Airglow OH(8,3) rotational temperatures Svalbard (78°N) 2003
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Blue airglow on the edge of the Earth with the Andes Mountains below, as seen from Gemini 7. Image: NASA.
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ABSTRACT

Measurements of OH(8,3) airglow was performed with the HiTIES spectrograph on Svalbard, 2003-2007. The data for 2003 was analyzed, and rotational temperatures were calculated from the ratios of P$_1$ lines; and compared to another dataset of OH(6,2), collected by a Ebert-Fastie spectrometer, also located on Svalbard. For the analysis, 11 clear days in December 2003 with the most useable data were selected. The mean temperature for these 11 days is 198 ± 35 K when derived from the ratio P$_1$(2)-P$_1$(3) and 206 ± 22 K when derived from P$_1$(2)-P$_1$(4) giving a total mean of 202 ± 29 K. The comparison of mean temperatures to the dataset of OH(6,2) shows a separation of about 2-20 K and follows the same pattern.

SAMMANFATTNING

RÉSUMÉ

L'étude de la luminescence des bandes de Meinel du radical hydroxyle OH(8,3) permet d'accéder à des paramètres nouveaux sur la mésosphère de la Terre vers 87 km d'altitude. Des données observationnelles sont ainsi disponibles sur l'archipel de Svalbard (Norvège) situé dans l'océan glacial arctique. Depuis 2003, le spectrographe proche infrarouge haute résolution HiTIES (Université de Southampton) a ouvert une nouvelle voie dans l'interprétation des données grâce à une haute résolution. Les températures vibrationnelles de OH ont pu être calculées et comparées aux données des spectromètres Elbert-Fastie pour les bandes OH(6,2). La température moyenne observée est de 202 ± 29 K. La variation de la température ne montre aucune tendance particulière, ce qui est corrélé avec les mesures des bandes OH(6,2).
Acknowledgements

...a person needs new experiences. They jar something deep inside, allowing him to grow. Without change something sleeps inside us, and seldom awakens.

Frank Herbert, Dune

This thesis brought me, literally, to the end of the world...Svalbard.

The first time I came to Longyearbyen I remember stepping of the plane into snow, blasting right through me and I remembered a scene in my favourite movie "Dune" - the main character, coming from a planet full of water, travels to a planet consisting only of perilous and dry deserts. He felt the hot wind and realized he was completely out of place.

I felt exactly the same - I had come to this desolate, freezing cold place where polar bears roam free, the night sky blinds you with stars and snow behaves in very peculiar ways. I was definitely out of place!

I was met up at the airport and Margit gave me a tour of Longyearbyen, the Auroral station, all the way to EISCAT.

I remember the pitch black darkness and the snow drifting across the road, and I thought that it couldn’t get any more lonely than this.

Then I started doing some work at the Auroral station and met strange, interesting people and I worked with fascinating research. I saw glorious displays of aurorae and slowly it started to grow on me.

I began anticipating the next day and the next adventure or whatever new things Svalbard could give me, and then suddenly it happened.

When I went to Stockholm the third time in March it struck me as I sat on the plane looking out the window. I saw the snow dunes below and once more I thought of the movie "Dune" - just as Paul had adapted and learnt to love the planet that was so foreign to him in the beginning, I had also adapted and begun to love this desolate place. It had become part of me.

After that I have had several moments when the craving to see the open sky, the cool blue colours of ice and breath the crystal clear air of Svalbard has nearly overpowered me.

I have learnt the lesson of the desert: No one returns unchanged...
I must thank everyone who guided me, worked with me and laughed with me.

I want to send my thanks to my supervisor Nickolay Ivchenko for putting his trust in me, giving me this chance of a lifetime and making me a better person...

The LPACI-team: Olli, my bestest friend and ally at the deepest hours at the station, Dan - a gentleman to the fingertips, Hanna - the person who kept us all sane by showering us in positive thinking.
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Cyril, You had me at Hello!

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Chapter 1

Introduction

There has always been an interest the study of long-term changes in the atmosphere and its possible relationship with the impact of humans. Some[31] say that parts of the atmosphere, such as the thermosphere and the mesosphere, have changed during the last thirty years.

1.1 Human vs Nature

The atmosphere does not react as one might assume it should. At the areas of the mesosphere and lower thermosphere a greenhouse cooling, instead of heating, is expected[61, 28] caused by the increase in the concentration of greenhouse gases. Earth is heating up and the mesosphere and thermosphere are cooling down.

The mesopause temperature is, however, quite variable. The variations are both geographical and time dependant but also caused by seasonal and dynamical processes. To deduce if there might be an environmental change researchers have a need to separate trends, caused by natural variations: such as the 11-year solar cycle or turbulence in the atmosphere and then interpret the influences of human activities, such as increases in greenhouse gases. Also, to understand the atmosphere measurements of variables such as the variation of the temperature can contribute.

1.2 Hydroxyl Temperature and Variations

There are many reasons for using the OH rotational line spectrum. The OH rotational temperature is a useful parameter to study the variable atmospheric temperature in the mesopause region. The reason for this is since the line strengths follow a Maxwell-Boltzmann distribution, and the hydroxyl molecule is in equilibrium with the major atmospheric ingredients, at least for
the lower rotational levels[56], it is possible to derive the local atmospheric temperature - the intensity of the spectral line of a band are simply a function of the rotational temperature. Therefore using two lines from a single band one can estimate the rotational temperature by a simple equation[42]. OH in the area of the neutral atmosphere, 90 km of altitude, has a collision hit-rate of an order of $10^4$ s$^{-1}$ and the lifetime of the excited OH state is around $3 \times 10^{-3}$ seconds[42, 81]. It works as an indicator that the excited OH molecules in the rotational energy levels are in a thermal equilibrium with the atmospheric gas[65]. More reasons to use the hydroxyl spectra is that the rotational lines are an open structure, separating 10-20 Å between the lines, which makes it easy to measure individual lines by even a low resolution ($\sim 10$ Å) spectrometer. For this reason the OH airglow emissions have been utilized a lot for studying atmospheric temperature variation in the mesopause region since Meinel’s (1950)[39, 40] first publications.

A very interesting aspect of airglow is that, although assumed to be uniform, it has a recurring variation in intensity during the day. This is currently being investigated by several authors[44, 1, 79, 69] but is hard to determine since datasets for entire days are needed - something that is not possible on lower latitudes since the daylight interferes. It can also, at times, be difficult to achieve datasets that are complete during full days due to interference in the spectra.

### 1.3 Location Svalbard

Svalbard is an Arctic island north of Norway at 78°N and 15°E, in the North Atlantic ocean. Svalbard, being subject to “polar amplification” is, in many models[74] assumed to heat more than most of the rest of the Earth. “Polar amplification” means that the climate change more close the poles than the rest of the hemisphere - often connected to a change in global climate - such as the concentration of greenhouse gases or solar output[43]. So generally speaking the Arctic is the first place where the human or natural changes in nature can be observed.

What also makes just measurements from Svalbard so interesting is that, during the winter period, the airglow can be measured around the clock - making the datasets advantageous for deriving eventual periodicity that could occur during the day. Svalbard is also a very interesting atmospheric area because of its location close to the Arctic both because most airglow studies have been performed on lower latitudes but also because Svalbard lies in the region of the arctic front, an area generating low-pressure systems leading to a turbulent atmosphere. Svalbard is also vastly unpopulated so influences from human activities, such as lightpollution, is diminished in the data sets.

### 1.4 Purpose of Thesis

As a step to understand the entire chain from theory to practice involving operation of the HiTIES spectrograph, data collecting and analysis - I spent the
1.4. Purpose of Thesis

winter campaign (December-January 2006-2007) on Svalbard at the Auroral sta-

tion outside of Longyearbyen. I was part of the team making sure that the data
gathering ran smoothly, a hard but rewarding work with many long hours in
the auroral station. I had an excellent teacher who patiently and methodically
taught me the ways of the HiTIES. I also learnt that the way between idea and
making it happen can be a lot harder than it seems and that behind every piece
of data collected stands someone who made the hard work.

As a contribution to understanding the temperature in the mesosphere and its
variations, this thesis, though touching on many aspects of airglow, will focus
on winter temperatures in the mesopause region derived through spectral mea-
surements of the OH(8,3) airglow 2003. The spectral data used was recorded
with HiTIES, an imaging spectrograph with high spectral resolution installed
at the Auroral Station in Adventdalen, Svalbard (78°N, 15°E).

This is the first time the data from HiTIES is evaluated for the OH(8,3) band
of airglow and main focus of this thesis lies on the semidiurnal variations of this
band and its comparison to a dataset recorded by the Ebert-Fastie spectrometer
run by UNIS and also located at the Auroral Station in Adventdalen. This is
mostly due to the fact that the data set used is more suited for short term
analysis then long term since there are only approximately three years of data
recorded.
Chapter 2

Theoretical Background

2.1 Earth’s Atmosphere

Earth is our home in the vastness of space. A tiny planet with the extraordinary power of sustaining life - supported by the atmosphere, solar energy, and the planet’s magnetic field.

The Earth is enveloped by a blanket of air, which is called the atmosphere. It extends over 600 kilometers from the surface of the Earth. The outmost layer of the atmosphere absorbs the energy from the Sun while the bottom part recycles water and other chemicals to provide a moderate climate. The atmosphere acts as a shield from high-energy radiation and the vacuum of space.

The atmosphere is primarily composed of Nitrogen (N$_2$, 78%), Oxygen (O$_2$, 21%), and Argon (Ar, 1%). A multitude of other influential components are also present including water (H$_2$O, 0-7%), greenhouse gases or Ozone (O$_3$, 0-0.01%), and Carbon Dioxide (CO$_2$, 0.01-0.1%).

There is no absolute boundary of the atmosphere and outer space. A lower limit of 80 km is usually referred to as space[31] but the atmosphere just slowly becomes thinner and fades into space (Figure 2.1).

2.1.1 History

Before the 20th century the atmosphere above 10 kilometers height was considered to have a simple structure. It was believed that the temperature in the atmosphere was decreasing linearly with height, until the height at which the mixing time due to diffusion is considerably less than the time required for
2.1. Earth’s Atmosphere

establishing gravitational separation of the gases. Above this height the atmosphere was believed to consist of lighter gases. It was therefore quite surprising that the first measurements from a balloon in 1902 indicated that the temperature here was constant with respect to height\(^7\) - referred to as one of the most surprising events in the history of meteorology. Later it was found that the temperature higher up in the stratosphere increases with height, until the gradient turns negative once again, and the expected negative gradient is found in the region now defined as the mesosphere.

