Classical Novae — Theory and Observations

Jordi José
Dept. Física i Enginyeria Nuclear, Univ. Politècnica de Catalunya,
& Institut d’Estudis Espacials de Catalunya (IEEC), Barcelona
Nova (*stella nova*): sudden appearance of a luminous object in the sky (at a spot where nothing was clearly visible before), that fades away in a matter of ~ weeks

*Stellae novae* = supernovae, novae, comets...

**Novae vs. Supernovae**

S Andromedae 1885 in M31
(Too) Early Explanations of the Nova Phenomenon

* G. B. Riccioli, *Almagestum Novum* (1651), lib. 2, pp. 177-179

14 (im)possible explanations!


So fixed stars, that for a long time, may emit light and heat, may emit from them this fresh supply of new fuel those old stars, acquiring new splendor, may pass for new stars!
Observations

* Huggins & Miller perform the first (optical) spectroscopic study of a nova [T CrB 1866]

* Sidgreaves (1901) finds [Ne III] 3869, 3968 Å in GK Per, revealing different nova types (chemically) \( \rightarrow \) Ne-novae!

* Pickering (1894), Pike (1929) and others explain the spectral features by ejection of a shell from a star

* Stratton & Manning (1939) propose that the minimum in DQ Her light curve is due to dust formation

* Walker (1954) unveils the binary nature of DQ Her

* Kraft (1963, 1964) demonstrates that binarity is a common property of CVs (novae, in particular)
Hartmann (1925): shortest paper ever?

RR Pic (1925): “Nova problem solved: star expands, and bursts”

**Theory**

* Schatzmann (1951): outburst triggered by nuclear reactions $[^3\text{He}]$

REMARQUES SUR LE PHÉNOMÈNE DE NOVA (IV)

L’onde de détonation due à l’isotope $^3\text{He}$

par Evry Schatzman

Sommaire. — L’isotope $^3\text{He}$ peut s’accumuler en faible quantité dans les étoiles. Une faible concentration de $^3\text{He}$ est suffisante pour que puisse se former une onde de détonation, à condition que l’amortisseur convenable existe. On en conclut que l’isotope $^3\text{He}$ est vraisemblablement à l’origine du phénomène de Nova.

* Sparks (1969): first hydrodynamic simulation of a nova outburst

DYNAMICAL MODELS OF NOVAE*

WARREN M. SPARKS

Department of Astronomy, Indiana University, and Goddard Space Flight Center
National Aeronautics and Space Administration, Greenbelt, Maryland

Received June 26, 1968; revised September 27, 1968

ABSTRACT

The dynamics of a nova outburst are studied by means of a time-dependent hydrodynamics computer program which includes transport of energy by radiation and convection. Two distinct types of ejections which could give rise to novae are identified. The “flash” nova (e.g., T CrB) has a very rapidly rising and falling light curve and a nearly constant velocity curve. A strong shock wave which imparts a velocity greater than the escape velocity to the outer layers of the star will produce this behavior. A less rapidly rising and falling light curve and a nearly constant velocity are characteristic of the “ordinary” nova (e.g., GK Per). These features will result when the stellar material is forced outward by a pressure front which is not a shock wave. The pre-maximum halt, which is characteristic of the latter type of nova, results from the temperature dependence of the opacity of neutral hydrogen.
The Classical Nova ID Card:

Moderate rise times (<1 – 2 days):
8 – 18 magnitude increase in brightness

L_{Peak} \sim 10^4 – 10^5 \, L_{\odot}

Stellar binary systems: WD + MS
(K-M dwarfs)

Recurrence time: \sim 10^4 – 10^5 \, yr (CN)
10 – 100 yr (RN)

Frequency: 30 \pm 10 \, yr^{-1}
[Observed frequency: \sim 5 \, yr^{-1}]

E \sim 10^{45} \, ergs

Mass ejected: 10^{-4} – 10^{-5} \, M_{\odot}
(\sim 10^3 \, km \, s^{-1})

Novae have been observed in all wavelengths (but never detected so far in \gamma-rays)
Classical Nova: term first coined (likely) by Gerasimovic (1934)

