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**H₂O with Elodie at
OHP**

A. Sarkissian and
J. Slusser

Water vapor total column measurements using the Elodie Archive at Observatoire de Haute Provence from 1994 to 2004

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Abstract

Water vapor total column measurements at Observatoire de Haute Provence (5°42' E, +43°55' N), south of France, were obtained using observations of astronomical objects made between July 1994 and December 2004 on the 193-cm telescope with the high-resolution spectrometer Elodie. Spectra of stars, nebulae, and other astronomical objects were taken regularly during 10 years. More than 18 000 spectra from 400 nm to 680 nm are available on-line in the Elodie Archive. This archive, usually explored by astronomers, contains information to study the atmosphere of the Earth. Water vapor absorption lines appear in the visible in delimited bands that astronomers often avoid for their spectral analysis. We used the Elodie Archive with two objectives: firstly, to retrieve seasonal variability and long-term trend of atmospheric water vapor, and secondly, to remove signatures in spectra for further astronomical or geophysical use. The tools presented here are developed following, when possible, formats and standards recommended by the International Virtual Observatory Alliance.

1 Introduction

The Elodie archive is a database of high-resolution spectra of astronomical objects (spectral domain: 385 nm to 680 nm; sampling 0.005 nm; resolution: 0.0065 nm) obtained with the Elodie spectrograph on a 193-cm diameter telescope at Observatoire de Haute Provence (5°42' E, +43°55' N, altitude 681 m) from July 1994 to December 2004 (Moultaka et al., 2004). More than 18 000 spectra of stars, galaxies, and other astrophysical objects are available in the Elodie archive, accessible using an online web service or php protocol. This database is updated regularly, when spectra with restricted access are opened to the community, or after updating the pipeline of the processing. The archive allows wider use of existing data sets, and this paper applies Virtual Observatory (VO) concepts of the workflow (Appendix A), see the International Virtual Observatory Alliance (IVOA) web site at <http://www.ivoa.net/> (2007) and refer-

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ences therein for details. Initially developed for presentation to students using the “hot”
thema of exoplanet search (Sarkissian, 2007), this tool is used here in geophysical
application of the atmospheric water vapor budget.

The composition of the Earths atmosphere is of great interest not only to atmospheric
scientists but also to astronomers for whom the atmosphere is an annoyance to be
removed in order to interpret astronomical observations without interference from Ter-
restrial gases and aerosol. Intensive astronomical stellar spectroscopic observations
began in the early 20th century. Fowle (1912) pioneered the determination of atmo-
spheric ozone from UV astronomical stellar spectral observations followed by Chal-
longe and Divan (1952). We present a study of terrestrial atmospheric water vapor
derived from astrophysical observations. Water vapor in the atmosphere has become
increasingly important due to its impact on global climate change and greenhouse
gases, its involvement in stratospheric ozone equilibrium in the troposphere, and in
the tropospheric water cycle. The current paper makes available water vapor column
measurements from both recent and long term astrophysical observations. Common
techniques to retrieve water vapor on site have always been without telescope depen-
dent instruments, for instance: surface humidity sensors or precipitable water vapor
sensor. Spectrometric observational methods are difficult, however, because line or
band intensity and broadening depend on ambient temperature and pressure, requir-
ing vertical profile rather than altitude on the line of sight, see Angione (1987), and
references therein. We believe that this difficulty is now partly solved by improvement
of spectral analysis techniques.

Water vapour in the atmosphere plays a crucial role since water vapour absorbs
the longwave radiation of the Earth’s surface. The amount of water vapour is ex-
pected to increase with temperature (Clausius-Clapeyron equation) so that a water
vapor feedback can amplify global warming by anthropogenous greenhouse gas emis-
sions. Long-term monitoring of atmospheric water vapor is mandatory for a better
understanding and prediction of climate change (Held and Soden, 2000).

