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ABSTRACT

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Thermospheric temperatures deduced from satellite drag observations are compared with the intensity of extreme ultraviolet radiation measured on the first Orbiting Solar Observatory (OSO-1). The comparison leads to a conclusion that, for the two complete solar rotation periods during which the EUV data are available, the 27-day periodic variation in upper atmospheric density was due to corresponding changes principally of ultraviolet rather than corpuscular radiation.

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INTRODUCTION

It generally has been accepted that the absorption of solar extreme ultraviolet (EUV) radiation constitutes an important mechanism for atmospheric heating. The possibility of an additional heat source of importance comparable to the EUV effect has been introduced by many investigators to explain semi-annual, diurnal and 27-day variations in atmospheric densities deduced from satellite drag observations. However, the need for a heat source as important as EUV radiation in order to explain temporal density changes does not appear to be conclusive.

Paetzold and Zschörner (1960) first suggested that semi-annual variations in atmospheric density could be associated with corresponding changes in geomagnetic activity and thus with possible slow changes in a second heat source associated with the solar wind. However, they depended on correlating satellite deceleration data for the period 1958-1961 with geomagnetic indices for the corresponding months averaged over the previous solar cycle. According to Bartels (1963), a positive correlation is not obtainable if the satellite deceleration data are compared with simultaneously-observed geomagnetic indices. This sheds doubt on the need for a solar wind effect to explain semi-annual density variations.

Harris and Priester (1962), by solving the heat balance equation have proposed that the EUV effect should result in a diurnal maximum in atmospheric density at 17^h local time. The observed maximum deduced from satellite drag studies occurs at about 14^h local time (Jacchia, 1963). To account for the difference between the observed and their theoretically-computed time for the diurnal maximum, Harris and Priester empirically introduce a second heat source equivalent to the EUV effect and which they identify with the solar wind. However, an alternative explanation for the phase shift is that the heat source is entirely EUV but a transport mechanism exists which shifts the absorbed energy toward the west. (Priester, private communication).

MacDonald (1963) has suggested that there is a systematic 56-hour phase delay between the 27-day cycles in observed decimetric solar flux and satellite-drag inferred densities, a delay corresponding to a straight line velocity from the sun of 750 km sec^{-1}. Since 750 km sec^{-1} is characteristic of solar wind velocities, Mac Donald concludes that the 27-day period in atmospheric density is entirely due to corpuscular rather than EUV radiation.

In this paper daily averages of 170-370 Å radiation measured by use of the first Orbiting Solar Observatory during March-May 1962 are time-corelated with satellite drag observations and with geomagnetic activity. The comparison leads to a conclusion that for the two complete solar rotation periods during which the EUV data are available, the 27-day periodic and the day-to-day variations in upper atmospheric density are principally due to EUV radiation, a conclusion which is not in harmony with MacDonald's.

MEASURED ULTRAVIOLET SPECTRUM

The solar radiation data used in our analyses were obtained by the use of a grazing incidence spectrometer pointed at the center of the solar disk within several minutes of arc. In this orientation the spectrometer analysed radiation from the entire solar disk and inner corona, covering the nominal spectral range from 10 Å to 400 Å with a resolution of 0.85 Å once every 8.5 minutes. Variations in several of the more intense lines in the observed spectrum have already been associated with solar flares (Behring, et al, 1963) and the slowly varying component of solar activity (Neupert, et al, 1964). In this paper, we present time variations of the EUV flux representing the sum of the intensities of the twenty-two most prominent lines in the range 170-370 Å. These lines are identified by asterisks in the two spectral scans shown in Figure 1.

Since an absolute calibration of the OSO-1 spectrometer has not yet been completed, an indirect method of calibration has been used to derive flux from measured counting rates. This method consists of comparing the counting rates obtained from the OSO-1 instrument with fluxes measured by Hall et al, (1963) who used a calibrated rocketborne spectrometer. The comparison could only be made in the spectral region for which the two instruments overlapped, 250 Å to 370 Å. Furthermore, the comparison is meaningful only if the solar radiation on the day of the rocketborne measurement was indeed the same as on the days of OSO-1 observations chosen for comparison. The mean daily solar radio flux at 2800 Mc, measured by the National Research Council, Ottawa, Canada, was used as a measure of solar activity to obtain equivalent days of OSO-1 observations. Calibration of the instrument was extrapolated below 250 Å using the measured reflectivity of the grating and an estimate of the detector sensitivity.

