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# Use of spectroscopic observations of the sun and other stars to study global variations of the earth's atmosphere

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We would like to alert astronomers carrying out high-resolution observations of stars, and especially of the sun as a star, to the possibility of using results containing telluric lines to study global changes in the composition of the earth's atmosphere and other atmospheric characteristics. This possibility is illustrated with solar observations carried out in Moscow in the visible and near infrared. A comparison of the equivalent widths of the $O_2$ ($\lambda$ 6295 Å) and $CO_2$ ($\lambda$ 20,700 Å) lines, recorded with the spectrograph on the ATB-1 large vertical solar telescope at the Shternberg Institute in 1969 and in 1993 reveals that during the last 22–24 years, the oxygen content in the atmosphere above Moscow has remained constant (within the limits of observational accuracy), whereas the carbon dioxide content has increased significantly.

## 1. INTRODUCTION

The first measurements of the composition of the air were carried out using chemical methods as early as the end of the 18th century. It was established that the main components of Earth's atmosphere are oxygen, nitrogen, and carbon dioxide. More precise data on the air composition were subsequently obtained, using the physicochemical method of chromatography[1] and using mass spectrometry.[2]

Enhancing the accuracy of the old methods and developing new methods has made it possible to detect such subtle effects as diurnal, seasonal, and multiyear variations in the minor constituents of the atmosphere (CO, $SO_2$, $NO_2$, NO, $O_3$, etc.). The new methods did not, as a rule, supplant the older methods, but rather supplemented and broadened their capabilities. A good example of this is the study of the variation of the $CO_2$ content of the atmosphere.

Widespread interest in this problem is due to the realization that the uncontrolled burning of fossil fuels may so increase the $CO_2$ content that the rise in mean temperature will become irreversible and lead to catastrophic consequence.[3-7]

Measurements with high-precision gas analyzers, operating on small (10–100 cm) spatial scales under urban conditions, reveal a high variability and, as a rule, complex nature of the spatio-temporal distribution of the $CO_2$ concentration. The data are naturally greatly affected by the presence or absence of nearby local sources of $CO_2$: factories, power stations, transport routes, etc. In order to obtain representative data characterizing the overall situation in some industrial region, an averaging period of about one month is necessary.[8] This is why the most practical and suitable means of investigating such large-scale variations is the astrophysical method.[5]

The essence of the method consists in studying the absorption spectrum of a given component of the air in the spectrum of the sun or some other star, obtained with a telescope/spectrograph combination of sufficiently high resolving power. As noted in Ref. 9, this method is considerably more laborious, but this is compensated for by the much higher accuracy of the results, compared with spectral modeling. Astronomers realized this long ago, and they succeeded in studying various characteristics of the atmosphere (chemical composition, convection and circulation, and seasonal variations of density and temperature; see Ref. 4. In resolving contemporary metrological problems, the accuracy of the measurements is of primary importance.

Of course, any sufficiently bright star can serve as a source of radiation for the spectroscopic astronomical method of studying Earth's atmosphere. Artificial sources with prescribed spectral properties can also be used. The astrophysical method makes if possible to find the total amount of the air constituent being studied, over the entire depth of atmosphere. Thus, it is to be hoped that this method will be an effective tool for determining global changes in the composition of the Earth's atmosphere for purposes of ecological monitoring, in particular. The method is described in more detail below.

## 2. POSSIBLE VARIATIONS IN THE OXYGEN CONTENT

Detailed studies of telluric oxygen lines in the solar spectrum were carried out in 1970[11] at the Solar Physics

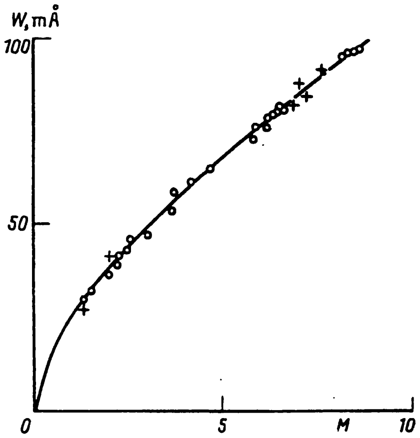

FIG. 1. Equivalent width of $O_2$ λ6295 Å line as a function of depth of the atmosphere. Points indicate values obtained on 4 and 5 August 1970; crosses pertain to 3 May and 27 December 1990. Both blocks of data obviously lie on the same continuous curve, the curve of growth.