2.1.2 Segmentation

Several enunciated atmospheric layers have been identified using thermal characteristics, chemical composition, movement, and density (Figure 2.2).

The lowest part is referred to as the homosphere since the molecules and atoms mingle together, producing an homogeneous gas with even concentration and gradually varying temperature. In the homosphere there are three layers: the troposphere, the stratosphere and the mesosphere. Above the homosphere lies the heterosphere. The name heterosphere refers to the composition that changes with altitude due to that each component acts as if it were alone resulting in a variation in their exponential concentration with different decrease rate. This area is usually referred to as the thermosphere, since the neutral temperature increases, or the ionosphere since the gas here is ionized from the solar radiation and particle precipitation.

The regions of the stratosphere and the mesosphere, with the stratopause and mesopause, are named the middle atmosphere. The lowest part of the thermosphere is also located in the middle atmosphere.
2.1. Earth’s Atmosphere

**Homosphere**

- **Troposphere**: The troposphere is the lowest layer of the atmosphere which starts at the Earth’s surface and extends to between 7 km at the poles and 17 km at the equator, with variations caused by weather factors. Almost all weather is located in this region. The troposphere is a very turbulent area due to solar heating at the surface of Earth. This heating warms air which then rise and releases heat that further uplifts the air, therefore temperature decreases with height due to this expansive cooling.

- **Stratosphere**: The stratosphere begins above the troposphere and extends to about 50 km. It is here that incoming solar radiation creates the ozone layer, which absorbs and scatters the solar ultraviolet radiation leading to an increase in temperature with height in this region. 99 percent of the air is located in the stratosphere and troposphere. The stratopause is the barrier between the stratosphere and the mesosphere.

- **Mesosphere**: The mesosphere, which lies above the stratosphere reaches from about 50 km to about 80-85km. The density of ozone is low in this layer making the temperature in the mesosphere decrease with height. Here the atmosphere is beginning to get thinner and at the top of the mesosphere the air temperature reaches its coldest average value. The atmosphere at this height is both tenous with only 0.01% of the air located here compared to the ground, and turbulent, since the cold air overlying the warm air makes the atmosphere quite unstable. In this region, the temperatures can fall below -90°C Celsius as you increase in altitude. Molecules here are in an excited state, as they absorb energy from the Sun. The mesopause, at an altitude of about 80 km is the boundary between the mesosphere and the thermosphere.

**Heterosphere**

- **Thermosphere**: At heights of 80 km to about 600 km, is the thermosphere. At these altitudes, the atmospheric gases arrange themself into layers according to molecular mass. The temperature increases with altitude, mostly because of the absorption of highly energetic solar radiation by oxygen and is highly dependent on solar activity. Here the lifetime of atomic oxygen exceeds a day and the energy can be stored as chemical energy, releasing thermal energy when the atom recombines. The radiation causes the particles to become electrically charged. In this region of space, above 90 km altitude, species do not mix any more through eddy motions but instead behave independently and diffuse separately: the hydrostatic balance is verified for each species alone.

Airglow is mainly located in between the mesosphere and the thermosphere at a height of about 87 km.
2.1. Earth’s Atmosphere

Figure 2.2: Layered view of Earth’s atmosphere showing changes in temperature and pressure with altitude. Airglow is located just below the mesopause. Image Institute of Geophysics and Planetary Physics, University of California, Los Angeles (UCLA)
2.1. Earth’s Atmosphere

- **Ionosphere**: The ionosphere is the partially ionized plasma coexisting with the usually heated neutral atmosphere, the thermosphere, and situated above the mesosphere.
  
  The ionosphere is composed of many layers depending on the main ionized species involved which were named historically D, E and F:
  
  * **D Layer**: below 80 km, where negative ions prevail.
  * **E Layer**: between 90-120 km, where positive molecular ions are in majority (mainly O$_2^+$ and NO$^+$).
  * **F Layer**: between 120-400 km where there is a transition between the molecular ions (primarily NO$^+$) and the positive atomic ions (mainly O$^+$).

- **Exosphere**: Extends from 500-1000 km up to 10,000 km out into space.

2.1.3 Heating and Cooling

The explanation of the highly stratified stratosphere is the heating that occurs due to ozone molecule absorption of ultraviolet radiation. The presence of these chemically unstable ozone molecules was first explained by Chapman (1930)[13] who, by considering a pure oxygen atmosphere, could explain that photodissociation of molecular oxygen would produce atomic oxygen that quickly combines with an oxygen molecule to produce ozone.

Other atmospheric molecules and atoms that contribute to the thermal structure of the stratosphere and mesosphere also exist. Molecular oxygen, for example, causes heating by absorbing ultraviolet radiation in the upper mesosphere and the thermosphere and also a slight heating occurs due to stratospheric absorption of long wave radiation by carbon dioxide.

The atmosphere is believed to have a thermal structure mostly controlled by heating from absorption of short wave radiation from the sun. Strong energetic solar radiation heats the thermosphere to very high temperatures. This heating is by cooling coupled to the emissions in the infrared part of the spectrum. This radiative cooling is caused by the vibrational relaxation in the infrared 15 mm band of carbon dioxide (CO$_2$). In addition, the 9.6 mm band of O$_3$ contributes to the cooling, especially near the stratopause[7].

Water vapour (H$_2$O) also adds to the cooling, but to a minor degree compared to CO$_2$ and O$_3$[27, 34].

2.1.4 Perturbations

The atmosphere is very turbulent.

In studies of the middle atmosphere climate, the atmospheric temperature and the wind speed are usually the two fields of most interest since they affect the turbulence in the atmosphere. The atmosphere has also a circulation with oscillations caused by tidal and planetary waves.

These are all factors that affect the radiative equilibrium of the mesosphere. There is also a vast array of external perturbations: variations in the solar flux, energetic particle precipitation. Anthropogenic emissions are also additional sources of concern to the thermal structure of the mesosphere. See below for further information on some of these phenomena.
2.1. Earth’s Atmosphere

- **Tides**: Tidal effects in the atmosphere can be compared to the tides of the water on Earth. Just as the gravitational effects of the Sun and Moon causes the water to pool to the side of Earth closest to the source of attraction - so does the atmosphere, affecting the OH layer.

- **Gravity Waves**: Gravity waves which propagate through the mesosphere can cause significant temporal variations since they pack the atmosphere into areas of varying density, causing fluctuations in the data recorded\cite{75, 76, 22} (Figure 2.3). Most of these waves, and the tides, are excited in the troposphere and lower stratosphere and propagate upward in the mesosphere.

- **Geomagnetic storms**: Long-term disturbances of the Earth’s magnetosphere are known under the generic name of geomagnetic storms, leading to the intensification of the ring currents around the Earth. During a storm, short intervals of substorms can occur. A substorm is characterized by global electromagnetic perturbations reaching the lower ionospheric layer and triggering instabilities down to the ground. The shape of the F2 layer can be changed and can separate or even vanish. Increases in the electron fluxes recorded at the top of the ionosphere are observed while the ionosphere becomes extremely dynamical. This is the main onset for aurora at polar latitudes, see Figure 2.4.

- **X-rays**: When the sun is at solar maximum, strong solar flares occurs that hit the Earth with hard X-rays and cause sudden ionospheric disturbances. These will penetrate to the D layer, releasing electrons which will increase absorption causing radio blackouts.
2.2 Airglow

Airglow is the collective name of the weak emissions of light from the middle layer of the Earth’s atmosphere, this means that the night sky is never as completely dark as one might think. The name was coined by C. T. Elvey in 1950[17].

Airglow does not exhibit any dynamic movements on its own and it is emitted from the entire sky at all latitudes at all times. Since it is so weak it is almost impossible to detect with the naked eye. However since it is covering the entire sky, looking about 10-20 degrees from the horizon makes it brighter because the lower one looks the greater the depth of atmosphere one is looking through.

Sometimes a wavelike pattern can be seen in the sky. This is airglow perturbed by gravity waves, forming denser parts of airglow - so dense that it becomes visible to the naked eye (Figure 2.3).

All photos taken from airglow in daytime, and nighttime, are mostly taken by astronauts who have the advantage of photographing the Earth from above and

- **Protons**: Associated with solar flares is a release of high-energy protons in the range of 10-100-10^2 eV. Protons spiral down the Earth’s magnetic field lines and precipitate in the atmosphere near the magnetic poles. This increases the ionization of the D and E layers, usually referred to as polar cap absorption.

This effects all influence the mesopause region in various ways, and may manifest themselves in the airglow variations.

Figure 2.4: Aurora in the sky over Svalbard. Aurora is a perturbation in the atmosphere caused by precipitating charged particles. Image Cyril Simon
2.2. Airglow

along the horizon of Earth, which gives a much thicker layer of airglow to observe.
Airglow is very feeble in the visible region of the spectrum whereas it is much stronger in the infrared region - so strong that it limits the sensitivity of telescopes[37].

2.2.1 History

Airglow was first noted, purely as a nuisance, since it interfered with astronomical spectroscopic observations. In 1895 W. W. Campbell noticed that a green line was omnipresent in the night sky although there were no auroras present at the time. He writes, quoted by Meinel(1951)[41]

visual observations of faint nebular and comet spectra are often interfered with by the aurora and sky spectra. ...I have looked for it (green line) in all parts of the sky ... always with success

Many years after, in 1919, it was re-discovered photographically by V. M. Slipher[66].
Other scientists who led the pioneering investigations of the light of the night sky as a detached phenomena are Fabry (1910), Lord Rayleigh (1920) and Dufay (1923). Even though discovered so early it was not until the turn of the 20th century that scientists were increasing their pursuit of understanding the emission lines in aurora and of the sky itself and what was causing them.
This research was greatly accelerated at the end of World War II with the instrumental advances that followed.
Early researchers realized that a study of the light in the night sky could become a powerful tool to yield important information about the structure of the upper atmosphere. In their way stood a mountain of obstacles to solve before anything would be revealed from the airglow.

2.2.2 Mechanisms

The sources of airglow come from the fact that the atmosphere on Earth exhibits an absorption of solar UV- and X-radiation by air molecules and atoms.
The atmosphere at the airglow emission height is very thin and partly ionized, allowing a collisional plasma to form.

There are three kinds of airglow[41]: dayglow, twilightglow and nightglow. These are all classified as different phenomena although they share certain characteristics such as global spatial location, uniform luminosity and the solar or cosmic radiation as the energy source.

