EMERGING TOPICS IN
PHYSICAL
VIROLOGY

This page intentionally left blank

EMERGING TOPICS IN PHYSICAL VIROLOGY

Editors

Peter G Stockley

University of Leeds, UK

Reidun Twarock

University of York, UK

Imperial College Press

Published by

Imperial College Press
57 Shelton Street
Covent Garden
London WC2H 9HE

Distributed by

World Scientific Publishing Co. Pte. Ltd.
5 Toh Tuck Link, Singapore 596224
USA office: 27 Warren Street, Suite 401-402, Hackensack, NJ 07601
UK office: 57 Shelton Street, Covent Garden, London WC2H 9HE

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library.

EMERGING TOPICS IN PHYSICAL VIROLOGY

Copyright © 2010 by Imperial College Press

All rights reserved. This book, or parts thereof, may not be reproduced in any form or by any means, electronic or mechanical, including photocopying, recording or any information storage and retrieval system now known or to be invented, without written permission from the Publisher.

For photocopying of material in this volume, please pay a copying fee through the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, USA. In this case permission to photocopy is not required from the publisher.

ISBN-13 978-1-84816-464-2
ISBN-10 1-84816-464-5

Typeset by Stallion Press
Email: enquiries@stallionpress.com

Printed in Singapore.

Contributors

Peter G. Stockley

Asbury Centre for Structural Molecular Biology,
University of Leeds, Leeds, LS2 9JT, UK
p.g.stockley@leeds.ac.uk

Reidun Twarock

Departments of Mathematics and Biology,
York Centre for Complex Systems Analysis,
University of York,
York, YO10 5DD, UK
rt507@york.ac.uk

Nicola G. A. Abrescia

Structural Biology Unit, CICbioGUNE,
Bizkaia Technology Park,
48160 Derio, Spain
nabrescia@cicbiogune.es

Javier Arsuaga

Department of Mathematics,
San Francisco State University,
San Francisco, CA 94132, USA
jarsuaga@sfsu.edu

Dennis H. Bamford

Institute of Biotechnology and Department of
Biological and Environmental Sciences,
Viikki Biocenter, University of Helsinki,
00014 University of Helsinki, Finland
dennis.bamford@helsinki.fi

Robijn F. Bruinsma

Department of Physics and Astronomy,
University of California, Los Angeles,
Los Angeles, CA 90024, USA
bruinsma@physics.ucla.edu

Martin Castelnovo

Laboratoire de Physique,
Ecole Normale Supérieure de Lyon,
69364 Lyon Cedex 07, France
martin.castelnovo@ens-lyon.fr

Alex Evilevitch

Department of Physics,
Carnegie Mellon University,
Pittsburgh, PA 15213, USA
alex.evilevitch@biochemistry.lu.se

Elizabeth E. Fry

Division of Structural Biology
and the Oxford Protein Production Facility,
The Wellcome Trust Centre for Human Genetics,
University of Oxford,
Headington, Oxford, OX3, 7BN, UK
Liz@strubi.ox.ac.uk

William M. Gelbart

Department of Chemistry and Biochemistry,
University of California, Los Angeles,
Los Angeles, CA 90095-1569, USA
gelbart@chem.ucla.edu

Jonathan M. Grimes

Division of Structural Biology
and the Oxford Protein Production Facility,
The Wellcome Trust Centre for Human Genetics,
University of Oxford,
Headington, Oxford, OX3 7BN, UK
jonathan@strubi.ox.ac.uk

Thomas Keef

Department of Mathematics,
University of York, York, YO10 5DD, UK
tk506@york.ac.uk

William S. Klug

Department of Mechanical and Aerospace Engineering,
University of California, Los Angeles,
Los Angeles, CA 90095, USA
klug@seas.ucla.edu

Charles M. Knobler

Department of Chemistry and Biochemistry,
University of California, Los Angeles,
Los Angeles, CA 90095-1569, USA
knobler@chem.ucla.edu

Kristopher J. Koudelka

Department of Cell Biology,
The Scripps Research Institute,
La Jolla, CA 92037, USA
koudelka@scripps.edu

Marianne Manchester

Skaggs School of Pharmacy and Pharmaceutical Sciences,
University of California San Diego,
9500 Gilman Drive, MC 0749,
La Jolla, CA 92093, USA
mmanchester@ucsd.edu

