WD star → recurrent phenomenon

- ***classical nova***: P_{rec}~10^4-10^5 yr, *~35/yr* in the Galaxy
- ***recurrent nova***: P_{rec}< 100 yr, <*10* known in the Galaxy

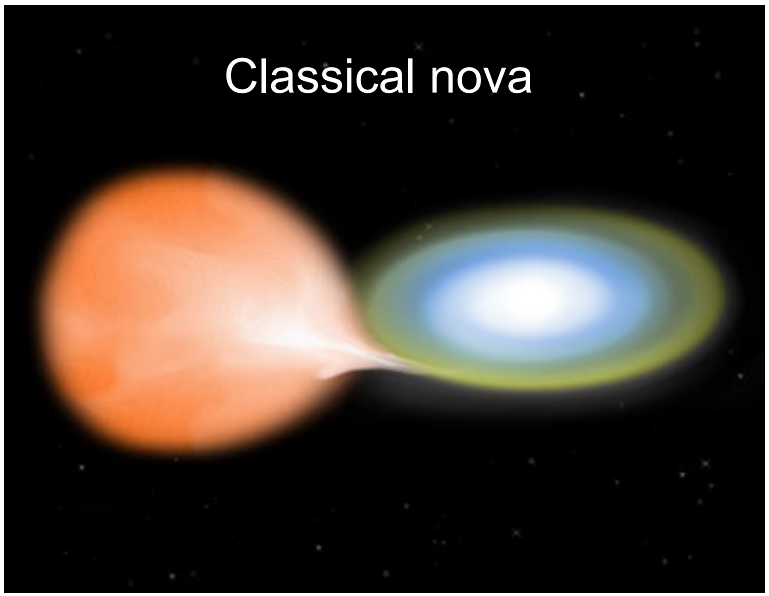
Nova explosions: white dwarfs in close binary systems (single degenerate)

Cataclysmic variable:

WD + Main Sequence

↓

Roche lobe overflow



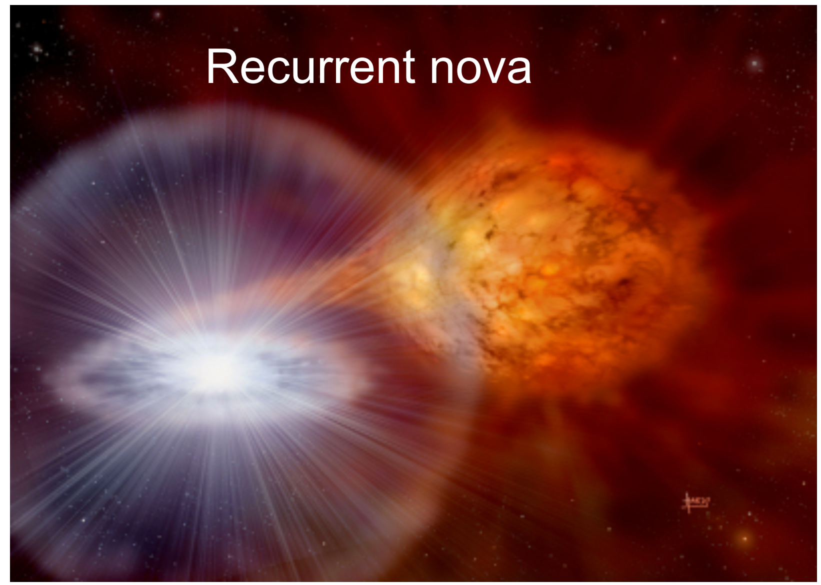
$P_{recurrence}$~10^4-10^5 yr

Symbiotic binary:

WD + Red Giant

↓

accretion from a red giant wind



- **$P_{recurrence}$<100 yrs**
- **Occur in massive WDs**
- **M_{wd} can increase → possible scenarios of type Ia supernova explo.**

White dwarf in a binary system: scenario of nova explosions

Mass transfer from the companion star onto the white dwarf

↓

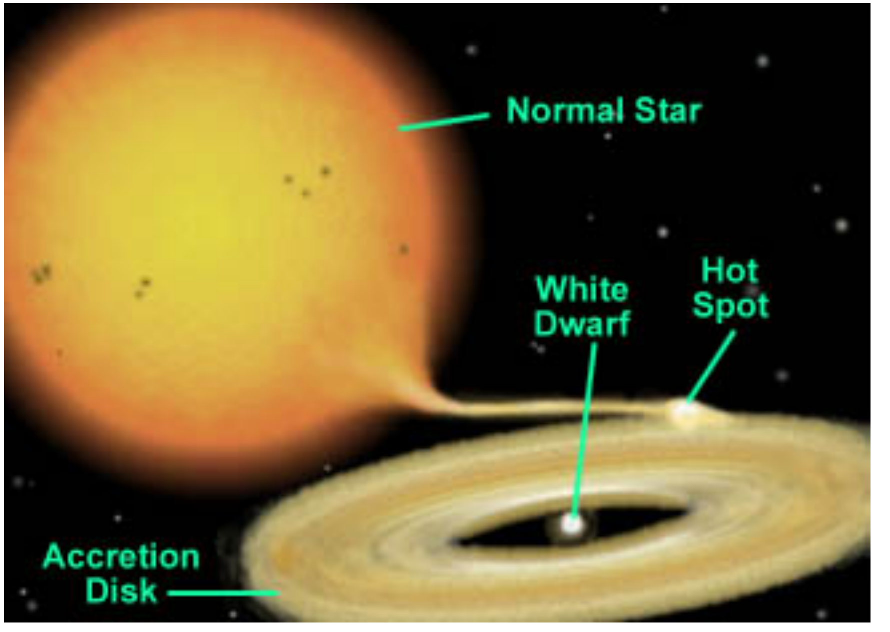
Hydrogen burning in degenerate conditions on top of the white dwarf

↓

Thermonuclear runaway

↓

Explosive H-burning ↗

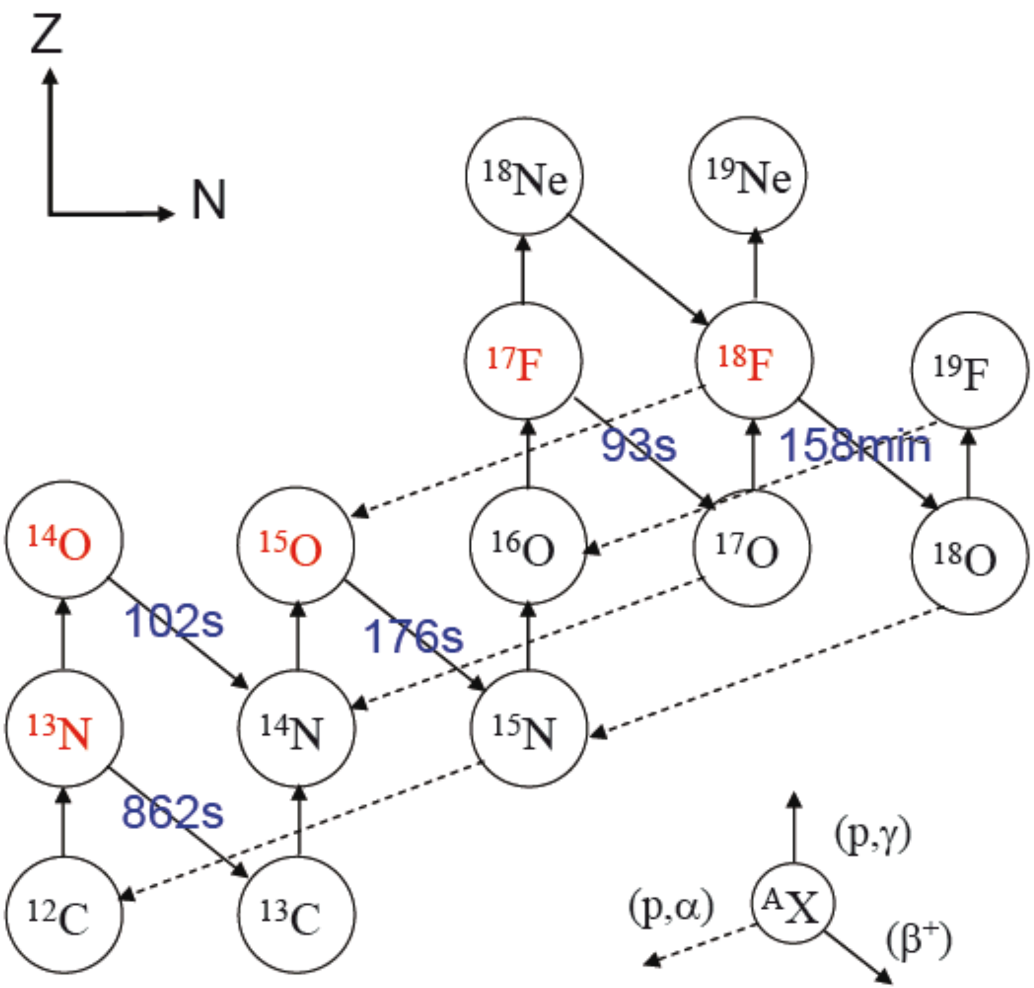


Decay of short-lived radioactive nuclei in the outer envelope (transported by convection)

↓

Envelope expansion, L increase and mass ejection

Nova Models: Thermonuclear Burning of Hydrogen. CNO cycles



- Start: $\tau_{\beta+} < \tau(p,\gamma)$

  ↓

  CNO cycle operates in equ.
- T ~10^8 K: $\tau_{\beta+} > \tau(p,\gamma)$

  ↓

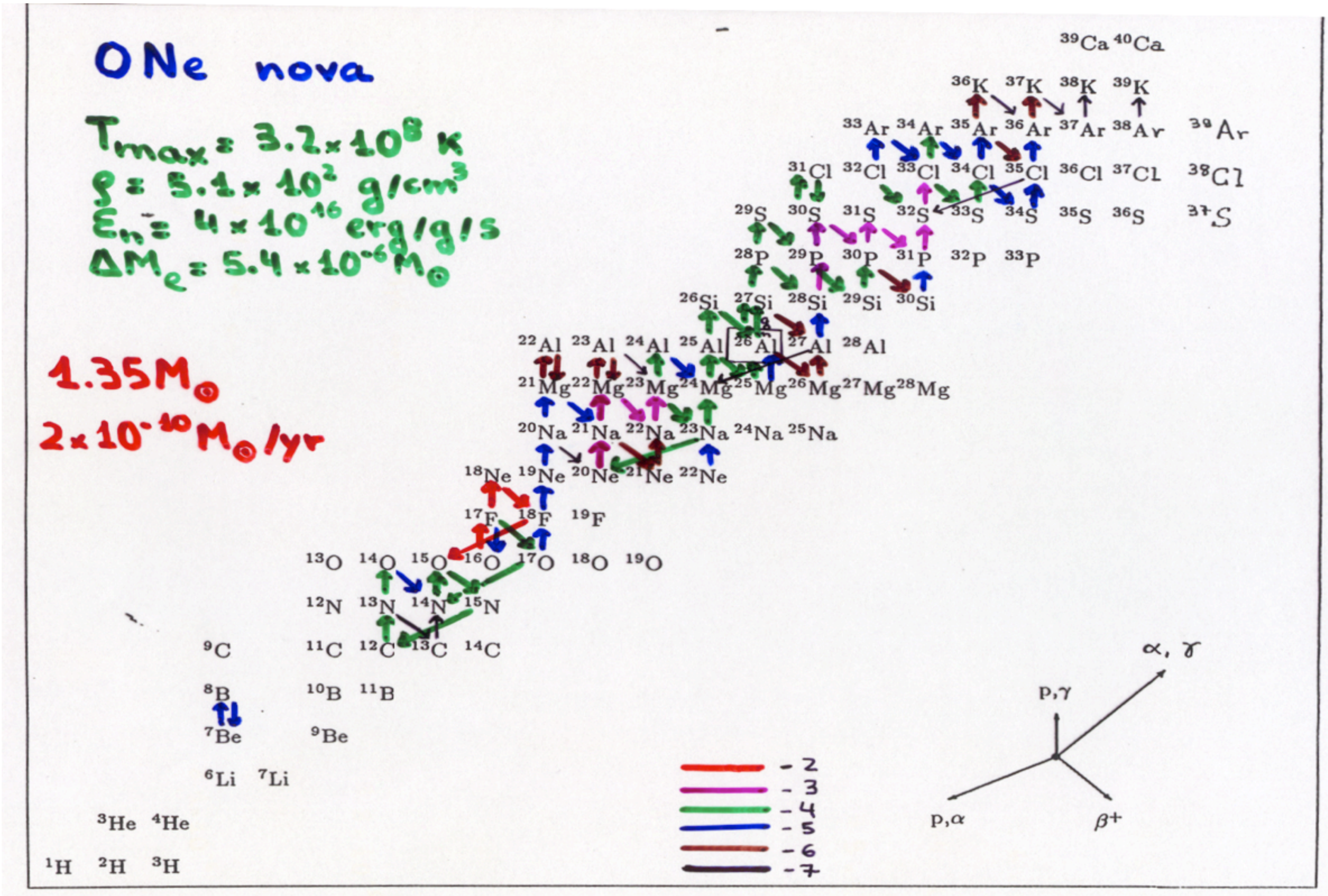
  CNO cycle β^+-limited (bottle neck)
- Convection:

➢ fresh fuel brought to the burning shell

➢ $\tau_{conv} < \tau_{\beta+}$: β^+-unstable nuclei to external cooler regions where they are preserved from destruction

<u>Later decay on the surface leads to expansion and luminosity increase</u>

Nova models: main nuclear reactions (NeNa-MgAl)



Recent review on nova nucleosynthesis: José, Hernanz & Iliadis, NuPhA 2006

Implications of observed properties of CNe for the scenario of SNIa explosions

Ejecta enhanced in C, N, O, Ne w.r.t. solar

(Z observed >> solar) in classical novae

↓

proof of mixing between WD core and envelope → M_{wd} *decreases*

BUT ***no enhancements*** observed in ***recurrent novae*** → does M_{wd} increase?

Are novae (classical or recurrent) scenarios for thermonuclear supernovae?

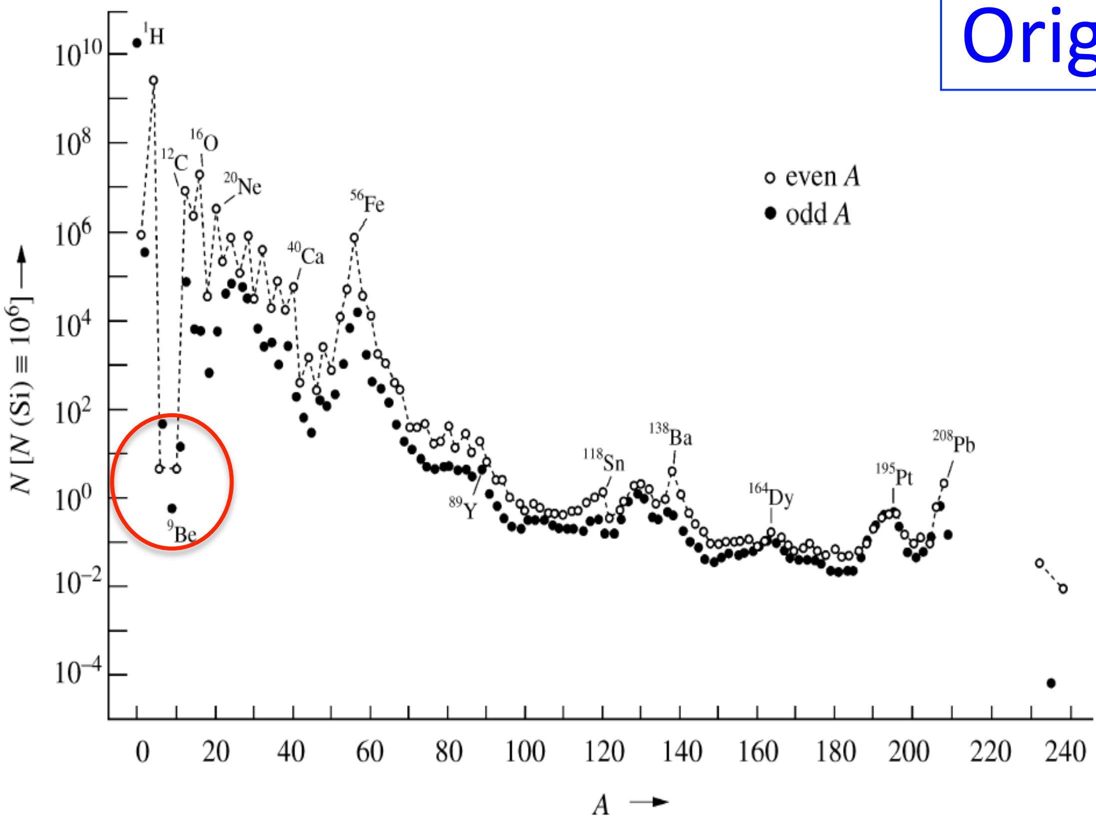
Additional issue: (originally) massive WDs are made of ONe and not CO, and thus would not explode

Origin of Lithium (^{7}Li)