Each of the spectral lines used in the intensity estimate was observed 75 to 100 times during each day of observation, thereby yielding an accuracy of about one percent in the determination of the counting rate for each line, assuming a constant line intensity throughout the averaging period. The estimated error of the sum of intensities of the twenty-two brightest lines is therefore significantly smaller than the observed day-to-day variations. It has been found that the details of the time variations are relatively insensitive to likely changes in the assumed calibration of the instrument and also to the inclusion of numerous fainter lines in the sum of intensities. The daily averages of the sum of the intensities of the twenty-two discrete lines are illustrated in Figure 2a. Because of the uncertainties in calibration, the absolute value of the overall curve should not be taken as reliable but the time variations should be valid.

PHASE COMPARISON BETWEEN ATMOSPHERIC TEMPERATURE AND MEASURED ULTRAVIOLET RADIATION

Thermospheric heating can occur as a result of photodissociation and of photoionization. The region of the ultraviolet spectrum principally responsible for photodissociation heating (1350-1750 Å) is absorbed most strongly below 120 km. Photoionization heating is more important above 120 km because most of the responsible radiation (1027-170 Å) is absorbed above that altitude. Since our analysis deals only with temperatures above 120 km we will be considering the more important heating process (photoionization heating). Summaries of EUV measurements (Hinteregger and Watanabe, 1962; Watanabe and Hinteregger, 1962) indicate that the twenty-two discrete lines identified in Figure 1 represent approximately one-third of the ultraviolet radiation pertinent to our analysis. Thus, conclusions derived from the EUV data presented here will depend on the validity of our present working assumption that the entire spectrum between 1026-170 Å exhibits the same temporal variation as the sum of the twenty-one lines in the 170-370 Å regions. Conclusions drawn from the EUV data additionally will depend on the assumption that the contribution of individual lines to thermospheric heating is proportional to their respective intensities. One weakness in this assumption arises from the probability that the absorption and photoionization cross sections of the atmospheric constituents vary with wavelength. The uncertainties in our knowledge of these cross sections prevent us from taking this possibility into account.

Plotted in Figure 2b are the daily values of the temperature (T) representative of diurnal maximum conditions in the isothermal altitude region. These values of T were computed by Jacchia and Slowey (1963) from their observations of the deceleration of the Explorer 9 satellite and a theoretical model (Nicolet, 1961) of atmospheric density profiles as a function of temperature. It should be emphasized that, although the absolute value of T and the EUV intensity may be somewhat uncertain, we are interested here only in the validity of the time variation.

By comparing Figures 2a and 2b, we conclude both from visual inspection and from a least-square fit performed by a computer analysis that the phase difference between T and the measured EUV radiation for the March and April solar rotations is of the order of one day. A one day delay can be explained either by the uncertainty of the satellite deceleration data or by the relaxation time of the atmosphere. Thus, it can be considered that there is a positive correlation between T and the EUV flux, leading to the conclusion that the day-to-day and the 27-day periodic variation of T are due principally to the EUV effect, at least for the months of March and April, 1962. It should be noted that despite the uncertainty in the individual T points, the short term variations in the atmospheric temperature correlate quite well with corresponding EUV radiation changes. Note, for example, the existence of double peaks in both the T and the EUV data during the maxima of the March and April solar rotations.

The 10.7 cm decimetric radiation has been plotted in Figure 2c. Comparison with Figure 2a shows that decimetric flux is an approximate but not precise index of the EUV effect. MacDonald (1963) has suggested that there is a systematic 56-hour delay between the emission of solar decimetric radiation and the response of the atmosphere. Since this corresponds to typical velocities of the solar wind, this delay led him to conclude that the 27-day density fluctuations are entirely due to interaction of the upper atmosphere with the solar wind. It should be noted that Jacchia (1963) reports that there was not appreciable lag between 10.7 cm solar flux and atmospheric density for the same period analyzed by MacDonald.