Spectroscopy (abundances)
Photometry (lightcurves)
Hydrodynamics

Thermonuclear runaway model of classical nova explosions
Close binary systems

$P_{\text{orb}} \sim 1 - 12^{\text{hr}}$

Mass transfer:
Roche lobe overflow ($L_1$)

Build-up of an **envelope** in semi-degenerate conditions:
Thermonuclear runaway (TNR)

Strength of the explosion:
$P_{\text{base}}(\Delta M_{\text{env}}, \text{gravity})$

More violent outbursts for:

a) massive $M_{\text{wd}}$

b) larger $\Delta M_{\text{env}}$

$Z \sim Z_\odot \sim 0.02$

WD Star

MS Companion

Accretion disk

CO or ONe WD
Triggering reaction: $^{12}\text{C}(p,\gamma)^{13}\text{N}$ → $^{13}\text{N}(\beta^+)^{13}\text{C}(p,\gamma)^{14}\text{N}$ (cold CNO)

As T increases: $\tau_{(p,\gamma)}[^{13}\text{N}] < \tau_{(\beta+)}[^{13}\text{N}]$ → $^{13}\text{N}(p,\gamma)^{14}\text{O}$ (hot CNO)

$^{14}\text{N}(p,\gamma)^{15}\text{O}$

$^{16}\text{O}(p,\gamma)^{17}\text{F}$

The presence of intermediate-mass (CNO) elements in the envelope has remarkable consequences for the energy transport:

* low Z regime  →  p-p chains  →  radiation

* high Z regime  →  CNO-cycle  →  radiation + convection

Critical role of convection: carrying the short-lived, $\beta^+$-unstable nuclei $^{14},^{15}\text{O},^{17}\text{F}$ ($^{13}\text{N}$) to the outer, cooler layers of the envelope (escaping deadly p-capture reactions)

Sudden release of energy from these short-lived species powers the expansion and ejection stages [Starrfield et al.1972]:

$^{15}\text{N},^{17}\text{O}$ ($^{13}\text{C}$)
The Nova Nuclear Symphony

* Classical Novae: ~ 100 relevant isotopes (A<40) & a (few) hundred nuclear reactions ($T_{\text{peak}} \sim 100 - 400$ MK)

Novae as unique stellar explosions for which the nuclear physics input will be soon (?) primarily based on experimental information (JJ, Hernanz & Iliadis, Nucl. Phys. A 2006)
1.35 M⊙ ONe

JJ, Hernanz, Coc & Iliadis (2010), in preparation
Model 1.35 M⊙
(50% ONe enrichment)

- \[ T = 3.2 \times 10^8 \text{ K} \]
- \[ \rho = 5.1 \times 10^2 \text{ g cm}^{-3} \]
- \[ \varepsilon_{\text{nuc}} = 4.3 \times 10^{16} \text{ erg g}^{-1} \text{ s}^{-1} \]
- \[ \Delta M_{\text{env}} = 5.4 \times 10^{-6} \text{ M}_\odot \]

Negligible contribution from any \((n,\gamma)\) or \((\alpha,\gamma)\) reaction (that also applies to \(^{15}\text{O}(\alpha,\gamma)\)!)"
...talks (this morning) by:
* A. Sallaska: $^{22}\text{Na}(p,\gamma)$
* M. Matos: $^{31}\text{S}(p,\gamma)$

...and posters by:
* D. Bardayan: $^{7}\text{Be}(p,\gamma),\quad^{17}\text{F}(p,\gamma)$
* K. Chipps: $^{25}\text{Al}(p,\gamma)$
* C. Herlitzius: $^{33}\text{Cl}(p,\gamma)$
* A. Laird: $^{18}\text{F}(p,\alpha)$
* A. Saastamoinen: $^{22}\text{Na}(p,\gamma)$
* N. de Séréville: $^{25}\text{Al}(p,\gamma)$
* K. Setoodehnia: $^{29}\text{P}(p,\gamma)$