Measurements of water vapor by UV-visible spectrometers from the ground on direct

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sun, zenith sky, or from space on nadir sky has been demonstrated by Wagner et al. (2003). The most common method to measure atmospheric absorbants by UV-visible spectrometry is the Differential Optical Analysis Spectroscopy (DOAS), (Perner and Platt, 1979; Vaughan et al., 1997; Fayt and Van Roozendael, 2001; Sarkissian, 1992, 2000). Using Global Positioning System (GPS) and its time dependent spectral shift due to the atmosphere, one can make use of the satellite network of detectors and readily available handheld units to measure column water vapor (Bastin et al., 2005; Champolion et al., 2004). Infrared atmospheric sensors (Schneider et al., 2006), lidar (Hoareau et al., 2009), passive microwave radiometry (Westwater et al., 2005) and radio techniques also provide measurements of water vapor, vertical profiles or total amount. The existing network of these instruments, developed at the end of the last century for long term studies, will probably not grow to include more sites. The water vapor measurement presented here would continue to be available with regular updates to the scientific community.

The following section presents the description of the building of a water vapor absorption cross-section. Section 3 describes the spectral analysis, and Sect. 4 presents the results on 18 000 spectra. Description of a workflow in the VO is given in Appendix A.

2 Water vapor absorption cross-section

Building the water vapor cross-section from the line list was made in two steps: first, building a very high resolution and over-sampled set of cross-sections that can be adapted, as a second step, to each Elodie spectra when making spectral analysis. The high resolution cross-section is then kept as an input for the spectral analysis. This approach is time consuming, but guarantees the accuracy of the final resolution reached. In our case, a water vapor absorption cross-section is calculated from the on-line list at <http://www.ulb.ac.be/cpm> (2007), of water vapor line parameters, from 26 000 to 13 000 cm⁻¹ (respectively, 770 nm to 385 nm) measured at 291.3 K (Coheur et al., 2002; Fally et al., 2003), with a portable high-resolution (0.06 cm⁻¹) Fourier transform

spectrometer within a 602-m long absorption cell. Table 1 summarizes modifications applied to the original list to build water vapor cross-section for Elodie spectra. Water vapor lines have a Voigt profile dominated by self-broadening and air-broadening modulated by air temperature and pressure variability on the line-of-sight of the telescope.

5 We used a Gaussian weighting function when building the water vapor cross-section, because during analysis, an empirical Gaussian fit had a lower residual compared to other simple convolutions (see part 5 for explanation on residuals). We also noted that vertical retrieval of atmospheric pressure and temperature seems to be possible using the water vapor line shape at these wavelengths, something to be explored in the future (Liu et al., 2006). Also, wavelength shift is calculated during spectral analysis, and no corrections were made compared to vacuum values when building the cross-section. Figure 1 shows atmospheric water vapor lines convoluted with a Gaussian of 0.2 cm^{-1} width sampled at 0.01 cm^{-1} . Markers indicate the spectral position and the intensity in the original list. This set, converted into wavelength scale, was used as the starting point for the analysis of all spectra. This high resolution cross-section is convoluted by a Gaussian of $R_{\text{H}_2\text{O}}$ nm Half Width Half Maximum (HWHM), resampled at Elodie spectral sampling, i.e., at 0.005 nm (0.13 cm^{-1} at 590 nm) for each spectrum individually. $R_{\text{H}_2\text{O}}$ varies during the spectral analysis in order to cover all possible resolutions for Elodie spectra, i.e., from approximately 0.08 to 0.12, see Table 2.

20 The wavelength range chosen for the analysis is 591.5 to 593 nm because it includes two water vapor triplets (see Figs. 3 and 4) and is easy to identify visually as well as through dedicated software. The choice of a narrow (few nanometers wide) wavelength spectral range is due to the low probability of interference with similar intensity stellar spectral lines, as indicated by several runs made during analysis improvements. Also, the compromise between fast spectral analysis and the accuracy needed justifies such a narrow spectral range.

