PROCEEDINGS OF SPIE

# *Optics for EUV, X-Ray, and Gamma-Ray Astronomy V*

**Stephen L. O'Dell**
**Giovanni Pareschi**
*Editors*

**23–25 August 2011**
**San Diego, California, United States**

*Sponsored and Published by*
SPIE

**Volume 8147**

Proceedings of SPIE, 0277-786X, v. 8147

The papers included in this volume were part of the technical conference cited on the cover and title page. Papers were selected and subject to review by the editors and conference program committee. Some conference presentations may not be available for publication. The papers published in these proceedings reflect the work and thoughts of the authors and are published herein as submitted. The publisher is not responsible for the validity of the information or for any outcomes resulting from reliance thereon.

Please use the following format to cite material from this book:
Author(s), "Title of Paper," in *Optics for EUV, X-Ray, and Gamma-Ray Astronomy V*, edited by Stephen L. O'Dell, Giovanni Pareschi, Proceedings of SPIE Vol. 8147 (SPIE, Bellingham, WA, 2011) Article CID Number.

ISSN 0277-786X
ISBN 9780819487575

Published by
**SPIE**
P.O. Box 10, Bellingham, Washington 98227-0010 USA
Telephone +1 360 676 3290 (Pacific Time) · Fax +1 360 647 1445
SPIE.org



Printed in the United States of America.

Publication of record for individual papers is online in the SPIE Digital Library.


SPIEDigitalLibrary.org

---

**Paper Numbering:** Proceedings of SPIE follow an e-First publication model, with papers published first online and then in print and on CD-ROM. Papers are published as they are submitted and meet publication criteria. A unique, consistent, permanent citation identifier (CID) number is assigned to each article at the time of the first publication. Utilization of CIDs allows articles to be fully citable as soon as they are published online, and connects the same identifier to all online, print, and electronic versions of the publication. SPIE uses a six-digit CID article numbering system in which:

- The first four digits correspond to the SPIE volume number.
- The last two digits indicate publication order within the volume using a Base 36 numbering system employing both numerals and letters. These two-number sets start with 00, 01, 02, 03, 04, 05, 06, 07, 08, 09, 0A, 0B … 0Z, followed by 10-1Z, 20-2Z, etc.

The CID number appears on each page of the manuscript. The complete citation is used on the first page, and an abbreviated version on subsequent pages. Numbers in the index correspond to the last two digits of the six-digit CID number.

# Contents

# Conference Committee

*Program Track Chair*

**Oswald H. Siegmund,** University of California, Berkeley (United States)

*Conference Chairs*

**Stephen L. O'Dell,** NASA Marshall Space Flight Center (United States)
**Giovanni Pareschi,** INAF - Osservatorio Astronomico di Brera (Italy)

*Program Committee*

**Marcos Bavdaz,** European Space Agency, European Space Research and Technology Center (Netherlands)
**Webster C. Cash, Jr.,** University of Colorado at Boulder (United States)
**Finn E. Christensen,** DTU Space (Denmark)
**Peter Friedrich,** Max-Planck-Institut für extraterrestrische Physik (Germany)
**Paul Gorenstein,** Harvard-Smithsonian Center for Astrophysics (United States)
**Fiona A. Harrison,** California Institute of Technology (United States)
**René Hudec,** Astronomical Institute of the ACSR, v.v.i. (Czech Republic)
**Hideyo Kunieda,** Nagoya University (Japan)
**Mikhail N. Pavlinsky,** Space Research Institute (Russian Federation)
**Robert Petre,** NASA Goddard Space Flight Center (United States)
**Peter Predehl,** Max-Planck-Institut für extraterrestrische Physik (Germany)
**Brian D. Ramsey,** NASA Marshall Space Flight Center (United States)
**Paul B. Reid,** Harvard-Smithsonian Center for Astrophysics (United States)
**Suzanne E. Romaine,** Harvard-Smithsonian Center for Astrophysics (United States)
**Mark L. Schattenburg,** Massachusetts Institute of Technology (United States)
**John F. Seely,** U.S. Naval Research Laboratory (United States)
**Gerald K. Skinner,** NASA Goddard Space Flight Center (United States) and University of Maryland (United States)
**Daniele Spiga,** INAF - Osservatorio Astronomico di Brera (Italy)
**Yuzuru Tawara,** Nagoya University (Japan)
**Peter von Ballmoos,** Institut de Recherche en Astrophysique et Planétologie (France)
**Richard Willingale,** University of Leicester (United Kingdom)

**David L. Windt,** Reflective X-Ray Optics LLC (United States)
**William W. Zhang,** NASA Goddard Space Flight Center (United States)

