Astronomical Spectrographs and their History

Astronomical spectrographs analyse light emitted by the Sun, stars, galaxies and other objects in the Universe, and have been used in astronomy since the early nineteenth century. This book provides a comprehensive account of spectrographs from an historical perspective, from their theory and development over the last 200 years, to the recent advances of the early twenty-first century.

The author combines the theoretical principles behind astronomical spectrograph design with their historical development. Spectrographs of all types are considered, with prism, grating or grism dispersing elements. Included are Cassegrain, coudé, prime focus, échelle, fibre-fed, ultraviolet, nebular, objective prism, multi-object instruments and those which are ground-based, on rockets and balloons, or in space.

The book contains several tables listing the most significant instruments, around 900 references, and over 150 images, making it an indispensable reference for professional astronomers, graduate students, advanced amateur astronomers, and historians of science.

JOHN HEARNSHAW is Professor of Astronomy in the Department of Physics and Astronomy at the University of Canterbury, New Zealand. He has won the Mechaelis Prize for astronomy in New Zealand, and has twice been awarded the Alexander von Humboldt Fellowship in Germany. He chairs the International Astronomical Union Program Group for the Worldwide Development of Astronomy.

Astronomical Spectrographs and their History

John Hearnshaw
University of Canterbury, New Zealand

CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo, Delhi

Cambridge University Press
The Edinburgh Building, Cambridge CB2 8RU, UK

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9780521882576

First published 2009

Printed in the United Kingdom at the University Press, Cambridge

A catalogue record for this publication is available from the British Library

Library of Congress Cataloging-in-Publication Data
Hearnshaw, J. B.
Astronomical spectrographs and their history / John Hearnshaw.
p. cm.
ISBN 978-0-521-88257-6
1. Spectrograph – History. 2. Spectrum analysis – History. I. Title.
QB873.H43 2009
522′.67–dc22
2008045408

ISBN 978-0-521-88257-6 hardback

Contents

Preface *page* ix
Acknowledgements xi

1 The historical development of astronomical spectroscopes and spectrographs 1
1.1 Colour, refrangibility and wavelength 1
1.1.1 The refraction of light 1
1.1.2 Wavelength, colour and spectral lines 2
1.2 The collimator in prism spectroscopes 2
1.3 Some notable astronomical prism spectroscopes of the mid nineteenth century 3
1.4 Improvements in prism spectroscope design in the later nineteenth century 5
1.4.1 Spectroscope slits 10
1.4.2 Projected scales and automatic line recorders 10
1.5 The development of the prism spectrograph 11
1.5.1 The spectrographs of Henry Draper and William Huggins 11
1.5.2 Further prism spectrographs: Potsdam, Paris and Lick 13
1.6 The development of the diffraction grating 17
1.7 Grating mountings for laboratory and astronomical spectrographs 24
1.7.1 Concave grating mountings 25
1.8 Early grating spectroscopes and spectrographs 29
1.8.1 Early solar grating spectroscopy 29
1.8.2 Stellar grating spectroscopy before 1900 30
1.8.3 Astronomical grating spectrographs and their development from 1900 31
1.9 Prism spectrographs in the twentieth century 36
References 42

2 The theory of spectroscopes and spectrographs 46
2.1 General properties of a spectrograph 46
2.2 The spectrograph figure of merit 46
2.3 Resolving power and throughput of prism instruments 48
2.3.1 Dispersive properties of prisms and the diffraction-limited resolving power 48
2.3.2 Slit-limited resolving power of prism spectrographs 50
2.3.3 Properties of glasses used in prisms 52
2.3.4 Prism spectrograph throughput 53
2.3.5 Figure of merit for prism spectrographs 54
2.4 Resolving power and throughput of diffraction grating spectrographs 55
2.4.1 The diffraction-grating equation and angular dispersion 55
2.4.2 Fourier analysis of diffraction gratings 56
2.4.3 Diffraction-limited resolving power of a grating 57
2.4.4 Slit-limited resolving power of grating spectrographs 58

2.4.5 Comparison of the figure of merit of prism and grating spectrographs 60
2.5 Cameras and detectors: some simple requirements 60
2.5.1 Reciprocal dispersion and free spectral range 61
2.5.2 Detector resolution and the Nyquist sampling theorem 62
2.5.3 Number of detector pixels required 63
2.6 Grating efficiency, shadowing and the quasi-Littrow angle 63
2.7 Gratings not illuminated in the normal plane 66
2.8 The grism as a dispersing element 67
2.9 Some miscellaneous aspects of spectrograph design 68
2.9.1 Baranne's white pupil concept 68
2.10 Some general principles of spectrograph design 69
References 70