Dayglow

Dayglow is the term describing the uniform faint glow covering the entire sky during the day (Figure 2.5).
Airglow is more intense during daytime but scattered light from the Sun makes it impossible to see and extremely hard to measure from Earth.
The Sun emits UV radiation that hits the thermosphere and excites the molecules and atoms present in the medium, transferring energy through excitation and
2.2. Airglow

Figure 2.5: Photo taken by Clementine spacecraft of dayglow in the visible and infrared. The airglow is visible as the blue sharp line outside of the edge of Earth. Image by the IAPE Aeronomy Group - Image has been slightly retouched.

heating. In order to get back to their equilibrium state, the excited species emit light in various wavelengths, from UV to IR ranges. The brightest emissions of the nightglow are green and red, which is the spectral signature of atomic oxygen \( \text{O}^*(1S) \) 557.7 nm and \( \text{O}^*(1D) \) 630.0 nm at 120 and 250 km altitude respectively.

**Twilightglow**

Twilightglow is the definition of airglow emissions from when the sun is shining on the atmosphere from below and not from above as with dayglow\(^{[12]}\). Therefore twilightglow is easier to observe than dayglow since it isn’t overpowered by scattered sunlight. Twilightglow is in the boundary between day- and nightglow and therefore shares a lot of characteristics between the two. There is, for example, a post-twilight effect that is studied under twilightglow but rather physically belongs to nightglow.

**Nightglow**

The night airglow also derives its energy from the sun, but stores the energy in the upper part of the atmosphere and gives it off when the sun is gone. Nightglow (Figure 2.6) is due to chemiluminescent recombination at the night side of the atmosphere and luminescence by cosmic rays hitting the upper atmosphere. Many of these emissions have been identified\(^{[41]}\) as shown below, but will not be further analyzed in this thesis, where the Meinel bands of OH is of eclipsing importance. For a graphical overview of the nightsky spectrum, please see Figure 2.7.
2.2. Airglow

Figure 2.6: Nightglow seen as a strong green line around the Earth. Just above aurora in green and red add to the display. Image NASA

Ultraviolet Region from 3000 Å to 4000 Å
- Herzberg bands of $O_2$
- Vegard-Kaplan bands of $N_2$
- Barbier bands of $CO$

Visible Region from 4000 Å to 7000 Å
- Atomic lines: the biggest contributions come from atomic oxygen, which produces the green line at a wavelength of 5577 Å and a deep red emission triplet at 6300, 6364 and 6392 Å. There is also a yellow emission at 5893 Å from sodium atoms.
- First Positive bands of $N_2$
- Vegard-Kaplan bands of $N_2$

Near Infrared Region from 7000 Å to 11000 Å
- First Positive bands of $N_2$
- Meinel bands of $OH$: the radical hydroxyl with its continuum of wavelengths between 3800 – 5000Å. citeChamberlain, see further in Chapter 3.
- Kaplan-Meinel bands of atmospheric system of $O_2$

Infrared Region beyond 11000 Å
- This region is still being researched

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Figure 2.7: Example of the vastness of the night sky spectra - between wavelengths 1200 Å and 9000 Å, recorded by GLO during the flight of STS-53, December 1992
Image: Ultraviolet Spectroscopy and Imaging Group, Lunar and Planetary Laboratory, University of Arizona.
2.3 Molecular Spectra

Derivation of the temperatures from the airglow spectra is based on the theory of molecular spectra, briefly reviewed below:

2.3.1 Atoms

The most common model of the atom is Bohr’s model, named after the Danish physicist Niels Bohr who proposed the idea in 1913. In the Bohr model neutrons and protons occupy a compact region in the center -the nucleus- while the electrons move on specified stationary circular orbits around the nucleus.

The quantization of the energy of the particles in the Bohr model is a postulate to account for the observations and the nature of the observed spectra, following the quanta interpretation of Einstein for the photoelectric effect proposed in 1905. It means that only specific orbits with specific radii are allowed for the electrons. Every allowed level is labelled by an integer n, called a quantum number. The lowest energy state is named the ground state. The first state following the ground state has more energy and is called the first excited state. Then follows the second excited state, and so on.

The spectrum of an atom is called a line spectrum since it only consists of one to several discrete lines coinciding with the discrete energy levels of the atom in question.

2.3.2 Molecules

Molecules are formed by joining two or more atoms. As soon as more than one atom is introduced in the concept it becomes increasingly difficult to establish how the molecules behave. A stable molecule is formed when the total energy of the union has lower energy than the separated atoms.

Bohr’s model limitations pointed for a better description, which was put forward in the next decade in 1926 by the Austrian physicist Erwin Schrödinger. Based on several postulates, the equation that bears his name, the Schrödinger equation, governs the behaviour of the atoms and molecules with a stunning precision at a quantum level. The molecular orbitals along which the electrons move are described in terms of a statistical wave function \( \Psi \) which is the solution of the eigenvalue Schrödinger equation:

\[
H \Psi = E \Psi
\]  

(2.1)

where \( H \) is the Hamiltonian of the molecules comprising the different terms of energy potentials which the electrons are undergoing and \( E \) the energy in the state of the molecule considered. To obtain from the general time-dependent Schrödinger equation the eigenvalue equation, \( H \) here is assumed to be time-independent: the system is conservative.

All the physics of the interaction is therefore contained in the Hamiltonian \( H \) while the general equation is intrinsically dynamical. \( \Psi \), solution of 2.1, describes the probability distribution for an electron to be located in a certain region of space at a certain time. The molecular wave function deals more particularly with valence electrons, the ones which are least connected to their...
atoms and more susceptible to interact. The quantization of energies arises from the resolution of the equation.

In the case of molecules, the spectra become more complicated than for single atoms since they become dependent on the atoms’ interactions with each other. The number of electronic transitions is far less in a molecule than in an atom. In an atom each transition gives one line while in a molecule all lines in a molecular band come from a single transition since they also have vibrational and rotational transitions integrated in the spectra.

### 2.3.3 Diatomic Molecular Spectra

In their simplest form, molecules formed of two atoms, of the same or different chemical elements, are the most abundant in the Earth’s atmosphere. The simplest model of diatomic molecules is a spring between two point masses. The various motions of the molecule can be divided into three categories, in decreasing order of energy (Figure 2.8). The energy of the molecule is a total of the energy of the electronic configuration ($E_e$), in nuclear vibration ($E_V$) and in nuclear rotation ($E_R$). Each of these contributions is quantized and they all add to the total quantum $\Delta E$ involved in the emission or absorption of light by the molecule.

The energy difference of a transition between an upper and a lower molecular state determines the emission wavelength of a diatomic molecule. The upper and lower states can differ in vibrational, rotational and electronic states.

Finally, the energy jump in the case of a diatomic molecule can be written \[ \Delta E = \frac{hc}{\lambda} = \Delta E_e + \Delta E_V + \Delta E_R \]
2.3. Molecular Spectra

Electronic state \((E_e)\)
In the case of a diatomic molecule, when you plot the potential energy against internuclear distance, electronic transitions appear as vertical lines. Physically, in a semi-classical approach, this property comes from the fact that an electronic transition occurs fast enough with respect to the internuclear distance variation (this property is linked to the Franck-Condon principle for vibronic transitions).

The electronic Hamiltonian for a molecule has to take into account three different energies, one kinetic and two potential. The kinetic energy of the electron has to be added, then the potential energies of repulsion between the nuclei and of attraction between the electron and nuclei. The general solution to the Schrödinger equation leads to a sequence of discrete energy levels characterized by the quantum number \(n\).

The electronic transition is by far the largest contribution of all three (rotation, vibration and electronic), typically around 1-10 eV, and locates the wavelength region of the whole band system in the spectra.

Electronic states are often designated by capital Greek letters to specify the axial component \(\Lambda\) of the electronic angular momentum. The numerical superscript to \(\Lambda\) indicates the multiplicity of the electronic state concerned. The lowest (ground) level is usually labelled \(X\).

Vibrational motion \(E_V\)
While the electronic state locates the wavelength region of the whole band system, the \(\Delta E_V\) locates the wavelength region of one band of lines.
For diatomic molecules, the lowest vibrational transitions can be usefully represented by a quantum harmonic oscillator. In this approximation the energy of vibration, typically in the range of \(\sim 0.1\) eV, becomes:

\[
E_V = \left( n + \frac{1}{2} \right) hf = 0, 1, 2, ... \tag{2.3}
\]

where \(n\) is an integer, \(h\) is Planck's constant and \(f\) is the frequency of the vibration.

Discrete vibrational energy levels of an electronic state are characterized by the vibrational quantum number \(\nu\) which takes the values 0, 1, 2, ... . When discussing a specific \((\nu', \nu'')\) transition, or band, the vibrational level of the upper electronic state is designated \(\nu'\) and the lower state \(\nu''\). Similarly, in discussing one particular line of the \((\nu', \nu'')\), which arises from transitions between a rotational level \(J'\) of the level \(\nu'\) and \(J''\) of the level of \(\nu''\), the same notation is maintained (Figure 2.9). Vibrational bands are often named after their discoverer, for example Meinel, Vegard-Kaplan, Herzberg etc.

Lines of a system include all allowed \(\nu', J' \rightarrow \nu'', J''\) transitions which are grouped into often overlapping bands. Emission bands are \(\nu' \rightarrow \nu''\) while absorption transitions are \(\nu' \leftarrow \nu''\). Bands may consist of tightly packed or widely spaced lines, a structure largely determined by the moment of inertia of the molecule in the two states. The lighter the molecule the wider spacing between
2.3. Molecular Spectra

A progression or sequence of the vibrational levels are defined such as

\[ \Delta \nu = \nu' - \nu'' = \ldots -3, -2, -1, 0, 1, 2, 3, \ldots \]  

(2.4)

The most common \( \nu' \) progression is for \( \nu'' = 0 \) which occurs in absorption spectra through cold gases.

**Rotational motion** \( E_R \)

If a diatomic molecule has an electric dipole moment it can react with electromagnetic waves creating a torque which will in turn excite the rotational levels of that molecule. The rotational energies for molecules, \( \sim 0.01 \text{ eV} \), are given by the solutions to Schrödinger’s equation.

The expression of the rotational energy giving the position of each rotational level for a diatomic molecule is

\[ E_R = \frac{l(l+1)\hbar^2}{2\mu r_0^2} \quad l = 0, 1, 2, 3, \ldots \]  

(2.5)

\( \hbar \) is Planck's constant, \( \mu \) is the molecular reduced mass and \( r_0 \) represents the average atomic distance in the molecule.