*Session Chairs*

1 Foil Optics
**Giovanni Pareschi,** INAF - Osservatorio Astronomico di Brera (Italy)

2 Electroformed Optics
**William W. Zhang,** NASA Goddard Space Flight Center (United States)

3 Silicon Pore Optics
**Mark L. Schattenburg,** Massachusetts Institute of Technology (United States)

4 Slumped Glass Optics I
**Paul Gorenstein,** Harvard-Smithsonian Center for Astrophysics (United States)

5 Slumped Glass Optics II
**Finn E. Christensen,** DTU Space (Denmark)

6 Coatings
**Daniele Spiga,** INAF - Osservatorio Astronomico di Brera (Italy)

7 Design and Analysis
**Daniel A. Schwartz,** Harvard-Smithsonian Center for Astrophysics (United States)

8 Optical Fabrication
**Marcos Bavdaz,** European Space Research and Technology Center (Netherlands)

9 Metrology and Testing Methods
**Suzanne E. Romaine,** Harvard-Smithsonian Center for Astrophysics (United States)

10 Laue Lenses I
**Brian D. Ramsey,** NASA Marshall Space Flight Center (United States)

11 Laue Lenses II
**Nicolas M. Barrière,** University of California, Berkeley (United States)

12 Spectrographs
**Oberto Citterio,** INAF - Osservatorio Astronomico di Brera (Italy)

13 Novel Optics
**Webster C. Cash,** University of Colorado at Boulder (United States)

Poster Preview Session
**Stephen L. O'Dell,** NASA Marshall Space Flight Center (United States)
**Giovanni Pareschi,** INAF - Osservatorio Astronomico di Brera (Italy)

# Introduction

The conference *Optics for EUV, X-Ray, and Gamma-Ray Astronomy V* met August 23–25 in San Diego, California, as part of the **SPIE Optics + Photonics 2011** international symposium ***Optical Engineering + Applications***. As with previous conferences in this series, it provided an effective forum for discussion of recent progress in imaging and spectroscopic optics for EUV, x-ray, and gamma-ray astronomy. With over 60 papers in 13 sessions, this volume attests to the vitality of research in this field. We thank the program committee for helping to organize the technical program and for fostering broad participation, and the session chairs and presenters for a successful and stimulating conference. We also appreciate the efforts of the SPIE staff in organizing and implementing the conference and in publishing these Proceedings.

Currently operating x-ray observatories—*Chandra* (AXAF), XMM-*Newton*, *Suzaku* (Astro-E2), *Swift*, and *Hinode* (Solar-B)—demonstrate the importance of focusing optics to high-energy astronomy. Launching within the next few years, four small-to-medium missions will utilize x-ray focusing optics to advance high-energy astronomy. NASA's NuSTAR (Nuclear Spectroscopic Telescope ARray) and JAXA's Astro-H will extend the power of focused imaging into the hard-x-ray band; Astro-H will also provide soft-x-ray (non-dispersive) high-spectral-resolution imaging. Russia's SRG (Spectrum Röntgen Gamma)—with the German eROSITA and Russian ART-XC telescope arrays—will conduct the most sensitive x-ray all-sky survey. Finally, NASA's GEMS (Gravity and Extreme Magnetism Small Explorer) will employ focusing optics to enhance its sensitivity for x-ray polarimetry. Collectively, these nine missions—all to have been launched in a 15-year period (1999–2014)—significantly advance x-ray technologies for high angular resolution, large collecting areas, high spectral resolution, polarimetry, and lightweight optical components.

While these recent and near-future x-ray missions continue to drive research in high-energy astrophysics, the prospects for new missions and the scientific discoveries they enable are currently unclear. Indeed, this year's conference took place at a particularly delicate moment for the scientific community. Programmatic and budgetary limitations have precluded or delayed advanced development and implementation of additional missions—e.g., NHXM (New Hard-X-ray Mission), which would bring high-resolution imaging to hard-x-ray astronomy. Of special concern is the fate of the next facility-class x-ray mission: After many years of development—first individually as ESA's XEUS (X-ray Evolving Universe Spectroscopy) and NASA's Constellation-X mission concepts—the joint NASA–ESA–JAXA *International X-ray Observatory* (IXO) is being de-scoped as the ESA-led mission ATHENA (Advanced Telescope for High-ENergy Astrophysics), a candidate L-class mission to be considered in early 2012.

Despite such uncertainties, these and other suggested future high-energy-astronomy missions continue to call for technology advances in optics for EUV, x-ray, and gamma-ray astronomy. Accordingly, Conference 8147 addressed all areas of optical science and technology relevant to such optics.

FOIL OPTICS (Session 1) addressed progress in aluminum foil segmented optics. Previously used for the ASCA and *Suzaku* telescopes, such mirror systems provide low-mass, low-cost, high-throughput x-ray imaging at moderate angular resolution. Papers in Session 1 described development and implementation of Astro-H telescopes, including efforts to reduce the imaging half-power diameter to HPD ≈ 60″.

