CLASSICAL NOVAE

Second Edition

Since the first edition of this book was published, knowledge regarding the nova phenomenon has grown significantly. This is due to the advent of new observational facilities, both on the ground and in space, and considerable advances in theoretical work. This second edition has been fully updated and revised and contains new contributions which comprehensively cover the important developments in this field, and reflect on interesting new insights into the outbursts of classical novae.

The book begins with an historical perspective and an overview of nova properties. It then examines in detail thermonuclear processes, the evolution of nova systems, nova atmospheres and winds, abundance studies, the evolution of dust and molecules in novae, nova remnants, and observations of novae in other galaxies. The book details knowledge gained from observations across the electromagnetic spectrum, from radio to gamma rays, and discusses some of the most important outstanding problems in classical nova research.

This is the only book devoted solely to the study of classical novae, and as such is an important reference for researchers actively engaged in the subject and graduate students seeking an introduction. The contributors to this book are internationally recognized experts in their field, and present a balanced mix of observation and theory.

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SECOND EDITION

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Preface to the first edition

Some years ago we blundered, almost by accident, into the field of classical novae. Our prime interest at the time was in their dust formation properties and infrared development; however, it soon became evident that a full understanding of this relatively restricted aspect of the nova outburst could not be achieved without considering *all* aspects of the nova phenomenon. Fortunately, from our point of view, the 1970s was a decade during which several significant advances were made in the understanding of classical novae on both observational and theoretical fronts. Accordingly we were able to take advantage of these advances as they appeared in the research literature. However, with the exception of occasional published conference proceedings, it was apparent that no text existed that covered all aspects – both theoretical and observational – of the classical nova phenomenon.

This book arose out of a casual conversation with Dr Jim Truran during which we bemoaned the fact that there seemed to be no modern equivalent of *the* classic book on the subject, Cecilia Payne-Gaposchkin's *The Galactic Novae*. It seemed to us that such a volume was long overdue. However, it was clear that, with rapid developments in several aspects of the study of novae, no single author could do justice to all the relevant theoretical and multi-wavelength observational material. It was for this reason that we decided to opt for the multi-author approach that the reader will find in this volume. Our initial hope was to produce an up-to-date replacement for *The Galactic Novae*. We now realize, of course, that such an aim was foolhardy, not to say arrogant: Payne-Gaposchkin's book will always remain a classic and we can only hope that present-day and future workers in the field will see fit to use *Classical Novae* to complement *The Galactic Novae*.

Our aim has been to put together a book that presents a balanced mix of observation and theory, without presenting any particular point of view too dogmatically. The book begins with an overview of the general properties of novae, then progresses to discuss the accretion process in nova systems and the physics of the nova outburst. Historically, of course, most of the published observational work on novae has been carried out in the optical, and it is therefore appropriate that a good deal of attention is devoted to a discussion of the available optical data. Also discussed in this context is the way in which optical data relate to major aspects of the nova outburst and to observations at other wavelengths. Subsequent chapters discuss in turn the observational data at radio, infrared, ultraviolet and X-ray wavelengths. The penultimate chapter seeks to place classical novae in the broader family of cataclysmic variables. We hope that the contents will prove useful not only to those familiar with the field of classical novae but also to those in other disciplines who may wish to find a balanced overview of a particular aspect, or who wish to find a particular reference; Chapter 13, on 'Data on Novae', should prove especially valuable in this respect.

This book has had an extremely long gestation period: it has taken far longer from initial conception to delivery than we had originally intended (indeed during this time one of the editors has taken up positions in four different research establishments!). However, even since the first drafts of the various chapters came to hand, there have been a number of significant developments in the field, including the discovery of the remarkable radio remnant associated with the old nova GK Per, the detection of X-ray emission from GQ Mus during its 1983 outburst, the availability of the IRAS satellite infrared data, the realization that the primary in some novae must be O-Ne-Mg white dwarfs and the proposed 'hibernation' of novae between outbursts. Had we kept to our original schedule the book would have become dated rather quickly. However, the time had now come to draw a line and to leave any further developments to future volumes. We would very much like, therefore, to express our heartfelt thanks to the contributing authors, some of whom must have despaired at times of ever seeing their chapters in print. We would also like to record our thanks to various workers and institutions who have granted permission to reproduce material from the published literature.

