

# Contents

|          |   |          |
|----------|---|----------|
| <b>1</b> | <b>Introduction</b> .....   | <b>1</b> |
| <b>2</b> | <b>Atmospheric Chemistry</b> .....  | <b>5</b> |
| 2.1      | Atmospheric Structure and Composition .....                                 | 7        |
| 2.1.1    | Trace Species in the Atmosphere .....                                       | 9        |
| 2.1.2    | Quantification of Gas Abundances .....                                      | 10       |
| 2.1.3    | Lifetime of Trace Gases in the Atmosphere .....                             | 14       |
| 2.2      | Direct Emission of Trace Gases<br>to the Atmosphere .....                   | 14       |
| 2.2.1    | Nitrogen Species .....  | 16       |
| 2.2.2    | Sulphur Species .....   | 18       |
| 2.2.3    | Carbon-Containing Species .....   | 19       |
| 2.3      | Ozone in the Troposphere .....  | 21       |
| 2.3.1    | Mechanism of Tropospheric Ozone Formation .....                             | 23       |
| 2.3.2    | Ozone Formation in Urban Centres<br>and Downwind .....                      | 25       |
| 2.4      | Radical Processes in the Atmosphere .....                                   | 27       |
| 2.4.1    | Sources of Hydrogen Radicals (OH and HO <sub>2</sub> ) .....                | 29       |
| 2.4.2    | Temporal Variation of the HO <sub>x</sub> Source Strength .....             | 32       |
| 2.4.3    | Chemistry of Hydrogen Radicals (OH and HO <sub>2</sub> ) .....              | 32       |
| 2.5      | Oxides of Nitrogen in the Atmosphere .....                                  | 38       |
| 2.5.1    | Classical Chemistry of Oxides of Nitrogen in the<br>Atmosphere .....        | 39       |
| 2.5.2    | Tropospheric Chemistry of Nitrate Radicals, NO <sub>3</sub> .....           | 41       |
| 2.5.3    | Nitrous Acid, HONO in the Atmosphere .....                                  | 45       |
| 2.6      | Tropospheric Chemistry of VOCs .....  | 47       |
| 2.7      | Tropospheric Chemistry of Sulphur Species .....                             | 50       |
| 2.7.1    | Sulphur Dioxide – SO <sub>2</sub> .....                                     | 50       |
| 2.7.2    | Reduced Sulphur Species: DMS, COS, CS <sub>2</sub> , H <sub>2</sub> S ..... | 52       |
| 2.7.3    | Influence of Sulphur Species on the Climate,<br>the CLAW Hypothesis .....   | 54       |

|          |   |           |
|----------|---|-----------|
| 2.8      | Chemistry of Halogen Radicals in the Troposphere . . . . .                                    | 55        |
| 2.8.1    | Tropospheric Sources of Inorganic Halogen Species . . . . .                                   | 55        |
| 2.8.2    | Tropospheric Cycles of Inorganic Halogen Species . . . . .                                    | 58        |
| 2.8.3    | Potential Impact of Inorganic Halogen Species<br>on Tropospheric Chemistry . . . . .          | 62        |
| 2.9      | Oxidation Capacity of the Atmosphere . . . . .  | 63        |
| 2.10     | Stratospheric Ozone Layer . . . . .   | 65        |
| 2.10.1   | Stratospheric Ozone Formation: The Chapman Cycle . . . . .                                    | 65        |
| 2.10.2   | Stratospheric Ozone Chemistry: Extension<br>of the Chapman Cycle . . . . .                    | 67        |
| 2.10.3   | Stratospheric Ozone Hole . . . . .  | 72        |
| 2.10.4   | Recovery of Stratospheric Ozone . . . . .   | 75        |
| <b>3</b> | <b>Interaction of Molecules with Radiation . . . . .</b>                                      | <b>77</b> |
| 3.1      | Electromagnetic Radiation and Matter . . . . .  | 77        |
| 3.2      | Energy Levels and Transitions in Atoms . . . . .  | 78        |