ELECTROFORMED OPTICS (Session 2) reported on development of x-ray mirror systems employing full-cylinder electroformed nickel shells. Previously used for the *Beppo*-SAX, *Swift*, and XMM-Newton telescopes, such mirror systems provide moderately low-cost and low-mass moderate-throughput x-ray imaging at good angular resolution (HPD ≈ 15″). Papers in Session 2 described development, implementation, and testing of the SRG eROSITA and ART-XC telescopes and of the Focussing Optics X-ray Solar Imager (FOXSI) balloon-borne telescopes, as well as research and development of technologies for future electroformed-nickel optics, such as proposed for the NHXM telescope.

SILICON PORE OPTICS (Session 3) covered research, development, fabrication, and testing of mirror modules utilizing Silicon Pore Optics (SPO) technology. With cosine BV as principal industrial partner, ESA initiated SPO technology development for a large-area x-ray telescope aboard a facility-class mission that evolved from XEUS to IXO to ATHENA. Papers in Session 3 described progress in maturing this technology toward constructing and launching a large-area (focusing) x-ray telescope with angular resolution HPD ≤ 10″.

SLUMPED GLASS OPTICS I and II (Sessions 4 and 5) covered research, development, fabrication, and testing of mirror modules utilizing slumped-glass technology. Session 4 reported on the status of x-ray optics for the NuSTAR mission, which employs thousands of multilayer-coated slumped-glass segments to perform the first satellite-borne focused imaging in the hard-x-ray band. In preparation for an early-2012 launch, the NuSTAR team completed assembly, testing, and calibration of the flight modules, demonstrating an angular resolution HPD ≈ 50″. Session 4 continued with overviews of progress in the United States and in Italy to develop the next generation of slumped-glass optics with finer angular resolution (HPD ≤ 10″). Session 4 concluded with reports on approaches for slumping glass segments, while Session 5 addressed issues in alignment and assembly of such mirror pairs into mirror modules.

COATINGS (Session 6) covered a range of topics, beginning with bilayer and graded multilayer x-ray optical coatings, which enhance reflectance at low and at high energies, respectively. The session next reported on the use of a sputtered titanium-nitride coating on mandrels, to serve as a hard release layer for electroforming shells—including the transference of multilayer coatings on the mandrel onto the shell. Session 6 concluded with a description of research in differential deposition as a low-force technique for correction of figure errors.

DESIGN AND ANALYSIS (Session 7) began with a description of a novel semi-analytical computation of the point spread function valid over all spatial wavelengths (figure, slope errors, and microroughness), followed by a report on modeling of x-ray scattering from multilayers. Other papers addressed mathematical and ray-trace tools for optimizing the design of x-ray telescopes and predicting their imaging performance. The final paper of Session 7 addressed optimization of the size of mirror segments for x-ray telescopes.

OPTICAL FABRICATION (Session 8) began with a description of precision figuring of mandrels for slumping glass, followed by a report on progress in direct precision fabrication of full-cylinder glass mirrors that are an order of magnitude thinner than the high-resolution mirrors of *Einstein*, ROSAT and *Chandra*. Session 8 concluded with a description of research in magnet-filed assisted polishing of the sidewalls of micropore x-ray optics.

METROLOGY AND TESTING METHODS (Session 9) addressed instrumentation and techniques for precision metrology and for EUV and x-ray testing. The session began with descriptions of full-surface normal-incidence interferometry and of grazing-incidence wave-front sensing. Session 9 also reported on the development of innovative metrology profilers for precision measurements of large mirrors, and on a test facility for EUV optics.

LAUE LENSES I and II (Sessions 10 and 11) covered the use of Laue lenses, based on natural crystals, for gamma-ray telescopes. Session 10 primarily provided overviews of Laue telescope concepts, prototypes, and test results. Session 11 mainly addressed the properties and characterization of mosaic and curved crystals for use in Laue-lens gamma-ray telescopes. The goal of this research is to bring to gamma-ray astronomy the power of focusing, in order to improve greatly the sensitivity for detection and measurement of cosmic gamma-ray sources.

SPECTROGRAPHS (Session 12) reported on instrumentation for high-resolution dispersive spectroscopy of the sun and of cosmic sources—including proposed measurement of the Warm-Hot Intergalactic Medium (WHIM) in x-ray absorption. The papers explored non-traditional grating designs for x-ray grazing-incidence spectrographs: a planar varied-line-spacing reflection grating; an off-plane radial-groove reflection grating; and a critical-angle transmission (CAT) grating.

NOVEL OPTICS (Session 13) concluded the Conference with an assortment of papers on novel concepts for x-ray imaging telescopes: micro-channel plate optics; a hybrid coded-mask lobster-eye wide-field telescope; and a grazing-incidence x-ray interferometer. The final papers of Session 13 reported on technology development for active (adjustable) x-ray telescopes.

**Giovanni Pareschi**
**Stephen L. O'Dell**