Three main sources

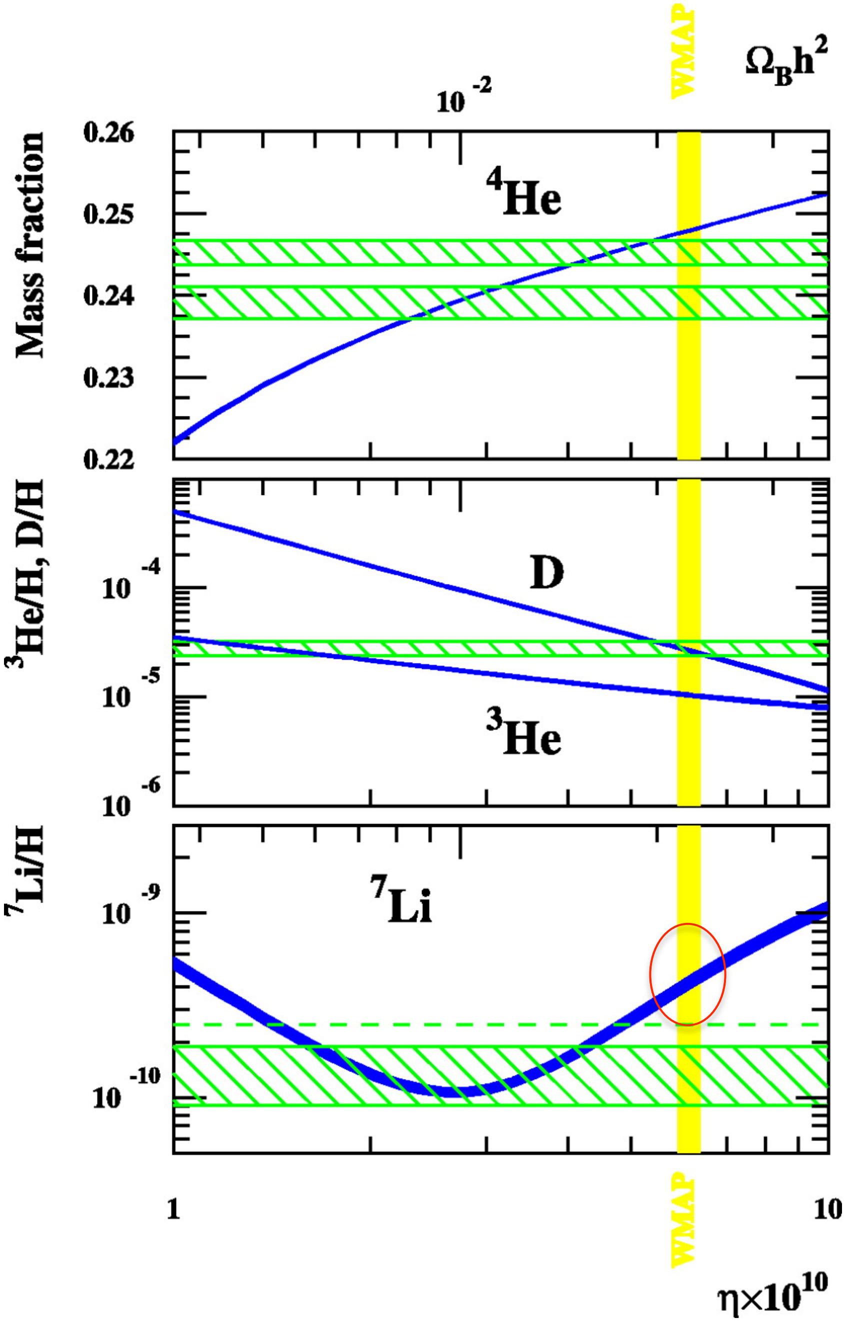
- Primordial origin: nucleosynthesis during the Big Bang
- Spallation reactions: interaction of cosmic rays with atoms in the interstellar medium
- Stellar origin: low-mass stars: red giants, nova explosions.
  - Detected for the first time in a nova explosion (^{7}Be-^{7}Li), by Tajitsu et al. Nature, 19 Feb. 2015. News & Views by MH, Nature same volume
  - Direct detection of ^{7}Li in V1369 Cen (Nova Cen 2013) by Izzo et al., ApJ Letters (2015)
  - *Prediction made several decades ago: Starrfield et al., ApJ 1978, Hernanz, José, Coc, Isern, ApJ L 1996*

Origin of the elements



- Stellar nucleosynthesis: all the elements up to Fe – except H, Li, Be, B – are produced inside stars. All larger Z elements come from explosive nucleosynthesis
- Enrichment of the galactic gas: stellar winds and supernova (+nova) explosions
- LiBeB not formed inside the stars, but they can be produced in ***external H-burning shells***: low-mass red giants, nova explosions

Big Bang Nucleosynthesis



Coc, Vangioni et al. 2004, ApJ

Predicted abundances

^{4}He, ^{2}H (D), ^{3}He, 7Li

WMAP - Wilkinson Microwave Anisotropy Probe: constraints on the baryonic density of the Universe (Spergel et al. 2003):

$\Omega_b h^2 = 0.0224 +/- 0.0009$

(h=H/100 km/s/Mpc)

$\eta = (6.14 +/- 0.25)\ 10^{-10}$ (baryon to photon ratio)

Big Bang Nucleosynthesis

Coc et al. 2004, ApJ

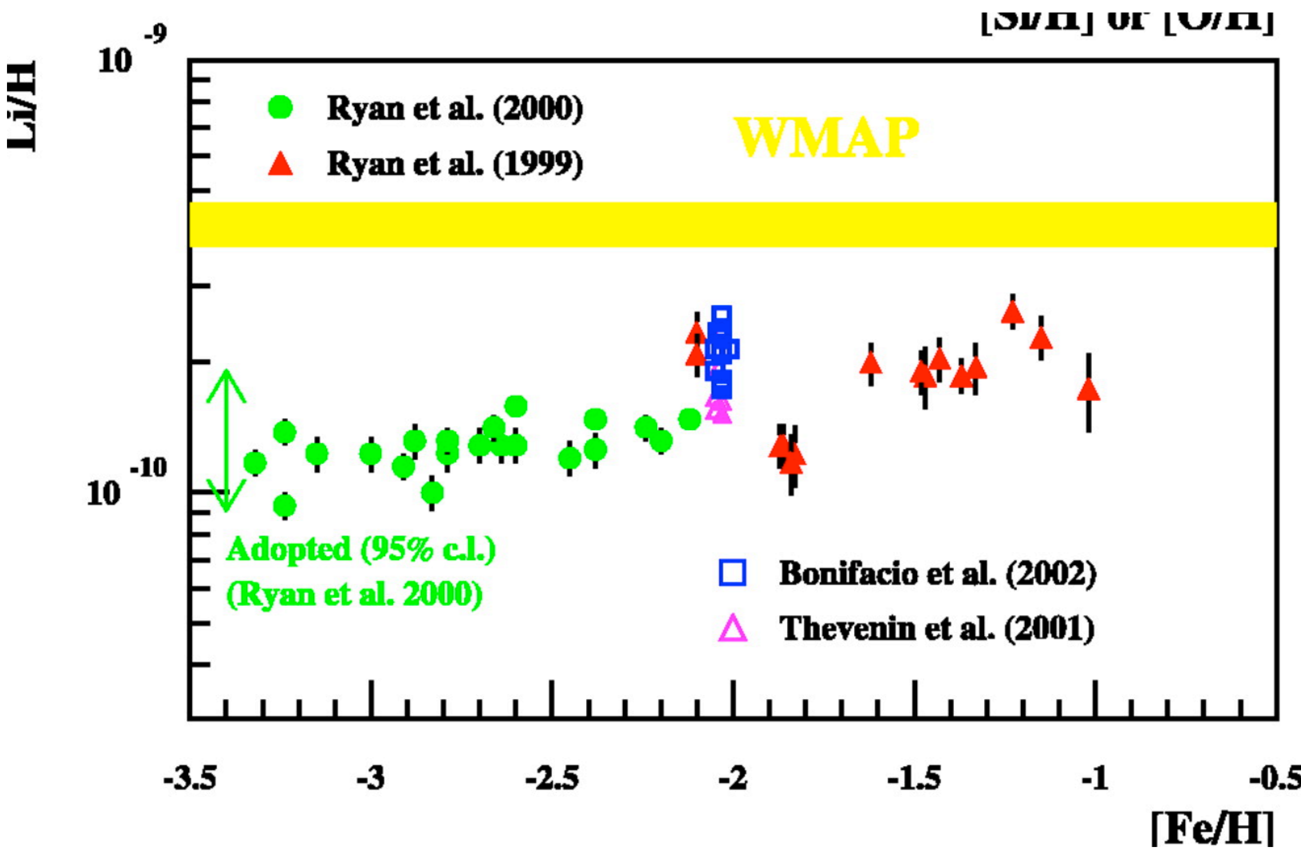


FIG. 2.—Observed abundances as a function of metallicity from objects that are expected to reflect primordial abundances.

Spite plateau (Spite & Spite 1982): ct. Li vs. metallicity for low metallicity stars

^{7}Li/H

- WMAP+SBBN: $(4.15+0.49/-0.45) \times 10^{-10}$
- Obs. halo stars: $(1.23+0.8/-0.32) \times 10^{-10}$

Big Bang Nucleosynthesis

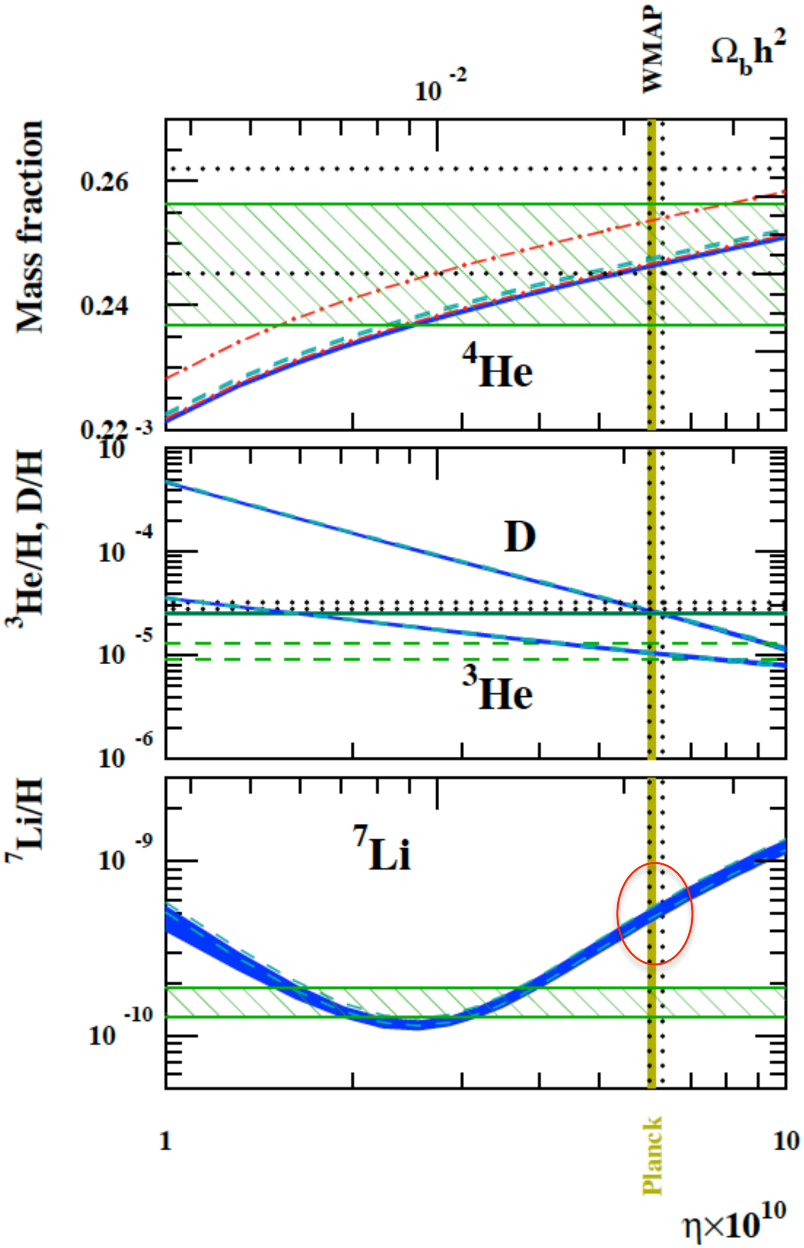
Primordial Abundances of H, He, and Li Isotopes
at WMAP7 Baryonic Density

Nb. Reactions	CV10 13 (+2)	This Work 15	This Work 424	Observations
Y_p	0.2476 ± 0.0004	0.2475	0.2476	0.2561 ± 0.0108
D/H ($\times 10^{-5}$)	2.68 ± 0.15	2.64	2.59	2.82 ± 0.2
^{3}He/H ($\times 10^{-5}$)	1.05 ± 0.04	1.05	1.04	1.1 ± 0.2
^{7}Li/H ($\times 10^{-10}$)	5.14 ± 0.50	5.20	5.24	1.58 ± 0.31
^{6}Li/H ($\times 10^{-14}$)	1.3[a]	1.32	1.23	~1000 (?)

Notes. CV10: Coc & Vangioni (2010), using $\Omega_b \cdot h^2$ from Spergel et al. (2007). This work uses the new Komatsu et al. (2011) value.
[a] Hammache et al. (2010).

- No large effect of new nuclear network and new reaction rates on ^{7}Li predicted primordial abundance
- Still large deviation from observations: *calculated abundance higher than spectroscopic observations by a factor of ~3.5*

Coc et al. 2012, ApJ: improved and extended nuclear network



Big Bang Nucleosynthesis update

Coc, Uzan, Vangioni 2014, JCAP

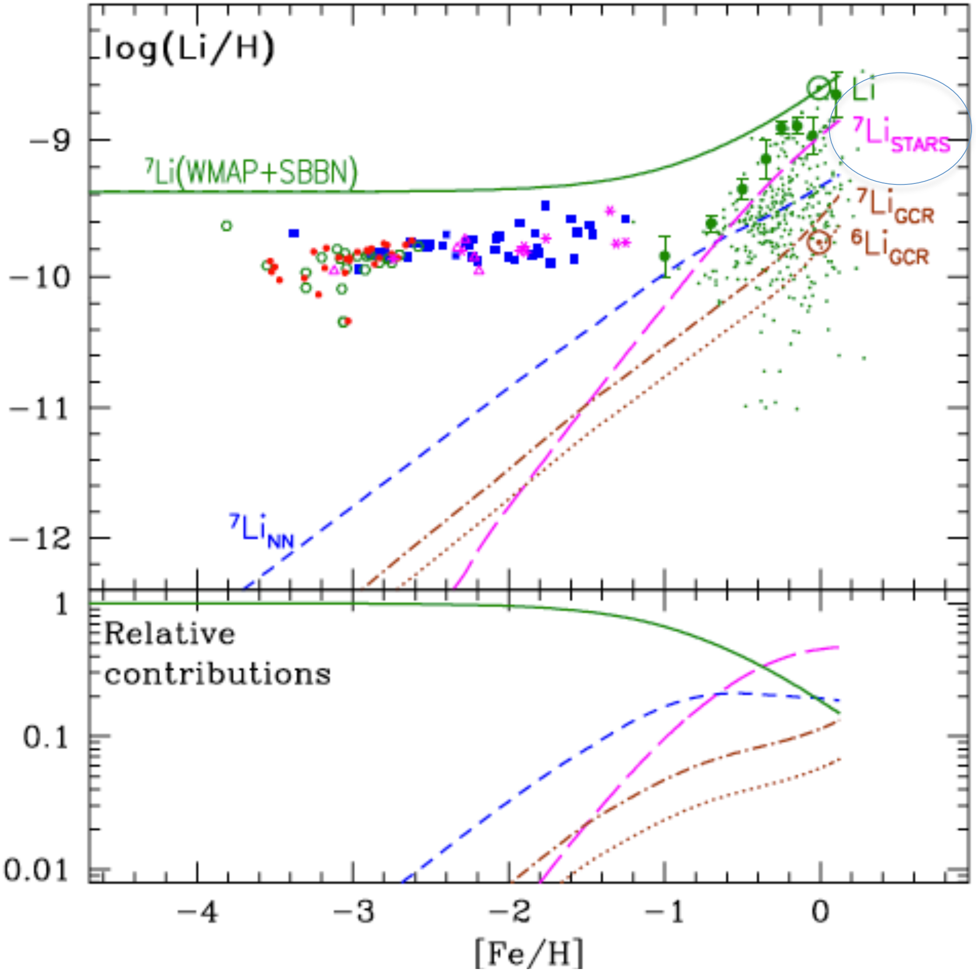
Predicted abundances of
^{4}He, ^{2}H (D), ^{3}He, ***^{7}Li***
versus the baryonic density Ω_b
or the baryon to photon ratio η

WMAP & Planck

constraints on baryonic density indicated

$\Omega_b\ h^2 = 0.022184 +/- 0.00026$
(Planck)

Models of chemical evolution of the Galaxy



Prantzos 2012, A&A

Spallation reactions (GCR)

Galactic cosmic rays (GCR) <–> Interstellar Medium (ISM)

- p, ^{4}He, ^{12}C, ^{14}N, ^{16}O from GCR interact with p, ^{4}He, CNO of the ISM
- ^{4}He + ^{3}He "fusion" → ^{6}Li and ^{7}Li

Fig. 16. Evolution of Li (*top*) according to our Model A (see Table 1) and percentages of its various components (*bottom*): ^{7}Li from GCR (dot-dashed), ^{6}Li from GCR (dotted), ^{7}Li from ν-nucleosynthesis (NN, dashed) and ^{7}Li from a delayed stellar source (novae and/or AGB stars, long dashed). Solid curves indicate total Li (*upper* panel) and primordial ^{7}Li (*lower* panel). Abundance data (*upper panel* for halo stars are

Astron. Astrophys. 352, 117–128 (1999)

^7Li

The galactic lithium evolution revisited*

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Received 26 April 1999 / Accepted 5 October 1999

Models of chemical evolution of the Galaxy

In order to reproduce the upper envelope of the A(Li) vs

Li sources: AGB stars, Type II SNe and novae. In particular, novae are required to reproduce the steep rise of A(Li) between the formation of the Solar System and the present time, as is evident from the data we sampled. On the other hand, ^{7}Li yields for SNeII should be lowered by at least a factor of two in order to reproduce the extension of the Spite plateau.