| 3.3      | Energy Levels and Transitions in Molecules . . . . .  | 79        |
| 3.3.1    | Rotational Energy Levels and Transitions . . . . .  | 80        |
| 3.3.2    | Vibrational Energy Levels . . . . .   | 81        |
| 3.3.3    | Electronic Energy Levels . . . . .  | 81        |
| 3.4      | Population of States . . . . .  | 82        |
| 3.5      | Molecular Spectra . . . . .   | 83        |
| 3.6      | Broadening Mechanisms and Line Width of Absorption Lines . . . . .                            | 84        |
| 3.6.1    | The Natural Line Width . . . . .  | 85        |
| 3.6.2    | Pressure Broadening (Collisional Broadening) . . . . .  | 85        |
| 3.6.3    | Doppler Broadening . . . . .  | 86        |
| 3.6.4    | Realistic Broadening in the UV- and Visible Spectral<br>Ranges . . . . .                      | 87        |
| 3.7      | Spectroscopic Techniques for Chemical Analysis . . . . .                                      | 88        |
| 3.7.1    | The Fluorescence Techniques . . . . .   | 88        |
| 3.7.2    | Absorption Spectroscopy . . . . .   | 89        |
| <b>4</b> | <b>Radiation Transport in the Atmosphere . . . . .</b>  | <b>91</b> |
| 4.1      | Basic Quantities Related to Radiation Transport . . . . .                                     | 91        |
| 4.2      | Interaction Processes of Radiation in the Atmosphere . . . . .                                | 92        |
| 4.2.1    | Absorption Processes . . . . .  | 92        |
| 4.2.2    | Rayleigh Scattering . . . . .   | 93        |
| 4.2.3    | Raman Scattering . . . . .  | 94        |
| 4.2.4    | Polarisation Properties of Vibrational Raman<br>Scattered Light and Line Filling in . . . . . | 98        |
| 4.2.5    | Scattering and Absorption of Radiation by Particles<br>(Mie Scattering) . . . . .             | 99        |
| 4.3      | The Radiation Transport Equation . . . . .  | 102       |
| 4.3.1    | Absorption of Radiation . . . . .   | 103       |
| 4.3.2    | Scattering of Radiation . . . . .   | 103       |

|          |   |            |
|----------|---|------------|
| 4.3.3    | Thermal Emission .....  | 104        |
| 4.3.4    | Simplification of the Radiation Transport Equation ....   | 105        |
| 4.4      | Light Attenuation in the Atmosphere .....   | 105        |
| 4.4.1    | Wide Beams in the Atmosphere, the Two-Stream Model  | 105        |
| 4.4.2    | Narrow Beams in the Atmosphere .....  | 107        |
| 4.5      | The Effect of Atmospheric Refraction<br>(El-Mirage Effects) .....                                     | 108        |
| 4.6      | The Effect of Atmospheric Turbulence .....  | 108        |
| 4.7      | Practical Considerations About Radiation in the Atmosphere .  | 110        |
| <b>5</b> | <b>Measurement Techniques for Atmospheric Trace Gas<br/>Concentrations and Other Parameters .....</b> | <b>113</b> |
| 5.1      | History of Measurement Techniques .....   | 114        |
| 5.2      | The Role of Measurements in Atmospheric Chemistry .....   | 114        |
| 5.2.1    | Long-term Observations .....  | 115        |
| 5.2.2    | Regional and Episodic Studies .....   | 115        |
| 5.2.3    | Investigation of Fast in-situ (Photo)Chemistry .....  | 116        |
| 5.3      | Requirements for Measurement Techniques .....   | 116        |
| 5.4      | Grouping Measurement Techniques in Categories .....   | 117        |
| 5.4.1    | In-situ Versus Remote Sensing Techniques .....  | 119        |
| 5.5      | Experimental Evidence for the Presence of Radicals in the<br>Atmosphere.....                          | 119        |
| 5.6      | Spectroscopic Techniques .....  | 124        |