The spectrum formed by rotational transitions is commonly situated in the micro-wave range (\( \lambda \propto 1 \text{ cm} \) typically).

The distribution of lines within a band is determined by the distribution of the rotational levels associated with each of the vibrational levels \( \nu' \) and \( \nu'' \) and the transitions which are allowed between them. Each band consists of a number of lines.
of groups of lines called branches of lines. The frequency of these lines is well represented by a simple power series often visualized in plots named Fortrat parabola diagrams.

In simple bands two P- and R-branches are observed. This is expanded by the Q-branch in more complex molecules.

The occurrence of only these branches is an immediate evidence of the strict rotational selection rule precised below:

\[
\Delta J = J' - J'' \begin{cases} 
-1 & \text{(P-branch lines)} \\
0 & \text{(Q-branch lines)} \\
1 & \text{(R-branch lines)} 
\end{cases}
\]

Thus not all rotational transitions are allowed.

This convention has been used as it is by most authors. However, Krassovsky (1962) or Chamberlain (1961) used a different writing and preferred to define the total molecular angular momentum separated from spin. In their papers, they introduced the integer quantum number k (the total angular momentum deprived of spin) to describe the rotational state separations. For the electronic ground state in this notation \( k = J - 1 \) and \( k = J + 1 \).
Chapter 3

Hydroxyl Airglow

The singular multiplicity of this universe draws my deepest attention.
It is a thing of ultimate beauty.
Frank Herbert, God Emperor of Dune

3.1 Hydroxyl

3.1.1 OH in the lower atmosphere

The hydroxyl radical is of utmost importance for the physico-chemistry of the atmosphere, from the troposphere to the mesosphere. Two properties have to be accounted for: its strong oxidizing power -the strongest in the atmosphere- and the high reactivity of the radical, which lifetime does not exceed 1 s[32] at tropospheric altitudes. Most air pollutants in the lower atmosphere and many of the gases responsible for the greenhouse effects (except CFCs and CO₂) can react with it and be destroyed.

The chain of reactions leading to the formation of OH in the stratosphere involves in a first step solar near-UV radiation. According to Chapman’s theory UV radiations with $200 \text{nm} \leq \lambda \leq 320 \text{nm}$ break the ozone O₃ molecule producing a singlet O atom. This atom can in turn be involved in the reaction with water H₂O producing OH radicals. Generally speaking, the short lifetime of OH radicals at tropospheric and stratospheric altitudes leads to relatively very small OH densities as they are immediately reacting with their environment. As H₂O is required to form OH radicals, when H₂O densities decrease, which occurs when altitudes increase, a decrease in OH formation rates is then expected.

3.1.2 OH in the mesosphere

The formation of OH in the mesosphere is a complex process involving minor species. The chemical reactions between the dominant species N₂, O₂ and the molecule H₂O produces minor components such as O₃, H, HO₂ or OH. Depending on their densities and neutral temperature these minor species drive the
kinetic reactions populating the vibrational levels OH($\nu$). The densities of O, O$_3$ and H, involved in the main reactions forming OH($\nu$) increase to reach a peak between 87 and 90 km altitude. On the other hand, the density of HO$_2$ decreases dramatically, but not enough to prevent the reactions to reach their maximum of efficiency at around 87 km altitude\[36\].

The region we are interested in is the mesosphere over Svalbard. The reactions below show two possible channels for the formation of excited OH-molecules in the upper mesosphere creating the system of bands of OH\[64\]. These reactions play a predominant role in the polar night over Svalbard\[65\]:

\[
\begin{align*}
O_3 + H \rightarrow OH(\nu \leq 9) + O_2 + 3.3eV \\
HO_2 + O \rightarrow OH(\nu \leq 6) + O_2 + 2.3eV
\end{align*}
\]

3.2 OH Spectra

Molecules excited in a higher vibrational and rotational states can transit to lower molecular states, resulting in the formation of the spectrum of hydroxyl airglow, composed of vibrational bands themselves splitting in rotational lines, see Chapter 2.3.3.

As mentioned before, the airglow originating in the excitation of hydroxyl spreads over a wide range of wavelengths between 3800 – 50000\AA\(Figure 3.2\). These spectral bands have been explored and identified by resolving the rotational structure by A. B. Meinel in the 1950s\[41\]. Therefore they are referred to as OH Meinel bands or Meinel OH ($\nu'$, $\nu''$) when applying the designation of Meinel (1950), where $\nu'$ and $\nu''$ designate the vibrational transitions from
3.2. OH Spectra

Figure 3.2: Photograph of hydroxyl nightglow taken by Don Pettit from aboard the International Space Station. The belt of Orion is seen just above the green-brown haze of the airglow Image NASA - Image has been cropped

higher to lower states. The transitions where $\Delta \nu = 2$ are the brightest, which occurs in the near-infrared. As $\Delta \nu$ increases the bands become less intense and appear at lower wavelengths\[18\].

3.2.1 Electronic State

The Meinel system of OH is composed of the vibration and rotation bands formed within the groundstate designated $X^2\Pi_{3/2}$ with an electronic total angular momentum $\Omega = 1.5$ and $X^2\Pi_{1/2}$, has $\Omega = 0.5[18]$. Each band has P-, Q- and R-branches with the latter forming the band head on the shortward side. The $X^2\Pi_{3/2}$ state gives rise to the so-called $P_1$-, $Q_1$- and $R_1$-branches.

The two rotational terms $X^2\Pi_{3/2}$ and $X^2\Pi_{1/2}$ are due to the fact that the electron spin can be either up or down, shown as $J$ in Figure 3.4, where $J$ is the splitting of $K \pm 1/2$ where $X^2\Pi_{3/2}$ is $K + 1/2$ and $X^2\Pi_{1/2}$ is $K - 1/2$. Because of this spin doubling the $X^2\Pi_{1/2}$ lies approximately 140 cm$^{-1}$ higher than $X^2\Pi_{3/2}[12]$. Its $P_2$, $Q_2$ and $R_2$ lines are weaker than those in the lower, more populated, state and consequently there is an alternation in intensity between $P_1$ and $P_2$ lines in the OH band.
3.2. OH Spectra

The total rotational angular momentum of the hydroxyl molecule can be any integer value above the electronic total angular momentum. Thus the ground state has, for $X^2\Pi_{1/2}$, $j = 1.5, 2.5, 3.5, \ldots$ and, for $X^2\Pi_{3/2}$, $j = 0.5, 1.5, 2.5, \ldots$.

Another splitting of these lines occurs due to $\lambda$-type doubling - an effect of the rotation of the nuclei\[25], though this has so far only been observed in laboratory experiments and has not been seen in the airglow\[12].

OH in the upper mesosphere is in its electronic ground state ($n = 0$) $X^2\Pi$ making the wavelength of an emission\[23]

$$\lambda = \frac{hc}{E_{\nu'} - E_{\gamma'} - E_{\nu} - E_{\gamma}} = (G(\nu') + F(J'\nu') - G(\nu'') - F(J''\nu''))^{-1}$$  \hspace{1cm} (3.3)

where $G(\nu)$ is defined as the vibrational term in vibrational state $\nu$ and $F(J, \nu)$ is the rotational term in rotational state $J$ and vibrational state $\nu$.

3.2.2 Vibrational Levels

The OH(8,3) band is the emission transition from $\nu' = 8$ to $\nu'' = 3$ which contains the P-, Q- and R-branches mentioned earlier. The emissions of this band lie in the range of 7200-7400 nm, making the light in the near-infrared part of the spectrum.

The vibrational term for OH(8,3), with the equation from Krassovsky (1962)\[25] is (Figure 3.3):

$$G(\nu) = \omega_e(\nu + 1/2) - \omega_e x_e(\nu + 1/2)^2 + \omega_e y_e(\nu + 1/2)^3 - ...$$  \hspace{1cm} (3.4)

and with vibrational constants\[11] the equation takes the form:

$$G(\nu) = 3737.90(\nu + 1/2) - 84.965(\nu + 1/2)^2 + 0.5398(\nu + 1/2)^3 - 0.01674(\nu + 1/2)^4 + 0.001637(\nu + 1/2)^5 \text{ [cm}^{-1}]$$  \hspace{1cm} (3.5)

3.2.3 Rotational Levels

The rotational energy terms for OH(8,3) is, with rotational constants taken from Krassovsky (1962):

$$^2\Pi_{3/2} : F_1(J) = B_\nu \left[ (J + 1/2)^2 - 1 - 1/2 \sqrt{4(J + 1/2)^2 + Y_\nu(Y_\nu - 4)} \right] - D_\nu J^4$$  \hspace{1cm} (3.6)

$$^2\Pi_{1/2} : F_2(J) = B_\nu \left[ (J + 1/2)^2 - 1 + 1/2 \sqrt{4(J + 1/2)^2 + Y_\nu(Y_\nu - 4)} \right] - D_\nu J^4$$  \hspace{1cm} (3.7)
3.2. OH Spectra

Figure 3.3: Potential curve of the ground state $X^2\Pi$ with vibrational levels. The OH(8,3) transition is marked with a blue arrow and the corresponding levels are marked in red. Image [25]

Figure 3.4: Rotational structure of vibrational levels in $X^2\Pi$ ground state hydroxyl airglow. $P_1$ branch is marked in blue. Image [25]
3.3 Temperature

\[ B_\nu = 18.867 \text{cm}^{-1} - 0.708 \text{cm}^{-1}(\nu + 1/2) + 0.00207 \text{cm}^{-1}(\nu + 1/2)^2 \]

\[ D_\nu = 0.00018 \text{cm}^{-1} \]

\[ Y_\nu = -10.95 \]

Here \( B_\nu \), \( D_\nu \) and \( Y_\nu \) are functions of the vibrational state\(^{[25]}\).

### 3.3 Temperature

Derivation of the rotational temperatures demands information about line intensity and line wavelength. The intensity depends on the probability of the transition and the population of the initial state. The wavelength depends on the energy of the state-to-state transition.

The intensity of a line in photons/s is the product of the number of molecules in the upper state and the transition probability to end up in the lower state

\[ I_{\nu', J' \rightarrow \nu'', J''} = N_{\nu', J'} A(\nu', J' \rightarrow \nu'', J'') \quad (3.8) \]

The prime (\( ' \)) and the double prime (\( '' \)) in equation 3.8 symbolizes the upper and lower state respectively.