Romano, Matteucci et al. 1999, A&A

Models of chemical evolution of the Galaxy

The Astrophysical Journal Letters, 808:L14 (5pp), 2015 July 20

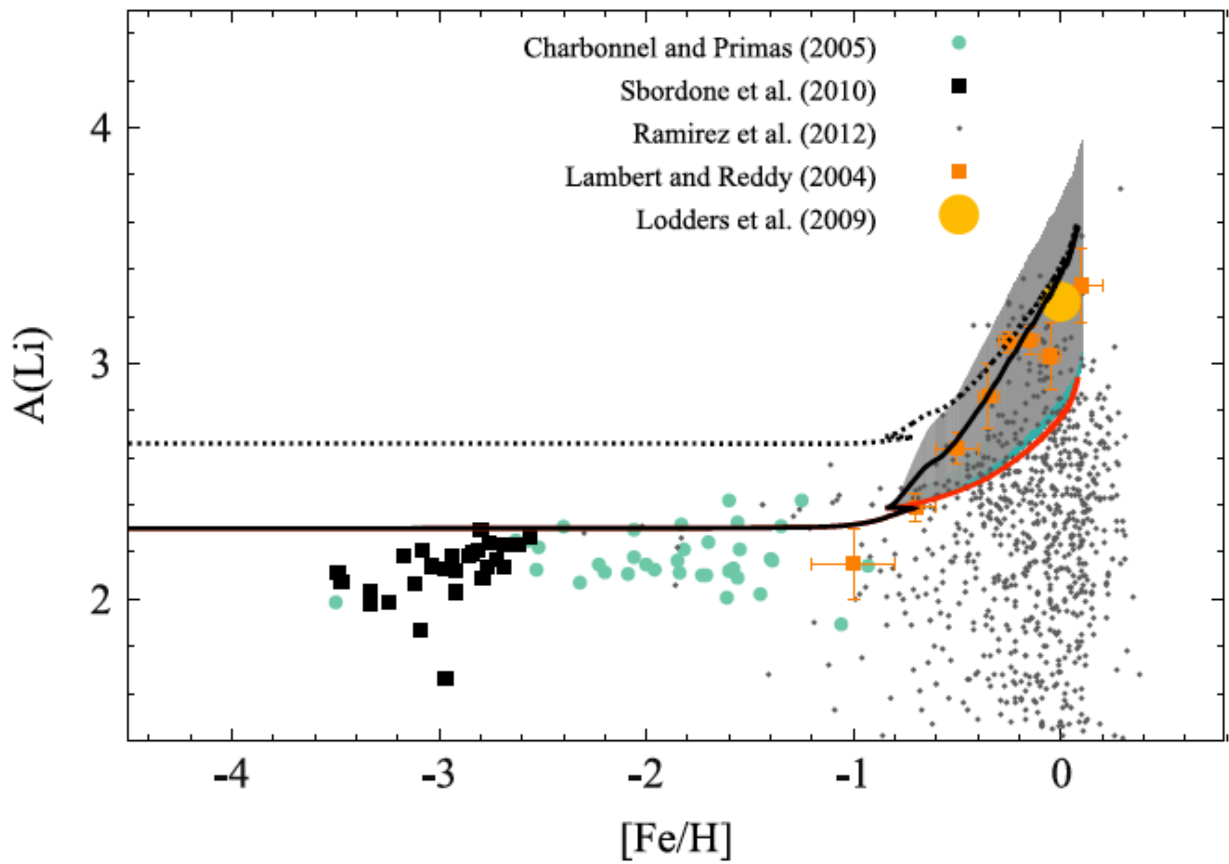

Figure 5. *A*(Li) vs. [Fe/H] for solar neighborhood stars and meteorites (symbols; see legend) compared to the predictions of chemical evolution models (lines and colored areas). The back and forth behavior in the theoretical curves around [Fe/H] = –0.8 is due to the transition between the halo/thick-disk and thin-disk formation phases (see the text).

Izzo et al., including Matteucci, 2015, **related to Li7 discovery in N Cen 2013**

Synthesis of ^7Li in novae

THE ASTROPHYSICAL JOURNAL, 222:600–603, 1978 June 1

Starrfield et al. 1978, ApJ

ON ^{7}Li PRODUCTION IN NOVA EXPLOSIONS*

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Received 1977 September 26; accepted 1977 December 5

Also:
Arnould & Nordgaard, 1975, A&A

ABSTRACT

Calculations of ^{7}Li production occurring as a concomitant of thermonuclear runaways in hydrogen envelopes of white dwarfs are reported. It is found that sufficient ^{7}Li can be produced in models displaying fast–nova-like features to suggest that the corresponding objects represent significant contributors to the ^{7}Li enrichment of galactic matter. The sensitivities of these results to various assumptions and uncertainties are discussed.

THE ASTROPHYSICAL JOURNAL, 465:L27–L30, 1996 July 1

Hernanz et al. 1996, ApJ Let.

ON THE SYNTHESIS OF ^{7}Li AND ^{7}Be IN NOVAE

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Received 1996 January 31; accepted 1996 April 15

ABSTRACT

The production of ^{7}Li and ^{7}Be during the explosive hydrogen burning that occurs in nova explosions is computed by means of a hydrodynamic code able to treat both the accretion and the explosion stages. Large overproduction factors with respect to solar abundances are obtained, the exact value depending mainly on the chemical composition of the envelope. Although the final ejected masses are small, these results indicate that novae can contribute to the ^{7}Li enrichment of the interstellar medium. Furthermore, since ^{7}Be decays by emitting a gamma ray (478 keV), with a half-life of 53.3 days, the synthesis of ^{7}Li could be tested during the *INTEGRAL* mission.

Thermonuclear burning of H: p-p chains

$^{1}H + {}^{1}H \rightarrow {}^{2}H + e^{+} + \nu$

$^{2}H + {}^{1}H \rightarrow {}^{3}He + \gamma$

86%

$^{3}He + {}^{3}He \rightarrow {}^{4}He + 2\,{}^{1}H$

pp1

14%

$^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$

14%

$^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu$

$^{7}Li + {}^{1}H \rightarrow {}^{4}He + {}^{4}He$

pp2

0.02%

$^{7}Be + {}^{1}H \rightarrow {}^{8}B + \gamma$

$^{8}B \rightarrow {}^{8}Be + e^{+} + \nu$

$^{8}Be \rightarrow {}^{4}He + {}^{4}He$

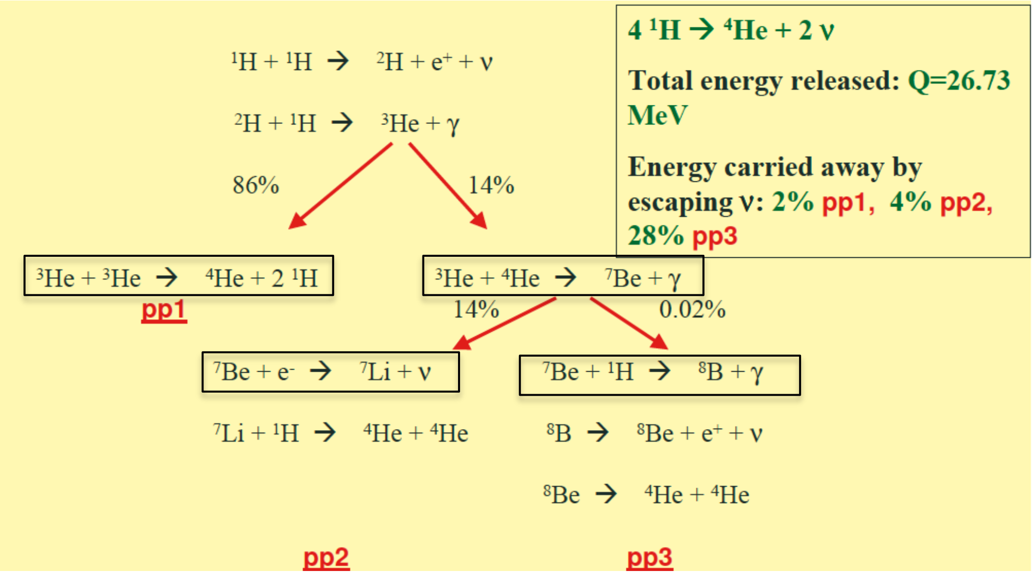
pp3

$4\,{}^{1}H \rightarrow {}^{4}He + 2\,\nu$

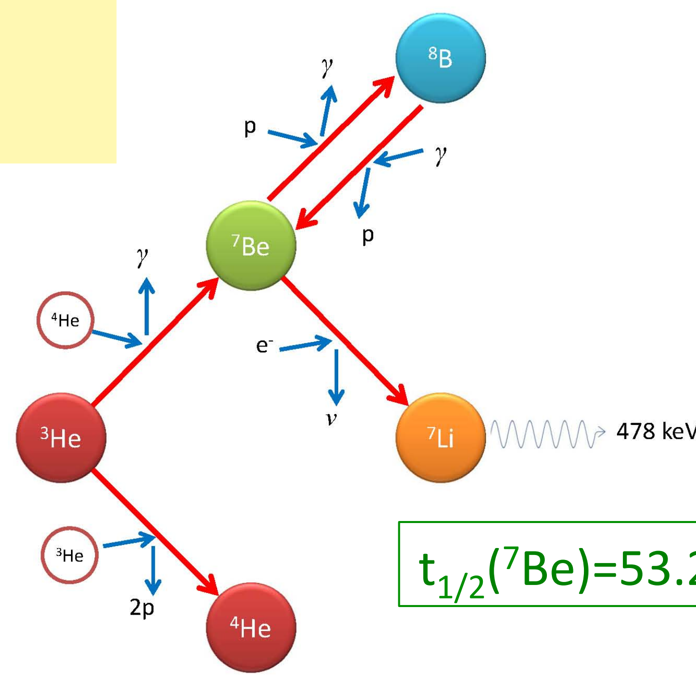
Total energy released: Q=26.73 MeV

Energy carried away by escaping ν: 2% pp1, 4% pp2, 28% pp3

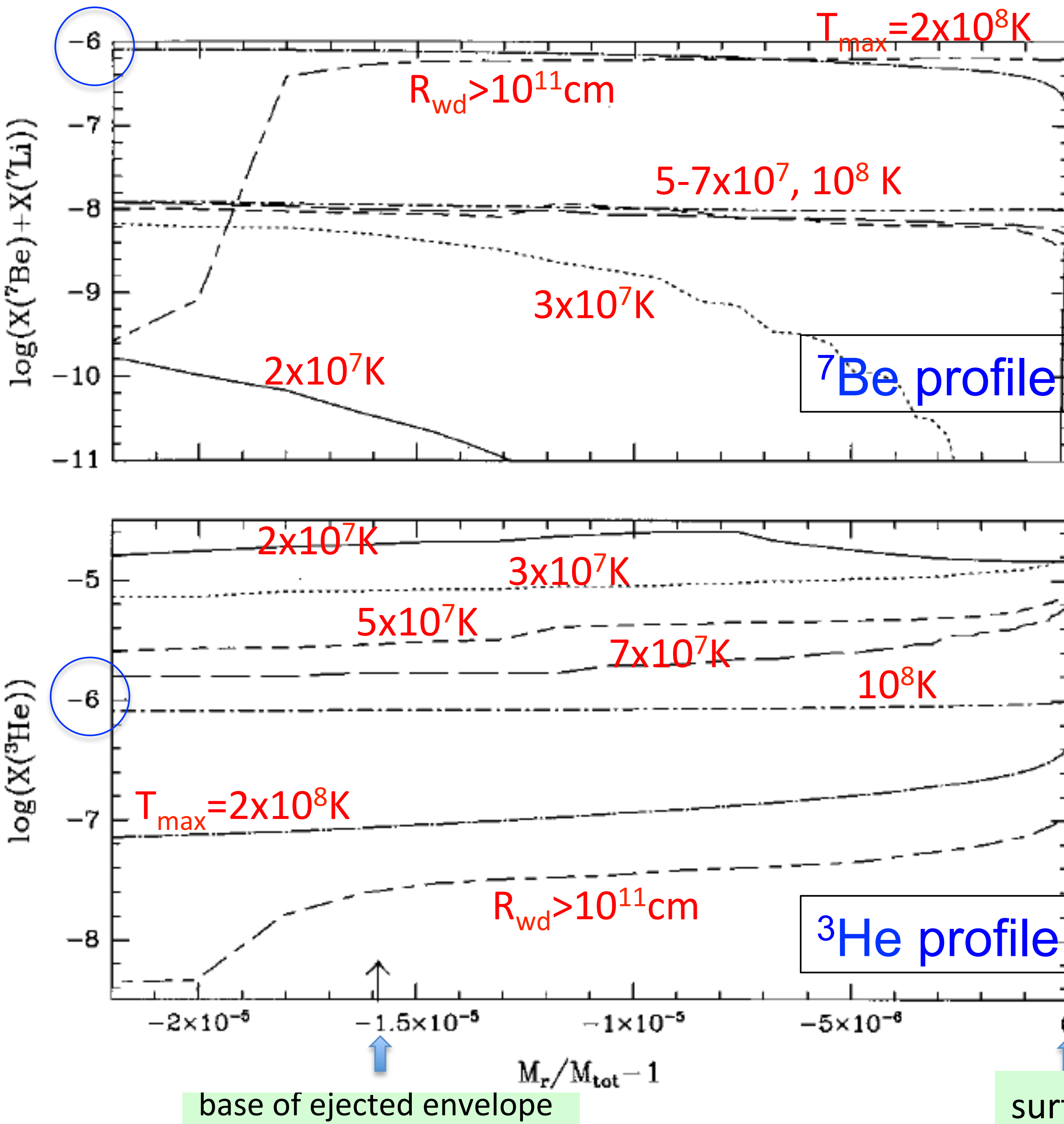
Nuclear reactions producing ^{7}Li



Cameron-Fowler ^{7}Be transport mechanism to produce ^{7}Li: fresh produced ^{7}Be should be transported outwards to cooler regions to avoid being destroyed



$t_{1/2}(^{7}Be)$=53.2 days



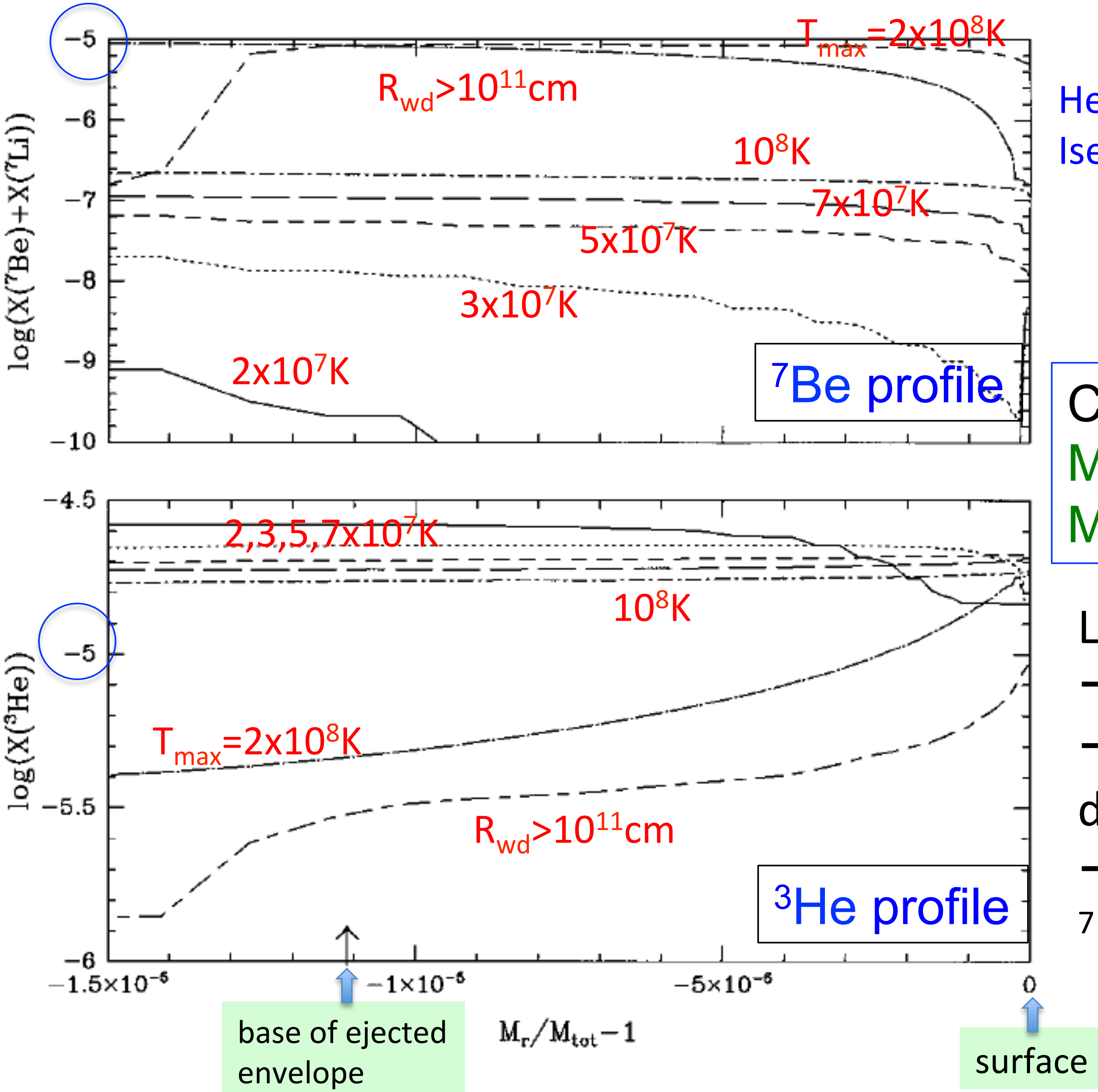
Hernanz, José, Coc, Isern 1996, ApJ Lett.

ONe nova

$M_{wd}=1.15\ M_\odot$

$M=2\times10^{-11}\ M_\odot/yr$

^{7}Be originates only from ^{3}He: enough ^{3}He should survive the accretion phase



Hernanz, José, Coc, Isern 1996, ApJ Lett.

