# Results of the Solar Disk-center Spectral Intensity Measurements in the Range 310–1070 nm

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**Abstract**

At the high-altitude station on the Peak Terskol (Central Caucasus, 3100 m a.l.s.) by the Main astronomical observatory of the National Academy of the Sciences of the Ukraine the spectral measurements of the solar disk-center intensity have been realized. Data published earlier (Solar Phys. **157**: 51–73, 1995) for near UV and visible range are now expanded on the longwave spectral region up to 1070 nm. The measurements are fulfilled with the specialized solar telescope. The method of of the solar disk-center brightness comparison with the brightness of the calibrated reference ribbon tungsten lamp was used. The atmosphere extinction was taken into account by Bouger's method with the parallel independent control of the atmosphere stability. The 1-nm integrals of the disk-center intensity in range 310—1070 nm now is available. The uncertainty of these values is estimated by 2%. In the regions with strong telluric absorption by oxygen and water vapour the supplementary reductions was interred, which was obtained from the synthetic atmosphere absorption spectra computed on the basis of molecular parameter atlas HITRAN and standard model of the atmosphere. With the help of solar disk darkening coefficients the values of the solar flux at 1 AU are derived. The comparison of the obtained data with the data by Neckel and Labs (Solar Phys. **90**: 205—258, 1984) is fulfilled as well as with the some other data. From the high-resolution FTS solar spectrum calibrated with our data we derived the solar continuum absolute location, which has proved more *smooth* than the continuum given by Neckel and Labs. Taking into account our previous measurements in the near UV and visible, we have compared the results of the solar and stellar spectro- and multicolor photometry in order to derive the most exactly adjusted data for solar spectral energy distribution, spectral energy distribution of Vega, and solar color-indices.

## 1 Objectives

- Last direct measurements of the absolute solar spectral radiation in wide UV, visible and IR region were performed at the beginning of 1960 (Labs and Neckel, Thekaekara et al., Arvesen et al.).

- The previous investigations fulfilled at the Peak Terskol have shown that the main uncertainties of our ground-based measurements were because of the uncertainty of standard radiation sources calibration, *not* because of the atmosphere extinction reduction procedure.

- The space platform oriented measurements has faced with the sufficient difficulties of calibration.

- The calibration for the ground-based measurements can be fulfilled much more precise and reliable then for the space-based ones.

## 2 Summary

- The spectral radiation data (disk-center intensity, irradiance at the 1 AU and continuum radiation temperatures) are now available for $\lambda\lambda$ 310—1070 nm range.

- Figure 1 shows the measured spectral (continuum + lines) intensity of the solar disk-center radiation in $10^{12}\ \mathrm{W} \cdot \mathrm{m}^{-3} \cdot \mathrm{ster}^{-1}$. The dot curve corresponds the data given by Neckel and Labs.

- Figure 2 shows the disk-center radiation temperatures for local maxima at 1-nm bands of the calibrated FTS Kitt Peak spectrum. Because of our integrals are free from atmosphere absorption but FTS spectrum is not, the *telluric* lines deviate *up* from continuum level while the *solar* lines deviate *down*. The continuum is located at the intervals free from the solar and telluric lines. Dashed line marks the data by Neckel and Labs, diamonds represent our results.

- The synthetic color-indices of the Sun are very close to that $U - B = 0.10$, $B - V = 0.62$ which are in the high accordance with the data for the normal G2V star. These values are in the contradiction with the measured by Tüg and Shmidt-Kaler ones (0.18 and 0.67). The synthetic value $V = -26.73$ is close to the commonly used $-26.75$.

