INTERNATIONAL GEOPHYSICS SERIES . VOLUME 2

Physics of the Aurora and Airglow

Joseph W. Chamberlain

Yerkes Observatory University of Chicago Williams Bay, Wisconsin



Contents

Prefa	ce	ix
Ackn	owledgments	xi
	Chapter 1	
	Radiation in Spectral Lines	
1.1.	Temperature and Thermal Equilibrium	1
	1.1.1. Maxwellian Distribution of Velocities. 1.1.2. Spectroscopic Nomenclature. 1.1.3. Boltzmann Excitation Equation. 1.1.4. Doppler Line Broadening	
1.2.	The Classical Theory of Spectral Lines	7
	1.2.1. Classical Theory of Line Emission. 1.2.2. Classical Theory of Line Absorption.	
1.3.	Quantum Concepts of Spectral Lines	13
	1.3.1. Transition Probabilities. 1.3.2. Line Strengths. 1.3.3. f-values. 1.3.4. Line Profiles.	
1.4.	Molecular Bands	20
	1.4.1. Intensities of Electronic and Vibrational Bands. 1.4.2. Intensities of Rotational Lines.	
1.5.	Excitation and Ionization Processes	27
	1.5.1. Radiative Excitation, Ionization, and Recombination. 1.5.2. Particle Collisions and Photochemical Reactions.	
	Chapter 2	
	Scattering of Radiation in Finite Atmospheres	
2.1.	Introduction	34
	2.1.1. Transfer Problems in the Physics of the Atmosphere. 2.1.2. Definitions and Terminology.	
2.2.	Equation of Radiative Transfer	38
2.3.	Applications of the Transfer Equation to Photometry	41
	2.3.1. Photometric Observations of Aurorae. 2.3.2. Photometric Observations of the Airglow.	
2.4.	The X- and Y-Functions in Problems of Radiative Transfer	49
	2.4.1. Formulation of the Transfer Problem with the Principles of Invariance. 2.4.2. Solution for the S- and T-functions.	

2.5.	Correction of Photometric Observations of the Airglow for Tropo-	55
	spheric Scattering	55
	Chapter 3	
Ma	gnetic Fields, Charged Particles, and the Upper Atmosphe	re
3.1.	The Geomagnetic Field	63
3.2.	Motions of Charged Particles in Electric and Magnetic Fields	73
	3.2.1. Uniform Magnetic Field. 3.2.2. Uniform Electric and Magnetic Fields. 3.2.3. Inhomogeneous Magnetic Field. 3.2.4. Constancy of the Magnetic Moment: Adiabatic Invariance.	
3.3.	Propagation of Electromagnetic Waves in an Ionized Atmosphere .	80
	3.3.1. Maxwell's Equations. 3.3.2. Propagation in the Absence of a Magnetic Field.	
3.4.	The Ionosphere	84
	3.4.1. A Chapman Layer. 3.4.2. Recombination Processes and Ion Formation in the Atmosphere.	
3.5.	Model Atmospheres	89
	3.5.1. Basic Theory of Atmospheric Structure. 3.5.2. Relative Abundances of the Major Constituents. 3.5.3. Temperature Structure of the Atmosphere.	
	Chapter 4	
	Occurrence of Aurorae in Space and Time	
4.1.	Geographic Distribution and Periodic Variations	100
	4.1.1. Recording Auroral Occurrence and Appearance. 4.1.2. Dependence on Geomagnetic Latitude: The Auroral Zones. 4.1.3. Periodic Variations.	
4.2.	Characteristics of Auroral Displays	116
	4.2.1. Appearance. 4.2.2. Height and Vertical Extent. 4.2.3. Orientations in Space. 4.2.4. Auroral Activity. 4.2.5. Synoptic View of Aurora.	
4.3.	Aurorae and Related Phenomena	138
	4.3.1. Geomagnetic Activity and Earth Currents. 4.3.2. Auroral Proton Bombardment. 4.3.3. X-Radiation. 4.3.4. Ionospheric Disturbances. 4.3.5. Radio Emission. 4.3.6. Cosmic Rays. 4.3.7. Miscellaneous Terrestrial Effects Related to Aurora. 4.3.8. Solar Phenomena.	
	Chapter 5	
	Auroral Spectroscopy and Photometry	
5.1.	Spectral Identifications	15
	5.1.1. An Atlas of the Auroral Spectrum. 5.1.2. Forbidden Atomic Lines. 5.1.3. Permitted Atomic Lines. 5.1.4. Molecular Band Systems.	