CO nova
M_{wd}=1.15 $M_\odot$
M=2x10^{-11} $M_\odot$/yr

Larger ^{12}C amount
→ faster evolution
→ less ^{3}He destruction
→ more ^{7}Be produced

Nova models: theoretical predictions of ^{7}Li ejected masses

^{7}Li Yields and Ejected Masses for Some Nova Models

Composition	M_{wd} ($M_\odot$)	$\dot{M}$ ($M_\odot$ yr^{-1})	$\bar{X}$ (^{7}Li)	$\frac{N(^7\mathrm{Li/H})}{N(^7\mathrm{Li/H})_\odot}$	M^{ej}_{tot} ($M_\odot$)	$M^{ej}_{^7\mathrm{Li}}$ ($M_\odot$)
CO............	1.0	2×10^{-10}	3.1×10^{-6}	742	2.3×10^{-5}	7.1×10^{-11}
CO............	1.15	2×10^{-10}	8.2×10^{-6}	1952	1.3×10^{-5}	1.1×10^{-10}
ONe	1.15	2×10^{-10}	6.0×10^{-7}	143	1.9×10^{-5}	1.1×10^{-11}
ONe	1.25	2×10^{-10}	6.5×10^{-7}	155	1.8×10^{-5}	1.2×10^{-11}
ONe	1.25	2×10^{-8}	7.9×10^{-7}	187	8.3×10^{-6}	6.7×10^{-12}

Hernanz, José, Coc, Isern 1996, ApJ Lett
José & Hernanz 1998, ApJ

Nova Nucleosynthesis and chemical evolution of the Galaxy

M_{ejec}(theor.) ~ $2\times10^{-5}\ M_\odot$/nova

R(novae) ~ 35 novae/yr

Age of the Galaxy ~ 10^{10} yrs

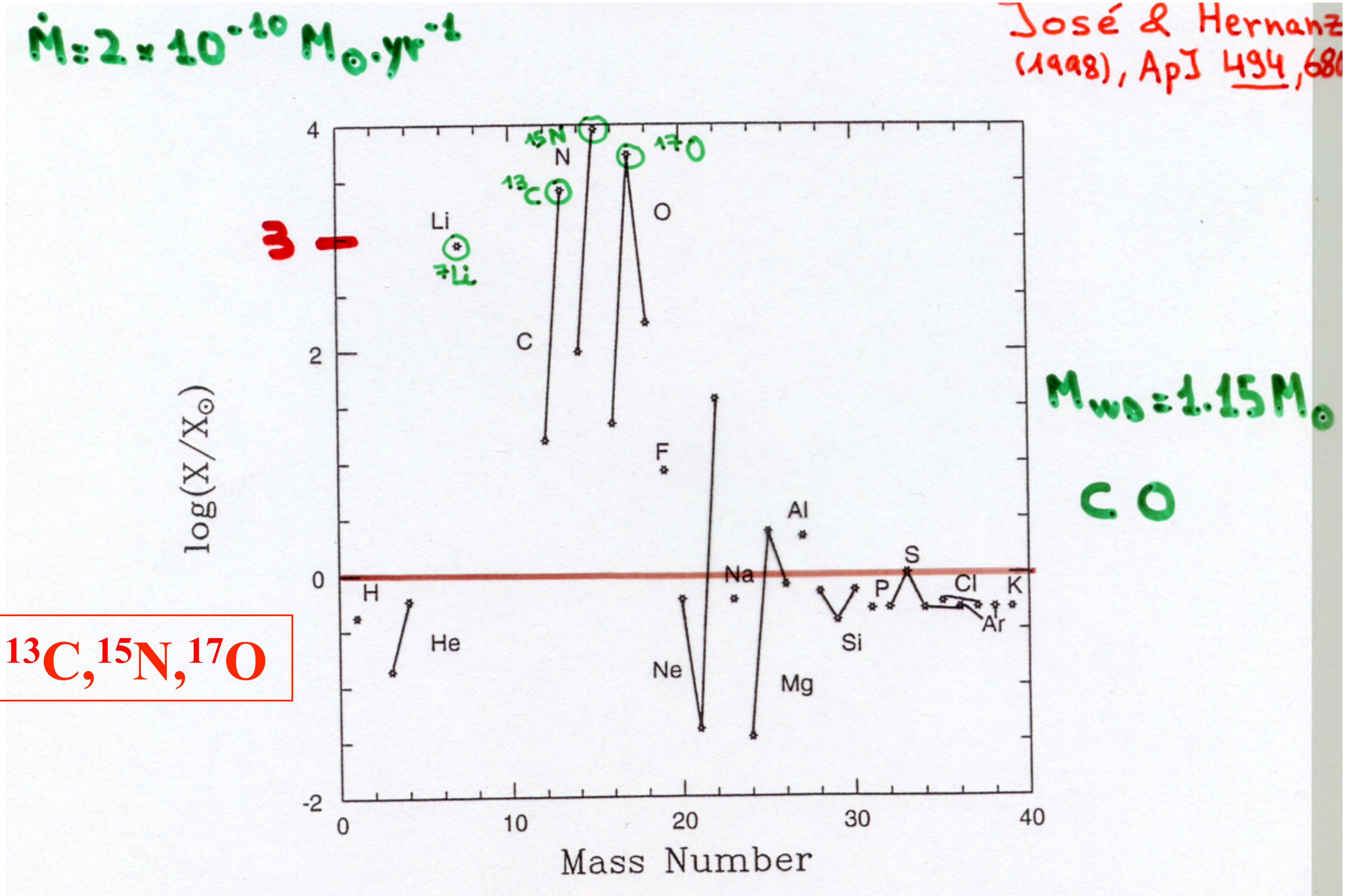
↓

$M_{ejec,total}$(novae) ~ $7\times10^{6}\ M_\odot = (7\times10^{-4}\ M_\odot/yr) \approx 1/3000\ M_{gal}$(gas+dust)

↓

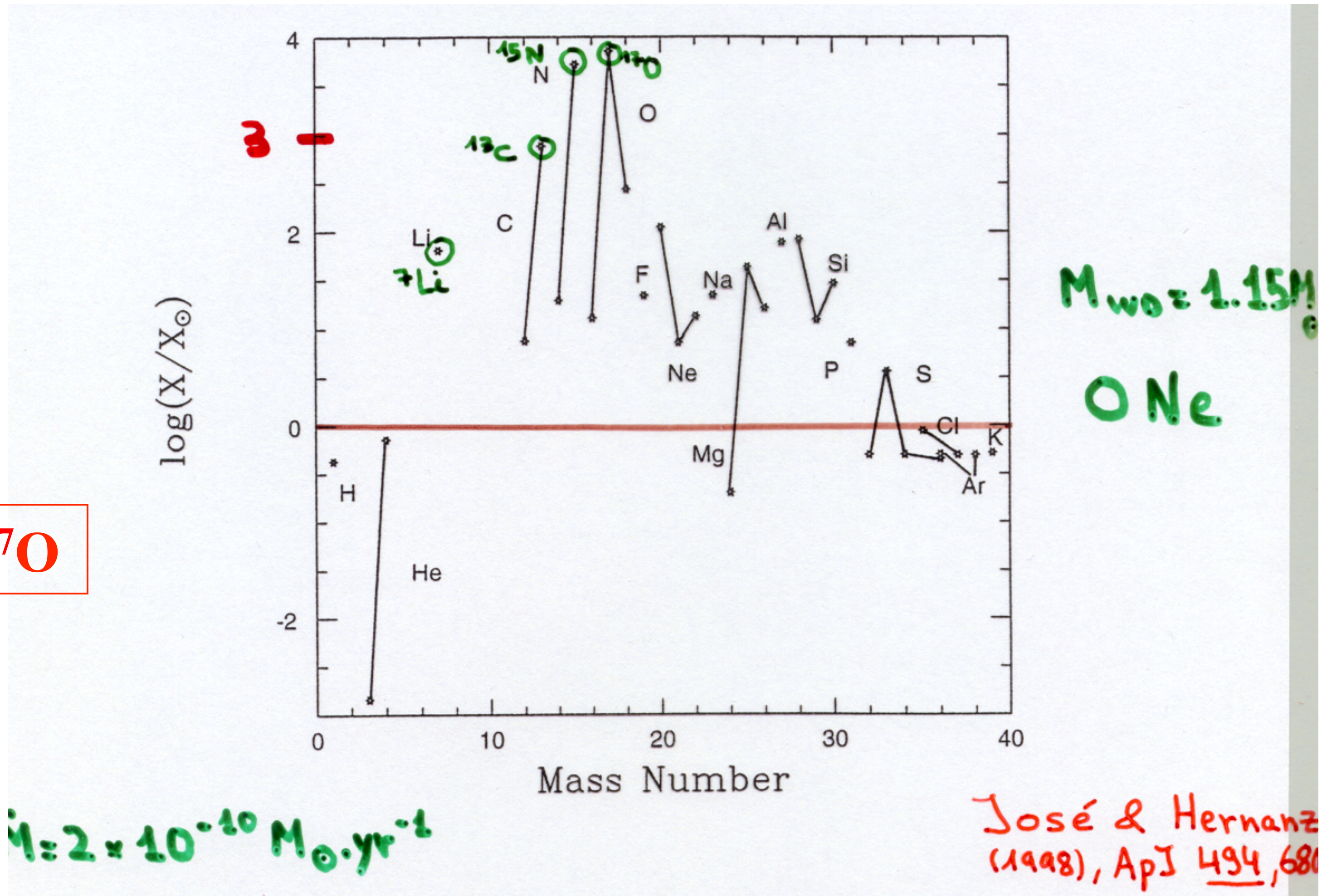
Novae can account for the galactic abundances of the isotopes they overproduce (w.r.t. sun) by factors ≥ ***3000***

Novae nucleosynthesis: overproductions w.r.t. solar



^{7}Li, ^{13}C, ^{15}N, ^{17}O

Novae nucleosynthesis: overproductions w.r.t. solar

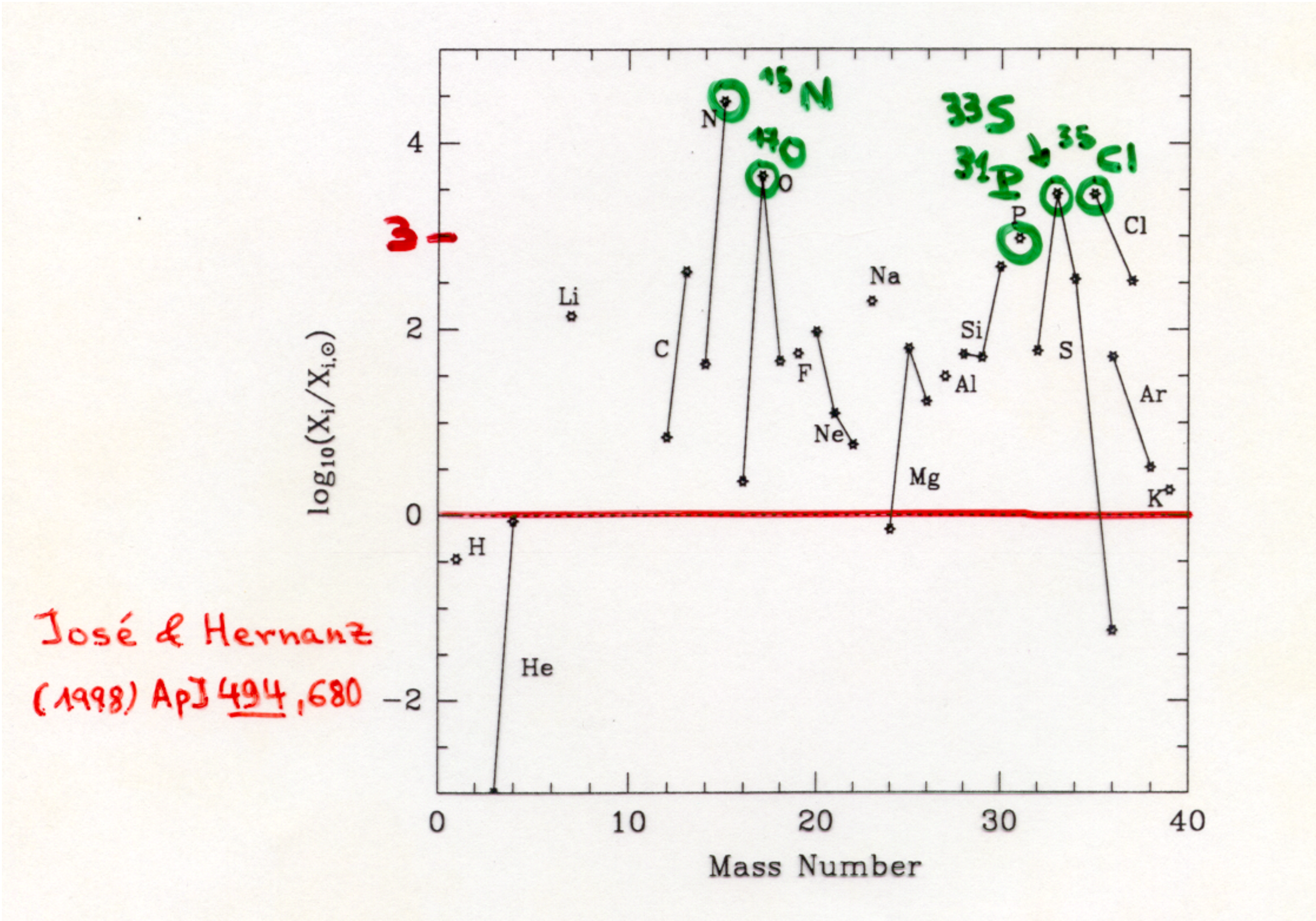


$^{13}C, ^{15}N, ^{17}O$

Novae nucleosynthesis: overproductions w.r.t. solar

ONe

$1.35M_\odot$



In spite of several observational efforts, ^{7}Li had never been detected in any nova until very recently, in 2015

19 FEBRUARY 2015 | VOL 518 | NATURE | 381

LETTER

doi:10.1038/nature14161

Explosive lithium production in the classical nova V339 Del (Nova Delphini 2013)

Akito Tajitsu[1], Kozo Sadakane[2], Hiroyuki Naito[3,4], Akira Arai[5,6] & Wako Aoki[7]

found. Here we report the detection of highly blue-shifted resonance lines of the singly ionized radioactive isotope of beryllium, ^{7}Be, in the near-ultraviolet spectra of the classical nova V339 Del (Nova Delphini 2013) 38 to 48 days after the explosion. ^{7}Be decays to form ^{7}Li within a short time (half-life of 53.22 days[4]). The ^{7}Be was created during the

ASTROPHYSICS

19 FEBRUARY 2015 | VOL 518 | NATURE | 307

News & Views

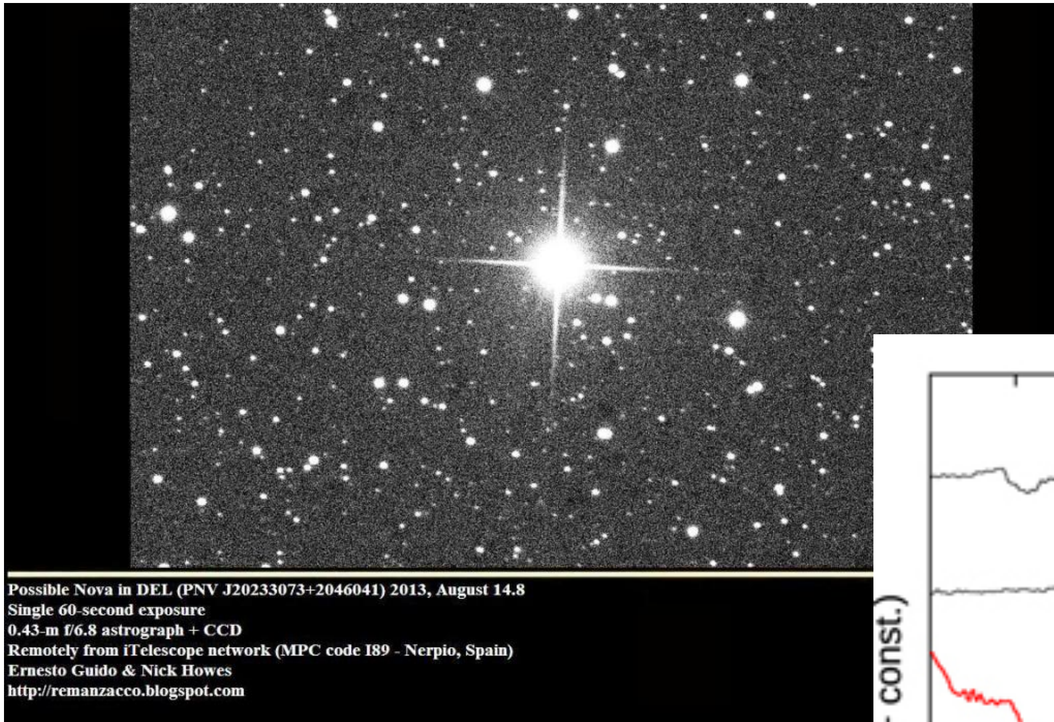
A lithium-rich stellar explosion

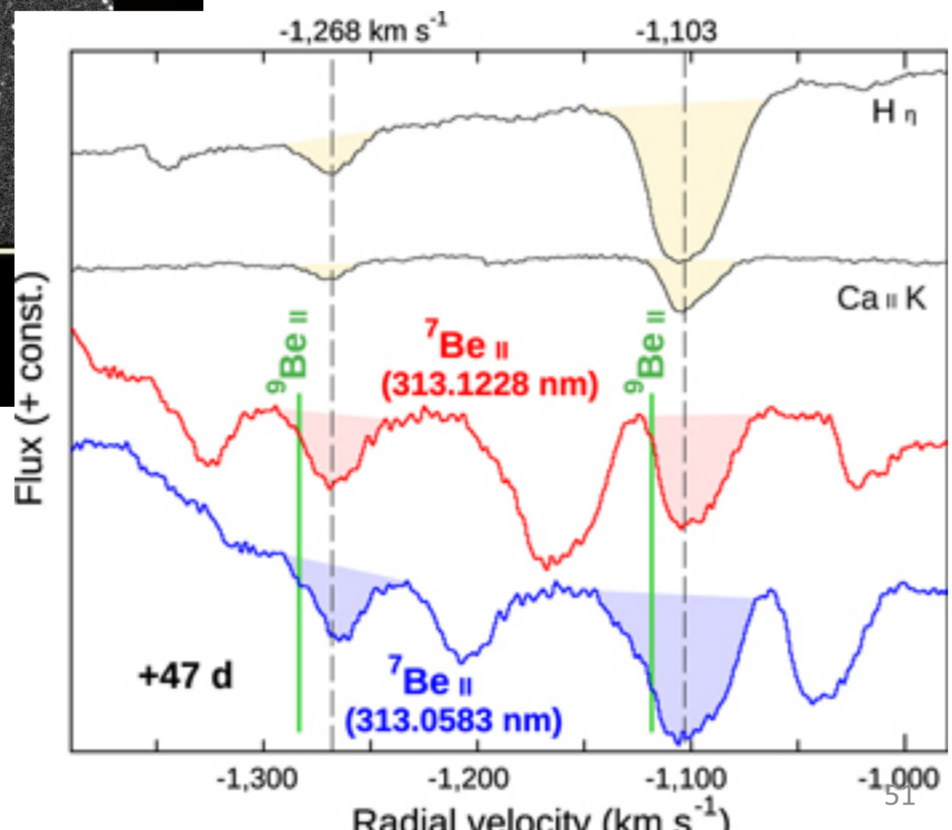
The contribution of explosions known as novae to the lithium content of the Milky Way is uncertain. Radioactive beryllium, which transforms into lithium, has been detected for the first time in one such explosion. SEE LETTER P.381