3 High resolution spectrographs 72
3.1 Theory of the coudé spectrograph 72
3.2 History of the coudé spectrograph 73
3.2.1 Early coudé refractors 73
3.2.2 Coudé prism spectrographs at Mt Wilson 73
3.2.3 The coudé grating spectrograph with Schmidt cameras 74
3.2.4 New coudé spectrographs 75
3.2.5 The image slicer in high resolution spectroscopy 79
3.3 Theory of the échelle spectrograph 81
3.3.1 Line tilt in échelles 83
3.3.2 Efficiency of échelles as a function of θ and γ 84
3.4 Historical development of échelle spectrographs 86
3.4.1 Coudé échelle spectrographs 86
3.4.2 Cassegrain échelle spectrographs 88
3.4.3 Fibre-fed échelle spectrographs 88
References 93

4 Solar spectrographs and the history of solar spectroscopy 96
4.1 Spectroscopy of the solar chromosphere 96
4.1.1 The discovery of helium 96
4.1.2 The structure of prominences revealed 100
4.2 The measurement of solar spectrum wavelengths 101
4.2.1 Solar wavelengths from Fraunhofer's gratings 101
4.2.2 Kirchhoff's drawing of the solar spectrum 102
4.2.3 New grating measurements from Ångström and others 102
4.3 Henry Rowland and the concave grating 103
4.4 The revision of the Rowland scale 105
4.5 Hale and Deslandres and the spectroheliograph 105
4.6 Hale and the dedicated solar spectrograph and observatory 113
4.7 Further developments in solar spectrographs and telescopes 117
4.8 The work of Francis and Robert McMath 120
4.9 New innovations in solar spectroscopy, 1940–1965 121
4.9.1 Photoelectric recording of the solar spectrum 121
4.9.2 Lead sulphide cells and the solar infrared 122
4.9.3 First use of the échelle grating for solar spectroscopy 125
4.9.4 Solar ultraviolet spectroscopy from rockets 128

4.9.5 The solar vacuum spectrograph 129
4.9.6 The double-pass solar spectrograph 131
4.9.7 The McMath solar telescope and spectrograph at Kitt Peak 133
4.10 Concluding remarks on solar spectrographs 136
References 136

5 Objective prism spectrographs 140
5.1 Theory of the objective prism spectrograph 140
5.2 The history of objective prism spectroscopy 143
5.2.1 Objective prism spectroscopy in the nineteenth century 143
5.2.2 Objective prism astrographs in the twentieth century 146
5.2.3 Spectrophotometry with objective prism astrographs 149
5.2.4 Objective prism radial velocities 152
5.2.5 Objective prism surveys with Schmidt telescopes 155
References 159

6 Ultraviolet and nebular spectroscopy 162
6.1 Ultraviolet and nebular spectroscopy 162
6.1.1 Henry Draper and William Huggins, pioneers in ultraviolet stellar spectroscopy 162
6.1.2 Ultraviolet spectrographs at Lick Observatory 164
6.1.3 Cameras for nebular and ultraviolet spectrographs 165
6.1.4 Nebular slit spectrographs at Yerkes and McDonald observatories 167
6.1.5 Ultraviolet spectroscopy with aluminized reflectors and Schmidt cameras 167
6.2 Ultraviolet spectroscopy from above the Earth's atmosphere 169
6.2.1 Some technical aspects of ultraviolet spectroscopy 169
6.2.2 Ultraviolet spectroscopy from rockets and balloons 170
6.2.3 The Orbiting Astronomical Observatories 175
6.2.4 Ultraviolet spectroscopy with Europe's TD-1 satellite 177
6.2.5 The International Ultraviolet Explorer 178
6.2.6 Ultraviolet spectroscopy from manned spacecraft 179
References 182

7 Multi-object spectrographs 184
7.1 Low resolution multi-object spectroscopy 184
7.2 Aperture plate multi-object spectroscopy 184
7.3 Multi-object spectroscopy using optical fibres and aperture plates 185
7.4 Multi-object spectroscopy with automated fibre positioning 190
7.5 Spectroscopy with an integral field unit 193
References 193

