Hard X-Ray Imaging of Solar Flares

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Foreword

High-energy solar flare physics has had an incredibly exciting journey over the past decades mainly driven by new observations from NASA's Small Explorer mission *RHESSI*; this book guides researchers along the path of this journey to our current understanding.

By astronomical standards, the Sun is in front of our nose, making it possible to study not only its spectral features, but also to obtain detailed resolved images. With the recent launch of ESA's Solar Orbiter mission, we now have observations from different vantage points allowing us to stereoscopically measure solar flares. This makes our Sun an exciting astrophysical object, and despite the many decades long advances that have been achieved, there are still many discoveries to be made.

Hard X-ray observations provide a key diagnostic tool to study the energy release in solar flares that provide quantitative measurements that are fundamental to the physical processes at work. However, imaging at hard X-ray wavelengths is challenging and observatories generally use indirect imaging methods. Compared to observations at other wavelengths where focusing optics can be readily used, hard X-ray images need to be reconstructed before they can be implemented in solar flare studies at multi wavelengths. Indirect imaging provides an exciting opportunity to develop cutting-edge algorithms optimizing the reconstructed images and therefore the science output.

The indirect imaging approach however has proven to be challenging for users outside the core instrument teams, as it often appears to be a black box for the general user. In addition, scientific publications do not properly address the fundamentals of imaging reconstructions, or even less so the hidden details of how to best apply the different algorithms. This has been a challenge for our solar flare community and it has limited our growth, despite the recent exiting advances achieved. With this book, the gap between the expert users and the solar flare community will be bridged. I am very pleased to see this book being published, and it will become an essential companion for anyone working with the *STIX* instrument onboard ESA's Solar Orbiter mission. I sincerely thank the authors for putting in the effort to make it happen.

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Preface

The idea for this book emerged over a number of years as the authors participated in various research projects related to analysis and interpretation of data from NASA's *RHESSI* Small Explorer mission. The data produced over the (unexpectedly long; February 2002–April 2018) operational lifetime of this mission inspired a large number of investigations related to the overarching science question that *RHESSI* was designed to address: the when, where, and how of electron acceleration in the stressed magnetic field environment of the active Sun.

As discussed in Chap. 1, a vital key to unlocking this science problem is the ability to produce high-quality images of the so-called "hard" X-rays produced by bremsstrahlung radiation from electrons that are accelerated over the course of a solar flare. To adequately address the science objectives, these images must cover the energy range from less than 10 keV up to more than 100 keV with keV energy resolution, spatial resolution in the arcsecond range, and a time cadence of order 1 s. The only practical way to do this within the technological and budgetary limitations of the *RHESSI* era was to eschew imaging via some form of focusing optics in favor of the indirect imaging technique described in some detail in Chap. 3. This technique involves the use of multiple "rotating modulation collimators," through which imaging information is encoded, not in the usual "pixel-by-pixel" fashion of direct imaging devices, but rather as a set of modulation "patterns" produced by rotating an instrument made up of multiple bi-grid X-ray collimators, with each one placed in front of a detector that has no inherent spatial resolution. It can be shown that each such pattern corresponds to a different two-dimensional spatial Fourier component of the source and can be identified through the appearance of a particular signature in the time profile of the measured count rate in the corresponding detector. The image is reconstructed from this information using one of many computational techniques that have been developed, in many cases expressly for this purpose.

It is fair to say that this way of thinking about imaging was not one with which the solar physics community was entirely comfortable, at least initially. Radio astronomers, working with large interferometer arrays, had employed Fourier imaging techniques for many years, primarily for observations of astronomical sources other than the Sun. They typically were able to utilize many hundreds of

Fourier components because of the many different baselines that can be formed with an array of radio telescope dishes. They also benefited from a strong signal-to-noise ratio, a consequence both of the very large collecting area of their Earth-based telescopes and of the very small energy per radio photon. By contrast, X-ray images produced by *RHESSI* had to be constructed from a much more limited number (typically ∼100) of sparsely distributed Fourier components. Furthermore, the limited collection area available on a space mission, combined with the relatively high energy per X-ray photon, meant that, despite the relative proximity of the Sun, there were many fewer photons available with which to construct each image. Consequently, the associated Poisson statistics for such low count rates meant that observers had to deal with much noisier data. Combined, these essential differences meant that the extensive analysis software that already existed for radio astronomy provided to be only a starting point for developing new techniques optimized for this new context. To make things more interesting, construction of images from sparse, noisy Fourier data is hardly intuitive, and extensive testing and validation of the methods was necessary to ensure that they produced images with sufficient accuracy and fidelity for solar scientists to employ them in addressing compelling science problems. And to make things more timely, this Fourier-based way of realizing image structure is also at the basis of two other space missions: *STIX* on-board the recently-launched ESA Solar Orbiter and the HXI instrument scheduled for the Chinese Advanced Space-based Solar Observatory.