MARGARITA HERNANZ

during supernova explosions and their dimmer

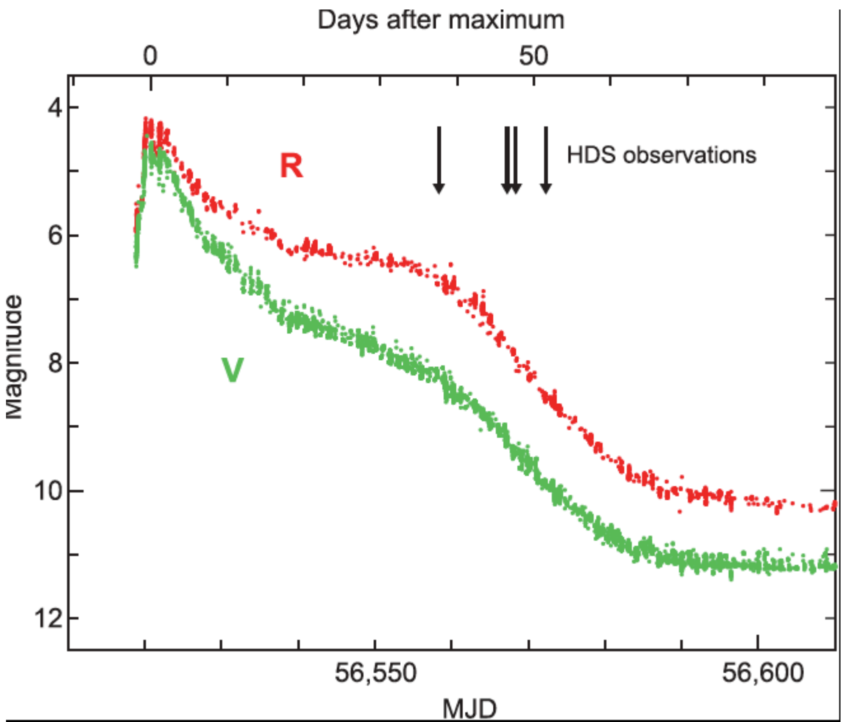
Detection of ^{7}Be (^{7}Li) in Nova Del 2013 (CO nova)





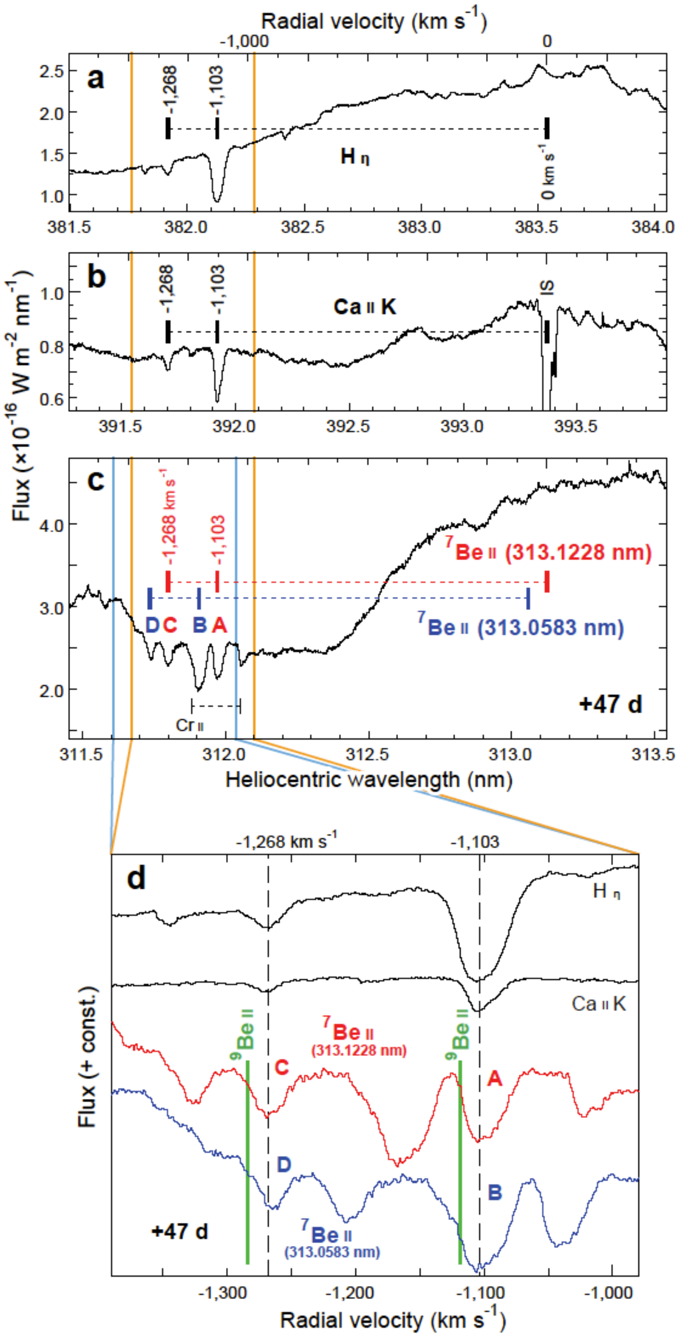
Tajitsu et al. 2015, Nature

Detection of ^{7}Be (^{7}Li) in Nova Del 2013



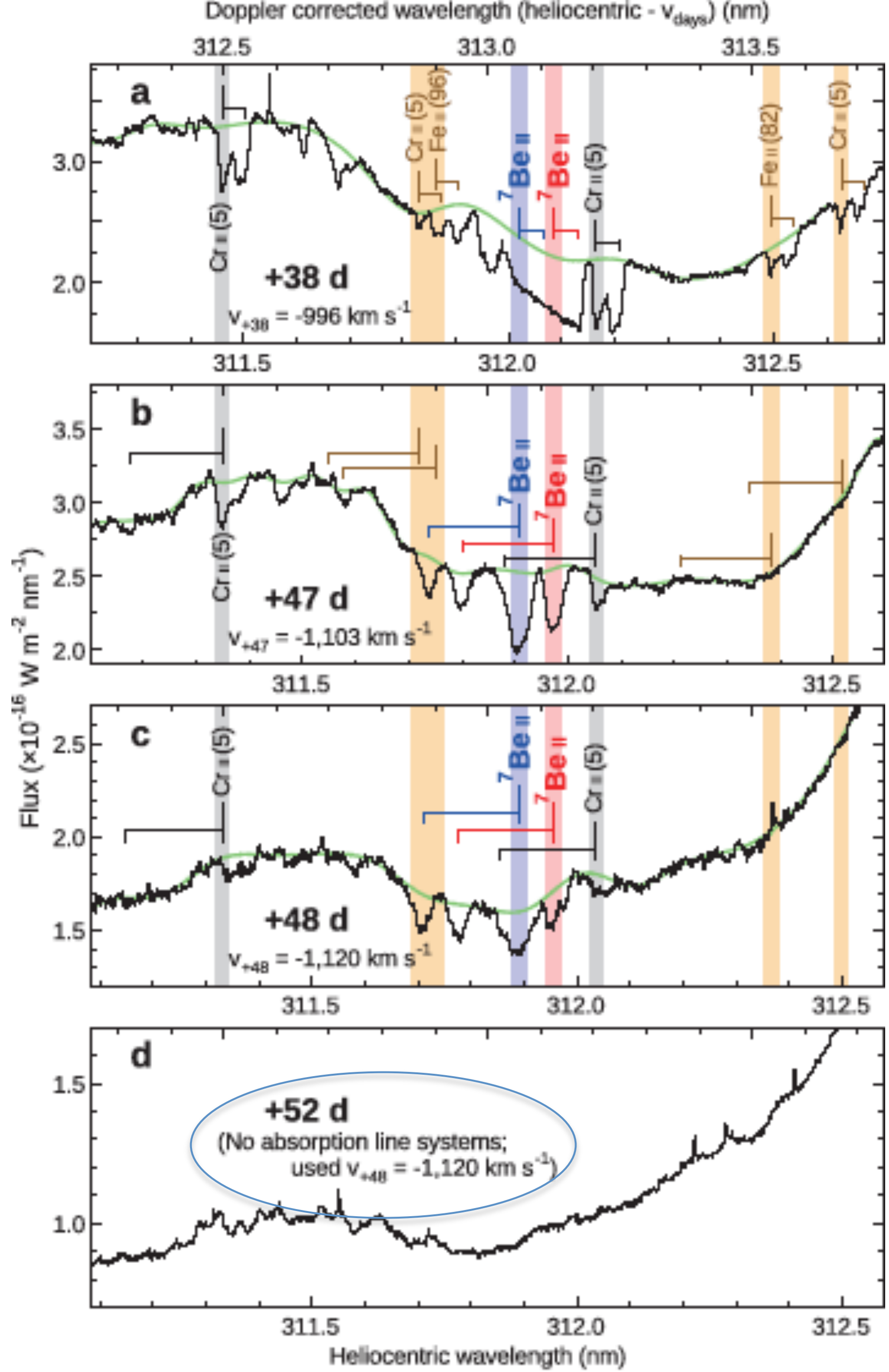
- Subaru Telescope: 8.2-m diameter. Mauna Kea (Hawaï)
- High Dispersion Spectrograph (HDS): spectral resolution 60 000 - 90 000 (0.0052 nm @ 312-313 nm)

Detection of ^{7}Be (^{7}Li) in Nova Del 2013



- Subaru Telescope: 8.2-m diameter. Mauna Kea (Hawaï)
- High Dispersion Spectrograph (HDS): spectral resolution 60 000 - 90 000 (0.0052 nm @ 312-313 nm)
- Able to distinguish ^{9}Be II doublet at 313.0422 nm & 313.1067 nm from the ^{7}Be II doublet at 313.0583 nm & 313.1228 nm
- Blueshifted lines with 1103 & 1268 km/s (also H and Ca)

Detection of ^{7}Be (^{7}Li) in Nova Del 2013



Detection of ^7Be (^7Li) in Nova Del 2013 - Summary

- $X(7Be, th, max.) = 10^{-5.1} = 8.2 \times 10^{-6}$
- $X(7Be, obs) = 10^{-4.3+/-0.3} = 5.0 \times 10^{-5}$
  - obs. factor 6 larger than predicted

- Novae could be much larger contributors to galactic ^7Li than expected
- Interesting way to detect ^7Li through its parent radioactive nucleus ^7Be

Detection of ^{7}Li in Nova Cen 2013

THE ASTROPHYSICAL JOURNAL LETTERS, 808:L14 (5pp), 2015 July 20 IZZO ET AL.

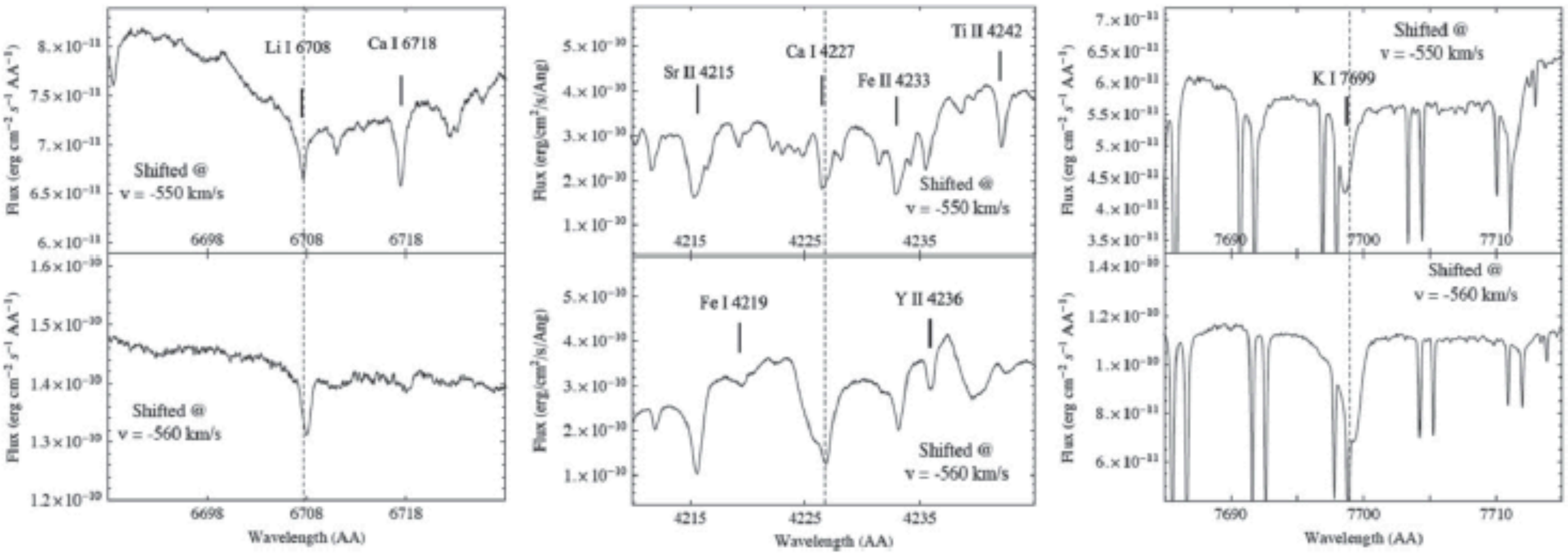


Figure 3. Identification of Li I 6708 (left), Ca I 4227 (middle), and K I 7699 (right) features by direct comparison with the Na I D2 5890 Å P-Cygni absorption in the day 7 (upper panels) and day 13 (lower panels) spectra. All the features share the same expansion velocity ($v_{exp,F1} = -550$ km s^{-1}, $v_{exp,F2} = -560$ km s^{-1}) as that of sodium.