5.2.	Spectral Photometry of Aurora	196
	5.2.1. Absolute Brightness of Spectral Features. 5.2.2. Latitude and Height Variations in the Composition of the Spectrum. 5.2.3. Spectral Variations with Type of Aurora; Variations in the Hydrogen Emission. 5.2.4. Rapid Fluctuations and Intensity Correlations. 5.2.5. Polarization of Spectral Lines. 5.2.6. Hydrogen-Line Profiles. 5.2.7. Rotational and Doppler Temperatures. 5.2.8. Vibrational Distributions.	
	Chapter 6 The Radio-Aurora	
6.1.	Observed Characteristics	217
	6.1.1. Introduction: The Distinction between Aurora and Radio-Aurora. 6.1.2. Types of Radar and Bistatic Echoes. 6.1.3. Location of Radio-Aurorae. 6.1.4. Periodic Variations. 6.1.5. Apparent Motions of Auroral Ionization. 6.1.6. Polarization. 6.1.7. Aspect Sensitivity and Echo Strength. 6.1.8. Relation to Other Phenomena.	
6.2.	Theory of Auroral Reflections	232
	6.2.1. Geometry of Reflections. 6.2.2. Critical and Partial Reflections from a Large Surface. 6.2.3. Scattering by Small-Scale Inhomogeneities in the Ionization. 6.2.4. Comparison of Reflection Mechanisms.	
	Chapter 7	
	Physical Processes in the Auroral Atmosphere	
7.1		
7.1.	Proton Bombardment	244
7.1.	Proton Bombardment	244
7.1.	7.1.1. Statistical Equilibrium for Hydrogen. 7.1.2. The Role of Protons in Producing Aurora. 7.1.3. Hydrogen-Line Profiles and the Spectrum of	244269
	7.1.1. Statistical Equilibrium for Hydrogen. 7.1.2. The Role of Protons in Producing Aurora. 7.1.3. Hydrogen-Line Profiles and the Spectrum of Proton Energies.	
	7.1.1. Statistical Equilibrium for Hydrogen. 7.1.2. The Role of Protons in Producing Aurora. 7.1.3. Hydrogen-Line Profiles and the Spectrum of Proton Energies. Electron Bombardment	
7.2.	7.1.1. Statistical Equilibrium for Hydrogen. 7.1.2. The Role of Protons in Producing Aurora. 7.1.3. Hydrogen-Line Profiles and the Spectrum of Proton Energies. Electron Bombardment	269
7.2.	7.1.1. Statistical Equilibrium for Hydrogen. 7.1.2. The Role of Protons in Producing Aurora. 7.1.3. Hydrogen-Line Profiles and the Spectrum of Proton Energies. Electron Bombardment	269
7.2.	7.1.1. Statistical Equilibrium for Hydrogen. 7.1.2. The Role of Protons in Producing Aurora. 7.1.3. Hydrogen-Line Profiles and the Spectrum of Proton Energies. Electron Bombardment	269
7.2.	7.1.1. Statistical Equilibrium for Hydrogen. 7.1.2. The Role of Protons in Producing Aurora. 7.1.3. Hydrogen-Line Profiles and the Spectrum of Proton Energies. Electron Bombardment	269
7.2.	7.1.1. Statistical Equilibrium for Hydrogen. 7.1.2. The Role of Protons in Producing Aurora. 7.1.3. Hydrogen-Line Profiles and the Spectrum of Proton Energies. Electron Bombardment	269
7.2.	7.1.1. Statistical Equilibrium for Hydrogen. 7.1.2. The Role of Protons in Producing Aurora. 7.1.3. Hydrogen-Line Profiles and the Spectrum of Proton Energies. Electron Bombardment	269