25 Saturation problems are common with strong water vapor absorption lines in the visible, and are usually corrected by a coefficient applied on the final result: a modified Langley technique (Michalsky et al., 1995; Wagner et al., 2003). Because the lines at

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592 nm are so weak, our water vapor cross section are not corrected, and therefore do not take into account this effect. Discussion on this non-linearity of water vapor cross-section will be discussed in Sect. 6.

3 Observations

5 Observation of astronomical objects with Elodie, on the 193-cm telescope at Observatoire de Haute Provence at the south of France, started in July 1994 and ended in July 2005 when the Sophie spectrometer replaced Elodie (Moultaka et al., 2004). We analyzed the spectra available when we began writing this paper in December 2006. Spectra of stars, galaxies, and other astronomical objects were taken regularly each
10 night when the sky was clear enough, over a 10-year period, and more than 18 000 spectra are available on-line for intensive use of the Elodie archive (which contains 34 825 spectra). The on-line data reduction procedure removes scattered light and makes spectral wavelength and relative flux calibrations. Spectra are stored in Elodie archive in FITS (Flexible Image Transport System) format, a standard data format used
15 in astronomy, endorsed by NASA and the International Astronomical Union (NASA and IAU, 2007). Observations have been made by numerous astronomers, but most necessary information has been stored in the archive (like the time of the observation needed for astronomers for variable processes, the air-mass factor of the line-of-sight needed for information of the amplitude of atmospheric absorption lines, etc.). Unfortunately,
20 some parameters such as atmospheric pressure around the observation site and humidity were not recorded or measured during observations. However, the astronomical data are so well referenced and the procedures identified so that the homogeneity of the data set is conserved. This paper is a demonstration of such homogeneity because no normalization factors have been applied from one result to another, or from one period to another. An example of a spectrum of the Elodie archive is presented in Fig. 2.
25 The spectral range around 592 nm is displayed in Fig. 3. Not all astronomical spectra have as many visible absorption lines that are proper to solar type stars, here 51 Peg

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of spectral type G2. Some astronomical objects have only broad or a few lines visible, like hot O stars, or sometimes emission lines like nebulas. The wide range of sources make the spectral analysis more difficult, as we will discuss in the next section.

4 Spectral analysis

5 The spectral analysis has been specially developed for water vapor removal for future astrophysical use of the spectra. The authors' initial objective was to develop a spectral analysis to search water vapor signatures in external sources like exoplanets and bodies of the solar system. First analysis shows that water vapor signature in the visible in exoplanets is so tiny (optical thickness of 10^{-9} at most) that its detection is not
10 possible with existing techniques, but in the infrared, water vapor, ozone and carbon dioxide absorption can reach a significant percentage, justifying development of this technique.

In atmospheric research, most spectrometric instruments use solar light as the source. The differential optical absorption spectroscopy (DOAS) method is used commonly because using scattered light increases the path length up to 20 air masses. Here, because the source is not always the same, the DOAS method cannot be applied and an absolute method had to be developed for Elodie. Absolute methods are often used when signal-to-noise ratio of observation is so low that differentiation will generate too much noise for use. Because of the very high quality of spectra needed
15 in astronomy, most spectra (up to 96.5%) were used in the analysis.

Our spectral analysis is composed of cyclic procedures, varying spectral resolution of water vapor cross-section, spectral shift of water vapor cross-section and $n_{\text{H}_2\text{O}}$, the total column of water vapor molecules per surface area in line-of-sight for each individual spectra. Note that there is no convergence procedure, and all possible cycles were
20 evaluated in sequence. At the end of the analysis of each spectrum, the water vapor calculated is removed from the spectrum, i.e., its spectral signature subtracted from the initial spectrum. The quality of the spectral analysis can be evaluated by the pres-

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ence of water vapor signatures in the obtained spectrum: an efficient spectral analysis should remove any water vapor signature.