| 5.6.1    | Microwave Spectroscopy.....   | 124        |
| 5.6.2    | IR Spectroscopy .....   | 125        |
| 5.6.3    | UV/Visible Absorption Spectroscopy .....  | 126        |
| 5.7      | Selection Criteria for Spectroscopic Techniques .....   | 127        |
| 5.7.1    | Tunable Diode Laser Spectroscopy (TDLS) .....   | 127        |
| 5.7.2    | Photo Acoustic Spectroscopy (PAS) .....   | 128        |
| 5.7.3    | Light Detection And Ranging (LIDAR) .....   | 128        |
| 5.7.4    | Differential Absorption LIDAR (DIAL) .....  | 130        |
| 5.7.5    | White Light LIDAR .....   | 130        |
| 5.7.6    | Laser-Induced Fluorescence (LIF) .....  | 131        |
| 5.7.7    | Cavity-Ringdown (CRDS) and Cavity Enhanced<br>Spectroscopy (CEAS) .....                               | 132        |
| 5.7.8    | Mask Correlation Spectroscopy (COSPEC) .....  | 132        |
| 5.7.9    | Differential Optical Absorption Spectroscopy (DOAS) ..  | 133        |
| <b>6</b> | <b>Differential Absorption Spectroscopy .....</b>   | <b>135</b> |
| 6.1      | The History of Absorption Spectroscopy .....  | 135        |
| 6.2      | Classical Absorption Spectroscopy .....   | 137        |
| 6.3      | The DOAS Principle .....  | 138        |
| 6.4      | Experimental Setups of DOAS Measurements .....  | 141        |
| 6.4.1    | Active DOAS .....   | 141        |
| 6.4.2    | Passive DOAS .....  | 144        |

|          |  |            |
|----------|--|------------|
| 6.5      | Trace Gases Measured by DOAS                             | 146        |
| 6.6      | Precision and Accuracy of DOAS                           | 152        |
| 6.7      | Mathematical Description of the DOAS Approach            | 155        |
| 6.7.1    | Fundamentals of the DOAS Approach                        | 155        |
| 6.7.2    | Application of the DOAS Approach in Practical Situations | 158        |
| <b>7</b> | <b>The Design of DOAS Instruments</b>                    | <b>175</b> |
| 7.1      | Design Considerations of DOAS Instruments                | 175        |
| 7.2      | Key Components of DOAS Systems                           | 177        |
| 7.3      | Light Sources for Active DOAS                            | 178        |
| 7.3.1    | Characteristics of Artificial Light Sources              | 178        |
| 7.3.2    | Natural Light Sources                                    | 190        |
| 7.3.3    | Calibration Light Sources                                | 192        |
| 7.4      | Optical Elements for DOAS Systems                        | 194        |
| 7.4.1    | Some Principles of Optics                                | 194        |
| 7.4.2    | Mirrors  | 198        |
| 7.4.3    | Prisms   | 202        |
| 7.4.4    | Lenses   | 202        |
| 7.4.5    | Apertures, Entendue, Lagrange Invariant                  | 204        |
| 7.4.6    | Diffraction at Apertures                                 | 205        |
| 7.4.7    | Quartz-fibres, Mode Mixers, and Cross-section Shaping    | 206        |
| 7.4.8    | Filters  | 208        |
| 7.4.9    | Retro-reflectors   | 209        |
| 7.5      | Spectrometers/Interferometers for DOAS Systems           | 212        |
| 7.5.1    | Diffraction Gratings                                     | 213        |
| 7.5.2    | Spectrometers  | 215        |
| 7.5.3    | Interferometers (FT Spectrometry)                        | 219        |
| 7.5.4    | Characteristics of Spectrometers                         | 219        |
| 7.6      | Detectors for UV/Visual Spectrometers                    | 223        |
| 7.6.1    | Geometrical Focal Plane Sampling Requirements            | 223        |