Izzo et al. 2015, ApJ

Models of chemical evolution of the Galaxy

THE ASTROPHYSICAL JOURNAL LETTERS, 808:L14 (5pp), 2015 July 20

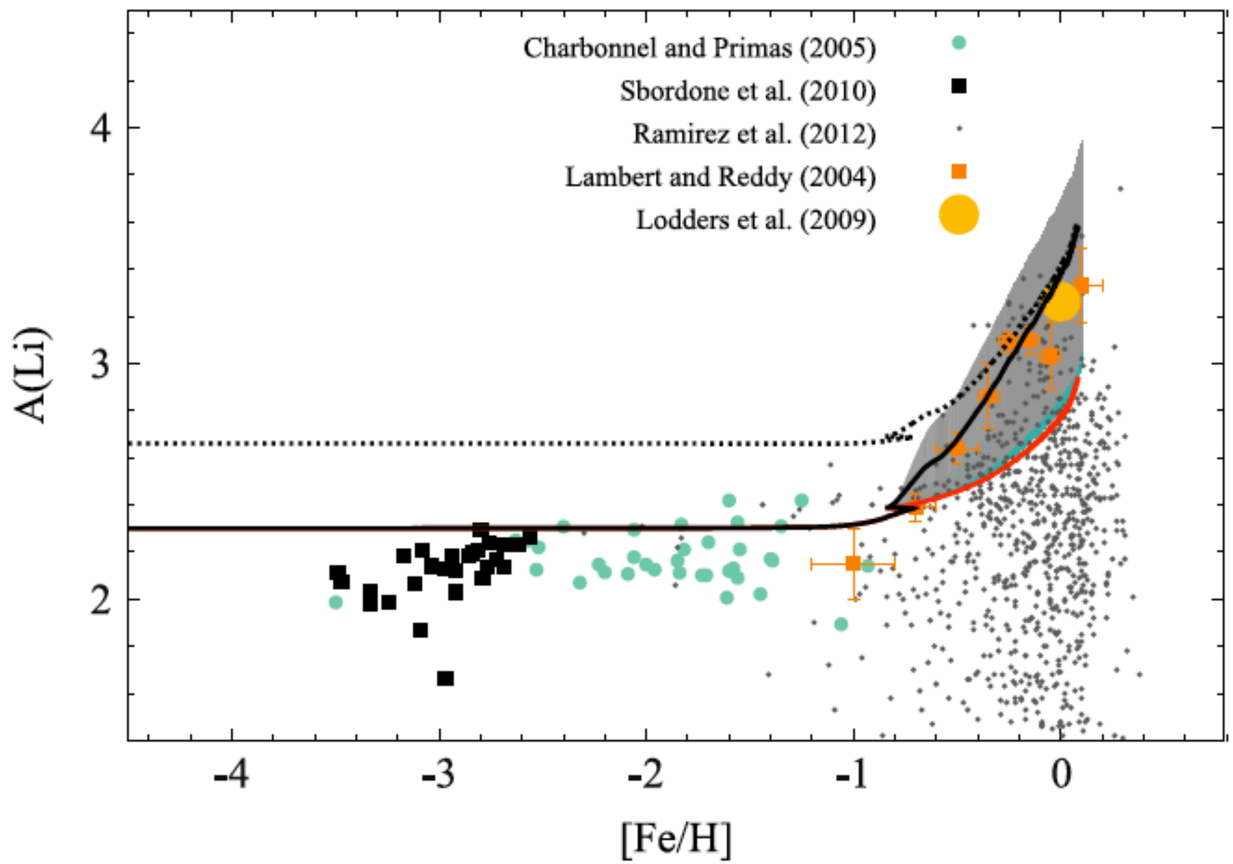
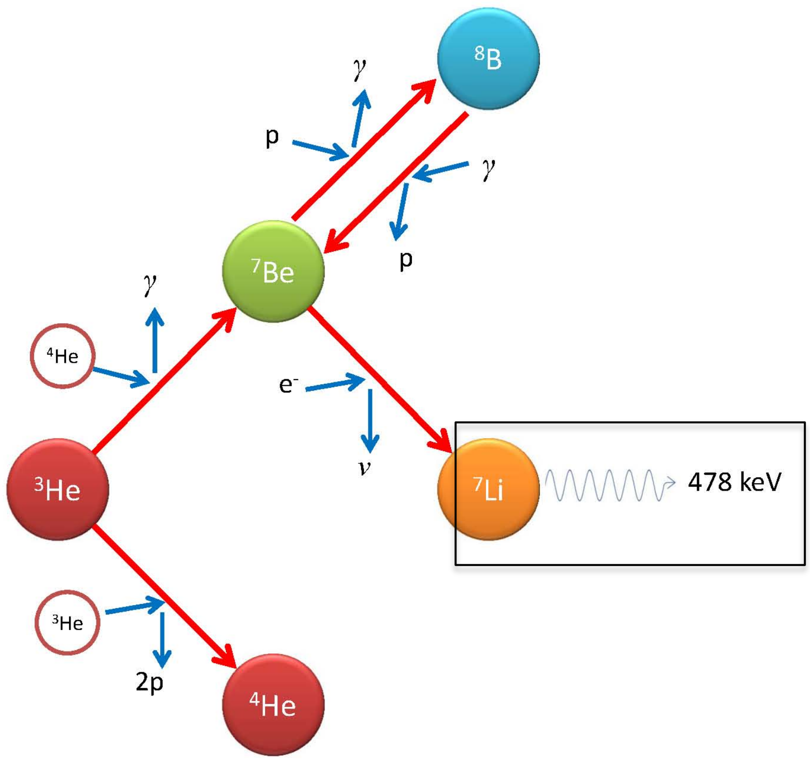


Figure 5. A(Li) vs. [Fe/H] for solar neighborhood stars and meteorites (symbols; see legend) compared to the predictions of chemical evolution models (lines and colored areas). The back and forth behavior in the theoretical curves around [Fe/H] = –0.8 is due to the transition between the halo/thick-disk and thin-disk formation phases (see the text).

Izzo et al. 2015

^7Li is also important for the gamma-ray emission - MeV range - of novae

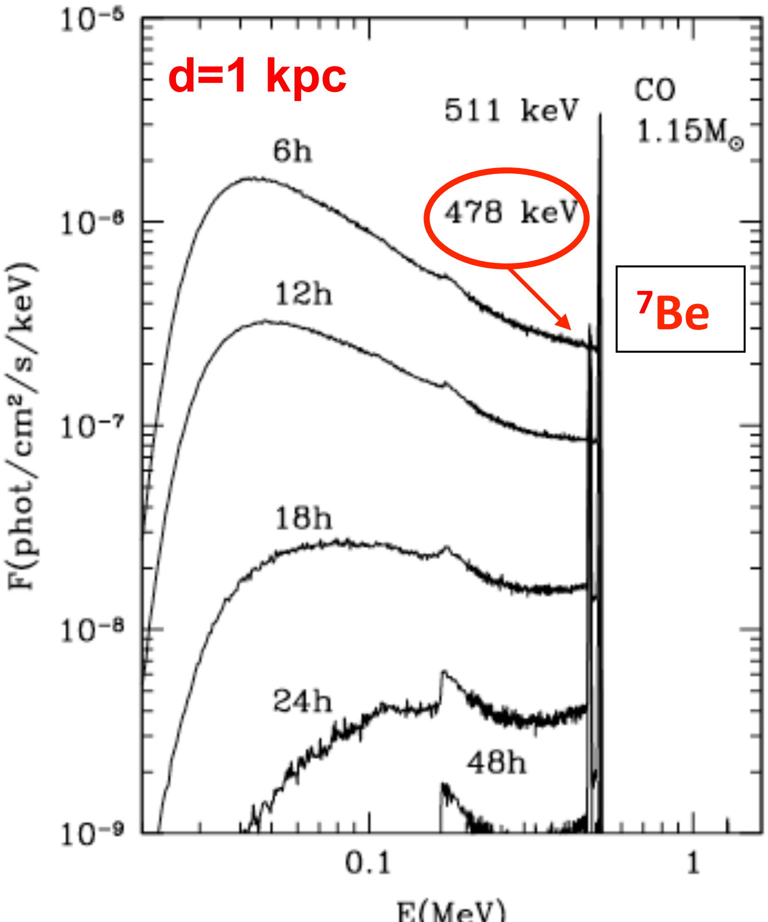


Why do novae emit gamma-rays with E~1 MeV? Main radioactive isotopes synthesized in novae

Nucleus	τ	Type of emission	Nova type
^{13}N	862 s	511 keV line continuum (E<511 keV)	CO and ONe
^{18}F	158 min	511 keV line continuum (E<511 keV)	CO and ONe
→ ^{7}Be	77 days	478 keV line	CO mainly
^{22}Na	3.75 yr	1275 keV line	ONe
^{26}Al	1.0×10^{6} yr	1809 keV line	ONe

Spectra of CO novae

$M_{WD} = 1.15\ M_\odot$



- e^--e^+ annihilation and Comptonization → continuum and 511 keV line
  e^+ from ^{13}N and ^{18}F

→ photoelectric absorption
  → cutoff at 20 keV

→ transparent at 24-48 h

- 478 keV line from ^7Be decay

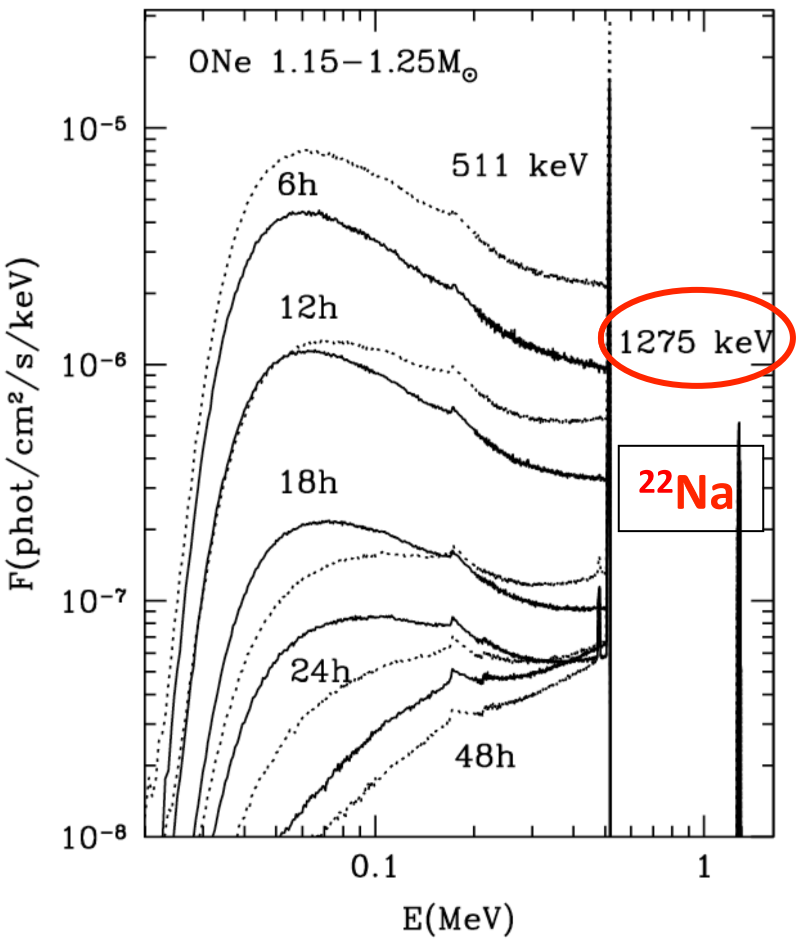
Hydrodynamics & nucleosynthesis:SHIVA JH98
MC code for gamma-ray spectra: Gómez-Gomar et al.1998, MNRAS; Hernanz et al 1999, ApJL

***New nucleosynthesis from José, with Iliadis et al. nucl. react. 2010-2011: less ^{18}F* – Chaffa et al., DeSéréville et al., …**

Spectra of ONe novae

d = 1kpc

M_{WD} = 1.15-1.25 $M_\odot$



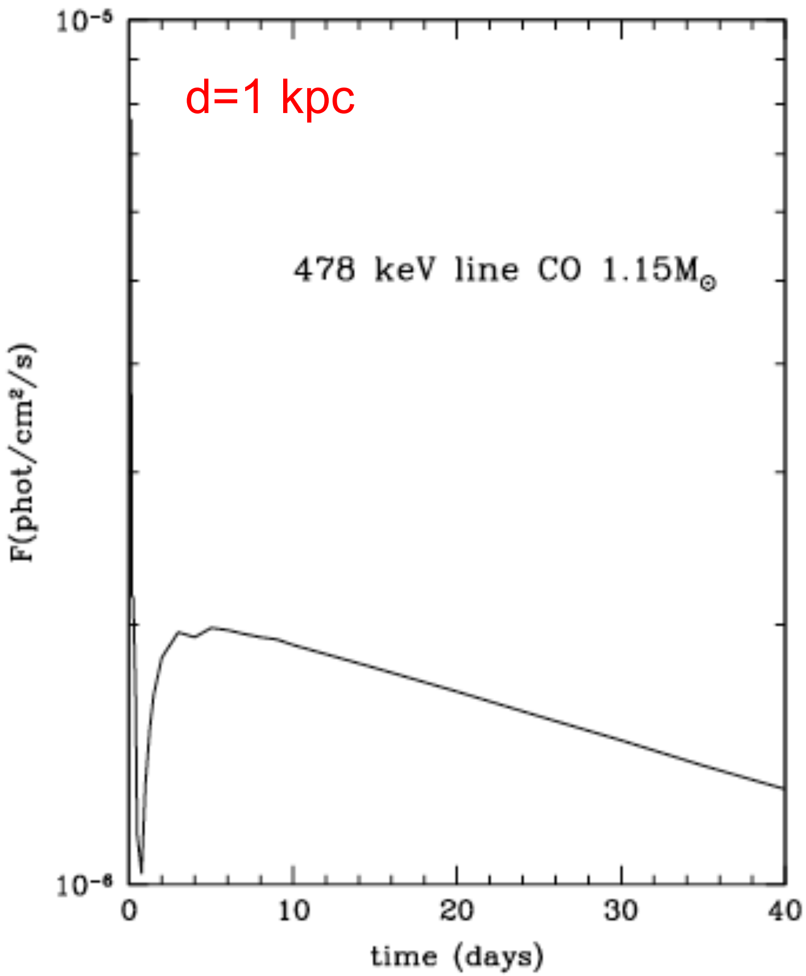
- continuum and 511 keV line
  ➡ as in CO novae but photoelectric absorption
  ➡ cutoff at 30 keV

- 1275 keV line from ^{22}Na decay

- 1.15 & 1.25 $M_\odot$: 1.25 more transparent → larger emission early and smaller later

New nucleosynthesis from José, with Iliadis et al. nucl. react. 2010-2011:
less ^{18}F – **Chaffa et al., DeSéréville et al., …**

Light curves: 478 keV (^{7}Be) line



Mainly in CO novae

t_{max}: 5 days (1.15 $M_\odot$)

duration: some weeks

Flux : (1-2)x10^{-6} ph/cm^2/s

Line width: 3-7 keV

→ ^{7}Be decays into ^{7}Li

Gamma-rays from radioactivities: E ~ 1 MeV

478 keV line from ^{7}Be decay into ^{7}Li searched but not found yet: in agreement with models, because fluxes are too low for typical distances of novae. d<0.5 kpc would be required. Similar for 1275 keV line from ^{22}Na decay

Wait for new missions like ASTROGAM (Compton camera)

Discovery of HE (E > 100 MeV) gamma-ray emission from novae, with the Fermi satellite

Proof of acceleration of cosmic rays in novae

Two types of gamma-ray emission from novae

- **Radioactivity** in the ejecta:
  - traces nucleosynthesis directly
  - photons with E ~ MeV expected
  - not detected yet (CGRO/Comptel, INTEGRAL/SPI)
- **Particle acceleration** in strong external shocks between ejecta and circumstellar material (or internal shocks within the ejecta):
  - red giant wind in symbiotic recurrent nova
  - *"dense circumstellar matter"*
  - IC (leptonic) or π^0 decay (hadronic) ➔ photons with E>100 MeV
  - detected with the Fermi/LAT satellite

High Energy (HE) Gamma-rays : E > 100 MeV, GeV
“Fermi/LAT novae”

First Nova detected in (HE) gamma-rays
Fermi/LAT - E>100 MeV

Gamma-Ray Emission Concurrent with the Nova in the Symbiotic Binary V407 Cygni

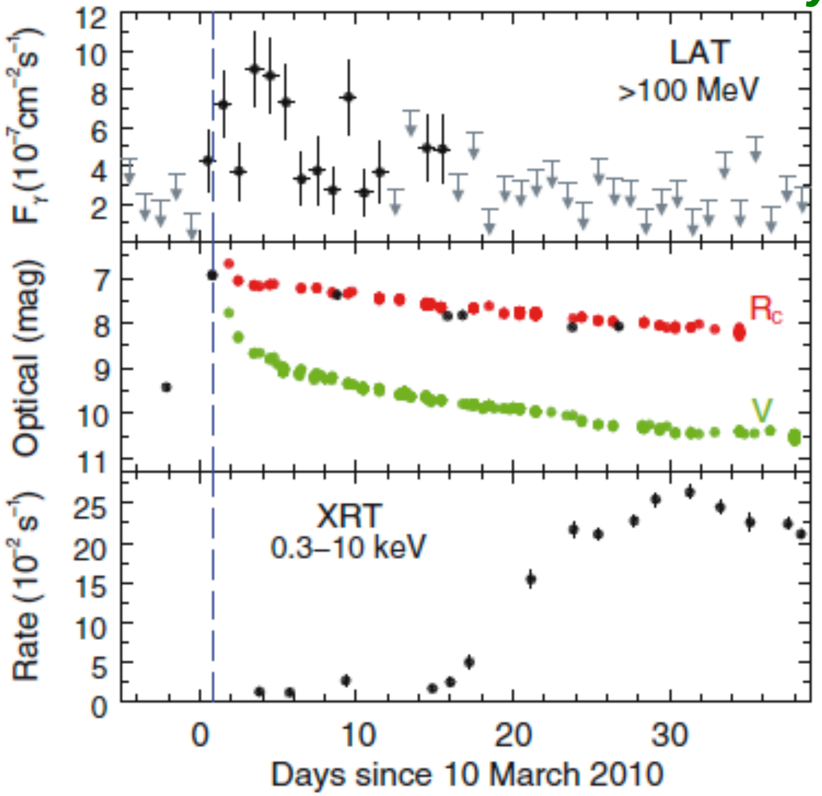
SCIENCE VOL 329 13 AUGUST 2010

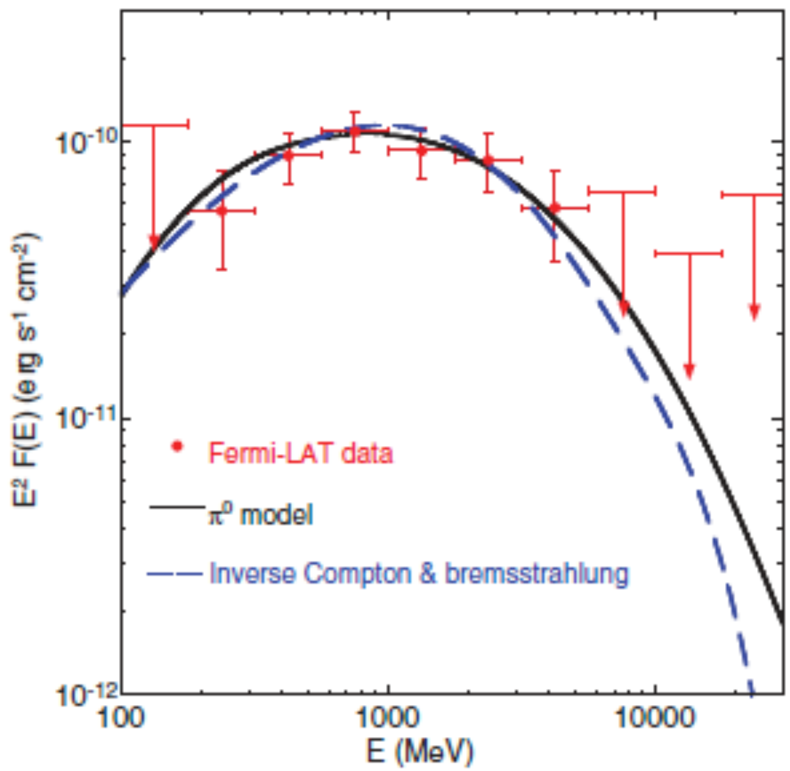
The Fermi-LAT Collaboration*†

Novae are thermonuclear explosions on a white dwarf surface fueled by mass accreted from a companion star. Current physical models posit that shocked expanding gas from the nova shell can produce x-ray emission, but emission at higher energies has not been widely expected. Here, we report the Fermi Large Area Telescope detection of variable γ-ray emission (0.1 to 10 billion electron volts) from the recently detected optical nova of the symbiotic star V407 Cygni. We propose that the material of the nova shell interacts with the dense ambient medium of the red giant primary and that particles can be accelerated effectively to produce π^0 decay γ-rays from proton-proton interactions. Emission involving inverse Compton scattering of the red giant radiation is also considered and is not ruled out.