If the molecules are in thermodynamical equilibrium the distribution of rotational levels in a certain vibrational state is defined by the Boltzmann distribution. The population in the upper state becomes then:

\[ N_{\nu', J'} = \frac{N_{\nu', J'} 2(2J' + 1) \exp(-F(J') hc/k T_{\text{rot}})}{Q_R} \quad (3.9) \]

\[ Q_R = 1 + 3\exp\left(-\frac{2B_\nu hc}{k T_{\text{rot}}}\right) + 5\exp\left(-\frac{6B_\nu hc}{k T_{\text{rot}}}\right) + \ldots \approx \frac{k T_{\text{rot}}}{B_\nu hc} \quad (3.10) \]

\( T_{\text{rot}} \) is the rotational temperature, \( Q_R \) is the partition function and \( k \) is Boltzmann’s constant. The relative strengths of the lines are the only ones that can be computed since \( N_{\nu'} \) and \( T_{\text{rot}} \) are both unknowns. Two or more lines in a vibrational-rotational band are necessary to yield a temperature.

Since \( N_{\nu'} \) is unknown, equation 3.8 is substituted in equation 3.9

\[ \frac{I_{\nu', J' \rightarrow \nu'', J''}}{A(\nu', J' \rightarrow \nu'', J'')} = \frac{N_{\nu', J'} 2(2J' + 1) \exp(-F(J') hc/k T_{\text{rot}})}{Q_R} \quad (3.11) \]

which with values for two lines combines to give the equation below\(^{[58, 18]}\)

\[ T_{\text{rot}} = \frac{(hc/k)(F_b - F_a)}{\ln(I_a A_a(2J'_a + 1)/I_b A_b(2J'_b + 1))} \quad (3.12) \]

\( F_a \), \( F_b \) are the energy levels of the initial rotational states, \( I_a \), \( I_b \) are the emission intensities of the OH lines from different upper states. \( A_a \), \( A_b \) are the transition probabilities, while \( J_a \), \( J_b \) are the upper state, total angular momentum quantum numbers and \( h \), \( c \) and \( k \) are Planck’s constant, the speed of light and
3.4 Factors

There are some issues that need to be resolved before the temperatures can be used to draw any conclusions.

a) There are evidence of latitudinal variations in the temperature calculations.

b) There is the problem of assigning a height, with a reasonable degree of certainty, to the airglow emission.

c) The thermodynamic equilibrium has to be ascertained since, without it, the temperatures derived would be of little importance to the atmosphere at the ascribed height.

d) The methods of calculating the temperature is very dependent on the derivations from quantum mechanics - resulting in diverse factors influencing the coefficients used to calculate the temperatures.

3.4.1 Latitudinal Variations

This was first disclosed by Chamberlain and Oliver (1953)[10], who found high temperatures located near the geomagnetic pole. In general there is a trend in higher temperatures towards the polar areas than at temperate areas, a concept that was studied in the 1950s[50]. Krassovskiy et al. (1961)[24] also discovered a seasonal variation which was twice as great at higher latitudes than in lower areas.

A higher temperature in the Arctic would not be expected if the upper atmosphere were heated entirely by local absorption of solar radiation, therefore there need to be some other explanation to the observations.

If conduction of heat from the solar corona and interplanetary medium were important[14] it is not unreasonable to expect a greater heating in the Arctic, where the magnetic field has less inhibiting effect on the vertical motion of ionized particles and therefore on the inward flow of heat.

Meridional circulation at high altitudes may also be important in governing the temperature in the influence of the temperature in the polar mesosphere[50].

3.4.2 Height

Physico-chemistry models have computed the height of the OH-layer at approximately 85 km altitude. On the other hand, in-situ or remote measurements of OH have yielded a mean height of 87 km with a corresponding thickness of 8 km, either from rockets [3], from ground-based LIDAR[8] or from satellites like WINDII[82] or Aura[59]. These theoretical and empirical results agree well, placing the OH airglow at the top of the middle atmosphere, also called the mesopause.
3.4. Factors

3.4.3 Thermodynamical Equilibrium

For the temperatures $T_{\text{rot}}$, derived from the hydroxyl airglow, to have any relevance, the molecule has to be in thermodynamical equilibrium with the rest of the atmosphere.

Spectral OH(7,4) measurements have been performed\textsuperscript{54, 55} in this way and determined that rotational levels above $J' = 5$ are not in thermal equilibrium and this because of the vibrational and rotational levels. With higher levels increasing, the lifetime of the excited molecule decreases and the molecule does not live long enough to be in thermal equilibrium with the atmosphere.

In this range of altitudes, the collision frequency reaches $10^4 \text{s}^{-1}$, and the lifetime of OH($\nu=6$) is on average $10^{-2} - 10^{-3} \text{s}$\textsuperscript{73}. It is then probable that at least this band is in thermal equilibrium for the lower rotational states. This is not true however for higher levels where the rotational populations can strongly deviate from the equilibrium values\textsuperscript{15}.

Since OH(8,3) belongs to the higher levels there is therefore a big concern that the temperatures derived do not coincide with the ambient temperatures of the atmosphere. This can be solved by plotting a Boltzmann diagram of $\ln(I/(2(2J' + 1)A))$ against $F(J')$ (see equation 3.12), which, for the P$_1$-lines yields a straight line if the assumption of thermodynamical equilibrium stands true. This was shown by Sivjee and Hamwey (1987)\textsuperscript{65} to be true for OH(8,3), which in that study had a correlation coefficient of almost 1.0.

3.4.4 Coefficients

To calculate the temperature of hydroxyl airglow, a set of coefficients commonly referred to as Einstein coefficients is needed. Calculations of the Einstein coefficients depend on the accuracy of the electric dipole moment function and the wave function used.

There have been several groups calculating these coefficients with various degrees of certainty, some of these are Mies (1974)\textsuperscript{42}, Langhoff et al. (1986)\textsuperscript{30} and Turnbull & Lowe (1989)\textsuperscript{73}. Theirs are the coefficients most commonly used. To continue the edict set by others before the three sets of Einstein coefficient are referred to as: Mies (M), Langhoff et al. (LWR) and Turnbull & Lowe (TL)\textsuperscript{73}. French et al. (2000)\textsuperscript{18} noted that the use of the three sets of coefficients triggered uncertainties in the calculation of the rotational temperature.

In the different sets of calculations the Einstein coefficients for the OH ground state and lower vibrational levels are in consistency\textsuperscript{49} while a discrepancy appears for the upper vibrational levels.

The TL coefficients yield higher relative intensities while LWR coefficients produce lower values since the larger the vibrational transition, the larger the temperature variance from the choice of transition probabilities (T&L). Greet et al. (1998)\textsuperscript{21} reported a 12 K variation in OH(6,2) temperatures depending on the choice of transition probabilities.
3.5 Periodicity

There are several variations of periodic movements in the hydroxyl airglow, of course, affecting the measured temperatures. If one assumes long- and short-term periodicity the temperature can be summarized as:

\[ T_{OH} = \text{solar cycle} + \text{long-term trend} + \text{annual/semi-annual variations} \]
\[ + \text{periodic (diurnal, gravity waves)} + \text{residual} \]

This is further excavated below.

- **Long-term variations**: The release of greenhouse gases show specific trends. Hydroxyl is very sensitive towards these trends since it works as an oxidizing chemical, destroying many air pollutants. A study made by Prinn et al. (2001)\[60\] shows an extreme increase in the hydroxyl levels between 1978 and 1988, however the growth rate was decreasing so that after 1988 OH levels declined. This lead to levels in 1998 reaching almost the same levels as in 1978, before the increase.

The first indication on negative temperature trends in the mesosphere was reported by Gadsden and Schroder (1990)\[20\]. In observing the increasing number of noctilucent clouds, the mean temperature estimation of the summer mesosphere was assumed to decrease at a rate of 2.5 K per decade. Since ice crystals are believed to be the major part of the cloud particles this lower temperature could be the reason to their larger frequency in forming and sightings at lower latitudes than earlier.

Many authors have been reflecting on this issue, for instance Shepherd (2006)\[63\] and references therein. Concerning the emission of OH, the variability due to the sun is either small or negligible, a result endorsed by Fukuyama (1977)\[19\] and more recently Bittner et al. (2002)\[6\] using spectrographs located at mid latitudes, but in contradiction with the early measurements of Shefov (1969)\[62\] who reported a 5.5-year period (roughly 0.5 solar cycle). For higher latitudes (Svalbard 78°N) no correlation between the sun’s activity and the OH emission has been detected over 20 years of statistics, reported by Sigernes et al. (2003)\[64\].

- **Annual and semi-annual variations**: A study made by Shefov (1969)\[62\] supports the idea of an annual variation for the OH emission whatever the latitude between 55°N to 2°. Other works like Wiens and Weill (1973)\[79\] note a significant semi-annual variation.

The advantage of a high-latitude location is the possibility to measure data over a 24-hour period. Studies have then been performed using this unique opportunity since the beginning of the 1980s: Myrabø and Deehr (1984)\[46\], Myrabø (1986)\[48\]. They reported on OH(8,3) a clear tendency with emission rates and temperatures reaching a maximum during the winter.

- **Diurnal variations**: Many authors have studied the diurnal variations of the OH emission intensity since the beginning of the 1970s \[44, 1, 79, 69\].
3.5. Periodicity

According to these studies, there is a maximum of the OH intensity variation in the beginning of the night, which tends to minimize towards dawn. Theoretically, this observed decrease could be caused by densities of odd hydrogen and oxygen dropping down as the photolysis of O$_2$ and H$_2$O disappears[1, 45]. Furthermore, between low- and mid-latitudes a change in the diurnal pattern is observed. The diurnal variations studied by Wiens and Weill (1973)[79] at three different stations showed that, although the results were variable, at mid-latitudes the OH airglow has a minimum in the early evening, rising to a maximum in the morning while the opposite was found at lower latitudes.

As mentioned earlier high latitudes are most interesting to make observations over a full 24 hours, since the sun stays below the horizon during winter. This makes Svalbard perfect for diurnal/semi-diurnal variation studies. This is the focus of the present thesis.

- **Short-term variations**: These are assumed to be gravity wave triggering perturbations. Takahashi et al. (1999)[70] investigated this and found that gravity waves with periods of 2-9 hours perturbed airglow. Krassovsky (1972)[25] determined a connection between emission rate and temperature for OH airglow, their ratio $\eta$ being a marker of the dynamical physical phenomena caused by gravity waves. The propagation of gravity waves perturbations in the atmosphere has been studied through theoretical models by Walterscheid and Schubert (1987)[78] and by Liu and Swenson (2003)[33], which succeeded in showing the connection between emission rate and temperature and gave some predictions on the $\eta$ ratio.
Chapter 4

Instrumentation

You do not beg the Sun for mercy
Frank Herbert, Dune Messiah

4.1 HiTIES Spectrograph

HiTIES, High Troughput Imaging Echelle Spectrograph, is an imaging spectrograph with high spectral resolution and throughput, covering the entire visible region, though only some wavelength regions can be observed simultaneously. It is installed at the Auroral station near Longyearbyen on Svalbard (78°N, 15°E) to study the auroral and airglow emissions produced by precipitating electrons and protons in the region of the polar cusps.