See 's talk, later today…
$^{33}\text{S}(p,\gamma)$

JJ, Hernanz, Coc & Iliadis (2010), in preparation
Radioactivities from novae

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Lifetime</th>
<th>Disintegration</th>
<th>Nova type</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{17}$F</td>
<td>93 sec</td>
<td>$\beta^+$-decay</td>
<td>CO &amp; ONe</td>
</tr>
<tr>
<td>$^{14}$O</td>
<td>102 sec</td>
<td>$\beta^+$-decay</td>
<td>CO &amp; ONe</td>
</tr>
<tr>
<td>$^{15}$O</td>
<td>176 sec</td>
<td>$\beta^+$-decay</td>
<td>CO &amp; ONe</td>
</tr>
<tr>
<td>$^{13}$N</td>
<td>862 sec</td>
<td>$\beta^+$-decay</td>
<td>CO &amp; ONe</td>
</tr>
<tr>
<td>$^{18}$F</td>
<td>158 min</td>
<td>$\beta^+$-decay</td>
<td>CO &amp; ONe</td>
</tr>
<tr>
<td>$^{7}$Be</td>
<td>77 day</td>
<td>$e^-$-capture</td>
<td>CO</td>
</tr>
<tr>
<td>$^{22}$Na</td>
<td>3.75 yr</td>
<td>$\beta^+$-decay</td>
<td>ONe</td>
</tr>
<tr>
<td>$^{26}$Al</td>
<td>1.0 Myr</td>
<td>$\beta^+$-decay</td>
<td>ONe</td>
</tr>
</tbody>
</table>

* $^{14, 15}$O, $^{17}$F ($^{13}$N): Expansion and ejection stages (No $\gamma$-rays)
* $^{13}$N, $^{18}$F: Early $\gamma$-ray emission ($511$ keV + continuum); $D < 2$ kpc
* $^{7}$Be, $^{22}$Na, $^{26}$Al: $\gamma$-ray lines; $D < 0.2$ kpc, 0.5 kpc, -

No $^{34}$Cl $\gamma$-ray emission anymore...

THE EFFECTS OF THERMONUCLEAR REACTION-RATE VARIATIONS ON NOVA NUCLEOSYNTHESIS: A SENSITIVITY STUDY

CHRISTIAN ILIADIS AND ART CHAMPAGNE
Department of Physics and Astronomy, University of North Carolina, Chapel Hill, NC 27599-3255; and Triangle Universities Nuclear Laboratory, Durham, NC 27708-0308; iliadis@unc.edu, aec@tunl.duke.edu

JORDI JOSÉ
Departament de Física i Enginyeria Nuclear (UPC), Avinguda Victor Balaguer, s/n, E-08800 Vilanova i la Geltrú, Barcelona, Spain; and Institut d’Estudis Espacials de Catalunya, Edifici Nexus-201, Calle Gran Capità 2-4, E-08034 Barcelona, Spain; jjose@ieec.fcr.es

SUMNER STARRFIELD
Department of Physics and Astronomy, Arizona State University, Tempe, AZ 85287-1504; sumner.starrfield@asu.edu

AND

PAUL TUPPER
Scientific Computing–Computational Mathematics Program, Stanford University, Stanford, CA 94305; tupper@scem.stanford.edu

Received 2002 January 19; accepted 2002 April 25

≈7350 nuclear reaction network calculations

Main nuclear uncertainties: \([^{18}\text{F}(p,\alpha)^{15}\text{O}}, {^{25}\text{Al}(p,\gamma)^{26}\text{Si}}, {^{30}\text{P}(p,\gamma)^{31}\text{S}}]\)
The mixing mechanism: the *Holy Grail* of nova modeling

* Shear mixing [MacDonald 1983; Livio & Truran 1987]
* Convective Oveshoot Induced Flame Propagation [Woosley 1986]
* Convection Induced Shear Mixing [Kutter & Sparks 1989]


Composition of the ejecta:

a) \[ Z \rightarrow Z \sim 0.50 \] (up to 0.86, for V1370 Aql 1982)? Limited \( T_{\text{peak}} \rightarrow \)

CNO-breakout unlikely! \( \rightarrow \) Mixing at the core-envelope interface

b) Depends on the nature of the WD (cf., CO vs. ONe): \( M_{\text{WD}} \) & \( X_i \)
Multi-dimensional simulations agree with 1-D’s, but!