A spectral shift of $\Delta\lambda_{\text{H}_2\text{O}}$ is also applied to convert vacuum wavelength into air wavelength. The Shannon scheme (Shannon, 1949) is built for interpolation of cross-sections, and the the water vapor optical thickness $\tau_{\text{H}_2\text{O}}$ measured with the Beer-Lambert law for the observation allows us to deduce water vapor line-of-sight amount of water vapor,

$$\tau_{\text{H}_2\text{O}} = \sigma_{\text{H}_2\text{O}} \times n_{\text{H}_2\text{O}} . \quad (1)$$

The best values of $n_{\text{H}_2\text{O}}$ are obtained by minimizing residuals after removing water vapor from spectra. A high quality residual reaches 0.005 while a low quality spectrum, or a spectrum with a dominant non-water vapor absorption or emission line in the spectral domain, increases residual up to 0.3. Values higher than 0.1, representing 0.1% of the data, are rejected in this analysis.

Figure 4 (dotted line) shows a water vapor cross-section calculated for spectrum of 51 Peg (Fig. 5) taken on November 1995. Applied spectral shift is not visible at this scale. The amount $n_{\text{H}_2\text{O}}$ calculated is 7×10^{21} molecule cm^{-2} , giving an optical thickness represented in green on Fig. 5. The red line shows the spectrum before subtraction of water vapor signature, i.e., before analysis. The blue line shows the spectrum after subtraction of water vapor signature, i.e., after analysis. Water vapor total column, $N_{\text{H}_2\text{O}}$ is obtained by:

$$N_{\text{H}_2\text{O}} = \frac{n_{\text{H}_2\text{O}}}{\text{AMF}} . \quad (2)$$

AMF is the air-mass factor of the observation, i.e., the ratio between line-of-sight air column and vertical column above the observational point, a value provided in the Elodie archive and equivalent to $1 \div \cos$ of the source zenith angle for elevations larger than 20° . Note that for astronomers, objects are observed close to the meridian when possible, i.e. when the zenith angle is minimum. In present data set, less than 1.5% of observations are made at zenith angle higher than 70° .

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5 Results and discussion

Results of spectral analysis of all the spectra are summarized in Table 2, and values of $N_{\text{H}_2\text{O}}$ are presented in Fig. 7. Mean values measured during the analysis correspond to theoretical ones presented in Table 2 except for HWHM, because atmospheric turbulences and effects on integration time and integration on the line-of-sight, i.e., with variable properties difficult to evaluate. The seasonal variation can be easily seen with higher values in summer and lower values in winter, an effect due to the variability of the dew point with atmospheric temperature. Sometimes, in winter, extremely low values are reached indicating the dryness of the atmosphere above Observatoire de Haute-Provence. For further interpretation, daily (nightly), weekly, and monthly means have been calculated from these results, as well as a simple sine curve fit. A negative trend of $-0.44 \pm 0.24 \times 10^{22}$ molecule cm^{-2} per 10 years is obtained after removing sine fit.

The first point for the discussion concerns the improvement of the building of water vapor cross-section, and its effect on error budget. Then, because most of the atmospheric parameters are not known, the retrieval process can be made using climatological atmospheric variability.

Saturation effects on strong absorption lines in the 5ν range are not negligible and can reach up to 5% (Wagner et al., 2003). Such effects can be corrected by applying a linear correction factor depending of the quantity of water vapor, but we did not apply it at this stage. Our observations are made at low air-mass reducing enhancements of column amounts. Multiple scattering effects are reduced because astronomers make observations during clear skies. The spectral range chosen needs a lower correction factor than spectral ranges at higher wavelength. The very high spectral resolution of Elodie makes correction factor even lower than for low resolution instruments because individual lines are resolved. The amount of water vapor in the line-of-sight measured without correction is always lower than 30×10^{22} molecule cm^{-2} , and then saturation affects the linearity of Langley relation by less than 3% on less than 1% of all measure-

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ments, rendering correction negligible when making monthly averages.