The instrument has a potential to achieve a resolution of up to 0.29 Å at 5893 Å (sodium doublet) corresponding to a resolving power R=λ/Δλ = 20000.

HiTIES gives new opportunities to measuring spectral characteristics from multiple wavelengths, at the same time as it uses an echelle grating without the a usual cross disperser. The spectral regions are selected thanks to a filter mosaic which can segregate between different diffraction orders.

4.2 Optical Layout

The HiTIES spectrograph consists in four autonomous parts (Figure 4.1)

- Foreoptics
- Grating
- Optics and mosaic filter assembly
- Detector
4.2. Optical Layout

The foreoptics is composed of a camera lens, a slit and a field lens allowing for an easy change of the focal length of the objective lens which is focused onto the slit. The field lens redirects light onto the collimator which in turn hits the grating.

The diffracted light is imaged on the mosaic filter, which is used to sort out the diffraction orders and choose the spectral lines.

Finally the spectrum is re-imaged onto a position sensitive detector. Though there have been a few detectors depending on the period, an example is the ultra low-noise CCD camera, equipped with thermoelectric coolers to reduce its operating temperature to around 220 °C. The resolution of the CCD is about 1100 x 1050 elements with a resolution of 1 Å slit width of 0.05° and slot length of 8°. Typically 10 to 60 seconds exposure are necessary for auroral studies as mentioned in [38].

4.2.1 Calibration

Absolute intensity calibration of the HiTIES spectra uses catalogued spectral fluxes of background stars as they cross the input slit of the instrument. This is then compared to the apparent brightness in the instrument.

4.2.2 Mosaic Filter

A conventional spectrograph disperse light in an ever-increasing or decreasing order, which is very suitable if the size in pixels of the detector can fit the...
4.2. Optical Layout

Figure 4.2: Layout of the mosaic filter. It has four spectral panels: H-\(\beta\) (4861 Å), O\(^+\) and OH (7280-7400 Å), O\(_2^+\) (5580-5650 Å) and O (8446 Å). These combinations allow various studies of proton- and electron aurora and airglow. Image University of Southampton, Space environment group.

A spectral region as a whole. If we want to study with a high resolution (less than 1 Å) a very wide wavelength range (typically 4000 - 10,000 Å), a detector with at least 40,000 pixels would be necessary \([9]\). As of now, no such CCD exists while the solution of many CCD detectors stacked together brings more technology issues (interfaces, etc.) than it actually answers.

We lose temporal resolution in this context as traditional spectrographs can only observe one small spectral range at a time.

The design of HiTIES has solved this problem by using several interference filters arranged as a mosaic.

The mosaic measures 50 mm rectangles of narrow-bandwidth interference filter (Figure 4.2) - each being perpendicular to the dispersion axis and enabling the selection of a specific spectral region.

The narrow bandpass filters (50 Å) act as a separator of the different orders possibly overlapping. We can select the orders by a refined tuning of the grating angle, imaging five wavelength regions at the same time.

The mosaic filter is located in a cassette that can be removed from the spectrograph box. This cassette also contains field lenses located on both sides of the filter, which eases the mobility and the flexibility of the entire instrumental apparatus.

4.2.3 Operation

The HiTIES spectrograph is part of the Spectrographic Imaging Facility (SIF), operated at the Auroral station in Adventdalen on Svalbard, which was designed to work in coordination with the Eiscat Svalbard Radar (ESR) supplying the radar sounding by high spatial and time resolution spectra of the aurora.

The platform was primarily built to enhance the statistics on the dynamics and high resolution spectra of proton aurorae through the study of H\(_\beta\) lines. It can be also extended to the study of the airglow of OH Meinel(8,3) bands in the range 7280-7400 Å upon which this thesis is based upon.
4.2. Optical Layout

The versatile platform consists of four instruments: The HiTIES imaging spectrograph, two photometers and a narrow-field video camera. All instruments are centered on the magnetic zenith and can be partly remotely operated.
Chapter 5

Analysis

A process cannot be understood by stopping it. Understanding must move with the flow of the process, must join it and flow with it.

Frank Herbert, Dune

5.1 Treating Data

The spectral analysis is done in several steps. Firstly the data is analyzed for external conditions such as weather or contamination, sorting out the poorest spectra (Chapter 5.1.2). The remaining spectra are averaged and then compiled to see if there is enough data to be statistically interesting.

Then the data is pre-processed with a program to create spectrum files which are later processed with a program to derive the rotational temperatures (Chapter 5.1.3). The temperatures and other information are stored in files which are then plotted and compared to other datasets (Chapter 6).

5.1.1 Collecting

The raw data is gathered continuously during 10-30 seconds, based on settings, and saved. This data contains the wavelengths filtered through the mosaic filter for all four panels. An example of this can be seen in Figure 5.1.

Some problems that can come up are mostly due to the focusing on the different panels. Chromatic aberration, caused by the lens in conjunction with the filter, gives a different refractive index for different wavelengths causing some lines to go out of focus when focusing on other lines. Since the HiTIES is mainly used to record aurora the focus on the first panel, which gives airglow lines, is not of highest priority. This causes some data to be blurry and unfocused and for such reasons more difficult to use.
5.1. Treating Data

After collecting the data the emission intensities can be plotted and presented as keograms (Figure 5.2). A keogram is the intensity along a line in each image, stacked for consecutive images. This makes it easy to see visually when the data is acceptable and when it isn’t. Acceptable data should be free from external contamination such as auroral emissions, clouds, light pollution and more, but also it must contain enough data to be considered statistically interesting. The data should also be both wavelength and intensity calibrated, which, in some events, was not the case. This, of course, also reduces the useable data. A first scan through the keograms picks out data in intervals of 20 minutes where it was observed to be clear sky with visible stars and no auroral contamination. Also features such as sunrise/sunset and other unexplained aspects, further excavated below, were noted and avoided. This choice of interval also reduces the background noise, giving clear resolved spectra (Figure 5.3 and 5.4).

Contamination

One problem with hydroxyl airglow data is the contamination with aurora in the spectral lines. Also the weather is a large pollutant in the data. The band should, if possible, be in a wavelength region where clouds do not stop it and contamination from auroral bands should be avoided as far as possible. The OH(8,3) measured in the HiTIES is well situated for these reasons since the contamination can be resolved, in most cases, from the airglow lines.
Figure 5.2: Example of a keogram (four top panels) and spectral intensity plot (four last panels) of the 23 December 2003 Image Marcus Glad, Alfvén Laboratory, KTH.
5.1. Treating Data

Figure 5.3: Enlargement of a keogram from the 31 December 2003 showing an example of a contamination free hydroxyl spectrum plotted in Figure 5.4. Image: Marcus Glad, Alfvén Laboratory, KTH.

Figure 5.4: OH(8,3) airglow spectrum taken from 31 December 2003 20:35-20:55, as an example of a spectra without any visible contamination. The rotational peaks are printed below the spectra.
5.1. Treating Data

The contamination of the OH(8,3) band can be summarized below

- **Lightpollution**: In this case the lightpollution comes from Longyearbyen, since there are no other settlements close by. It mostly originates from the high pressure sodium lamps used to light the streets and no real examination of this has been made. There has been no notice or correction in the data for this. Also the sodium lamps have only a minor constituent in the interval of OH(8,3), so the conclusion has been drawn that it does not affect the data. However this could be interesting to investigate further.

- **Moon**: The only influence the moon has is that it reflects the sunlight which then scatters in clouds inferring with the data making the background intensity rise in both strength and variability, making the background non-linear. This is not an issue in this data since the data has been chosen for clear cloudless/near-cloudless skies and even for the moon to above the horizon is not a direct problem for measuring the OH(8,3) emissions, as these are measured in the zenith and the moon never rises very far above the horizon at Svalbard[64].

- **Weather conditions**: Clouds scatter light either from lightpollution, the moon or the sun or other ambient light so of course cloud free data is valued.

- **Sun**: Since the data collecting has only been performed during late November-early February there is no risk for sun scattering in the data since the sun
5.1. Treating Data

was more than 18 degrees below the horizon, a criteria also used by other authors[21]

- **Aurora**: Auroral contamination from O\(^+\) ions in the thermosphere gives two distinct peaks in the measured interval (Figure 5.5) at wavelengths 7319 and 7330 Å. However these can be resolved thanks to HiTIES high resolution. At least for the P\(_1\)(2)-line this is possible but for the P\(_2\)(3)-line this is not true, making that line unusable at events of O\(^+\)-aurora. N\(_2\) aurora gives an increase in the background so high it almost completely covers the OH(8,3) peaks (Figure 5.6).

- **Water vapour**: This contaminant is always present in the atmosphere and acts as an absorber of the spectral lines observed. In OH(8,3) there are concerns that absorption affects the P\(_1\)(4)-line up to as much as 2.3%[58], while others pay it no attention[52]. In this data set there has been no accounting for the water absorption in the spectral lines.

All these criteria were checked visually, when possible, by observing the keograms and spectral plots for the dates involved.

After the data was selected and collected in 20-minute intervals the data set was compiled and checked for statistical significance in examining the amount
of data collected each day and deciding on a limit for the minimum time limit used. This interval has, by other authors\cite{65}, been about four hours but due to the large contamination of aurora in this data set limiting the number of days with good measurements, that amount has been reduced to three hours, an interval also used by the Ebert-Fastie data set which this data will be compared to. All data collected that does not amount to this are discarded.

5.1.3 Calculating

The calculation of the temperatures themselves was done with the IDL program S.M.S, written by the author. S.M.S is an abbreviation for Servant, Master, Slave, the three programs that together create the spectra and calculate the temperature.

A brief description of the programs follows below. For more details see the programs in Appendix B.

The calculation of the temperatures from the OH(6,2) dataset recorded by the Ebert-Fastie spectrometer was done in the program SyntheticOH\cite{53}, which utilizes synthetic spectra to remove background noise and contamination. Since the dataset for OH(6,2) used the coefficients provided by Mies\cite{42} that is also the coefficients used for the OH(8,3), this is to eliminate any incoherence in the datasets caused by the use of different sets of coefficients.