The build-up of convective eddies at the envelope’s base causes shear flow at the core/envelope interface [Kelvin-Helmholtz instability]: pure “solar-like” accreted material can be enriched at the late stages of the TNR by some sort of convective overshoot (Woosley 1986), leading to a powerful nova event!
Kercek et al. (1998), 2-D

Very limited dredge-up and mixing episodes → fainter events!
LETTER TO THE EDITOR

On mixing at the core-envelope interface during classical nova outbursts

J. Casanova¹, J. José¹, E. García-Berro², A. Calder³, and S. N. Shore⁴

¹ Dept. Física i Enginyeria Nuclear, EUETIB, Universitat Politècnica de Catalunya, c/Comte d’Urgell 187, 08036 Barcelona, Spain, & Institut d’Estudis Espacials de Catalunya, c/Gran Capità 2-4, Ed. Nexus-201, 08034 Barcelona, Spain
e-mail: jordi.jose@upc.edu
² Dept. de Física Aplicada, Universitat Politècnica de Catalunya, c/Esteve Terrades 5, 08860 Castelldefels, Spain & Institut d’Estudis Espacials de Catalunya, c/Gran Capità 2-4, Ed. Nexus-201, 08034 Barcelona, Spain
³ Department of Physics & Astronomy, Stony Brook University, Stony Brook, NY 11794-3800, USA
⁴ Dipartimento di Fisica “Enrico Fermi”, Università di Pisa and INFN, Sezione di Pisa, Largo B. Pontecorvo 3, 56127 Pisa, Italy
MareNostrum (Barcelona Supercomputing Center), 94.21 Tflops, 10,240 processors
2-D Hydro Simulations with the FLASH Code

Observational constraints

Andrëa et al. (1994)

**PW Vul 1984**

<table>
<thead>
<tr>
<th></th>
<th>H</th>
<th>He</th>
<th>C</th>
<th>N</th>
<th>O</th>
<th>Ne</th>
<th>Na-Fe</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observation</td>
<td>0.47</td>
<td>0.23</td>
<td>0.073</td>
<td>0.14</td>
<td>0.083</td>
<td>0.0040</td>
<td>0.0048</td>
<td>0.30</td>
</tr>
<tr>
<td>Theory</td>
<td>0.47</td>
<td>0.25</td>
<td>0.073</td>
<td>0.094</td>
<td>0.10</td>
<td>0.0036</td>
<td>0.0017</td>
<td>0.28</td>
</tr>
</tbody>
</table>
Presolar grains and dust

Evidence for dust formation (IR) accompanying nova outbursts

Gehrz et al. (1998)

© 1976. The American Astronomical Society. All rights reserved. Printed in U.S.A.

Gehrz et al. (1998)

**Grains of Anomalous Isotopic Composition from Novae**

Donald D. Clayton and Fred Hoyle*

Department of Space Physics and Astronomy, Rice University

Received 1975 April 28; revised 1975 June 26

Isotopic peculiarities: $^{13}$C, $^{14}$C, $^{18}$O, $^{22}$Na, $^{26}$Al, $^{30}$Si
PRESOLAR GRAINS FROM NOVAE

SACHIKO AMARI, XIA GAO,1 LARRY R. NITTLER,2 AND ERNST ZINNER
Laboratory for Space Sciences and the Physics Department, Washington University, St. Louis, MO 63130-4899;
sa@howdy.wustl.edu, ekz@howdy.wustl.edu

JORDI JOSÉ3 AND MARGARITA HERNANZ
Institut d'Estudis Espacials de Catalunya (IEEC/CSIC), E-08034 Barcelona, Spain; jjose@ieec.fcr.es, hernanz

AND

ROY S. LEWIS
Enrico Fermi Institute, University of Chicago, Chicago, IL 60637-1433; r-lewis@uchicago.edu

Received 2000 September 15; accepted 2000 December 18
Presolar Nova Grains: The Magnificent Seven

Five SiC and two graphite grains, whose isotopic ratios point toward a nova origin: low $^{12}$C/$^{13}$C and $^{14}$N/$^{15}$N ratios, high $^{30}$Si/$^{28}$Si, and close-to-solar $^{29}$Si/$^{28}$Si. $^{26}$Al/$^{27}$Al and $^{22}$Ne/$^{20}$Ne ratios have been determined for some of these grains, with values compatible with nova model predictions Dilution with $Z_\odot$ material!