It also is possible to conclude that the two 27-day cycles in T considered here are not significantly associated with the solar wind from simultaneously-measured indices of geomagnetic activity. Snyder et al, (1963) have measured the velocity of the solar wind and have quantitatively related this parameter to the geomagnetic index, Σk_p.. Consequently, we have plotted the Σk_p index for each day of the pertinent period in Figure 2d. Using the relationship between solar wind velocity and Σk_p established by Snyder and et al, we estimate that if the solar wind is entirely responsible for the 27-day variation of the upper atmosphere temperature there should be an average phase delay of 4 days between the EUV flux and T, a delay much in excess of the average value derived from Figures 2a and 2b. Thus, we conclude that the solar wind was not significantly effective in heating the upper atmosphere during March and April, 1962. This does not contradict the findings of Jacchia (1963) who has associated significant transient increases in atmospheric density with geomagnetic activity generally much more intense than what was characteristic of the time interval studied here.

There is a suggestion of a significant enough phase delay between T and the EUV radiation during the May rotation to support the need for another heat source. However, it would be dangerous to draw any firm conclusion from this cycle without data throughout the complete solar rotation.

COMPARISON BETWEEN DIURNAL AMPLITUDE OF ATMOSPHERIC TEMPERATURE AND MEASURED ULTRAVIOLET RADIATION

It is important to compare the respective amplitudes as well as the phases of the 27-day temperature and EUV variations. In Figure 2, even though the amplitudes of the two complete EUV cycles are approximately the same, the amplitudes of the corresponding T cycles differ significantly from each other. Due to the motion of the perigee of the satellite under study with respect to the sun-earth line, the diurnal temperature variation shows up in the data of Jacchia and Slowey in addition to the day-to-day variation. For our purposes, we should have temperatures reduced to the same local time. For this reason we will now compare the differences between diurnal temperature maximum (T) and minimum (T_o) with heat source variations. It will be shown that the amplitudes of the 27-day variation of ($T - T_o$) and of the EUV cycles present a consistent picture. Jacchia (1963) has suggested the following empirical formula which relates day and night temperatures deduced from drag observations:

$$T = T_o \ (1 + 0.33 \cos^n \frac{\psi}{2}), \qquad (1)$$

where T_o corresponds to the nighttime temperature minimum, ψ is the angular distance between satellite perigee and a point 30 degrees east in longitude of the subsolar point and where $n = 4$.

In Figure 3, we have set n = 1, 2, 4 and compare the three resultant $T - T_o$ curves with the EUV data, using observed values of ψ applicable to the Explorer 9 satellite. It is seen that by the use of n = 4, one tends to over-correct for the change in ψ with time in that now the amplitude of the second temperature cycle is larger than the first. An appropriate value for n seems to be between 1 and 2, as demonstrated by the very favorable comparison between the relative amplitudes of the two EUV cycles with the relative amplitudes of the two temperature cycles for n = 1 and 2. Jacchia (private communication) independently concludes that a much lower value of n than was previously used is more consistent with satellite drag observations.

CONCLUSIONS

Daily values of atmospheric temperature have been compared with EUV radiation data and also with indices of geomagnetic activity. The analysis which includes both a phase and amplitude study favors the EUV rather than the solar wind effect as principally responsible for the 27-day variations in atmospheric temperature at least for the months of March and April 1962. The question as to whether this conclusion applies at all times and whether a second source of heating is required to explain semi-annual and diurnal temperature variations remains open.