Finally we must record our gratitude and debt to John Wiley & Sons Ltd and their officers, not only for taking on this venture but also for their ready help and patience during its preparation and production.

MIKE BODE September 1988

NYE EVANS

Preface to the second edition

First conceived around 1981, the first edition of *Classical Novae* was published in 1989, after rather a long gestation period. This was at a time when the International Ultraviolet Explorer observatory was still going strong, the Hubble Space Telescope and the ROSAT X-ray observatory still lay in the future, and observatories that are now delivering data of stunning quality, such as Chandra, XMM and Spitzer, were still on the drawing board. Despite the comment in the preface to the first edition 'had we kept to our original schedule the book would have become dated rather quickly', *Classical Novae* dated *very* quickly, as was inevitable.

We had toyed with the idea of a second edition for some time. It was clear that tinkering at the edges of the first edition would not do: so much had changed since the publication of what we began to refer to as 'CNI'. There were of course the inevitable advances in the quality and nature of the observations' over the entire electromagnetic spectrum, and in our theoretical understanding of the classical nova phenomenon as computing power grew. However, there was also the advent of the NASA Astrophysics Data System (ADS), and the facility to prepare a finding chart at the click of a mouse button (R. A. Downes & M. M. Shara 1989, *PASP* **105**, 127): who could have foreseen this when CNI was being compiled? The latter two rendered the *Data on Novae* chapter of the first edition completely obsolete. There was no alternative but to start what inevitably became known as 'CNII' effectively with a clean sheet.

The catalyst for reinvigorating our enthusiasm for the second edition was the highly successful *Classical Nova Explosions* meeting, held at Sitges, Catalonia, Spain, in May 2002 (M. Hernanz & J. Jose, eds., *American Institute of Physics Conference Proceedings*, Vol. **637**, New York: Melville). This gave us the opportunity to corner several potential authors and invite them to contribute. Even so at least 18 months passed before we were able to negotiate our release from Wiley and to enter discussions with Cambridge University Press.

On the whole the content of CNII differs from that of CNI, and much has changed in this edition (not least the wanderlust of editors). However, several of the authors who contributed to the first edition have also been persuaded to contribute to the second, and the general mix of observation and theory is retained. As far as possible the notation used in the first edition is carried over into the second edition.

We take this opportunity of thanking the authors for their contributions and their willingness to take on board comments and suggestions from the editors, Jacqueline Garget, Vince Higgs, Dawn Preston, and Lindsay Nightingale of Cambridge University Press, and Suresh Kumar and Johnny Sebastian of TEX support, for their advice and support; and the officers of J. Wiley & Sons for releasing us and the contributors to CNI from our obligations with them.

List of symbols

We have attempted to standardize the notation and, as far as possible, the symbols used are the same as those used in the first edition. Included in the right hand column of the listing under 'other symbols' below is the chapter number where each symbol is first defined. Inevitably, some symbols are used for more than one quantity, but where this does occur, the correct meaning should be clear and there should be no ambiguity.

Physical and astronomical constants

c	velocity of light
G	gravitational constant
h	Planck's constant
k	Boltzmann's constant
$\mathrm{L}_\odot$	solar luminosity
m_H	mass of hydrogen atom
$\mathrm{M}_\odot$	solar mass
N_A	Avogadro's number
$\mathrm{R}_\odot$	solar radius
σ	Stefan–Boltzmann constant

Other symbols

Roman characters

a	grain radius	8
a_grav	gravitational acceleration	5
a_max	maximum grain radius	8
a_n	MMRD constant	2
a_rad	radiative acceleration	5
A	amplitude in magnitudes of outburst	2
	atomic mass	11
	constant in the law describing the density profile	7
	semimajor axis of orbit	3
A_V	visual extinction in magnitudes	8
A_0	density parameter at $t = t_0$	7