8 Ten pioneering spectrographs of the late twentieth century 195
8.1 Introduction to spectrographs of the late twentieth century 195
8.2 The ESO faint object spectrograph and camera: EFOSC 195
8.3 The Keck High Resolution Echelle Spectrometer: HIRES 196
8.4 The Keck Low Resolution Imaging Spectrometer: LRIS 200
8.5 ELODIE at Haute-Provence 201
8.6 The 2dF spectrographs at the Anglo-Australian telescope 203
8.7 The Space Telescope Imaging Spectrograph: STIS 205
8.8 The Ultraviolet Echelle Spectrograph at ESO Paranal: UVES 206
8.9 The Sloan Digital Sky Survey spectrographs 208

8.10 The Hercules spectrograph at Mt John 210
8.11 HARPS, the high accuracy radial-velocity planet searcher 211
References 212

Figure sources and acknowledgements 214
Name index 220
Subject index 223

Preface

Few astronomers would dispute the pivotal rôle that the astronomical spectrograph has played in the development of astrophysics. Of all astronomical instruments other than the telescope itself, none other can compete with the spectrograph for the range of new astronomical knowledge it has provided, and for the insights it has given on the physical nature of the celestial bodies in the Universe. Together with the predecessor of the spectrograph, the visual spectroscope, these instruments have revolutionized our knowledge of the Sun, the planets, stars, gaseous nebulae, the interstellar medium, galaxies and quasars.

Without the spectrograph, we would know nothing of solar or stellar composition, nothing about stellar rotation rates, and much less than we do on stellar space motions and binary stars. Even the real nature of the stars themselves would be a matter of conjecture and debate. And we would have rudimentary knowledge of the conditions prevailing in gaseous and planetary nebulae and of the nature of external galaxies beyond the Milky Way. There would be no Hubble's law, and hence no direct knowledge of the expansion of the Universe other than indirect inference based on Olbers' paradox or on theoretical prediction. Quasars would not be easily distinguished from stars, and the study of radio galaxies and active galactic nuclei would be limited to their morphological properties in optical or radio images. In short, optical spectrographs have underpinned almost every branch of astrophysics in the past century and a half.

This monograph is concerned with the astronomical spectrograph and its predecessor, the spectroscope. Only optical spectrographs are considered, that is, those using visible or ultraviolet light, except for a brief discussion of near infrared solar spectroscopy. A chapter on infrared spectrometers would have been desirable, but neither time nor space permitted its inclusion. And only those employing prism or grating dispersing elements (including grisms) are included in the discussion.

Two aspects of astronomical spectrographs are considered, both their historical development and the theory underpinning their design. I believe each half of the story presented here complements the other; to understand the history of this subject, one needs a good grounding in the theory. Likewise, present-day designers and observers should never forget the history of their subject and the rich rewards it can confer.

In the first chapter, the historical development of the instrument from the earliest experiments of Fraunhofer to the present day are described in some detail. Secondly, the basic principles of spectrograph design are reviewed, with an emphasis on the principles of achieving the desired resolving power and the maximum light throughput. Properties of dispersing elements, be they prisms or gratings, are also discussed. The third and following chapters give further details of the history, theory and development of several important types of spectrograph, namely the coudé and échelle spectrographs, solar spectrographs, the objective prism spectrograph, ultraviolet and nebular spectrographs and multi-object spectrographs. A comprehensive list of references cited is given after each chapter.

The final chapter discusses ten pioneering spectrographs of the late twentieth and early twenty-first centuries. In the past decade or so, spectrograph design has made substantial advances. Notable are the development of high dispersion échelle spectrographs and of multi-object spectrographs with optical fibre feeds. Detector developments, especially the charge-coupled device (or CCD), have revolutionized the practice of astronomical spectroscopy, and these advances are amongst those reviewed.

Also in these pages, credit will be given to the people who have designed, built and used spectrographs in astronomy. This is because this is not a textbook, but a synthesis about the history, design and applications of astronomical spectrographs, as well as about spectroscopists.

Astronomical Spectrographs and their History should be seen as a natural sequel to my earlier book, *The Analysis of Starlight* (Hearnshaw, Cambridge University Press, 1986), which discussed the history of stellar spectroscopy, but which only briefly discussed instrumental history and eschewed theory altogether. The two volumes together give a comprehensive account of the development of this science over the past two centuries.