In order to perform a validation of our measurements, they were used to calibrate lidar water vapor profiles obtained from May 1999 until December 2000 (Hoareau et al., 2009), as well as using radiosondes from Nîmes (the distance between OHP and Nîmes is less than 100 km). The calibration gives better agreement with our measurements than with radiosondes, but we need more co-located and simultaneous observations for validation.

Our workflow is developed in the frame of the Astronomical Virtual Observatory and should be soon available online as a web service, with results in VOTable format ready for interoperability. The concept of interoperability is already difficult to develop for astronomy and is even more complicated in interdisciplinary research, but this study is a demonstration that science-driven application can be developed more easily when using tools and standards of the Virtual Observatory.

6 Conclusions

We have presented water vapor total column measured at Observatoire de Haute-Provence between 1994 and 2004 using the Elodie archive: 18 000 spectra obtained by the Elodie high-resolution spectrometer on the 193-cm telescope. Seasonal variability of water vapor as well as a preliminary study of its trend above the observatory was possible because of the high quality of the available data. Astronomy can provide valuable past and present observations useful for atmospheric science, and this should be explored further. The large number of spectral databases in astronomy and their covering time periods, starting at the beginning of the previous century gives perspectives for extension of this workflow to ozone in the visible and for NO₂ at around 430 nm. The next step is to explore water vapor line shape sensitivity to air temperature and pressure.

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Appendix A

Workflow in the virtual observatory

A the virtual observatory is comprised of workflow consisting of a group of tasks involving one or more sources, which may include data banks, web services, etc. The simplest workflow for an instrument in modern astrophysics is a series of tasks, usually called a pipeline. A pipeline has its own input and output parameters, fixed by instrument conditions, and does not interfere with or depend upon external programs, parameters, or data. This is the main difference from the workflow. Pipelines are needed because data sources are permanently in evolution (new observations, improvement of a pipeline, update of available resources), whereas a workflow must integrate a complex approach of data treatment, including interactivity with other centers. Then, the interoperability between data centers, which is the basis of the Virtual Observatory, is the only way to make a reliable workflow. Not all the conditions of a workflow as defined by the Virtual Observatory, are present in our workflow, but we consider this a first step towards the minimum requirement.

The main goal of the workflow presented herein uses spectral analysis to retrieve amounts of trace gases. Although we focus on atmospheric water vapor, we can retrieve other gases such as NO₂ and ozone (Michalsky et al., 1995).

Our workflow is composed of four parts: the menu, the search for sources (spectra, cross-sections, information on sources etc.), the spectral analysis, and the output. The menu is a user interface where one can select the type of workflow needed: some parameters like a selection of sources in time or high and low resolution analysis, and of course, the output format. Then, depending of selected parameters, the workflow searches for available components in an interoperable way. The search for sources is limited to the Elodie archive, but can easily be extended to other spectral archives. For example, a search for radial velocity variation studies is also plugged as an option, and this was the original objective during the initial development of this workflow. Today

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with limited options, our workflow will be extended and available as beta version to both astronomical and atmospheric communities. The main subject of this paper is the water vapor total column measurement whereas the spectral analysis contains several other outputs as well as a menu for input parameters. These are not presented in this study.

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H₂O with Elodie at OHP

A. Sarkissian and
J. Slusser

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H₂O with Elodie at OHPA. Sarkissian and
J. Slusser**Table 1.** Resolution, sampling, and spectral shift of H₂O at 592 nm.