Servant.pro

Since there are four panels on the mosaic but only one of them is interesting in the calculation of rotational temperatures for hydroxyl airglow, the need to separate data is persistent.

The program Servant.pro separates the panel data, reads in the raw data from panel 1, which coincides with the wavelength of OH(8,3) recorded. Then it integrates over the wavelength to create a spectrum of the chosen time and saves the data with both intensity and wavelength for further processing.

Master.pro

Program for analysis of datasets:

- Reads in the pre-processed files from program Servant.pro
- Calculates the rotational temperature of hydroxyl by calling on the function slave.pro to calculate the intensities, see below.

The temperature is given by equation 5.1 below (the same as 3.12)

\[
T_{\text{rot}} = \frac{(hc/k)(F_b - F_a)}{\ln(I_aA_b(2J'_b + 1)/I_bA_a(2J'_a + 1))} \tag{5.1}
\]

- \(F_a, F_b\) are the energy levels of the initial rotational states taken from Krassovsky (1962)
5.2. Compiling Data

- $I_a, I_b$ are the emission intensities of the OH lines, $P_1(X_a)$ and $P_1(X_b)$ calculated from the data, where $X_{a,b}$ refers to the the rotational level of the bands in use.
- $A_a, A_b$ are the transition probabilities. Mies, TL and LWR are used.
- $J'_a, J'_b$ are the upper state, total angular momentum quantum numbers
- $h$, Planck’s constant = $6.6262 \cdot 10^{-34} Js$
- $c$, Speed of light = $2.99792458 \cdot 10^8 ms^{-1}$
- $k$, Boltzmann’s constant = $1.3807 \cdot 10^{-23} Js^{-1}$

The constants are defined in Table 5.2.

slave.pro

Function that lists the background and all emission line intensities. The intensities is determined by summing counts over the decided wavelength interval, centered on the P-line wavelength, and subtracting background.

- Background is calculated as counting bins between
  - $\Delta \lambda 1 = 7307 - 7314 \text{ Å}$
  - $\Delta \lambda 2 = 7344 - 7356 \text{ Å}$
  
  then dividing by the number of bins and subtracted from the dataset after the peak intensity has been counted.

- Peak intensities are calculated as counting bins centered on the peak wavelength taken from Chamberlain (1961)[12]
  - $P_1(2) = 7316.4 \pm 2.5 \text{ Å}$
  - $P_1(3) = 7340.8 \pm 2.5 \text{ Å}$
  - $P_1(4) = 7369.0 \pm 2.5 \text{ Å}$
  
  and is then added to equation 5.1 with all the other constants together with their respective upper and lower rotational state numbers and Einstein coefficients.

5.2 Compiling Data

The OH-rotational temperatures through the 2003-2004 winter

The measurements for this time period, with the four-panel mosaic, started on Svalbard on the 17th of December 2003 and lasted until the 15th of January 2004. All data was not salvageable due to several factors so the interval was reduced to 22 December to 31 December.

The temperature was calculated for each of the intervals during the days and then averaged to get a daily mean. In Figure 5.7 the daily mean temperature is plotted.
The total average temperature, for the $P_1(2)$-$P_1(4)$ lines, in the interval observed in December 2003 was around 208 K. For the $P_1(2)$-$P_1(3)$ lines the temperature was about 201 K, a difference of about 7 K. However the temperatures vary a lot during the interval and as much as a difference of 20 K was observed at several times between the two data sets. All data is compiled in Table A.1 in Appendix A.

Mean spectra for each day of data, corresponding to the mean temperature, is shown in Figure 5.9

A simple method, used for example by Walterscheid[77] to see if there is some unbalance in given dataset, is to plot a temperature ratio, expressing the deviation from the average (Figure 5.8):

$$\frac{T_{rot} - \bar{T}_{rot}}{\bar{T}_{rot}}$$ (5.2)
5.2. Compiling Data

Figure 5.7: Mean temperature calculated for every day for two sets of ratios and compared to a dataset of OH(6,2) for the same period

Figure 5.8: Normalized temperatures
5.2. Compiling Data

Figure 5.9: Mean spectra for each day of the interval
## 5.2. Compiling Data

### Transitions

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<th>Rotational</th>
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<th>Einstein coefficients</th>
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Table 5.1: \(x^2\Pi_{1/2}\) which equals P₁

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Table 5.2: \(x^2\Pi_{1/2}\) which equals P₂
Chapter 6

Synthesis

The person who takes the banal and ordinary and illuminates it in a new way can terrify
Frank Herbert, Dune

6.1 Discussion

The main onset for this thesis was to make a first assessment of the OH(8,3) airglow data collected during four years, between 2003 and 2007 with the HiTIES spectrograph.

As a first comment it is well worth mentioning that the HiTIES gives beautifully resolved spectra, where the peaks are so highly resolved that even O+ contaminated data can be used without applying synthetic spectra, as can be seen in Figure 5.5.

However, this data was at times not the main priority for the focusing making the analysis of the data more involved - as a result much of the airglow data collected is heavily contaminated and is at times unfocused or non-existent. This limits the amount and use of the data.

The choice of the OH(8,3) band in HiTIES came purely from the fact that it was in the same range as the data already being recorded. This does not limit its usefulness.

The OH(8,3) band is well documented since it was commonly used for temperature measurements in past years[65][46][68]. The extent of the time series in this band plays an important part; hydroxyl airglow OH(8,3) band measurements have been made in Antarctica as early as 1979[67]. This gives a timespan for references, both for finding discrepancies and to have the possibility to compare datasets, if needed.

HiTIES, with a splendid resolution and its location in Svalbard, makes this data highly interesting. Though the timeseries of this dataset is fairly short, just four years, there has not been much research on this band of airglow and on that high a latitude for the last couple of years. It also gives the chance to
analyze periods of airglow data that usually is not recorded. This is because most airglow data is recorded during night as the sunlight scatters the data too much during the day. This is not a problem on Svalbard due to the polar nights.

6.1.1 Temperatures?

The mean temperatures Figure 5.7 derived in this thesis were compared to other derived temperatures, of course only for those using the same coefficients of Mies. The result was that a total mean of $202 \pm 29$ K was derived from the OH(8,3). According to Sigernes et al. (2003)[64] the mean temperature for OH(6,2) derived from more than 20 years of data at winter on Svalbard, is $208 \pm 15$ K, which is within the 3-10 K limit for these two bands. Myrabø et al.[47] derived temperatures from the OH(8,3) band and found that for 1976-1978 winter temperatures of 229 K, 224 K and 213 K -though this was for latitude 65°N. They comment on temperatures of higher latitude being about 15 K lower than these values. Sivjee and Hamwey (1987)[65] derived temperatures of 213 ± 3 K for December 1984 while Mukherjee and Parihar (2004)[44] received $202 \pm 15$ K for the winter period of 2002-2003 at 17°N.

6.1.2 Periods?

In this thesis an attempt of locating the semidiurnal tide has been made since the data was reduced to only 11 days, a long enough time-span to identify tidal effects. It did not lead to any conclusive result. The data show no semidiurnal period at all. The reasons are manifold: the semidiurnal tide is not an always occurring phenomena, some have reported that the tide has been present in only about 50% of the data collected, or the data analysis needs to be more thorough. As can be mentioned the dataset of OH(6,2) also showed no sign of semidiurnal tide. This at least confirms that the data analysis is not erroneous.

The post-twilight and pre-dawn effect, as expected, is also not showing in the dataset (Figure 5.8). If present a long slow decrease after sunset and a corresponding increase before sunrise[16] would be observed. This should, of course, not show in the data since the sunrise/sunset is almost non-existent in the polar night of Svalbard in December.

The comparison to the dataset of OH(6,2) recorded with the Ebert-Fastie spectrometer can be seen in Figure 5.7. According to several authors these two bands should have a separation of about 3-10 K, since they are located at a slightly different height, and follow the same patterns or periods. As seen in the plot the two datasets are roughly follow the same pattern. This could be interpreted to give assurance that the temperatures derived from the OH(8,3) dataset can be trusted, of course within logical reasoning.

This comparison to the OH(6,2) spectra in Figure 5.7 also clearly shows that the temperature difference between the two ratios increase when there are O$^+$ contamination in the spectra. The OH(8,3) varies much more extreme than the OH(6,2), the reason for this is at this time unknown.
6.2 Conclusion

Measurements of OH(8,3) airglow was performed with the HiTIES spectrograph on Svalbard, 2003-2006. The data was collected, analyzed and compared to another dataset of OH(6,2), collected by the Ebert-Fastie spectrometer, also located on Svalbard.

The HiTIES gives beautifully resolved spectra, where the peaks are so highly resolved that even O\(^{+}\) contaminated data can be used without applying synthetic spectra. This can be compared to other datasets with a resolution of about 10 Å\(^{81}\) to about 20 Å\(^{68}\), making the HiTIES capable of maybe 10 times the sharpness than of other datasets.

The location (78\(^{\circ}\)N) and the time period (December) gives the chance to analyze periods of airglow data that usually is not recorded due to scattered daylight.

However, due to various factors of contamination and issues with the data collecting the amount of clear usable data was reduced to 11 days (22-31 December 2003), as a first assessment. The mean temperature derived from these 11 days show a mean temperature of 198 ± 35 K for the P\(_1\)(2)-P\(_1\)(3) lines and 206 ± 22 K for the P\(_1\)(2)-P\(_1\)(4) lines this gives a total mean of 202 ± 29 K. The separation in the lines increase with larger O\(^{+}\) contamination. This follows closely other values for temperature derived by other authors for the same period and location.

The OH(8,3) temperatures vary much more extreme than the temperatures from OH(6,2).

An attempt of locating the semidiurnal tide has been made. The dataset of OH(6,2) also showed no sign of semidiurnal tide. This confirms that the data analysis of OH(8,3) is not erroneous.

The post-twilight and pre-dawn effect is also not showing in the dataset.

The comparison to the dataset of OH(6,2) showed a separation of about 2-20 K and follow the same pattern.

The comparison also shows that the temperature difference between the two ratios increase when there are O\(^{+}\) contamination in the spectra.

6.3 Future Work

6.3.1 Some ideas for a future analysis of airglow

Airglow is a very versatile compound useful in many studies. Ideas that could be an interesting starting point for further investigation, though not in the scope of this thesis, are mentioned below:

- A spatial (longitude/latitude) comparison of airglow could be interesting. How does different bands of airglow compare at different locations on the globe? Does the temperature differ between different locations and if so why?