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TABLE I

| $M$ | 6,85 | 7,03 | 7,20 | 7,59 |
|---|---|---|---|---|
| $W$, mÅ | 81,4 | 87,9 | 83,5 | 91,1 |
| $W^T$, mÅ | 77,6 | 83,8 | 79,6 | 86,9 |

Department of the Shternberg Institute. An important consequence of this work was a quantitative study and theoretical explanation of the seasonal variations of the telluric lines. A number of lines, in particular, the $O_2$ λ6295.178 Å line, were also found to have characteristics that varied slightly with the season. At the Kuchinsk Astrophysical Observatory of the Shternberg Institute on 4 and 5 August 1970, this line was recorded photoelectrically with a horizontal solar telescope (diameter of primary mirror 300 mm, focal length 15,000 mm) and a spectrograph providing a dispersion of 1.6 Å/mm and a resolution of 0.04 Å in the first spectral order. The detector was a multialkali photomultiplier.

The equivalent line widths $W$ were measured for atmospheric masses $M$ from $M = 1.30$ ($W = 30.0$ mÅ) to $M = 8.59$ ($W = 91.2$ mÅ) at an air temperature $T = 20°\text{C}$. For each atmospheric mass at least three recordings of the spectrum were made. The data were used to construct the plot of $W = f(M)$ in Fig. 1. Individual observations are indicated here by points; their deviations from the average curve, constructed using the least-squares method, do not exceed 1%.

Repeat observations of this line were carried out in the spring and winter of 1990 in Moscow at the Shternberg Institute, using the ATB-1 vertical solar telescope (diameter of primary mirror 300 mm, focal length 15,100 mm) and a diffraction spectrograph with a dispersion of 0.8 Å/mm and a resolution of 0.03 Å. On 3 May 1990 the line was recorded twice for $M = 1.3$ ($W = 29.0 \pm 0.4$ mÅ) and five times for $M = 2.05$ ($W = 42.4 \pm 1.0$ mÅ).

According to Ref. 11, this line is one of the "intermediate" lines, for which $W\alpha(\ln \tau_0)^{1/2}$, where $\Gamma_0$ is the optical depth at the center of the line. For this functional dependence of $W$ on $\tau_0$, the equivalent widths vary only slightly with season. Calculations carried out with the formulas from Ref. 11 indicate that in order to reduce the observations of 3 May 1990 ($T = 10°\text{C}$) to the system of observations on 4-5 August 1970 ($T = 20°\text{C}$), the equivalent width of the weaker line (with a smaller equivalent width) has to be reduced by 3%, while that of the stronger line has to be reduced by 1%. After this reduction we get for the first line $W = 28.1 \pm 0.4$ mÅ, and for the second line $W = 42.0 \pm 1.0$ mÅ.

On 27 December 1990 the equivalent widths of the line at λ6295.178 Å were determined for atmospheric masses $M$ from 6.85 to 7.59. Four records were made. Table I gives the values of the atmospheric mass $M$ corresponding to the observation times, the measured equivalent widths $W$ of the $O_2$ line in mÅ, and the equivalent widths $W^T$ of this same line, corrected for the seasonal variations (see Eq. (1)).