Source	Sampling	HWHM	Shift
Reims, provided (cm ⁻¹)	list	0.096	-0.03
Reims, convolved (cm ⁻¹)	0.01	0.17	0.
Elodie, theoretical (cm ⁻¹)	0.14	0.18	-4.93
Reims, convolved (nm)	0.00035	0.0065	0.
Elodie, theoretical (nm)	0.005	0.0065	-0.163
This analysis (nm)	0.005	0.0090	-0.164
Equivalent (m s ⁻¹)	2532	3544	-83 050

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**H₂O with Elodie at
OHP**A. Sarkissian and
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Value unit	Line-of-sight amount 10^{22} molecule cm^{-2}	HWHM nm	Spectral shift nm
Mean	6.00	0.00912	-0.163750
Minimum	0.00	0.00824	-0.16200
Maximum	20.00	0.01000	-0.16600
Δ	0.02	0.00003	0.00002

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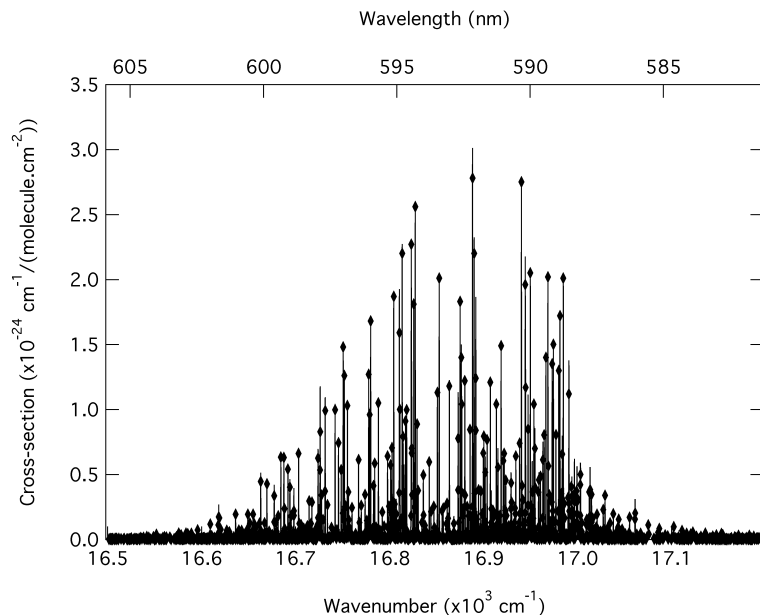
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Fig. 1. H₂O absorption cross-section between 585 and 605 nm. Line list presented as markers is provided by (Coheur et al., 2002; Fally et al., 2003). Cross-section is calculated by convolution of the line list using a 0.17 cm^{-1} (0.0065 nm) HFWM Gaussian.

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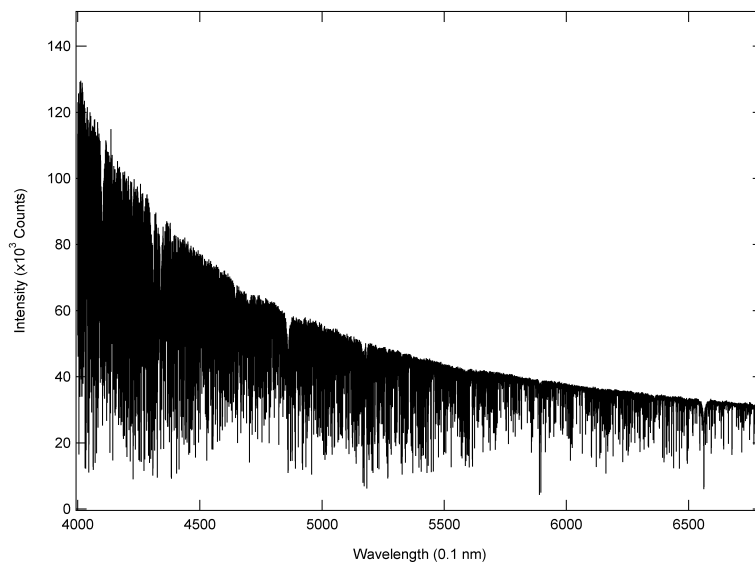
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Fig. 2. Example of Elodie spectra: 51 Peg of spectral type G2 taken by Mayor and Queloz on 6 November 1995.