$b_{\rm crit}$	impact parameter (of wind accretion)	3
b_n	MMRD constant	2
B	magnetic field	2
	blue magnitude	2
B_λ, B_ν	Planck function in wavelength/frequency units	7, 8
$C(m)$	completeness function	14
D	distance to nova	7
$\mathbf{D}$	gradient of rotational velocity	3
$D_{\rm max}$	maximum observable distance	3
$E(B-V)$	colour excess due to dust extinction	9
$E_{\rm H}$	energy released per unit mass by fusion of hydrogen	3
$E_{\rm sp}$	specific energy	3
f	flux density	7
$f_{\rm max}$	maximum flux density	7
$f_{\rm min}$	minimum detectable flux	3
$f_{\rm ONe}$	fraction of ONe novae	11
f_λ, f_ν	flux in unit wavelength/frequency interval	7, 8
g	acceleration of gravity	5
$h_{\rm p}$	pressure scale height	6
$H_{\rm disk}$	scale height of Galactic disk	3
i	inclination to the plane of the sky	12
I	intensity	8
$j_{\rm b}$	emission measure at time $t_{\rm b}$	9
J	mean intensity of radiation field	5
$J_{\rm orb}$	orbital angular momentum	3
$J_{\rm s}$	spin angular momentum	3
$\dot{J}_{\rm GWR}$	rate of change of angular momentum due to gravitational radiation	3
$\dot{J}_{\rm MSW}$	rate of change of angular momentum due to magnetic stellar wind	3
$\dot{J}_{\rm orb}$	rate of change of orbital angular momentum	3
K	infrared (K) magnitude	14
$K_\rho^{\rm (H)}$, $K_\rho^{\rm (V)}$	material diffusivity in the horizontal and vertical directions	3
ℓ	length scale of emitting region	7
	thickness of ejected shell	8
$l_{\rm max}$	maximum length scale of eddies	6
	characteristic length scale of hydrodynamic instabilities	3
$l_{\rm mix}$	mixing length	3
L	luminosity	3
$L_{\rm bol}$	bolometric luminosity	5

$L_{\rm bp}$	luminosity at blue point of central star of planetary nebula	3
$L_{\rm d}$	luminosity of donor star	3
$L_{\rm Edd}$	Eddington luminosity	8
$L_{\rm H}$	luminosity due to hydrogen burning	3
$L_{\rm He}$	luminosity of helium star	3
$L_{\rm hx}$	hard X-ray luminosity	10
$L_{\rm IR}$	infrared luminosity	8
$L_{\rm max}$	maximum luminosity	9
$L_{\rm RG}$	luminosity of red giant	3
$L_{\rm nova}$	luminosity of nova	3
$L_{\rm peak}$	peak luminosity of TNR	4
$L_{\rm pl}$	plateau luminosity	3
$L_{\rm u}$	Lyman continuum luminosity	7
$L_{\rm WD}$	luminosity of white dwarf	3
L_0	luminosity at outburst	8
m_V	apparent visual magnitude	2
$m_{\rm min,max}$	apparent magnitude at minimum, maximum	14
$m_{\rm pg}$	apparent photographic magnitude	14
$m_{\rm pg}({\rm lim})$	limiting apparent photographic magnitude	14
$\dot{m}_V$	light curve decline rate	14
M	mass	3
M_*	total mass of star	3
$M_{\rm a}$	mass of accretor star	3
$M_{\rm acc}$	mass accreted	3
$M_{\rm bol}$	absolute bolometric magnitude	9
$M_{\rm Ch}$	Chandrasekhar mass	9
$M_{\rm CO}$	mass of electron-degenerate CO or ONe core	3
$M_{\rm crit}$	critical accreted mass for TNR	3
$M_{\rm CS}$	mass of convective shell	3
$M_{\rm d}$	mass of donor star	3
$M_{\rm dust}$	mass of dust shell	8
$M_{\rm dg}$	dredge-up mass	3
$M_{\rm e}$	mass of hydrogen-rich envelope	3
$M_{\rm ej}$	mass of ejecta	7
$M_{\rm gas}$	mass of ejected gas	8
$M_{\rm H}$	mass of hydrogen in shell	10
$M_{\rm He}$	mass of helium core	3
$M_{\rm He}^{\rm init}$	initial mass of helium layer on white dwarf	3
$M_{\rm min,max}$	absolute magnitude at minimum, maximum	2
$M_{\rm pg}$	absolute photographic magnitude	14
$M_{\rm nova}({\rm A})$	Galactic mass isotope A contributed by novae	11
$M_{\rm PN}$	mass of planetary nebula central star	3
$M_{\rm rem}$	net remnant mass	3
$M_{\rm rm}$	critical hydrogen-rich envelope mass	3
$M_{\rm S}$	mass of shocked gas	10