- Temporal (time) comparison, maybe coupled with spatial location, could be very interesting to examine. This has been done by several groups\(^{[57, 63]}\)
6.3. Future Work

but not OH airglow and coupling to location. (This includes deeper analysis of diurnal-, semidiurnal- or longterm trends.)

• A coupling of the different models, old and newer ones, could be done and analyzed. Maybe there are differences between different bands or spatial locations.

• A thorough analysis of the different Einstein coefficients for the higher rotational levels needs to be done. This has been performed earlier but the results have been varied and incoherent[15, 18]. Also a deeper analysis of the variation of the coefficients between the different bands need to be clarified as they are related to the dipole moment function[72].

• It could be very interesting to make a thorough compilation and re-analyzing of all airglow data from different groups since the earliest date possible. This has never been done since many groups use different coefficients or analysis methods, leaving the datasets incomparable with eachother.

• Does airglow have any coupling to auroral phenomena?

• What is the coupling between the different atmospheric layers and phenomena connected to airglow? See for example J. Kristl et al. (2000)[20]

• How does the trends of tropospheric OH affect the mesospheric distribution? See for example R. G Prinn (2001)[60]

• An extensive study on the effect of earthshine[80] on the datasets could reveal hidden periods affecting the analysis of the temperatures.

• A deeper coupling of the solar cycle effect to the airglow data could reveal periods essential to the understanding of airglow behaviour[3].
Bibliography


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BIBLIOGRAPHY


63


[58] Phillips, F., Burns, G., French, W., Williams, P., Klekociuk, A., and Lowe, R., Determining rotational temperatures from the OH(8-3) band, and a comparison with OH(6-2) rotational temperatures at Davis, Antarctica, Annales Geophysicae, vol. 22, Issue 5, 1549-1561, 2004


[62] Shefov, N.N., Hydroxyl emission of the upper atmosphere-I. The behaviour during a solar cycle, seasons and geomagnetic disturbances. Planetary and Space Science 17, 797-813, 1969


[71] Teisserenc de Bort, L., Décroissance de la température avec la hauteur dans la région de Paris, Ciel et Terre, Vol. 24 579, 1903


[81] Wrasse, C. M., Takahashi, H., Gobbi, D., Comparison of the OH (8-3) and (6-2) band rotational temperature of the mesospheric airglow emissions, Rev. Bras. Geof, 22 no.3 Sao Paulo, 2004

[82] Zhang, S. P., Shepherd, G. G., The influence of the diurnal tide on the O(1S) and OH emission rates observed by WINDII on UARS, Geophysical Research Letters, Vol. 26 Issue 4 529-532, 1999
## Appendix A

### Summary of Data

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Table A.1: Table of all data processed
Appendix B

Program S.M.S

B.1 Servant.pro

pro Servant
; Program that reads in a list of spectrum files (.fits) (one by one),
; reads in data from the mosaic to create a spectrum - saving it
; in an .txt file
; by Mea Wedlund, mea.wedlund@wedco.se
; 07 July 2007
; Data is read in as list.txt, a simple .txt file of date and time in the
; format: 'yyyy/mm/dd hh:mm' l where l is length in hours
; 
openr, 32, 'Datum.txt'
while not (eof(32)) do begin
year=0
month=0
day=0
hour=0
minute=0
readf, 32, year, month, day, hour, minute, length, format='(i4,4(x,i2),f5.1)'

; To make the read/print process easier the date format is simplified as below
stringdate=string(day, month, year, hour, minute, format='(i2.2,"/",i2.2,"/",i4.4," ",i2.2,"":"",i2.2,"":00")')
stringtxt=string(year, month, day, hour, minute, format='(i4,i2.2,i2.2," ",i2.2)')

; converts a date to modified julian seconds -> mjs
FOR TT=0, length*60., step DO BEGIN
mjs1=mjs+TT*60.0
mjs, TT, mjs1, year, month, day, hour, minute, sec, msec
stringtxt=string(year, month, day, hour, minute, format='(i4,i2.2,i2.2," ",i2.2,"":00")')

; reads the sequence of spectro-images from specified time,
; l=length in hours, dseq=sequence of spectro-images, mjs=for
; first image, time=rel. time for sequence
read_tim,stringdate,length,mjs,time,dseq,/nophot

step=20.0
FOR TT=0, length*60., step DO BEGIN
mjs, TT, mjs1, year, month, day, hour, minute, sec
mjs, mjs1, year, month, day, hour, minute, sec, nsec
stringtxt=string(year, month, day, hour, minute, format='(i4,i2.2,i2.2," ",i2.2,"":00")')

; FOR TT=0, length*60., step DO BEGIN
mjs, TT, mjs1, year, month, day, hour, minute, sec, nsec
stringtxt=string(year, month, day, hour, minute, format='(i4,i2.2,i2.2," ",i2.2,"":00")')

; FOR TT=0, length*60., step DO BEGIN
mjs, TT, mjs1, year, month, day, hour, minute, sec, nsec
stringtxt=string(year, month, day, hour, minute, format='(i4,i2.2,i2.2," ",i2.2,"":00")')

; FOR TT=0, length*60., step DO BEGIN
mjs, TT, mjs1, year, month, day, hour, minute, sec, nsec
stringtxt=string(year, month, day, hour, minute, format='(i4,i2.2,i2.2," ",i2.2,"":00")')
program that reads in a list of spectrum files (.txt) one by one, and calculates the rotational temperature and saves the temp. in an .txt file

by Mea Wedlund, mea.wedlund@wedco.se
07 July 2007

Defining constants

h=6.62606896e-34; Planck's constant [J s]
c=2.99792458e10; lightspeed [cm s^-1]
k=1.3806504e-23; Boltzmann's constant [J K^-1]

J_a=3./2.; lower state, total angular momentum quantum numbers
J_b=7./2.; J_c=5./2.

energy levels of the initial rotational states taken from Krassovsky (1962) [cm^-1]

Your choice of transition probabilities

transition probabilities taken from Mies (1974) [s^-1]
A_a=0.243; p2
A_b=0.321; p4
A_c=0.298; p3

transition probabilities also known as Einstein coefficients taken from Turnbull and Lowe (1989) [s^-1]
A_a=0.825
A_b=1.034
A_c=0.984

transition probabilities taken from Langhoff (1986) [s^-1]
A_a=0.180
A_b=0.263
A_c=0.225

energy levels of the initial rotational states taken from Krassovsky (1962) [cm^-1]
F_a=-47.8 ; p2
F_b=96.; p4
F_c=12.1; p3

; folder where data is
numfold = '/xxx/'

; nr of files read in
nspectra = 1

; puts data in array
fname_spectra = strarr(nspectra)

numchar = strlen(numfold_master)

; DATASETS
; list them as below and number them
fname_spectra(0)= numfold_master+'yyyymmdd_hh_mm.txt'

T_rot=fltarr(nspectra)

for ispectra = 0,nspectra-1 do begin
    openr, flist_spectra, fname_spectra(ispectra), /GET_LUN
    print, 'Reading of = ', fname_spectra(ispectra)
    n_lines=205
data=fltarr(2,205)
readf, flist_spectra, data
close, flist_spectra
free_lun, flist_spectra
lambda=data(0,*)
intensity=data(1,*)
I=slave(intensity,lambda)
I_a=I(0)
I_b=I(1)
print, 'Binned intensities computed=', I(0), I(1)

; Computation of the rotational temperature

cst=h*c/k
a=I_a*A_b*(2*J_b+1)
b=I_b*A_a*(2*J_a+1)
print, a, b, cst
print, F_b, F_a
print, alog(a/b)
T_rot(ispectra)=cst*(F_b-F_a)/alog(a/b)
endfor

; opening a file for writing
openw, 1, '/xxx/yymmdd.txt'

for i=0, n_elements(spectrum)-1 do printf, 1, w1[i], spectrum[i], string(13B), form='$(F07.2, " ",F08.4,A1) 

endfor

; closing the file for writing
close, 1
B.3  slave.pro

function slave, intensity, lambda

; Function that lists the background and all the P-line peaks and calculates the counts of them.

; by Mea Wedlund, mea.wedlund@wedco.se
07 July 2007

; BACKGROUND

; Interval of background calculation, two areas are used to even it out
lambda_bgd1=7344.
lambda_bgd2=7356.
lambda_bgd3=7307.
lambda_bgd4=7314.

; Finding the nearest index of the given wavelengths
index_bkg=where( (lambda ge lambda_bgd1) and (lambda le lambda_bgd2))
index_bkg2=where( (lambda ge lambda_bgd3) and (lambda le lambda_bgd4))

; determination of the indexes of the arrays
near = Min(Abs(lambda - lambda_bgd1), ilamb_bgd1)
near = Min(Abs(lambda - lambda_bgd2), ilamb_bgd2)
near = Min(Abs(lambda - lambda_bgd3), ilamb_bgd3)
near = Min(Abs(lambda - lambda_bgd4), ilamb_bgd4)

; print, 'Indexes=', ilamb_bgd1, ilamb_bgd2

; Number of bins considered in the background
nlamb_bgd=abs(ilamb_bgd2-ilamb_bgd1)+1
nlamb_bgd=abs(ilamb_bgd4-ilamb_bgd3)+1

; print, 'Number of background bins=',nlamb_bgd

; P-LINE PEAKS

; For peaks P_i(x) the central wavelengths are given (according to Chamberlain) and a width is defined as 5
P_i(2) lambda1=7316.4
width1=5.0

; P_i(3) lambda2=7340.8
width2=5.0

; P_i(4) lambda3=7369.0
width3=5.0

; Finding the nearest index of the given wavelengths
index_1=where(abs(lambda - lambda1) le width1/2)
index_2=where(abs(lambda - lambda2) le width2/2)
index_3=where(abs(lambda - lambda3) le width3/2)

; INITIALISATION

; Initialisation of the intensities
intensity1=0.
intensity2=0.
intensity3=0.

; Calculation of the mean background
mean_bgk=mean(intensity(index_bkg))
mean_bgk2=mean(intensity(index_bkg2))
mean_bgk_mean=(mean_bgk+mean_bgk2)/2

; print, 'Mean background', mean_bgk_mean

; Removing background from calculated intensities
intensity1=total(intensity(index_1)-mean_bgk_mean)
intensity2 = total(intensity(index_2) - mean_bkg_mean)
intensity3 = total(intensity(index_3) - mean_bkg_mean)
;
i = [intensity1, intensity2, intensity3]
;
return I
;
end