ACKNOWLEDGEMENTS

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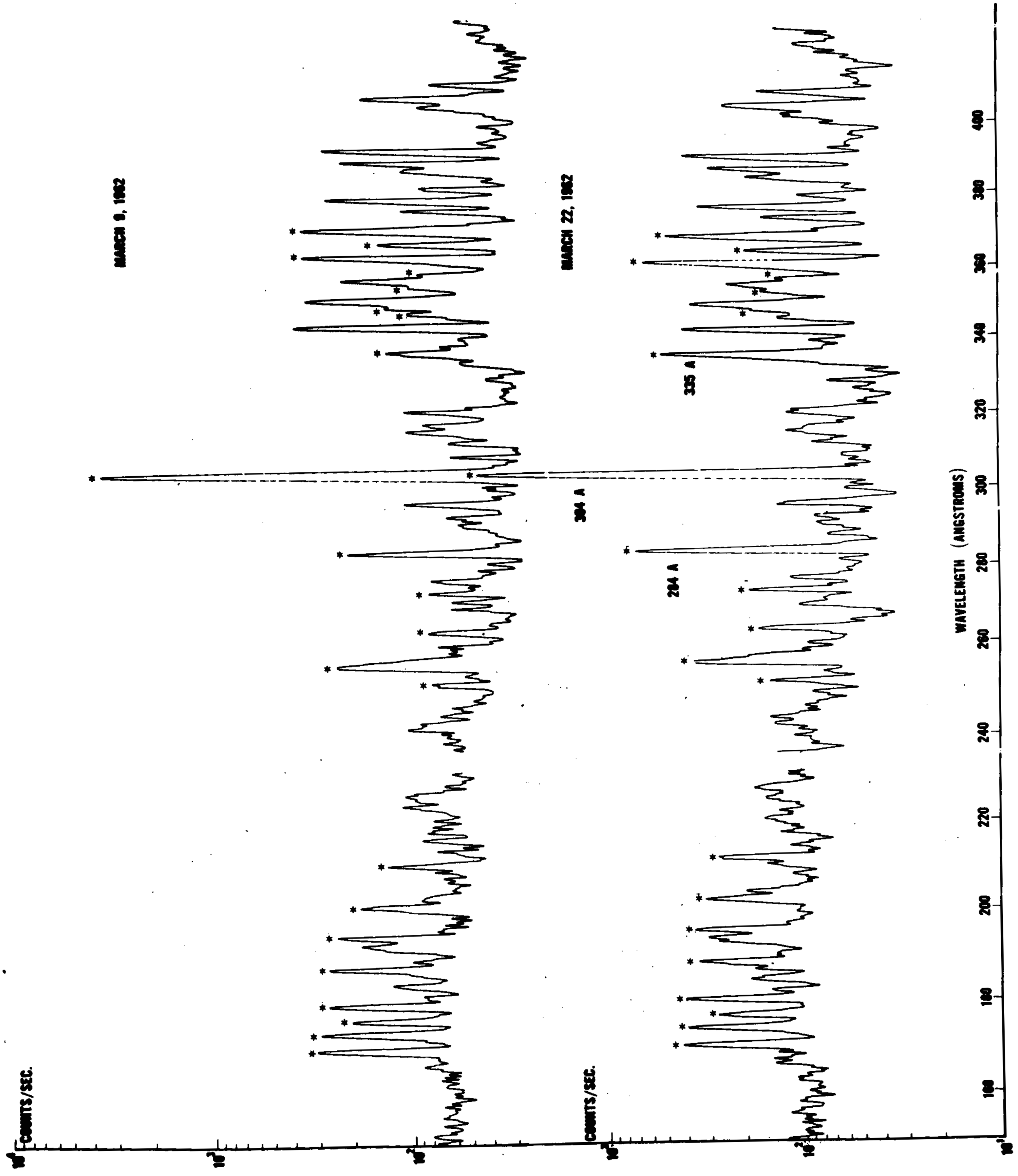
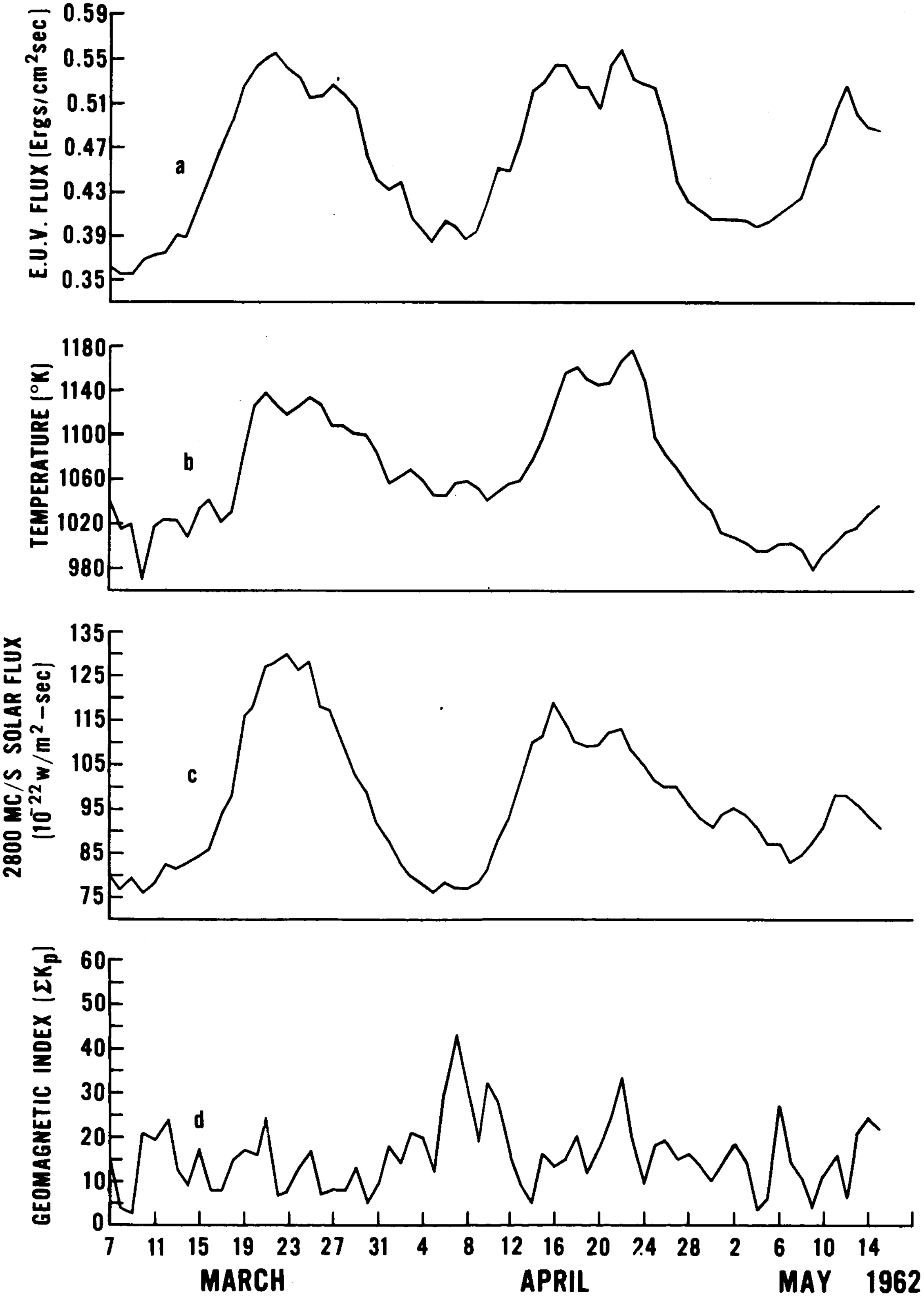
FIGURES