M_t	total binary mass	3
M_V	absolute visual magnitude	2
M_{WD}	mass of white dwarf	3
$\langle M_{15} \rangle$	absolute magnitude 15 days post-maximum	2
M_2	mass of secondary star	2
$\dot{M}$	mass transfer rate in binary	2
	mass loss rate	5
$\dot{M}_{acc}$	mass accretion rate	3
$\dot{M}_{bp}$	mass accretion rate at blue point	3
$\dot{M}_H$	rate of hydrogen burning	3
$\dot{M}_{nova}^{pl}$	rate of burning mass during plateau phase	3
$\dot{M}_{RG}$	mass loss rate from red giant or sub-giant	3
$\dot{M}_{rgw}$	mass loss rate from red giant or AGB star wind	3
$\dot{M}_{MSW}$	mass loss rate due to magnetic stellar wind	3
$\dot{M}_w$	wind mass loss rate from erupting star	3
n	number density	13
n_e	number density of electrons	3
n_H	number density of hydrogen	5
n_i	number density of ions	5
$\mathcal{N}$	Brunt–Väisälä frequency	3
N_X	abundance by number of element X	3
N_H	hydrogen column density	3
N_{GWR}, N_{MSW}	number of interacting binaries in Galaxy below/above period gap	3
N_{gap}	number of CVs in the Galaxy in the period gap	3
N_{nova}	number of novae observed	14
N_{obs}	number of observed systems	3
$\langle N_{fast} \rangle$, $\langle N_{slow} \rangle$	number of fast/slow accretion systems in the Galaxy	3
p	exponent in density law	7
P	pressure	13
P_{crit}	critical pressure for thermonuclear ignition	4
P_{orb}, P_{rot}	orbital/rotation period	2
q	mass ratio M_d/M_a	3
$\langle Q_a \rangle$, $\langle Q_e \rangle$	Planck mean absorptivity/emissivity	8, 13
r	radial coordinate	5
r'	Sloan r' magnitude	14
r_{red}	$= \dot{M}_w/\dot{M}_H$	3
R	apparent R magnitude	9
	radius	3
	spectral resolution	8
$\mathcal{R}$	nova rate	11

R_{bp}	radius at blue point of central star of planetary nebula	3
R_{cond}	dust condensation radius	8
R_d	radius of donor star	3
R_{He}	radius of helium star	3
R_{HeWD}	radius of helium white dwarf	3
R_i	inner radius of shell	7
R_{in}	inner radius of nova atmosphere	5
R_L	Roche lobe radius	3
R_{L1}	radius to L1 point	3
R_{max}	maximum radius	3
R_o	outer radius of shell	7
R_{out}	outer radius of nova atmosphere	5
R_{WD}	radius of white dwarf	3
Rf	flux-Richardson number	3
Ri	Richardson number	3
$R_{\tau_{std}}$	effective radius at τ_{std}	5
S	entropy	3
	superheat of grain	8
t	time	2
$\langle t \rangle$	mean period of nova visibility	14
t_b	time of break in He II emissivity	7
t_{blue}	lifetime of nuclear burning evolution of blue phase	3
t_{cond}	grain condensation time	8
t_d	time of maximum emission from forming dust shell	8
t_H	hydrogen burning time-scale	3
t_i	ionization time-scale of ejected shell	8
t_{max}	time of maximum radio flux	7
t_n	time for light curve to decay n magnitudes from peak	1
t_{PN}	time-scale for hydrogen burning by central stars of planetary nebulae	3
t_r	time between outbursts	2
t_{red}	lifetime of nuclear burning evolution of red phase	3
t_s	time-scale for increase in Strömgren sphere radius	9
t_T	time for spectral energy distribution to depart from black body	8
t_0	turn-off time of photoionizing source	9
	time parameter in wind mass ejection law	7
t_1	time-scale over which mass is ejected	7
T	temperature	4
T_b	temperature at base of envelope	6
	brightness temperature	7
T_{BB}	black body temperature	8
T_{blue}	theoretical prediction of lifetime of blue phase	3
T_{cond}	condensation temperature of grains	8
T_d	dust grain temperature	8
T_e	electron temperature	7
$(T_e)_{bp}$	effective temperature at blue point of central star of planetary nebula	3