In order to compare these figures with the data of 4 and 5 August 1970, it was necessary, as before, to allow for seasonal variations of the given line. According to Ref. 11 for the $M$ values in the table, the line can be considered "strong," so that seasonal variations of the equivalent line width can be calculated using the following formula[11]:

$$\frac{\Delta W}{W} = \frac{\Delta \rho}{\rho} + \frac{1}{2}\left(\frac{E_J}{kT} - \frac{1}{2}\right)\frac{\Delta T}{T}. \tag{1}$$

Here $\rho$ and $T$ are the air density and temperature, $E_j = BhcJ(J+1)$ is the energy of the lower molecular level, $J$ is the rotational quantum number of this level ($J = 7$ for the line considered here), $B = 1.44\ \text{cm}^{-1}$ is the rotation constant of the $O_2$ molecule, and the other notation is standard.

It is easy to show that on account of the change from $t = 293$ K on 4-5 August 1970 to $T = 265$ K on 27 December 1990, $\Delta W/W = 0.004$. On the other hand,[11] $\Delta\rho/\rho \leq 0.042$. Therefore, to reduce the 1990 data to the system of August 1970, we must reduce the derived equivalent widths by 4-6%. The equivalent widths $W^T$, corrected for seasonal variations, are given in the bottom row of Table I.

The data for 3 May and 27 December 1990, reduced to the system of 4-5 August 1970, are denoted in Fig. 1 by crosses. Inspection of the figure shows a good fit of these points with the 1970 curve. Thus it can be concluded that for the last 20 years, the oxygen content of Earth's atmosphere has remained constant to within about 5%.

## 3. VARIATIONS IN THE CARBON DIOXIDE CONTENT

The electronic bands of the $CO_2$ molecule lie in the ultraviolet, near 1750 Å, and thus are inaccessible to ground-based observations. The vibration–rotation bands cover a considerable part of the spectrum, from 7600 to 150,000 Å,[12] only a small part of which (shorter than 30,000 Å) can be recorded with the ATB-1 spectrograph at the Shternberg Institute. An analysis of the profiles of the $CO_2$ lines, based

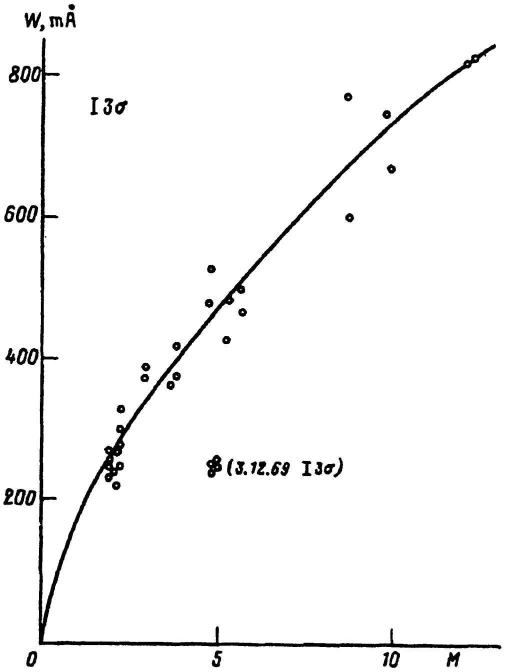

FIG. 2. Equivalent width of $CO_2$ lines near λ20,700 Å, as a function of the depth of the atmosphere. Points in the vicinity of the curve of growth (solid curve) obtained with ATB-1 vertical solar telescope at Shternberg Institute on 27 September 1991; observational error $3\sigma = 5\%$ is indicated. The four points obtained with this same telescope on 3 December 1969 lie considerably below the curve; observational error $3\sigma = 3.5\%$.

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on the tables in Ref. 13 and the atlas in Ref. 14, enabled us to select two individual lines with "clean" profiles in the 20,700 Å region: the lines at 20,756.11 Å and 20,758.51 Å. The lines were recorded photoelectrically, the detector being a lead sulfide photoconductive cell cooled with dry ice.

An analysis of the tables in Ref. 13 revealed certain inconsistencies between the theoretical calculations and the observed equivalent widths of the lines. Theory predicts that the first line should be about 5% stronger than the second, while the observations shows the opposite, the second line being about 16% stronger than the first. Because of this uncertainty, and the observational error, it was decided to average the data for the two lines.