See F. Gyngard’s Poster #239, for possible nova O-grains...

**Table 1.** Presolar grains with an inferred nova origin.

<table>
<thead>
<tr>
<th>Grain</th>
<th>composition</th>
<th>$^{12}$C/$^{13}$C</th>
<th>$^{14}$N/$^{15}$N</th>
<th>$^{30}$Si/$^{28}$Si</th>
<th>$^{30}$Si/$^{28}$Si</th>
<th>$^{26}$Al/$^{27}$Al</th>
<th>$^{20}$Ne/$^{22}$Ne</th>
</tr>
</thead>
<tbody>
<tr>
<td>AF15bB-429-3</td>
<td>SiC</td>
<td>9.4±0.2</td>
<td>...</td>
<td>28±30</td>
<td>311±44</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>AF15bC-126-3</td>
<td>SiC</td>
<td>6.8±0.2</td>
<td>2.2±0.1</td>
<td>-105±17</td>
<td>237±20</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>KJGM4C-100</td>
<td>SiC</td>
<td>7.2±0.2</td>
<td>2.1±0.1</td>
<td>105±17</td>
<td>237±20</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>KJGM4C-311</td>
<td>SiC</td>
<td>7.8±0.2</td>
<td>2.4±0.1</td>
<td>-110±17</td>
<td>237±20</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>KJC112</td>
<td>SiC</td>
<td>8.2±0.2</td>
<td>2.6±0.1</td>
<td>-120±17</td>
<td>237±20</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>KFC1a-551</td>
<td>SiC</td>
<td>8.6±0.2</td>
<td>2.8±0.1</td>
<td>-130±17</td>
<td>237±20</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>KFB1a-161</td>
<td>SiC</td>
<td>9.0±0.2</td>
<td>3.0±0.1</td>
<td>-140±17</td>
<td>237±20</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Solar models</td>
<td></td>
<td>89</td>
<td>272</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>14</td>
</tr>
<tr>
<td>Nova models</td>
<td></td>
<td>0.2–3</td>
<td>0.1–1900</td>
<td>-950 to 1800</td>
<td>-1000 to 47000</td>
<td>0.01–0.9</td>
<td>0.1–2900</td>
</tr>
</tbody>
</table>

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 1$\sigma$.!
A very preliminary 3-D SPH simulation of the interaction between the nova ejecta and the stellar companion

- Simulations of the interaction between the nova ejecta and the accretion disk
- Contamination(?) of the MS star and effect on next CN

Homework!
* Multi-D Simulations: J. Casanova, A. Calder, S. Shore, S.W. Campbell
* 1-D Simulations & Gamma-ray emission: M. Hernanz
* Nuclear Physics Inputs: C. Iliadis, A. Coc, A. Parikh, ... and more!
* Presolar Grains: S. Amari, E. Zinner, L. Nittler, F. Gyngard
**EuroGENESIS in brief**

**EuroGENESIS** (2010-2013) is a collaborative research programme in **nuclear astrophysics**. It involves researchers from 29 institutions from 16 countries (theoretical astrophysicists, observational astronomers, experimental and theoretical nuclear physicists, and cosmochemists).

**Web page**

http://www.esf.org/activities/eurocores/running-programmes/eurogenesis.html

**First general workshop** of EuroGENESIS, OPEN TO ALL INTERESTED RESEARCHERS IN THIS FIELD, will take place in **Dubrovnik, around Nov. 24, 2010** (tbc). Please, contact any of the members of the **Scientific Committee** for additional information

**Committees of EuroGENESIS**

**Scientific Committee**

Chair:  
Dr. Jordi Jose – Project Leader of EXNUC  
[Email: jordi.jose@upc.edu]

Members:  
Dr. Isabelle Cherchneff – Project Leader of CoDustMas  
Prof. Martin Asplund – Project Leader of FirstStars  
Prof. Friedrich-Karl Thielemann – Project Leader of MASHCE  
Dr. Roland Diehl – co-Project Leader of MASCH  
Dr. Aigars Ekers – ESF Programme Coordinator  
[Emails: isabelle.cherchneff@unibas.ch, asplund@mpa-garching.mpg.de, f-k.thielemann@unibas.ch, rod@mpe.mpg.de]