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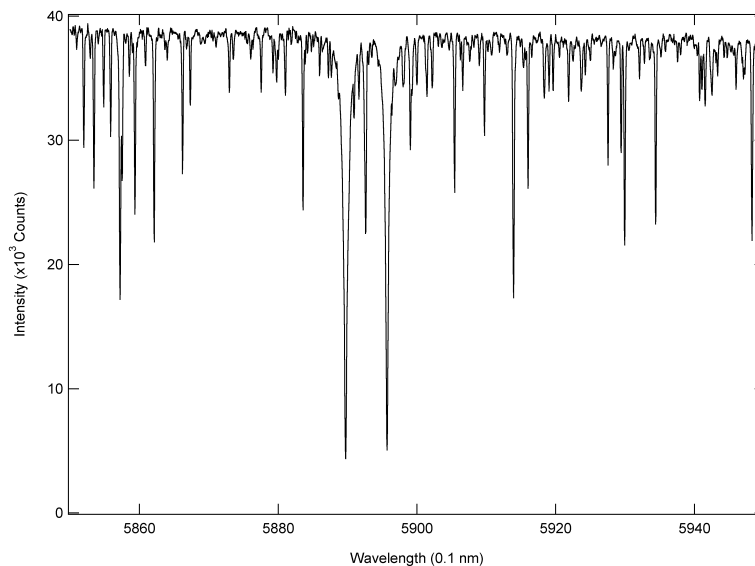
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Fig. 3. Example of Elodie spectra (see Fig. 2), but focused on the water vapor absorption region at around 590 nm. Note the triplet at 591.8 nm, followed by the triplet at 592.5.

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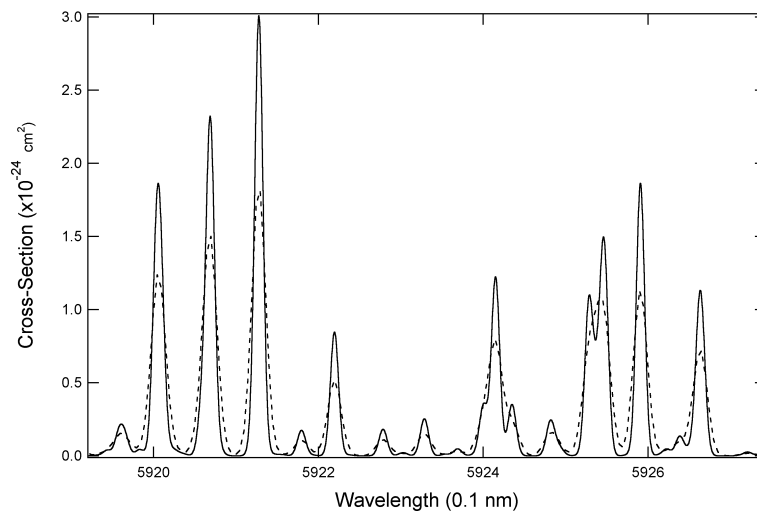
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Fig. 4. H₂O cross-section (dotted line) resampled to Elodie HWHM (calculated from spectrum 199511060011 of 51 Peg) from initial cross-section (full line). Broadening and shift are calculated by minimizing residual after subtraction (see text).