First nova detected in (HE) gamma-rays
Fermi/LAT - E>100 MeV

V407 Cyg: WD + red giant





Abdo et al. 2010, Science

Fermi establishes classical novae as a distinct class of gamma-ray sources

The Fermi-LAT Collaboration*†

Science **345**, 554 (2014)

A classical nova results from runaway thermonuclear explosions on the surface of a white dwarf that accretes matter from a low-mass main-sequence stellar companion. In 2012 and 2013, three novae were detected in γ rays and stood in contrast to the first γ-ray–detected nova V407 Cygni 2010, which belongs to a rare class of symbiotic binary systems. Despite likely differences in the compositions and masses of their white dwarf progenitors, the three classical novae are similarly characterized as soft-spectrum transient γ-ray sources detected over 2- to 3-week durations. The γ-ray detections point to unexpected high-energy particle acceleration processes linked to the mass ejection from thermonuclear explosions in an unanticipated class of Galactic γ-ray sources.

- ***V407 Cyg: WD + red giant (wind) system (symbiotic recurrent nova)***
- ***CNe: WD + MS have also been discovered by Fermi at E>100 MeV***

Science **345**, 554 (2014)

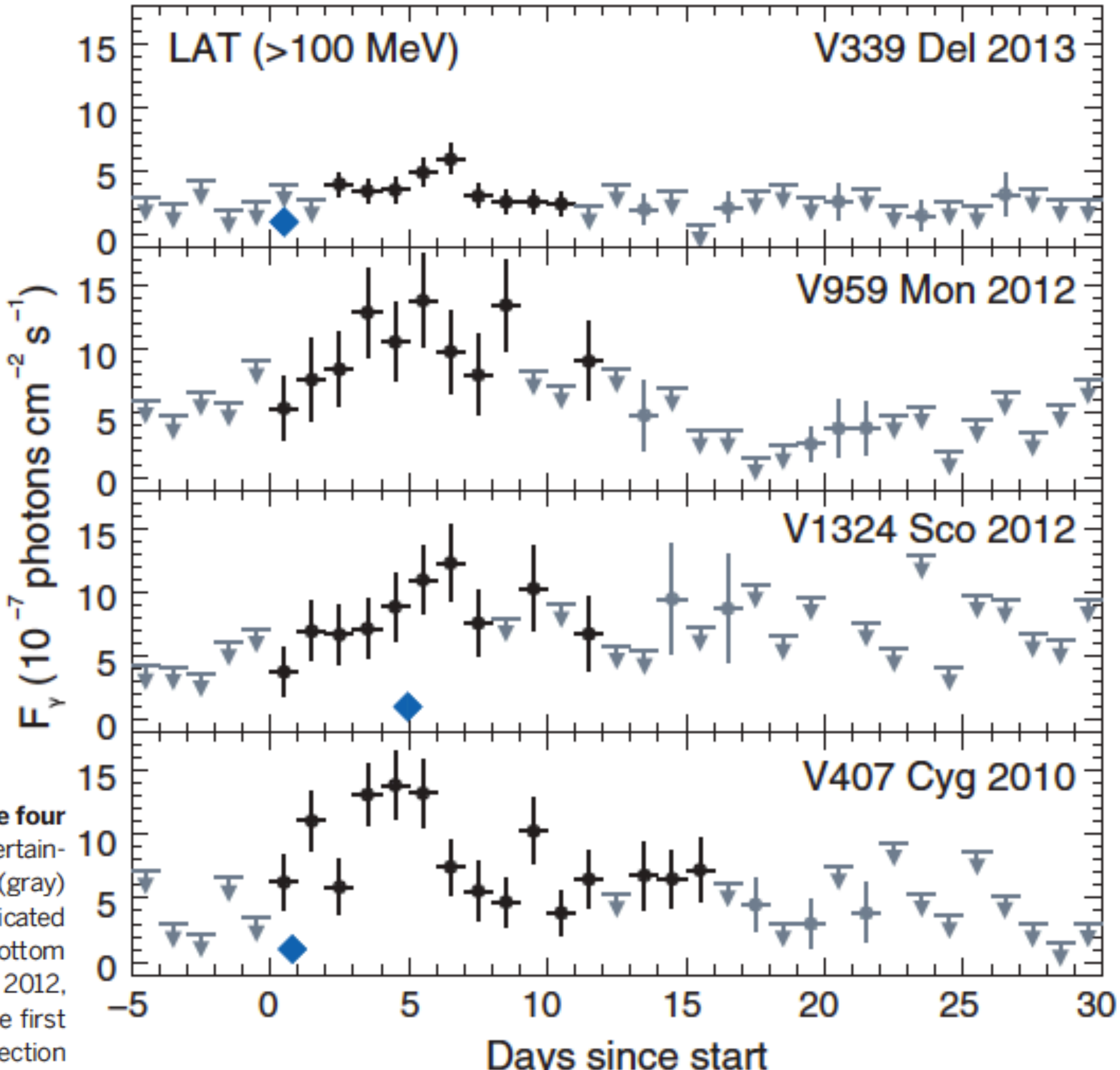


Fig. 2. Fermi-LAT 1-day binned light curves of the four γ-ray detected novae. Vertical bars indicate 1 σ uncertainties for data points with >3 σ (black) and 2 to 3 σ (gray) significances; otherwise, 2 σ upper limits are indicated with gray arrows. Start times t_s (from top to bottom panels) of 16 August 2013, 19 June 2012, 15 June 2012, and 10 March 2010 were defined as the day of the first γ-ray detection. In V339 Del, there was a 2.4 σ detection in 0.5-day binned data beginning 16.5 August (*13*), the epoch of the optical peak (blue diamond in each panel).

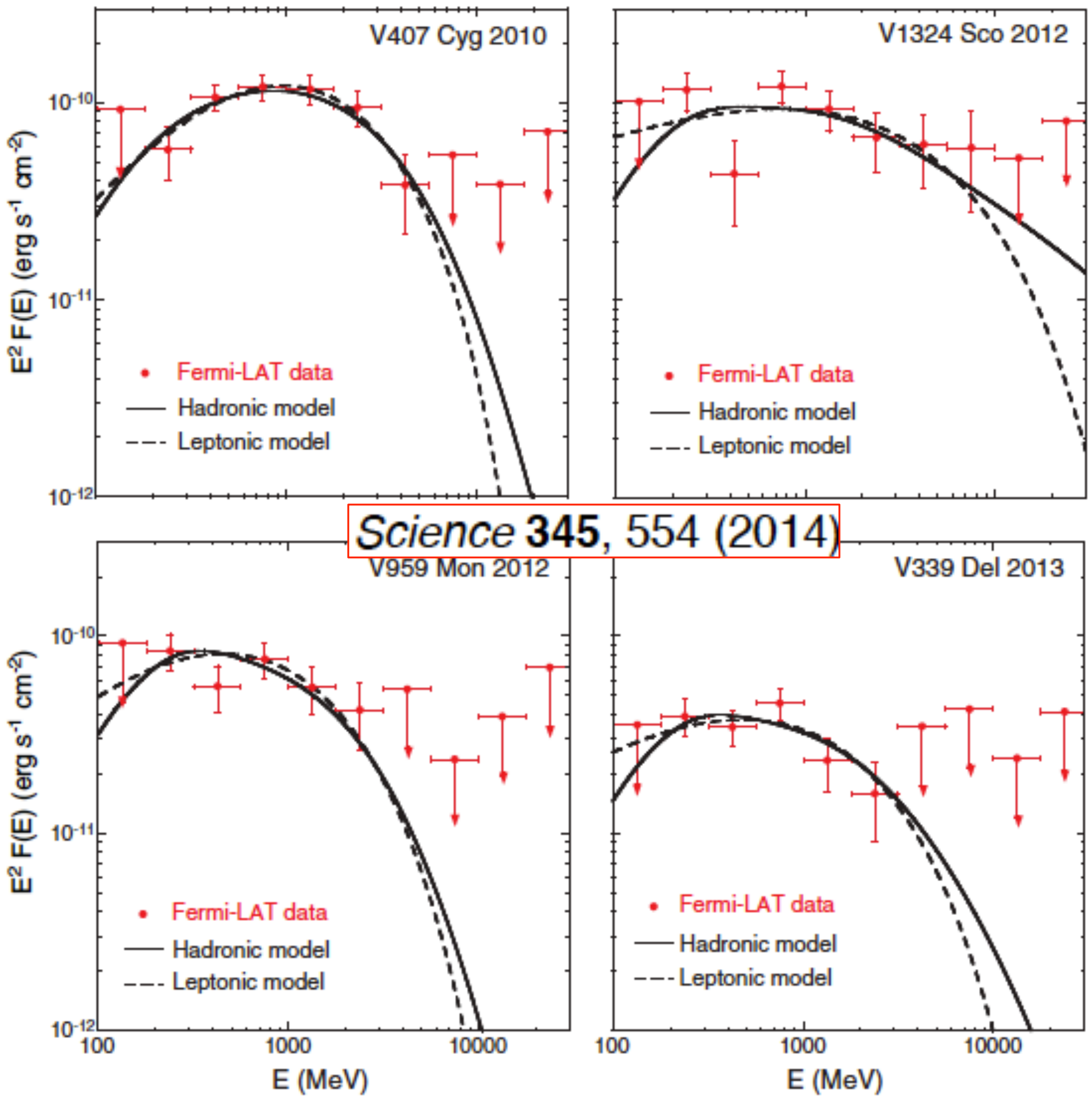


Fig. 3. Fermi-LAT >100-MeV average γ-ray spectra of the four novae over the full 17- to 27-day durations. Vertical bars indicate 1 σ uncertainties for data points with significances >2 σ otherwise, arrows indicate 2 σ limits. The best-fit hadronic and leptonic model curves are overlaid.

Discrimination between hadronic and leptonic emission models not easy with current sensitivities

Binary orbits as the driver of γ-ray emission mass ejection in classical novae

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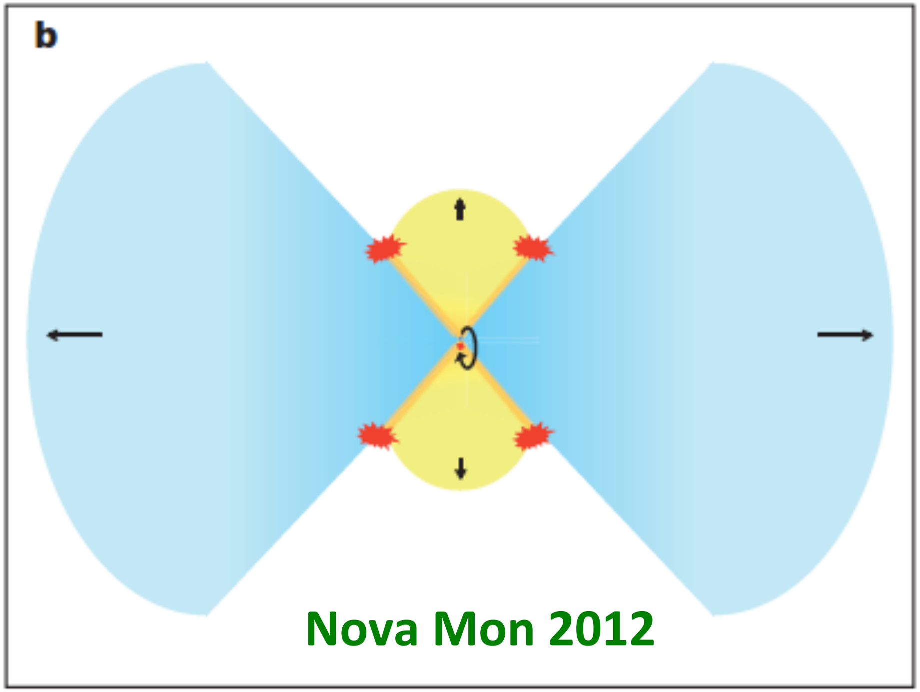
Nature, 2014



ejecta. Here we report high-resolution radio imaging of the γ-ray-emitting nova V959 Mon. We find that its ejecta were shaped by the motion of the binary system: some gas was expelled rapidly along the poles as a wind from the white dwarf, while denser material drifted out along the equatorial plane, propelled by orbital motion[6,7]. At the interface between the equatorial and polar regions, we observe synchrotron emission indicative of shocks and relativistic particle acceleration, thereby pinpointing the location of γ-ray production. Binary shaping of the nova ejecta and associated internal shocks are expected to be widespread among novae[8], explaining why many novae are

Fermi/LAT detection of Nova Cen 2013
ATels #5649, 5653 10-12/12/2013

Fermi-LAT Gamma-ray Observations of Nova Cen 2013

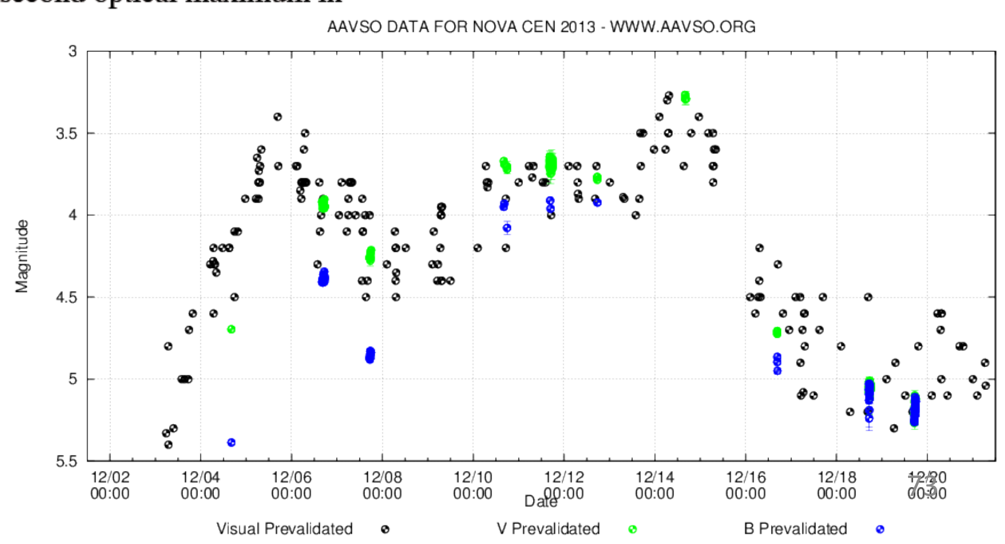
C. C. Cheung (NRL), P. Jean (IRAP, Toulouse), on behalf of the Fermi/LAT collaboration, S. N. Shore (U. Pisa and INFN)

The Fermi Gamma-ray Space Telescope began a Target of Opportunity (ToO) observation of the classical nova V1369 Centauri = Nova Cen 2013 (IAUC 9265) December 6. Preliminary analysis shows that the nova was detected at ~4 sigma by the LAT in three days of exposure from December 7-10, with an average flux, F(E>100 MeV) ~ (2.1 +/- 0.6) x 10^-7 ph cm^-2 s^-1. The gamma-ray detection began ~2 days after the optical peak (pre-validated AAVSO lightcurve), similar to the recent case of Nova V339 Del 2013 (ATEL #5302). The extinction toward V1369 Cen (ATEL #5639) is comparable to V339 Del and may be similarly close in distance.

Fermi-LAT Observations of Nova Cen 2013 Brightening in gamma-rays

Following the initial ~4 sigma Fermi-LAT detection of Nova V1369 Cen 2013 from December 7-9 (ATEL #5649), preliminary analysis indicates the nova brightened in gamma rays, with a two-day average flux, F(E>100 MeV) ~ (5.7 +/- 1.2) x 10^-7 ph cm^-2 s^-1 (7 sigma detection) during December 10-11. The flux is a factor of ~2.7 times greater than in the initial December 7-9 detection and the gamma-ray brightening appears to coincide with a second optical maximum in the pre-validated AAVSO light curve.