Since we had at our disposal two recordings of the $CO_2$ spectrum in the 20,700 Å region, obtained on 3 December 1969 for an atmospheric mass $M = 4.86$ and an air temperature $T = 272.8$ K ($-0.2$°C), we took the averages of the equivalent widths of these: $247 \pm 3$ mÅ for the first line and $257 \pm 4$ mÅ for the second. this gave an average for the two lines of $252 \pm 4$ mÅ.

The second set of data were obtained on 27 September 1991 for atmospheric masses $M$ from 1.88 to 12.00 at $T = 292$ K (19°C). The equivalent widths of the lines are plotted against the atmospheric mass in Fig. 2, the curve thus obtained being analogous to a curve of growth. For $M = 4.86$ the graph gives an equivalent width (averaged over the two lines) $W = 476 \pm 2$ mÅ, which is significantly higher than the value $W = 252 \pm 4$ mÅ for 3 December 1969.

To obtain from these data the actual variation in the $CO_2$ content of the atmosphere, we have to eliminate seasonal variations of the line widths due to variations in air temperature, air density, and photosynthesis. The results in Ref. 11 indicate that these $CO_2$ lines can be considered "weak." In this case the equivalent width can be expressed as a function of the temperature:

$$W = \frac{aN}{T} \exp\left(-\frac{hcF}{kT}\right), \qquad (2)$$

where $N$ is the total number of $CO_2$ molecules in the line of sight, $F$ is the energy of the lower level of the line in $cm^{-1}$, and $\alpha$ is a constant factor (other notation standard). According to Ref. 13, for the first line $F = 719$ $cm^{-1}$, and for the second $F = 719$ $cm^{-1}$, and for the second $F = 710$ $cm^{-1}$.

To calculate the variation of the equivalent width due to the temperature increase from 272.8 K on 3 December 1969 to 292 K on 27 September 1991, we substituted into (2) the temperature at the effective height of formation of the weak lines, which according to Ref. 11 is 6 km. Using the atmospheric model from Ref. 15, we see that the temperature differential between a height of 6 km and sea level is 42 K, while the temperature difference from season to season is about the same at 6 km as at sea level. Thus, for the calculations we took $T = 231$ K on 3 December 1969 at $h = 6$ km and $T = 250$ K on 27 December 1991 at this same altitude, which strengths the first $CO_2$ line by a factor of 1.303, and the second line by a factor of 1.297, giving an average increase of a factor of 1.3.

Consequently, taking $W = 252 \pm 4$ mÅ for 3 December 1969 as the initial value, we get for 27 September 1991 an equivalent width $W = 328 \pm 4$ mÅ just due to the increase in air temperature by 19 K.

The next most important seasonal effect influencing the equivalent width of the $CO_2$ lines is the summer drop in the $CO_2$ content associated with the summer photosynthesis maximum in the forests at northern midlatitudes. These variations can have an amplitude of up to 1.5%.[16]

Finally, the change from winter to summer is accompanied by a reduction in the equivalent widths of the telluric lines due to the additional drop in air density by approximately 0.5%.[11]

Thus, the "theoretical" value $W^T$ for 27 September 1991 is found from $W$ by reducing the latter by 2%, to give $W^T = 322 \pm 4$ mÅ. The observed value for this date $W = 476 \pm$ mÅ. This means that the equivalent width of the $CO_2$ lines increased by 154 mÅ, or 48%. According to formula (2), this increase corresponds to an increase in the $CO_2$ content of the air basin of Moscow by about 48% during the time from December 1969 to September 1991.

Now let us consider the effect on the results of spatial nonuniformities and temporal variations of the $CO_2$ concentration in the ground layer of the urban atmosphere.