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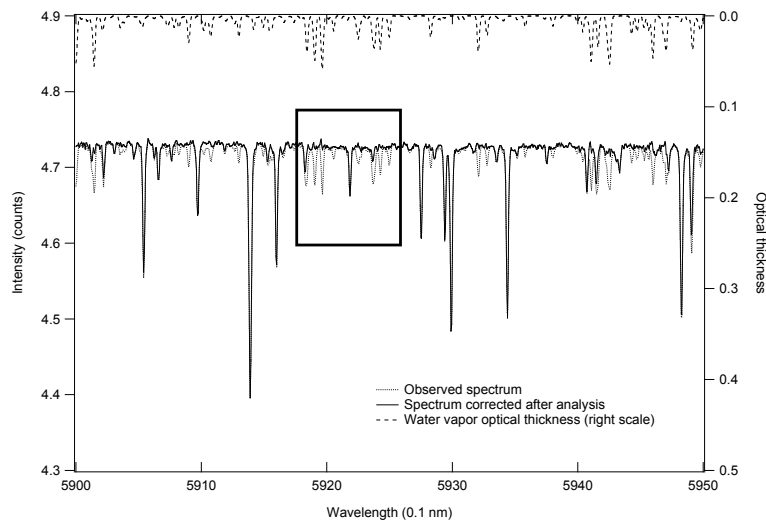
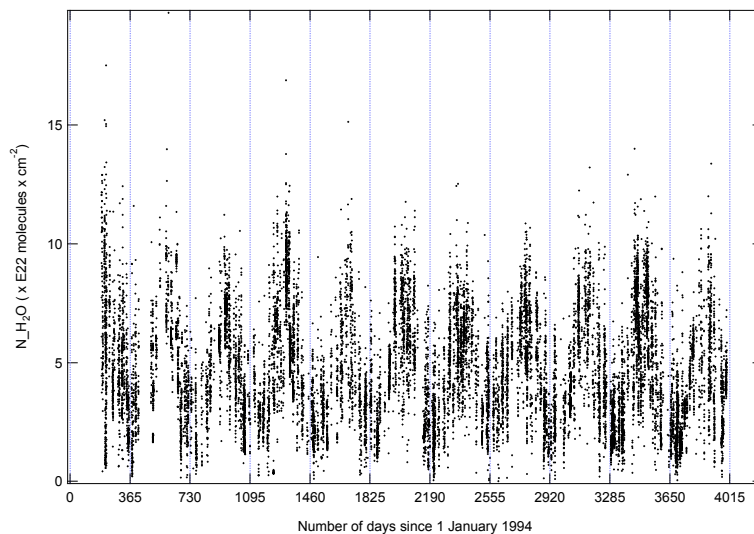
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Fig. 5. Optical thickness of H₂O in Elodie spectrum 199511010018 (right scale, dotted upper line). Respectively, full and dotted lines, spectrum and spectrum corrected from H₂O absorption.

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H₂O with Elodie at OHPA. Sarkissian and
J. Slusser**Fig. 6.** Result of spectral analysis on 18 318 spectra of Elodie.[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

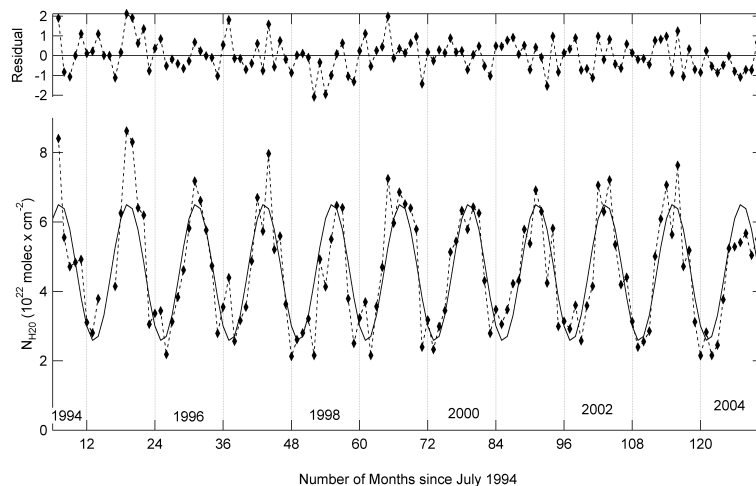
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Fig. 7. H₂O monthly mean at OHP from 1994 to 2004 and a sine fit curve (dotted line) to show seasonal variation. The residual after subtraction of sin fit, shown at the top of the graph, has a negative trend of $-0.44 \pm 0.24 \times 10^{22}$ molecule cm^{-2} per 10 years.

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