This book summarizes the results of this development of image reconstruction techniques specifically designed for this form of data. It covers a set of published works that span over two decades, during which it is fair to say that there was very little in the way of a guiding "script." Over this extended period of time, as the various image reconstruction techniques were introduced, developed, validated, and applied to observations, it became more and more apparent to the authors that it would be a good idea to put together a compendium of these methods and their applications, hence the book you are now reading. The order in which the various image reconstruction methods are presented reflects not so much the chronological order of their development but rather the similarities and differences among them, and the degree to which they may (or may not) be useful in addressing the science problems for which they were created.

The book is intended as a reference text for researchers who seek to better understand the scientific context for, and essence of, the various image construction methods appropriate to indirect-imaging instruments like *RHESSI* (and more recently *STIX* and HXI). We hope that it will help them select the best method(s) for the scientific task they wish to address. Students or newcomers to the field should find this book useful as a single reference of the various image reconstruction methods that have been developed, the relative strengths and limitations of each, and the scientific results that have emerged from their application to observations.

Many of the methods described in this book were developed during a series of focused week-long meetings in Bern, Switzerland, sponsored by the International Space Studies Institute (ISSI). We thank that institution for providing us with a quiet and comfortable place where we could focus on these scientific investigations.

We are pleased to thank a number of individuals who have inspired and/or encouraged us to produce this monograph. Various participants, far too numerous to list exhaustively, have engaged in discussions of *RHESSI* hard X-ray images and their scientific consequences at a number of both formal and informal meetings. This includes a series of over 20 specialized *RHESSI* science and data analysis workshops held at various locations (alternating between the US and Europe but also including Nanjing, China in 2011) over the period from 2001 to the present day.[1] We thank all of these individuals for their stimulating input, with especial appreciation to the following people for their unique contributions: Mike Appleby, Markus Aschwanden, Arnold Benz, Steven Christe, André Csillaghy, Martin Fivian, Lindsay Glesener, Hugh Hudson, Eduard Kontar, Säm Krucker, Tom Metcalf (deceased), Pascal Saint-Hilaire, Ed Schmahl, Gerald Share, Albert Shih, David Smith, Kim Tolbert, Frank van Beek, Astrid Veronig, Nicole Vilmer, and Alexander Warmuth.

We particularly acknowledge the unparalleled work of Gordon Hurford, who was largely responsible for the conception, design, and implementation of the *RHESSI* (and subsequently *STIX*) imaging capabilities. His contributions to the realization of these missions have been, and continue to be, crucial at many different levels.

Finally, all four authors recognize that our professional (and personal) lives have benefited enormously from the impressive competencies, and unforgettable friendships, of four individuals who are sadly no longer with us: Reuven Ramaty, a pioneer in the field of gamma-ray astronomy and a highly engaged contributor to providing the scientific justification for *RHESSI* so necessary for success in NASA's highly competitive proposal selection process (the "R" in *RHESSI* honors these contributions); Bob Lin, the original *RHESSI* Principal Investigator, whose vision (and tenacious pursuit of it in the face of a veritable cornucopia of challenges before its eventual launch in February 2002) led to the eventual availability of the unparalleled *RHESSI* data; John Brown, whose pioneering theoretical studies into the relationship between solar hard X-rays and the electrons that produce them set the stage for the *RHESSI* mission; and Richard Schwartz, whose unique combination of technical knowledge and scientific insight was responsible for the transformation of many of the methodologies described in this text into computational algorithms that could profitably be applied to actual data by mere mortals trying to understand the observations in their scientific context.

[1] https://hesperia.gsfc.nasa.gov/rhessi3/news-and-resources/meetings/index.html.

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Acronyms

AIA	Atmospheric Imaging Assembly; an instrument on SDO
AIPS	Astronomical Image Processing System
ASO-S	Advanced Space-based Solar Observatory; a proposed Chinese mission
AU	Astronomic Unit; a unit of length, the mean distance from Earth to the Sun
BAT	Burst Alert Telescope; an instrument on Swift
CCD	Charge Coupled Device; a type of detector used in digital imaging
CdTe	Cadmium Telluride; material used for STiX X-ray detectors
CHSKP	Carmichael-Hirayama-Sturrock-Kopp-Pneuman; a solar flare model defined by a sequence of influential papers
CME	Coronal Mass Ejection
CMOS	Complementary Metal-Oxide Semiconductor; a type of field-effect transistor
COMPTEL	COMPton TELescope; an instrument on the NASA Compton Gamma-Ray Observatory operational from 1991 to 2000
COSI	Compton Spectrometer and Imager; a SMEX soft gamma-ray survey telescope (0.2–5 MeV)
EM	Expectation Maximization
ESA	European Space Agency
EUV	Extreme Ultra-Violet; electromagnetic radiation
FFT	Fast Fourier Transform; an algorithm for the fast computation of the Fourier transform
FIERCE	Fundamentals of Impulsive Energy Release in the Corona Explorer; a NASA MidEX proposed in 2020
FOXSI	Focusing Optics X-ray Solar Imager; an instrument using focusing optics in the hard X-ray domain, flown on a series of rocket flights and proposed as a NASA SMEX in 2018
FWHM	Full Width at Half Maximum
GCV	Generalized Cross Validation; a technique used to regularize the function recovered from inversion of an integral equation