In Refs. 17 and 18 the results of $CO_2$ measurements in the air over different parts of Moscow using the sampling method indicated that technogenic emissions of $CO_2$ produce very significant spatial nonuniformities in the $CO_2$ distribution 350–500 m above the ground, the greatest nonuniformities being in the lower 50-meter layer. Here, under unfavorable meteorological conditions, man-made emissions may reach 10% of the background. Even greater variations, as high as 15%, are associated with the diurnal and seasonal cycles of the intensity of the anthropogenic emissions.

To evaluate the influence of these variations on the recorded equivalent widths of the $CO_2$ lines, we consider the contribution of the lower 500-meter layer with the aid of the CIRA-1961 model.[15] It turns out that only 9% of the total equivalent width of a line is produced in this layer. Assuming the maximum possible variation in the $CO_2$ content of this layer to be 15%, we conclude that a comparison of the equivalent widths of the $CO_2$ lines recorded during different years

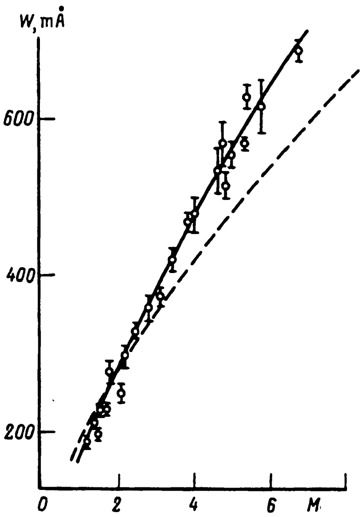

FIG. 3. Equivalent width of $CO_2$ lines near λ20,700 as a function of the depth of the atmosphere, according to observations from April 1992 through February 1993. Dashed curve pertains to observations of 27 September 1991.

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yields an uncertainty of at most 1.5% in the estimated global variation of the $CO_2$ content.

This is verified by Fig. 3, which gives results of $CO_2$ observations in Moscow using the ATB-1 at the Shternberg Institute from April 1992 through February 1993. The points indicate the equivalent widths observed during the given period, and the dashed curve pertains to the observations of 27 September 1991. Figure 3 shows that up to atmospheric masses $M \simeq 3$, the two sets of data agree well with one another. For $M > 3$ a systematic increase in the equivalent widths above the 1991 curve is observed for 1992-1993. Preliminary studies indicate that the winter points lie considerably above the summer points, which cannot be explained by the seasonal variations in temperature and which may be of anthropogenic origin. Actually, an atmospheric mass $M = 3$ corresponds to a 71° zenith distance of the sun. Since the sun is close to the horizon, the contribution of the ground layers to the equivalent widths of the $CO_2$ lines becomes greater than in the case of low $M$. In a separate article we intend to study in detail the distinction between the seasonal atmospheric factors and the seasonal anthropogenic factors.

## 4. CONCLUSION

The purpose of this article has been to alert astronomers carrying out high-resolution observations of stars, and the sun in particular, to the possibility (and necessity) of using telluric lines as a source of data on the chemical composition of the Earth's atmosphere, the convection and circulation in it, the seasonal variations of density and temperature, and long-period variations of these and other characteristics of the Earth's atmosphere. It is especially important to compare widely-spaced data (separated by at least 10 to 20 years), so as to be able to evaluate the global, possibly irreversible, changes in the composition of the atmosphere. More frequent observations at various observatories, as well as observations employing a larger number of specially selected lines, would enable us to discern the nature of the seasonal variations in the Earth's atmosphere, and to work out the general principles for a coordinate system of well-focused ecological monitoring in industrial regions.

Modern satellite data provide a great deal of information, albeit mostly qualitative, about the ecological state of the Earth's atmosphere. The main difficulty consists in the quantitative interpretation of the data, especially data from filter-band observations in the visible and infrared. A ground-based astronomical system for ecological monitoring, using high-resolution observations of the sun and other stars, is less susceptible to this difficulty, so that we can thereby hope for a solution to this important metrological problem.[19]

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