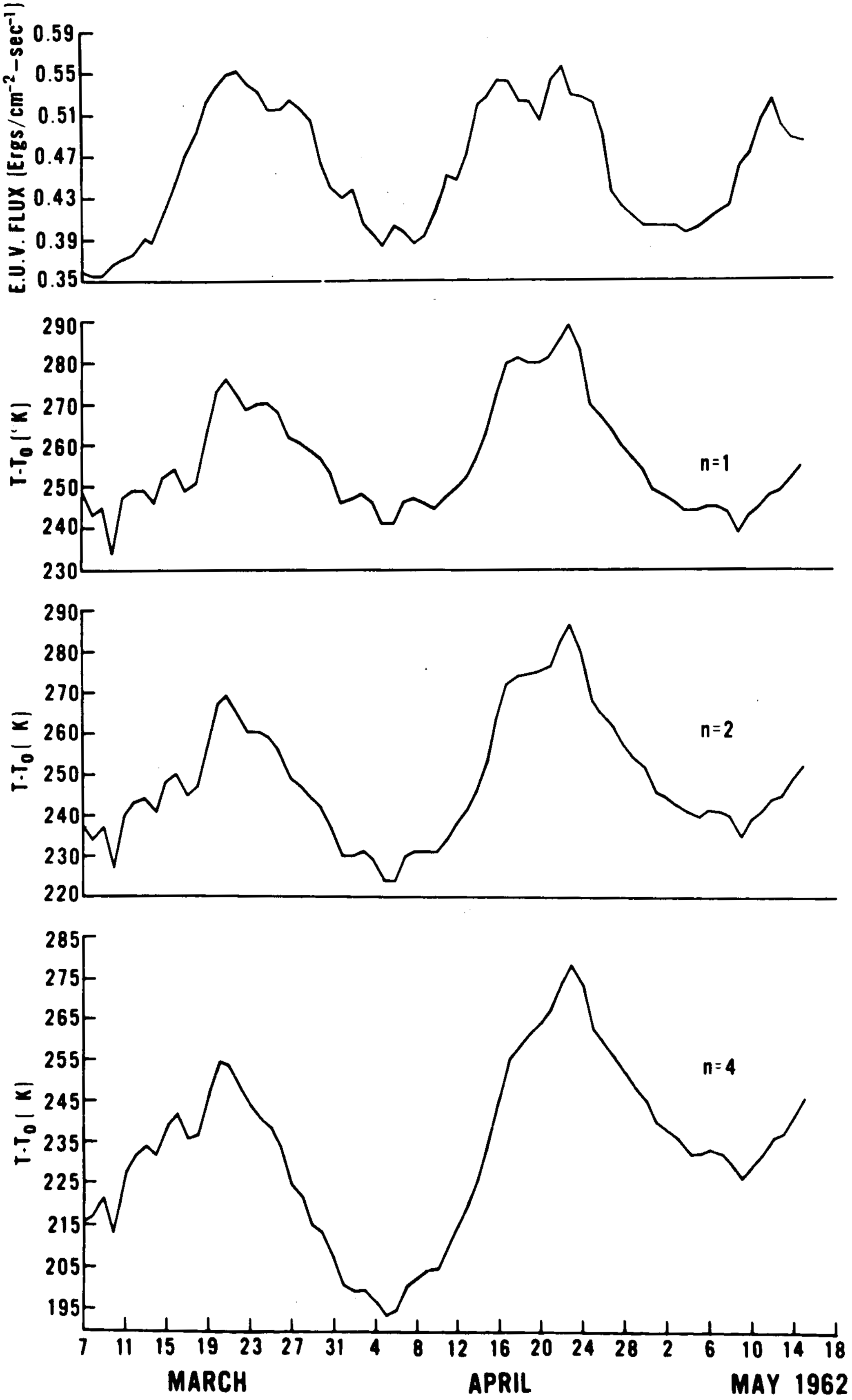
Figure 1. Spectra obtained by OSO-1, grating spectrometer for two days of different solar activity. The lines marked by asterisk were used in the present analysis. Unmarked lines above 340 Å represent second order images of lines observed at shorter wavelengths.