Eric B. Monroe

Department of Microbiology,
University of Alabama at Birmingham,
Birmingham, AL 35294-2170, USA
ebmonroe@uab.edu

Alexander Yu. Morozov

Department of Physics and Astronomy,
University of California, Los Angeles,
Los Angeles, CA 90024, USA
morozov@physics.ucla.edu

J. Zachary Porterfield

University of Oklahoma Health Sciences Center,
Dept of Biochemistry, Oklahoma City,
OK 73104, USA
zach-porterfield@ouhsc.edu

Peter E. Prevelige

Department of Microbiology,
University of Alabama at Birmingham,
Birmingham, AL 35294-2170, USA
prevelige@uab.edu

Neil A. Ranson

Asbury Centre for Structural Molecular Biology,
University of Leeds, Leeds, LS2 9JT, UK
n.a.ranson@leeds.ac.uk

Janne J. Ravantti

Institute of Biotechnology and Department
of Biological and Environmental Sciences,
Viikki Biocenter, University of Helsinki,
00014 University of Helsinki, Finland
janne.ravantti@helsinki.fi

Joaquim Roca

Instituto de Biologia Molecular de Barcelona,
CSIC, Barcelona, Spain
joaquim.roca@ibmb.csic.es

Wouter H. Roos

Fysica van complexe systemen,
Natuur- en Sterrenkunde, Vrije Universiteit,
1081 HV Amsterdam, The Netherlands
wroos@few.vu.nl

Joseph Rudnick

Department of Physics and Astronomy,
University of California, Los Angeles,
Los Angeles, CA 90024, USA
jrudnick@physics.ucla.edu

David I. Stuart

Division of Structural Biology
and the Oxford Protein Production Facility,
The Wellcome Trust Centre for Human Genetics,
University of Oxford,
Headington, Oxford, OX3 7BN, UK
dave@strubi.ox.ac.uk

De Witt Sumners

Department of Mathematics,
Florida State University,
Tallahassee, FL 32306-4510, USA
sumners@math.fsu.edu

Gijs J. L. Wuite

Fysica van complexe systemen,
Natuur- en Sterrenkunde, Vrije Universiteit,
1081 HV Amsterdam, The Netherlands
gwuite@nat.vu.nl

Adam Zlotnick

Department of Biology,
Indiana University,
Bloomington, IN 47405, USA
azlotnic@indiana.edu

This page intentionally left blank

Preface

Emerging Topics in Physical Virology is a state-of-the-art account of recent developments in the analysis and modelling of virus structure, function and dynamics. It pays tribute to the importance of interdisciplinary research by integrating an exposition of experimental techniques such as cryo-electron microscopy, atomic force microscopy and mass spectrometry with mathematical and biophysical modelling techniques. The number of chapters co-authored by experimentalists and theoreticians is testimony to the importance of interdisciplinarity in tackling some of the most challenging and exciting research problems in this area.

The aim of this book is to introduce the reader to recent developments in the field, and to provide a comprehensive review of the results that prompted them. It is therefore not only a primer for researchers working in the analysis and modelling of viruses, but also serves as an introduction for non-experts into this tantalising field of research. The book starts with a description of cryo-electron microscopy by Neil Ranson and Peter Stockley and demonstrates its power in determining the structure and dynamics of viruses. Structural insights gained from X-ray crystallography have revealed an intriguing phenomenon: there is a striking conservation in the topologies of the capsid proteins that form the containers encapsulating viral genomes. This has prompted Dennis Bamford, David Stuart and collaborators to classify viral families into lineages based on the concept of the viral 'self'. An important feature of this conservation of capsid protein folds is that it appears to be non-sequence-specific, i.e. the chemical structures of proteins with homologous folds can often be very different. This suggests that there must be a guiding principle for the formation of the capsid proteins that is independent of their sequences. Thomas Keef and Reidun Twarock suggest that the icosahedral symmetry of many viruses may provide such a guiding principle, and they introduce novel group theoretical techniques to model this effect. Their approach implies that a wide spectrum of viral features can be predicted based on symmetry, and that perhaps the limited number of structural folds is a

consequence of the fact that only a limited number of layouts are possible for viruses with such symmetry.