| 7.6.2    | Optomechanical Scanning Devices and Photomultiplier Tube | 228        |
| 7.6.3    | Solid-state Array Detectors and Characteristics          | 230        |
| 7.6.4    | PDA Detectors  | 236        |
| 7.6.5    | CCD Array Detectors                                      | 236        |
| 7.6.6    | CMOS Detectors   | 240        |
| 7.7      | Telescope Designs  | 241        |
| 7.8      | Optical Multi-pass Systems                               | 242        |
| 7.8.1    | White Multi-reflection Cells                             | 243        |
| 7.8.2    | Herriott Multi-reflection Cells                          | 245        |
| 7.8.3    | Passive Resonators (CEAS, CRDS)                          | 246        |
| 7.9      | Active DOAS Systems                                      | 247        |
| 7.9.1    | 'Classic' Active Long-path System                        | 247        |
| 7.9.2    | High-resolution DOAS Spectrometers                       | 248        |

|          |   |            |
|----------|---|------------|
| 7.9.3    | Recent Designs of Active Long-path<br>DOAS System .....       | 250        |
| 7.9.4    | DOAS Systems with Optical<br>Multi-pass Systems .....         | 252        |
| 7.10     | Passive DOAS Systems .....                                    | 253        |
| 7.10.1   | Direct Sun/Moon Setup .....                                   | 253        |
| 7.10.2   | Zenith Scattered Light DOAS .....                             | 253        |
| 7.10.3   | Off-axis, MAX-DOAS Instruments .....                          | 255        |
| 7.10.4   | Imaging DOAS (I-DOAS) Instruments .....                       | 257        |
| 7.10.5   | Aircraft-based Experiments .....                              | 259        |
| 7.10.6   | Balloon-borne Instruments .....                               | 260        |
| 7.10.7   | Satellite Instruments .....                                   | 260        |
| 7.11     | Light Utilisation in a Long-path Spectrometer .....           | 266        |
| 7.12     | Software Controlling DOAS Instruments .....                   | 269        |
| 7.13     | Optimising DOAS Instruments .....                             | 271        |
| 7.13.1   | Optimum Light Path Length in Active DOAS Systems .....        | 272        |
| 7.13.2   | Optimum Spectral Resolution .....                             | 274        |
| 7.13.3   | Optimum Measurement Time .....                                | 274        |
| 7.14     | Measurement Process Control .....                             | 277        |
| 7.14.1   | Active DOAS Systems – Standard Approach .....                 | 277        |
| 7.14.2   | Active DOAS Systems – MCST .....                              | 279        |
| 7.14.3   | Passive DOAS Systems .....                                    | 280        |
| 7.14.4   | Off-axis Scattered Sunlight DOAS Systems .....                | 280        |
| 7.15     | Mechanical Actuators .....                                    | 282        |
| 7.15.1   | Stepper Motors .....  | 283        |
| 7.15.2   | Other Actuators .....   | 284        |
| 7.16     | Information Needed for Later Analysis .....                   | 285        |
| <b>8</b> | <b>Evaluation of DOAS Spectra, Sensitivity, and Detection</b> |            |
|          | <b>Limits .....</b>   | <b>287</b> |
| 8.1      | Linear Fitting Methods .....                                  | 288        |
| 8.1.1    | Unweighted Linear Least Squares Fit .....                     | 289        |
| 8.1.2    | Weighted-Correlated Least Squares Fit .....                   | 290        |
| 8.2      | Non-linear Fitting Methods .....                              | 290        |