Much of this monograph was researched while I was on two sabbatical leaves from the University of Canterbury, New Zealand. The first occasion was from mid 1996 to mid 1997. I spent six months from July 1996 at the South African Astronomical Observatory in Cape Town, where the outstanding astronomical library was ideal for researching material for the first two chapters. In early 1997 I visited the Astrophysikalisches Institut Potsdam (AIP) for four months, and continued working in the Babelsberg library of that institution. Finally I spent the last two months of the sabbatical year at the Dominion Astrophysical Observatory in Victoria, British Columbia. I am grateful to all three institutions for access to their excellent library resources.

The second sabbatical was from September 2003 when I spent three months in the library at the Vatican Observatory in Castelgandolfo. From March 2004 I continued this sabbatical with four months in the library of Lund Observatory in southern Sweden. All these institutions have outstanding astronomical libraries.

Further work was undertaken in the library of the University of Canterbury in New Zealand and on a brief visit in 1997 to the US Naval Observatory library in Washington, DC.

Acknowledgements

I gratefully acknowledge the people who kindly made it possible for me to visit some of the great astronomical libraries of the world where I researched material for this book. In Cape Town, the late Professor Bob Stobie was director at the South African Astronomical Observatory in 1996 during my six months there, and he did everything possible to make my stay there as comfortable and productive as it was. The SAAO librarian, Ethleen Lastovica, did much to introduce me to her library and help me with locating materials in it. While in Cape Town, I read the pre-publication manuscript of Ian Glass' book *Victorian Telescope Makers* on Thomas and Howard Grubb. I am grateful to him for making available Fig. 1.9 showing a Grubb automatic prism spectroscope.

At the Astrophysical Institute Potsdam I am grateful for the support of the Alexander von Humboldt Stiftung during my four months in the Babelsberg branch of that institution in 1997. During this time, the late Dr Gerhard Scholz was my host, and I am grateful to him for his hospitality.

Also in 1997 I visited the Dominion Astrophysical Observatory in Victoria, BC for two months, and I thank the director, Dr Jim Hesser, for allowing me to work there. The late Dr Bev Oke kindly introduced me to the Keck low resolution imaging spectrometer (LRIS) during my stay in Victoria. Professor Colin Scarfe at the University of Victoria did much to facilitate my stay in that city.

In 2003 I spent three months working in the library at La Specola Vaticana, the Vatican Observatory, in Castelgandolfo. Father George Coyne was at that time director of the Specola, and he did everything to make my stay most comfortable and enjoyable. Father Juan Casanovas was in charge of the excellent library at La Specola, and he helped me on numerous occasions with locating material and discussing details of solar spectrographs. The chapter on solar spectrographs was written during my time there. Brother Guy Consolmagno assisted with the high resolution scanner used for some of the illustrations.

In 2004 I spent four months at Lund Observatory in Sweden. Professor Lennart Lindegren was at the time director and he and Professor Dainis Dravins did everything possible to facilitate my stay in the excellent Lund library.

I thank the late Professor Donald Osterbrock for information on the life and work of Frank Wadsworth, which I have included in Section 1.4. Professor David Gray commented on the theory of shadowing in échelle gratings. Drs Stephen Vogt and Harland Epps kindly received me at the University of California Santa Cruz, where I learnt more about the HIRES instrument at Keck. I also thank Drs Bob Tull and Phillip Macqueen (Phillip was my former Ph.D. student in New Zealand), both at Austin, University of Texas, for helpful discussions on spectrograph design. Another former graduate student, Dr Stuart Barnes, guided me in many aspects of the design of the Hercules spectrograph at Mt John, and this assistance will also have indirectly helped in the writing of this book. He also kindly provided Fig. 3.8.

I must also thank Dr David Latham at the Harvard-Smithsonian Center for Astrophysics, who first introduced me to the marvels of échelle spectrographs in 1974, long before I started to write this book. Without him, this work might never have been written. An even earlier mentor on coudé spectrographs was the late Dr Ted Dunham, who worked to develop the Mt Wilson coudé spectrograph, and who influenced me profoundly while I was a graduate student using his coudé spectrograph at Mt Stromlo in Canberra in the late 1960s and early 1970s.

Numerous other astronomers have kindly granted permission for me to use their diagrams and illustrations in this book. These are acknowledged in the table of figure sources at the end of the book.