GOES	Geostationary Operational Environmental Satellites; a series of synoptic monitoring satellites; the intensity of soft X-ray radiation measured by GOES provides a scheme for classifying the intensities of solar flares
GOES-R	Geostationary Operational Environmental Satellites-R Series; a specific series of four satellites in the GOES framework
GRIPS	Gamma-Ray Imager/Polarimeter for Solar flares; an instrument to perform imaging spectro-polarimetry on the hard X-ray and gamma-ray emission from solar flares, flown on a 10-day balloon flight from Antarctica in January 2016
GUI	Graphical User Interface; a user-friendly tool for use with the *RHESSI* software
HPD	Half-Power Diameter
HXI	Hard X-ray Imager; an instrument on the proposed Chinese ASO mission
HXIS	Hard X-ray Imaging Spectrometer; an instrument on SMM; operational from February until December 1980
HXT	Hard X-ray Telescope on Yohkoh
IDL	Interactive Data Language; a sequential programming language by Harris Geospatial Solutions, Boulder, Colorado
IR	Infrared; electromagnetic radiation
IXPE	Imaging X-ray Polarimetry Explorer; a mission to perform imaging spectropolarimetry on soft X-ray emission from astrophysical sources
KKT	Karush-Kuhn-Tucker; a theorem used in the EM method
KL	Kullbach-Leibler; a function used in the EM method
MEM	Maximum Entropy Method; a method used to optimize the output of an image reconstruction algorithm
MidEX	Mid-level Explorer; a type of NASA science-oriented satellite larger than a SMEX
MiSolFA	Micro Solar Flare Apparatus; a proposed small satellite similar in design to STIX
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NuSTAR	Nuclear Spectroscopic Telescope ARray; a NASA SMEX mission launched on June 13, 2012
OSO	Orbiting Solar Observatory; a series of NASA satellites launched in the 1960s, that made the first (spatially unresolved) measurements of X-rays from the Sun
OSPEX	Object SPectral EXecutive; an object-oriented package in IDL for spectroscopy and imaging spectroscopy analysis

PhoENiX	Physics of Energetic and Non-thermal plasmas in the X (= magnetic reconnection) region; a Japanese mission to probe the physics in the magnetic reconnection ("X"-point geometry) region in which the primary energy release in solar flares occurs
PSF	Point Spread Function; the response of an instrument to a point source
RAS	Roll Angle System; a system on *RHESSI* to determine roll orientation
RESIK	REntgenovsky Spekrometr Izognutymi Kristalami; an instrument on the Russian CORONAS-F satellite, launched on July 31, 2001
RHESSI	Ramaty High-Energy Solar Spectroscopic Imager; a NASA Small Explorer mission operational from February, 2002 until April, 2018
RMC	Rotating Modulation Collimator; a bi-grid system that modulates the transmission of X-rays as the grid system is rotated; used on *RHESSI*
SAPPHIRE	SolAr Polarimeter for Hard x-Rays; a CubeSat module to extract polarization information from solar X-rays
SAS	Solar Aspect System; a system on *RHESSI* that, when combined with the RAS data, provides precise pointing information
SDAC	Solar Data Analysis Center; serves data from recent and current space-based solar-physics missions, funds and hosts much of the SSW library, and leads the Virtual Solar Observatory (VSO) effort.
SDO	Solar Dynamics Observatory; a NASA mission launched on February 11, 2010
SEE	Solar Eruptive Event; an event that consists of both a solar flare and a coronal mass ejection (CME)
SEPs	Solar Energetic Particles
SHARPIE	The Solar HARd x-ray Polarimer/Imager Experiment; a proposed instrument for solar X-ray imaging spectropolarimetry using SAPPHIRE modules
SMC	Sequential Monte Carlo; a sampling method
SMEX	SMall EXplorer; a type of NASA science-oriented satellite
SMM	Solar Maximum Mission; a NASA satellite operational from February, 1980, until December, 1989
SSW	SolarSoftWare; a collection of IDL codes used extensively in analysis of data from *RHESSI* and other solar instruments
STIX	Spectrometer/Telescope for Imaging X-Rays; an instrument on the ESA Solar Orbiter mission, launched on February 9, 2020
SUVI	Solar Ultraviolet Imager; an instrument on the GOES-R series satellites
Swift	The Neil Gehrels Swift Observatory, a MidEX to study gamma-ray bursts, launched on November 20, 2004
SXT	Solar X-ray Telescope; an instrument on the Japanese Hinotori spacecraft launched on February 21, 1981
TRACE	Transition Region and Coronal Explorer; a NASA SMEX, operational between April, 1998, and June, 2010

URA	Uniformly Redundant Array; a type of coded mask layout used to construct hard X-ray images
URL	Uniform Resource Locator; an address in the World Wide Web
UV	Ultra-Violet; electromagnetic radiation
Yohkoh	Japanese for "Sunbeam," solar spacecraft, operational from September 1991 until December 2001