| 8.2.1    | Gradient Method .....   | 290        |
| 8.2.2    | Gauß-Newton Method .....                                      | 291        |
| 8.2.3    | Levenberg-Marquardt Method .....                              | 291        |
| 8.3      | DOAS Analysis Procedure .....                                 | 293        |
| 8.3.1    | The Linear Model .....  | 294        |
| 8.3.2    | High- and Low-pass Filtering .....                            | 295        |
| 8.3.3    | Wavelength Alignment .....                                    | 298        |
| 8.3.4    | Realisation .....   | 299        |
| 8.3.5    | Error Analysis .....  | 302        |
| 8.4      | Determination of Reference Spectra .....                      | 317        |

|           |   |            |
|-----------|---|------------|
| 8.4.1     | Theoretical Basis of Reference Spectra<br>Simulation: Convolution .....                                 | 318        |
| 8.4.2     | Practical Implementation of Reference Spectra<br>Simulation .....                                       | 320        |
| 8.4.3     | Optimum Resolution of Literature Reference Spectra ..   | 321        |
| 8.5       | Detection Limits .....  | 323        |
| 8.6       | Residual Spectra .....  | 324        |
| 8.7       | Systematic Errors in the Analysis .....   | 325        |
| 8.7.1     | Interferences .....   | 326        |
| 8.7.2     | Spectrometer Stray Light and Offsets .....  | 326        |
| <b>9</b>  | <b>Scattered-light DOAS Measurements .....</b>  | <b>329</b> |
| 9.1       | Air Mass Factors (AMF) .....  | 332        |
| 9.1.1     | Direct Light AMF .....  | 333        |
| 9.1.2     | Scattered Zenith Light AMF .....  | 335        |
| 9.1.3     | Scattered Off-axis and Multi-axis AMF .....   | 339        |
| 9.1.4     | AMFs for Airborne and Satellite Measurements .....  | 342        |
| 9.1.5     | Correction of Fraunhofer Structures Based on AMFs ...   | 343        |
| 9.1.6     | The Influence of Rotational Raman scattering, the<br>‘Ring Effect’ .....                                | 345        |
| 9.2       | AMF Calculations .....  | 347        |
| 9.2.1     | Single-scattering RT Models .....   | 348        |
| 9.2.2     | Multiple-scattering RT Models .....   | 350        |
| 9.2.3     | Applications and Limitations of the ‘Traditional’<br>DOAS Method for Scattered Light Applications ..... | 351        |
| 9.3       | AMFs for Scattered Light Ground-Based DOAS Measurements   | 354        |
| 9.3.1     | ZSL-DOAS Measurements .....   | 354        |
| 9.3.2     | Off-axis-DOAS Measurements .....  | 357        |
| 9.3.3     | MAX-DOAS Measurements .....   | 358        |
| 9.3.4     | Accuracy of MAX-DOAS AMF Calculations .....   | 366        |
| 9.3.5     | The Box-AMF Concept .....   | 369        |
| 9.4       | Aircraft Observed Scattered Light (AMAX-DOAS) .....   | 371        |
| 9.5       | Satellite Observed Scattered Light .....  | 372        |
| 9.5.1     | Radiative Transfer in Nadir Geometry – the Role of<br>Clouds .....                                      | 373        |
| 9.5.2     | The Analysis of Satellite-limb Scattered Light<br>Observations .....                                    | 377        |
| <b>10</b> | <b>Sample Application of ‘Active’ DOAS with Artificial<br/>Light Sources .....</b>                      | <b>379</b> |
| 10.1      | Air Pollution Studies and Monitoring Applications .....   | 380        |
| 10.1.1    | Measurement of Urban Pollutants .....   | 380        |
| 10.1.2    | Vertical Profiles of Air Pollution by Multiple<br>DOAS Light Beams .....                                | 398        |
| 10.2      | Investigation of Free Radical Processes in the Atmosphere ....  | 401        |