$T_{\rm eff}$	effective temperature	5
$T_{\rm gr}$	grain colour temperature	8
$T_{\rm peak}$	peak temperature of TNR	6
$T_{\rm rad}$	temperature of radiation field	9
$T_{\rm red}$	theoretical prediction of lifetime of red phase	3
$T_{\rm UV}$	temperature derived from ultraviolet observations	5
$\upsilon_{\rm K}$	luminosity-specific nova rate (at K)	14
V	velocity	3
	visual magnitude	9
$V_{\rm conv}$	velocity of convection	3
$V_{\rm d}$	equatorial velocity of donor star	3
$V_{\rm def}$	velocity of the deflagration front	6
$V_{\rm ej}$	velocity of ejecta	2
$V_{\rm G}$	volume of the Galaxy	3
$V_{\rm i}$, $V_{\rm o}$	velocity of inner/outer shell boundary	7
$V_{\rm max}$	maximum velocity	5
	maximum visual brightness	10
$V_{\rm rgw}$	velocity of red giant wind	3
$V_{\rm w}$	velocity of wind	3
V_{∞}	terminal velocity of wind	5
	velocity at infinity	3
X	mass fraction of hydrogen	3
X_i	abundance of the ith element	3
Y	mass fraction of helium	3
Z	atomic number	6
	mass fraction of metals	3
$Z_{\rm CNO}$	mass fraction CNO elements	3

Greek characters

α	recombination coefficient	9
	radio spectral index	7
β	ratio of velocity to velocity of light	5
	spectral index of emissivity of dust	13
γ	electron-to-ion number ratio	7
δ	power law exponent of mass ejection rate	7
$\Delta M_{\rm He}^{\rm det}$	critical mass helium layer for detonation of carbon core of white dwarf	3
$\Delta t_{\rm gap}$	time-scale for evolution through period gap	3

Δt_{RG}	time-scale for growth of red giant helium core	3
ΔX_{nuc}	mass fraction of H burnt	3
ΔY_{nuc}	mass fraction of helium produced in convective zone	3
ϵ_{nuc}	nuclear energy generation rate	4
ϵ_{grav}	gravothermal luminosity	3
θ	angular diameter	8
θ_{BB}	black body angular diameter	8
θ_{dust}	angular diameter of dust shell	8
θ_{gas}	angular diameter of ejected gas	8
θ_{max}	angular diameter at maximum radio flux	7
κ	absorption coefficient	7
κ_{ff}	Kramers (free–free) opacity	8
κ_T	Thomson scattering opacity	8
λ	wavelength	7
λ_c	free–free self-absorption cut-off wavelength	8
μ	mean atomic weight	7
μ_e	molecular mass per electron	3
ν	frequency	7
	viscosity	3
ξ	micro-turbulent velocity	5
ρ	mass density	5
ρ_{crit}	critical density for dust condensation	8
ρ_d	density of grain material	8
σ_{acc}	wind accretion capture cross-section	3
Σ_5	surface brightness at 5 GHz	12
τ	optical depth	5
	e-folding time of radioactive decay	11
τ_{burn}	nuclear burning time-scale	6
τ_{cycle}	duration of outburst cycle	3
τ_{ff}	free–free absorption optical depth	8
τ_{GWR}	time-scale for orbital shrinkage by gravitational wave radiation	3
τ_H	hydrogen burning time-scale	3
τ_{hyd}	dynamical time-scale	4
τ_J	time-scale for orbital angular momentum loss	3
τ_{lim}	mean nova lifetime	14
τ_{MSW}	lifetime of a long period CV	3
τ_{obs}^{blue}, τ_{obs}^{red}	observed lifetime of blue/red phase	3

$\tau_{\rm std}$	standardized optical depth	5
$\tau_{\rm th}$	gravothermal time-scale	3
$\tau_{\rm UV}$	optical depth in the ultraviolet	9
τ_λ, τ_ν	optical depth at wavelength λ/frequency ν	5, 7
$\tau_{1/2}$	radioactive half-life	4
ϕ	volume filling factor	7
$\omega_{\rm i,max}$	upper bound on growth rates of hydrodynamical instabilities	3
Ω	angular velocity	3
$\Omega_{\rm K}$	angular velocity of Keplerian rotation	3