Figure 2. Comparison of the EUV flux with the atmospheric temperature, the 2800 Mc/s solar flux, and the geomagnetic index ΣK_p.

Figure 3. Comparison of the EUV flux with the diurnal amplitude as computed from Equation 1 for n = 1, 2 and 4.


MARCH 9, 1962
MARCH 22, 1962
304 A
284 A
335 A
COUNTS/SEC.
COUNTS/SEC.
10^4
10^3
10^2
10^3
10^2
10^1
WAVELENGTH (ANGSTROMS)
160
180
200
220
240
260
280
300
320
340
360
380
400


E.U.V. FLUX (Ergs/cm²sec)
0.59
0.55
0.51
0.47
0.43
0.39
0.35
a
TEMPERATURE (°K)
1180
1140
1100
1060
1020
980
b
2800 MC/S SOLAR FLUX (10⁻²² w/m²–sec)
135
125
115
105
95
85
75
c
GEOMAGNETIC INDEX (ΣKp)
60
50
40
30
20
10
0
d
7
11
15
19
23
27
31
4
8
12
16
20
24
28
2
6
10
14
MARCH
APRIL
MAY 1962


E.U.V. FLUX (Ergs/cm^{-2}–sec^{-1})
0.59
0.55
0.51
0.47
0.43
0.39
0.35
T-T$_0$ (°K)
290
280
270
260
250
240
230
n=1
T-T$_0$ (°K)
290
280
270
260
250
240
230
220
n=2
T-T$_0$ (°K)
285
275
265
255
245
235
225
215
205
195
n=4
7
11
15
19
23
27
31
4
8
12
16
20
24
28
2
6
10
14
18
MARCH
APRIL
MAY 1962