Classical nova - No Red Giant companion



Fermi/LAT tentative detection of V745 Sco (a symbiotic recurrent nova): ATel #5879, 12 Feb. 2014

Fermi-LAT Gamma-ray Observations of Recurrent Nova V745 Sco

C. C. Cheung (NRL), P. Jean (IRAP, Toulouse), on behalf of the Fermi/LAT collaboration, S. N. Shore (U. Pisa and INFN)

We report Fermi Gamma-ray Space Telescope observations of the recurrent nova V745 Sco discovered in outburst on 2014 February 6.694 UT (CBET 3803). Preliminary analysis of the Fermi-LAT data indicates the largest observed significances on Feb 6th and 7th of 2 and 3 sigma, respectively, with a peak daily flux, F(E>100 MeV) ~ (3 +/- 1) x 10^-7 ph cm^-2 s^-1 (statistical error only; photon index of 2.2 was assumed). No significant emission was detected in the subsequent days (through the end of Feb 10th) with daily flux upper limits <(2-3) x 10^-7 ph cm^-2 s^-1 (95% confidence). Note that since Feb 5, Fermi recommenced a modified sky survey profile favoring the Galactic center region

Symbiotic recurrent nova: Red Giant companion. Nova ejecta - RG wind interaction

New Fermi/LAT nova detection: ATel #7283, 24/03/2015

Fermi-LAT Gamma-ray Observations of Nova Sagittarii 2015 No. 2

C. C. Cheung (NRL), P. Jean (IRAP, Toulouse), on behalf of the Fermi/LAT collaboration, S. N. Shore (U. Pisa and INFN)

$F(E>100\ \text{MeV}) = (1.4 \pm 0.6) \times 10^{-7}\ \text{ph/cm}^2\text{/s}$ (3.8 sigma)

Detectable gamma-ray emission was found ~1.5 days after the optical emission peak at around March 21.5, 2015, similar to previous cases

Classical nova - No Red Giant companion

Summary: 7 Fermi/LAT nova detections

5 CNe (WD + MS) & 2 SyRNe (WD + RG)

First evidence of particle acceleration – p & e - to TeV energies in nova *predicted before Fermi launch*

EVIDENCE FOR NONLINEAR DIFFUSIVE SHOCK ACCELERATION OF COSMIC RAYS IN THE 2006 OUTBURST OF THE RECURRENT NOVA RS OPHIUCHI

V. TATISCHEFF[1] AND M. HERNANZ

THE ASTROPHYSICAL JOURNAL, 663: L101–L104, 2007 July 10

- RS Oph: symbiotic recurrent nova (WD + RG companion)
- Two last nova eruptions: 1985 & 2006 (P_{rec} = 21 yrs)
- P_{orb}=456 days – d = 1.6 kpc (2.4 kpc)
- Expanding shock wave sweeps red giant wind

RS Oph (2006 eruption): blast wave evolution

RS Oph observations in X-rays with RXTE/PCA

Sokoloski et al. Nature (2006)

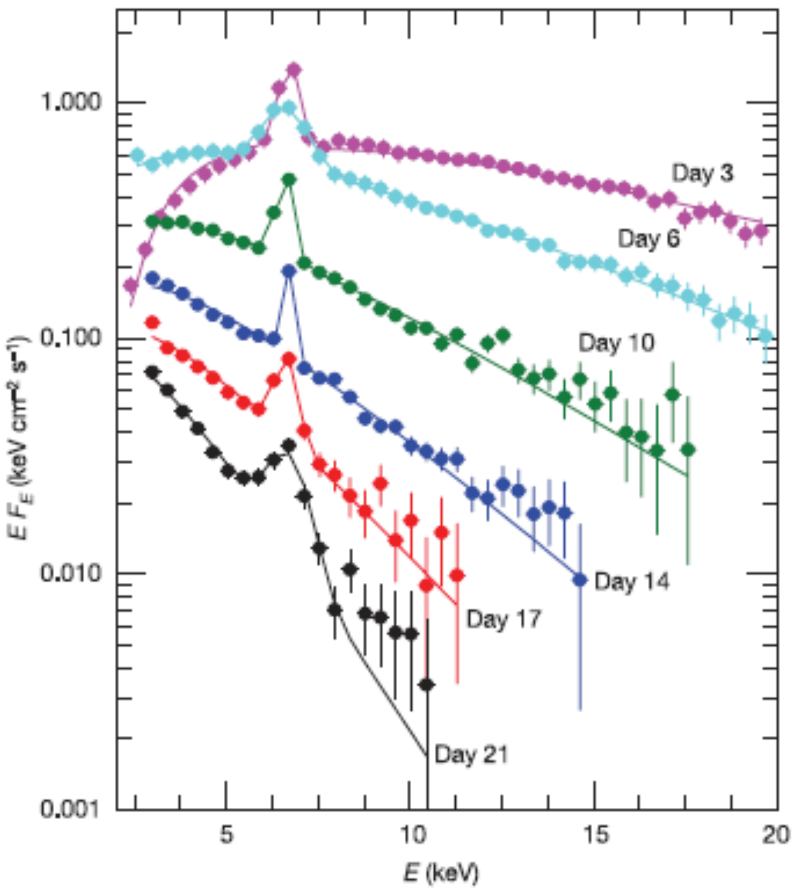


Figure 1 | X-ray spectra from the first 3 weeks of the 2006 outburst of RS Oph. These six spectra were taken with the PCA instrument on board the RXTE satellite. The abscissa is the energy, E, of the detected X-rays. The

- Early hard X-ray emission, decaying fast with time

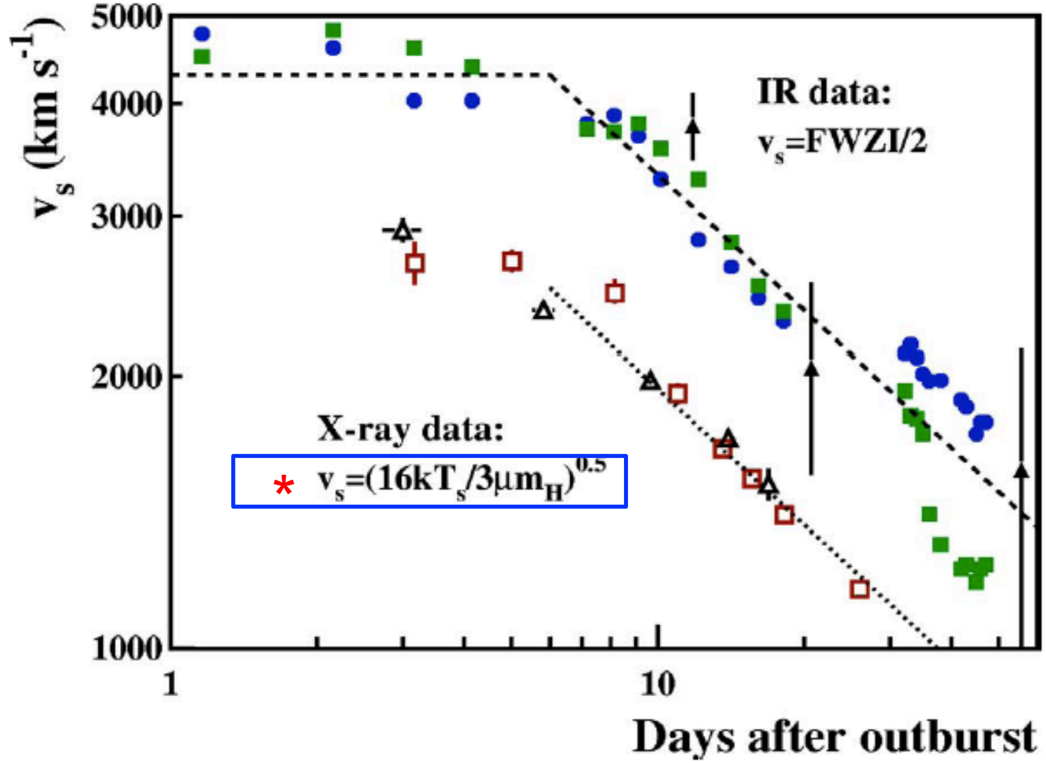
➔ T ~ (30-100) keV

➔ T_{shock} (t)

- Shock wave decelerated faster than expected: evidence was found of particle acceleration (p and e), up to TeV energies: see Tatischeff & Hernanz 2007, ApJL

RS Oph (2006 eruption): blast wave evolution

- IR: shock velocity
- X-rays: RXTE & Swift



Tatischeff & Hernanz, ApJL 2007

- Shock cooling started at 6 days, when T_s was 10^8K and radiative cooling was not important??
- v_{shock} (X-rays) * < v (IR)?? (* test particle adiabatic shock hypothesis)

➔ accel of particles in the blast wave and escape of highest E ions from shock region

RS Oph (2006 eruption): evidence of particle acceleration

Non-linear diffusive shock acceleration: model of Berezhko & Ellison (1999)

- accelerated proton spectrum and post shock temperatures as a funtion of η_{inj} - the fraction of shocked protons injected into the acceleration process

Tatischeff & Hernanz, ApJL 2007

First evidence of particle acceleration - p and e^- - to TeV energies in a nova *[prior to Fermi launch]*

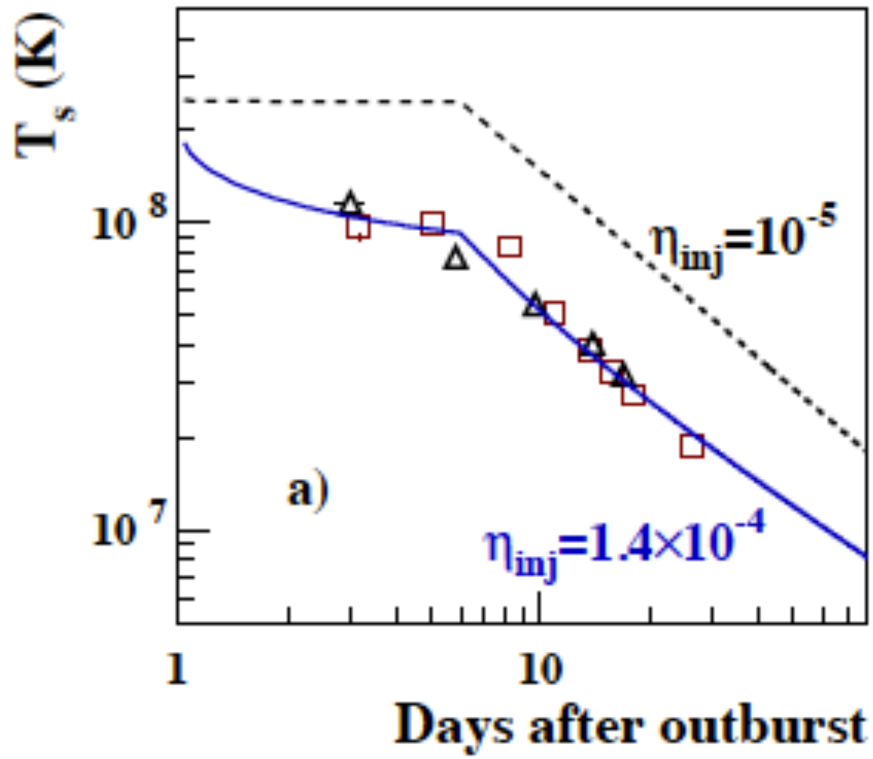
- Good agreement with X-ray measurements of T_{shock} for moderate CR accel. efficiency

$\eta_{inj} \sim 10^{-4}$ - fraction of shocked protons injected into the acceleration process

- Energy loss rate due to particle escape

$$2\times10^{38}\left(\frac{\varepsilon_{esc}}{0.15}\right)\left(\frac{t}{6\ \text{days}}\right)^{-1.5}\ \text{erg s}^{-1}$$

~100 times larger than L_{bol} of postshock plasma ➔ *energy loss via accelerated particle escape much more efficient than radiative losses to cool the shock*



Tatischeff & Hernanz, ApJL 2007

First evidence of particle acceleration - p and e^- - to TeV energies in a nova *[prior to Fermi launch]*

Acceleration of particles (p and e) to TeV energies in a nova - RS Oph (2006) - demonstrated for the first time

- Explains why the observed cooling of the shock started so early (6 days after outburst)
- *"Miniature SN remnant"- much dimmer & evolving much faster* → *study of time dependence of cosmic ray acceleration in a blast wave is possible*
- ***HE gamma-rays***

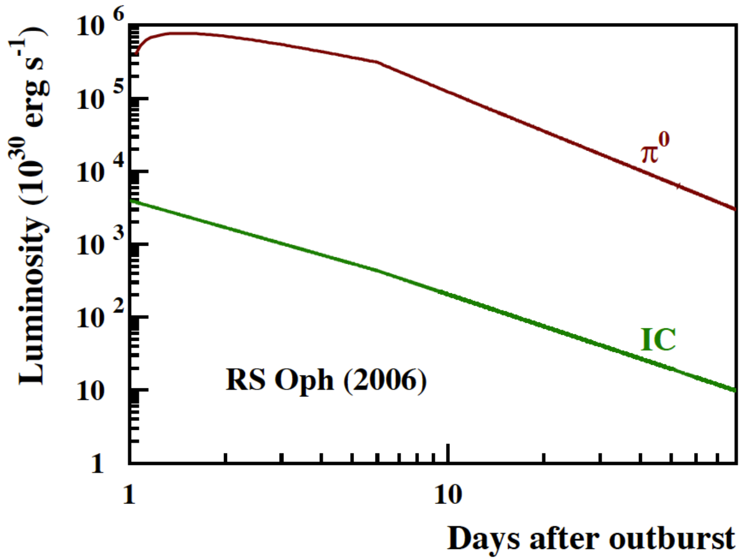
Tatischeff & Hernanz, ApJL 2007

RS Oph (2006): predicted HE gamma-ray emission

- π^0 production: (p-p coll.; hadronic)
- IC contribution: (e^- -photons; leptonic) derived from non thermal synchrotron (radio) and ejecta L_{ej}~L_{Edd}

➔ π^0 production dominates

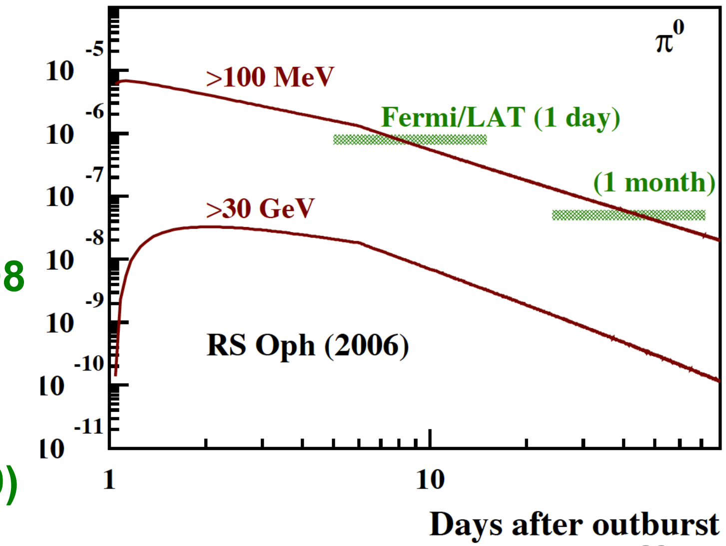
RS Oph would have been detected by Fermi!



Tatischeff, MH, ApJL 2007

TH, Cospar Symposium 2008

MH,Tatischeff, Balt. Astr. 2011 (arXiv:1111.4129)



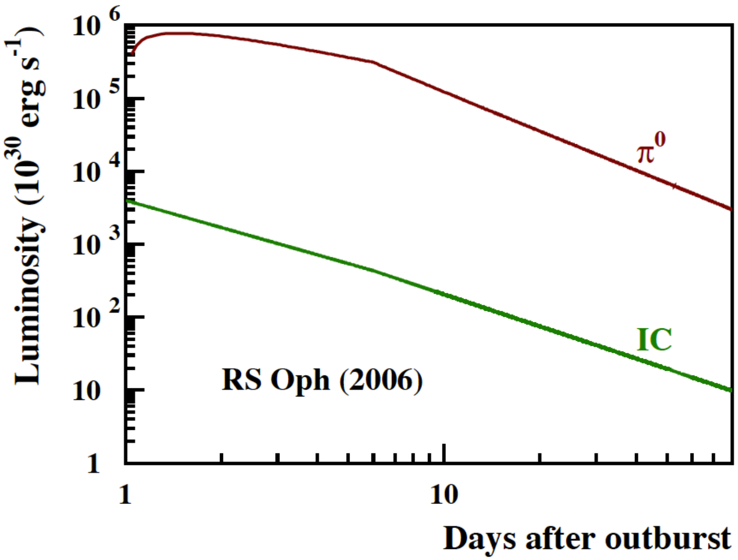
RS Oph (2006): predicted HE gamma-ray emission

- π^0 production: (p-p coll.; hadronic) from ε_{CR} and $(dM/dt)_{RG}$
- IC contribution: (e^--photons; leptonic) derived from non thermal synchrotron $L_{syn} \sim 5 \times 10^{33}\, t_d^{-1.3}$ erg/s, (Kantharia et al. 07, radio 1.4 GHz) and ejecta $L_{ej} \sim L_{Edd} = 2 \times 10^{38}$ erg/s:

$$L_{IC} = L_{syn} \times U_{rad}/(B^2/8\pi) \sim L_{syn}$$

➔ π^0 production dominates

RS Oph would have been detected by Fermi!



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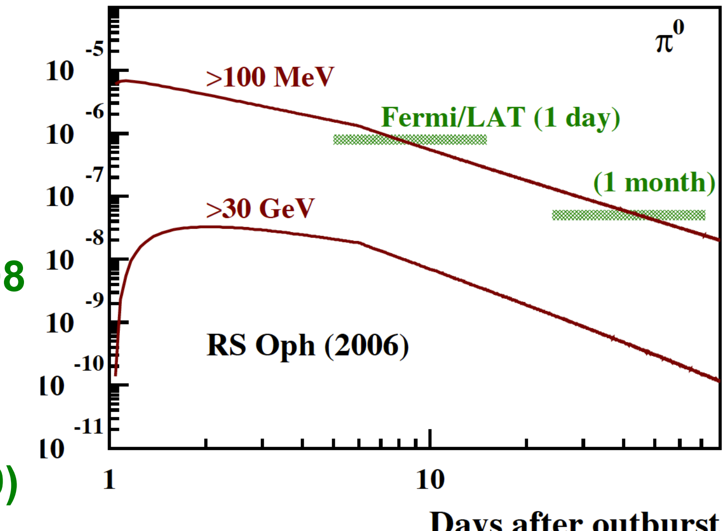

SUMMARY

- Discovery of ^{7}Li in novae, both directly and as radioactive ^{7}Be later decaying to ^{7}Li
  - proof of Cameron-Fowler mechanism in novae
  - relevance for the origin of cosmic lithium
  - better prospects for detection of novae in gamma-rays (MeV range)
- Novae are emitters of HE (E>100 MeV) gamma-rays: acceleration of particles because of the interaction of the ejecta with the surrounding medium
  - external shocks with the red giant wind of the RG companion in symbiotic recurrent novae
  - internal shocks not well understood yet in classical novae