|           |   |            |
|-----------|---|------------|
| 10.2.1    | Measurement of OH Radicals by DOAS  | 403        |
| 10.2.2    | Measurement of NO <sub>3</sub> Radicals   | 404        |
| 10.2.3    | Measurement of Halogen Oxides   | 412        |
| 10.3      | Investigation in Photoreactors (Smog Chambers) by DOAS                            | 417        |
| 10.4      | Validation of Active DOAS   | 418        |
| <b>11</b> | <b>Sample Application of 'Passive' DOAS</b>                                       | <b>429</b> |
| 11.1      | Atmospheric Measurements by Direct Light Spectroscopy                             | 430        |
| 11.1.1    | Ground-based Measurement of Atmospheric Species                                   | 431        |
| 11.1.2    | Balloon- and Aircraft-borne Measurement of Stratospheric Species                  | 432        |
| 11.2      | Stratospheric Measurements by Ground-based Scattered Light DOAS                   | 436        |
| 11.2.1    | Determination of Stratospheric NO <sub>2</sub> and O <sub>3</sub> from the Ground | 437        |
| 11.2.2    | Observation of Halogen Radicals in the Polar Stratosphere                         | 441        |
| 11.2.3    | Halogen Radical Observation in the Mid-latitude Stratosphere                      | 442        |
| 11.2.4    | Observation of Stratospheric Trace Gas Profiles                                   | 444        |
| 11.3      | Measurement of Tropospheric Species by Ground-based DOAS                          | 448        |
| 11.3.1    | MAX-DOAS Observations in Polluted Regions   | 449        |
| 11.3.2    | MAX-DOAS Observations of Halogen Oxides at Mid-latitudes                          | 450        |
| 11.3.3    | Halogen Oxide Radicals in the Polar Troposphere                                   | 453        |
| 11.3.4    | Halogen Oxide Radicals in the Free Troposphere                                    | 453        |
| 11.3.5    | Trace Gases in the Marine Environment   | 455        |
| 11.3.6    | Determination of Aerosol Properties from MAX-DOAS Observations                    | 456        |
| 11.3.7    | Determination of NO <sub>3</sub> Vertical Profiles                                | 459        |
| 11.3.8    | Emission from Point Sources   | 459        |
| 11.3.9    | Imaging Trace Gas Distributions (I-DOAS)  | 464        |
| 11.4      | Scattered Light Aircraft Measurements of Stratospheric Species                    | 466        |
| 11.5      | Scattered Light Aircraft Measurements of Tropospheric Species                     | 468        |
| 11.6      | Satellite Observations Using DOAS Techniques                                      | 469        |
| 11.7      | Satellite Observations of Stratospheric Species                                   | 473        |
| 11.7.1    | Stratospheric O <sub>3</sub>  | 473        |
| 11.7.2    | Stratospheric NO <sub>2</sub>   | 473        |
| 11.7.3    | Stratospheric OClO  | 475        |
| 11.8      | Satellite Observations of Tropospheric Species                                    | 477        |
| 11.8.1    | Tropospheric O <sub>3</sub>   | 478        |
| 11.8.2    | Tropospheric NO <sub>2</sub>  | 479        |
| 11.8.3    | Tropospheric Formaldehyde   | 481        |
| 11.8.4    | Tropospheric SO <sub>2</sub>  | 483        |
| 11.8.5    | Tropospheric BrO  | 485        |

|           |   |            |
|-----------|---|------------|
| 11.8.6    | Tropospheric Carbon Monoxide .....  | 487        |
| 11.8.7    | Tropospheric Methane .....  | 488        |
| 11.8.8    | Tropospheric Water Vapour .....   | 489        |
| 11.9      | Determination of Photon Path Lengths by ‘Reversed DOAS’ ..  | 491        |