xvi CONTENTS

8.2.	Auroral Particles in the Geomagnetic Field	326
	8.2.1. Detection and Artificial Production of Charged Particles. 8.2.2. Questions Concerning the Geographic Location of Particle Bombardment. 8.2.3. Questions Concerning the Energy Spectra and Angular Distribution of Auroral Particles.	
	Chapter 9	
	The Airglow Spectrum	
9.1.	Nightglow	345
9.2.	Twilight and Day Airglow	376
	Chapter 10	
	Analysis of Twilight Observations for Emission Heights	
10.1.	Apparent Heights z_s : The Shadow of the Solid Earth	394
10.2.	Height Measurements with Atmospheric Screening $10.2.1$. Actual Shadow Height z_0 , for a Known Screening Height h_0 . $10.2.2$. The Zenith-Horizon Method of Height Determinations. $10.2.3$. Calculation of Transmission Function and Screening Height.	404
10.3.	Height and Vertical Distribution of Observed Emissions	413
	Chapter 11	
	Theory of the Twilight and Day Airglow	
11.1.	Resonance Scattering and Fluorescence for an Optically Thin Layer 11.1.1. Scattered Intensity with Allowance for Deactivation. 11.1.2. Polarization of Resonance Radiation.	422
11.2.	Excitation of N_2^+ First Negative Bands	437

	CONTENTS	xvii
11.3.	Photon Scattering by Atmospheric Sodium	444
11.4.	Photochemistry and Ionization of Atmospheric Sodium	467
	11.4.1. Photochemistry. 11.4.2. Ionization. 11.4.3. Sodium Ejected from Rockets.	
11.5.	Theory of the Oxygen Red Lines	473
	11.5.1. Resonance Scattering and Ultraviolet Dissociation. 11.5.2. Collisional Deactivation. 11.5.3. Dissociative Recombination. 11.5.4. Dayglow in the Red Lines.	
11.6.	Excitation of Other Emissions	479
	11.6.1. The [NI] ₂₁ Lines. $11.6.2$. O ₂ Infrared Atmospheric Band. $11.6.3$. Ca II H and K Lines. $11.6.4$. Li I Resonance Lines. $11.6.5$. Additional Emissions to be Expected.	
	Chapter 12	
	Spectral Photometry of the Nightglow	
	,	
12.1.	Methods of Height Determinations	486
12.2.	Spectroscopic Temperatures	498
12.3.	Intensities, Polarization, and Geographic and Time Variations 12.3.1. Absolute Intensities and Polarization. 12.3.2. Geographic and Periodic Variations of the Intensities. 12.3.3. Spectral Correlations. 12.3.4. Structure and Motion of Excitation Patterns.	503
	Chapter 13	
	Excitation of the Nightglow	
13.1	Introduction: Mechanisms of Nightglow Excitation	521
	Excitation by Recombination in the Ionosphere	523
13 3	Excitation by Particle Collisions	533

13.3.1. Thermal Electrons. 13.3.2. Extraterrestrial Particles and Other Nonthermal Collisions. 13.3.3. Atomic and Molecular Thermal Collisions.

13.4. Photochemical Reactions in an Oxygen-Nitrogen Atmosphere	537
13.4.1. Excitation of O ₂ Band Systems. 13.4.2. Photochemical Excitation of [OI]. 13.4.3. The Continuum and Unidentified Blue-Green Bands. 13.4.4. Artificially Induced Airglow. 13.4.5. Regular Variations in Intensity. 13.4.6. Turbulence and Green-Line Patchiness.	
13.5. Excitation of Emissions from Minor Constituents	553
13.5.1. Photochemical Origin of the Meinel OH Bands. 13.5.2. Hydrogen Lines in the Night-Sky Spectrum. 13.5.3. Photochemical Excitation of Sodium D Lines.	
Appendixes	
APPENDIX I. A Table of Physical Constants	567
APPENDIX II. The Rayleigh: A Photometric Unit for the Aurora and	
. 0	569
APPENDIX III. A Short List of Airglow-Aurora Observing Stations	572
APPENDIX IV. Temperature, Density, and Composition of the Upper	
r	574
Appendix V. The Ionosphere	577
APPENDIX VI. Forbidden Atomic Oxygen and Nitrogen Lines	579
Appendix VII. Glossary of Symbols	582
APPENDIX VIII. A List of Books and Review Articles on the Aurora	
and Airglow	590
Bibliography	593
Author Index	671
Subject Index	684