Atomic force microscopy provides important insights into the mechanical properties of viruses as detailed in the chapter by Wouter Roos and Gijs Wuite. The authors discuss capsid shell structure, presence of encapsidated material, capsid failure, maturation and capsid protein mutations in relation to viral material properties and highlight similarities and differences for different types of viruses. Another important experimental technique in the study of viruses is mass spectrometry. Eric Monroe and Peter Prevelige show how this technique can be used to gain invaluable information on viral proteins. Mass spectrometry can also play a crucial role in the study of virus assembly, i.e. the process of formation of viral particles from their protein building blocks and genomic material. An overview of capsid assembly kinetics is provided by one of the pioneers in this area, Adam Zlotnick, and his collaborator Zachary Porterfield. Their chapter covers both modelling and experimental techniques and provides a comprehensive overview of viral capsid kinetics. An important factor in virus assembly and disassembly is the mechanical stress on different components of the viral capsid. A beautiful account of how stress distributions impact on the assembly and disassembly of viral capsids formed from pentamers and hexamers is provided by Robijn Bruinsma and collaborators.

Viruses may package genomic material in the form of DNA or RNA. An important question concerning the formation of RNA viruses is ‘what determines the size of an RNA virus?’ It is addressed by Chuck Knobler and Bill Gelbart in their discussion of the correlation between capsid and genome sizes. The impact of genome length versus capsid size on the physics of viral infectivity is also discussed with respect to double-stranded DNA (dsDNA) phages by Alex Evilevitch and Martin Castelnovo. Another intriguing feature of packaged DNA genomic material is its topology. Together with their experimental collaborator Joaquim Roca, Jarvier Arsuaga and De Witt Sumners provide a comprehensive account of the mathematical and experimental analysis of the topology of viral DNA.

A volume on emerging topics in physical virology would not be complete without a discussion of the fascinating applications of viruses and virus-like particles in biomedical nanotechnology that are opened up by

these recent theoretical and experimental approaches. We therefore conclude with a chapter by Kristopher Koudelka and Marianne Manchester that discusses the state of the art in this area.

We would like to express our special thanks to the authors of these fascinating chapters for making this volume possible by sharing their exciting research with us.

Peter Stockley and Reidun Twarock
March 2009

This page intentionally left blank

Contents

<i>Contributors</i>	v
<i>Preface</i>	xi
Chapter 1: Cryo-Electron Microscopy of Viruses <i>Neil A. Ranson and Peter G. Stockley</i>	1
Chapter 2: What Does it Take to Make a Virus: The Concept of the Viral ‘Self’ <i>Nicola G. A. Abrescia, Jonathan M. Grimes, Elizabeth E. Fry, Janne J. Ravantti, Dennis H. Bamford and David. I. Stuart</i>	35
Chapter 3: Beyond Quasi-Equivalence: New Insights Into Viral Architecture via Affine Extended Symmetry Groups <i>Thomas Keef and Reidun Twarock</i>	59
Chapter 4: Mechanical Properties of Viruses <i>Wouter H. Roos and Gijs J. L. White</i>	85
Chapter 5: Investigating Viral Structure, Function and Dynamics with Mass Spectrometry <i>Eric B. Monroe and Peter E. Prevelige</i>	103
Chapter 6: An Overview of Capsid Assembly Kinetics <i>J. Zachary Porterfield and Adam Zlotnick</i>	131
Chapter 7: Assembly and Disassembly of Deltahedral Viral Shells <i>Alexander Yu. Morozov, Joseph Rudnick, Robijn F. Bruinsma and William S. Klug</i>	159
Chapter 8: What Determines the Size of an RNA Virus? <i>Charles M. Knobler and William M. Gelbart</i>	185

Chapter 9: Physics of Viral Infectivity: Matching Genome Length with Capsid Size	217
<i>Alex Evilevitch and Martin Castelnovo</i>	
Chapter 10: Topology of Viral DNA	255
<i>Javier Arsuaga, Joaquim Roca and De Witt Summers</i>	
Chapter 11: The Use of Viruses in Biomedical Nanotechnology	289
<i>Kristopher J. Koudelka and Marianne Manchester</i>	
Index	313