| 11.9.1    | Average Path Lengths from Low Resolution<br>Measurement of Weak Absorbers .....                         | 491        |
| 11.9.2    | Path Length Distributions from High Resolution<br>Measurement of Strong Absorbers .....                 | 491        |
| 11.9.3    | Measurement of Trace Gases Inside Clouds .....  | 494        |
| <b>12</b> | <b>DOAS: Yesterday, Today, and Tomorrow .....</b>   | <b>495</b> |
| 12.1      | Passive DOAS Applications .....   | 495        |
| 12.1.1    | MAX-DOAS .....  | 497        |
| 12.1.2    | Aerosol and Cloud Monitoring .....  | 498        |
| 12.1.3    | Imaging DOAS .....  | 498        |
| 12.1.4    | Tomography .....  | 498        |
| 12.1.5    | Satellite Instruments .....   | 498        |
| 12.2      | Active DOAS Applications .....  | 499        |
| 12.2.1    | New Trace Gases .....   | 499        |
| 12.2.2    | Infrared Measurements .....   | 500        |
| 12.2.3    | Hydrocarbons .....  | 500        |
| 12.2.4    | Air Pollution Monitoring .....  | 500        |
| 12.2.5    | BTX Monitoring .....  | 500        |
| 12.2.6    | Fence-Line Monitoring .....   | 501        |
| 12.2.7    | Tomography .....  | 501        |
| 12.2.8    | Range Resolved Technology/Broadband LIDAR .....   | 501        |
| 12.3      | Development of the Underlying Technology .....  | 502        |
| 12.3.1    | New Light-Sources .....   | 502        |
| 12.3.2    | New Detectors .....   | 502        |
| 12.3.3    | New Software .....  | 503        |
| 12.3.4    | Improved System Design .....  | 503        |
|           | <b>Literature .....</b>   | <b>505</b> |
|           | <b>Appendix A: Spectral Positions of Emission Lines from<br/>    Calibration Lamps and Lasers .....</b> | <b>569</b> |
| A.1       | Cadmium Lines .....   | 569        |
| A.2       | Mercury Lines .....   | 570        |
| A.3       | Hydrogen Lines .....  | 570        |
| A.4       | Neon I Lines .....  | 571        |
| A.5       | Zinc Lines .....  | 572        |



|   |     |
|---|-----|
| <b>Appendix B: Absorption Spectra of Molecules Measurable by</b>          |     |
| <b>DOAS</b> .....   | 573 |
| B.1 Nitric Oxide, NO .....  | 573 |
| B.2 Nitrogen Dioxide, NO <sub>2</sub> .....                               | 573 |
| B.3 Ammonia, NH <sub>3</sub> .....  | 575 |
| B.4 Formaldehyde, HCHO .....  | 575 |
| B.5 Glyoxal, CHOCHO .....   | 576 |
| B.6 Sulphur Dioxide, SO <sub>2</sub> .....                                | 576 |
| B.7 Carbon Disulfide, CS <sub>2</sub> .....                               | 577 |
| B.8 Ozone, O <sub>3</sub> .....   | 577 |
| B.9 Monocyclic Aromatic Hydrocarbons .....                                | 578 |
| B.10 Polycyclic Aromatic Hydrocarbons .....                               | 581 |
| B.11 Nitrous Acid, HONO .....   | 581 |
| B.12 Halogen Monoxides .....  | 582 |
| B.12.1 Chlorine Monoxide, ClO .....                                       | 583 |
| B.12.2 Bromine Monoxide, BrO .....  | 583 |
| B.12.3 Iodine Monoxide, IO .....  | 584 |
| B.13 Halogen Dioxides .....   | 584 |
| B.13.1 Chlorine Dioxide, OClO .....                                       | 584 |
| B.13.2 Bromine Dioxide, OBrO .....  | 584 |
| B.13.3 Iodine Dioxide, OIO .....  | 585 |
| B.14 Molecular Iodine (I <sub>2</sub> ) .....                             | 585 |
| B.15 Water Vapour, H <sub>2</sub> O .....                                 | 585 |
| B.16 Nitrate Radical, NO <sub>3</sub> .....                               | 586 |
| B.17 OH Radicals .....  | 586 |
| B.18 Oxygen, O <sub>2</sub> .....   | 588 |
| B.19 Oxygen Dimer, O <sub>4</sub> or (O <sub>2</sub> ) <sub>2</sub> ..... | 589 |
| <b>Index</b> .....  | 593 |