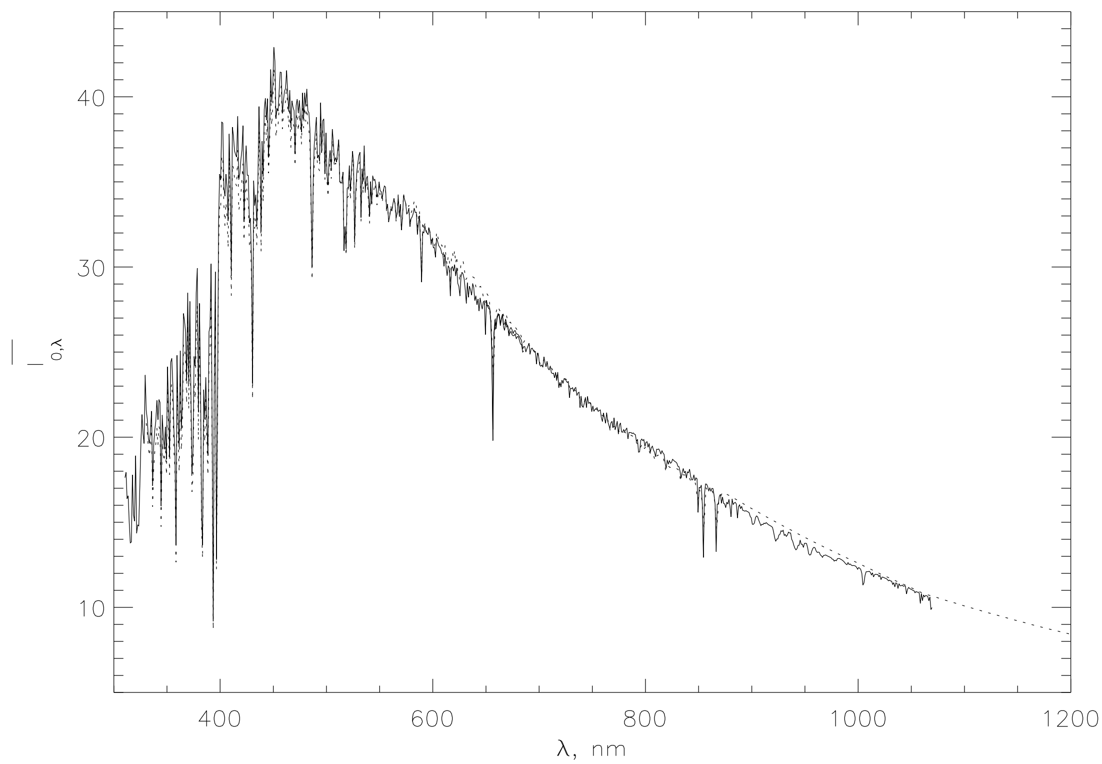


**Figure 1:** Spectral intensity of the solar disk-center radiation in $10^{12}$ W $\cdot$ m$^{-3}$ $\cdot$ ster$^{-1}$ versus wavelength in nm. The range $\lambda\lambda$ 645—685 is the common for both series of the measurements (UV and visible, 1989: Burlov-Vasiljev et al., 1995; IR, 1992: Burlov-Vasiljev et al., 1997). The dot curve corresponds to the data given by Neckel and Labs (1984).

## 3 Apparatus

The instrumentation adapted for quasi-simultaneous registration of the solar and standard ribbon tungsten lamp spectra was described by Burlov-Vasiljev *et al.* (1995). It has been installed at Peak Terscol (Central Caucasus, 3100 m a.l.s.) and consist of:

- **solar horizontal telescope** with coelostat group (main mirror $D = 230$ mm, $f = 3$ m)

- **grating spectrophotometer** with collimator ($D = 180$ mm, $f = 2$ m), camera mirror ($D = 230$ mm, $f = 2$ m), and grating (140 × 150 mm, 600 or 1200 grooves/mm) mounted in the vertical plane. Exit slit, quartz field lens and receiver (photodiode) are mounted on the scanning carriage, which is moved within 60 mm from the central point by a stepping motor. For the division of the diffraction orders and decreasing of the scattered light level the proper colored glasses is mounted just behind the entrance slit of the spectrometer

- **absolute calibration system** uses a ribbon tungsten lamp, which is placed at the focus of the collimating mirror ($D$ = 230 mm, $f$ = 3 m). Then the parallel beam is directed to the coelostat mirror and then along the same optical path as during observations of the Sun. The ribbon lamp was calibrated in units of the absolute spectral brightness

- **atmosphere halo photometer** is used for monitoring of the optical properties of the Earth's atmosphere

- **auxiliary equipment** to control the apparatus includes optical and electronical stuff for lamps feeding and control, for the investigations of the polarization properties of the coelostat group and spectrograph, for the measurements of spectral reflectivity of the lamp's collimator, etc.

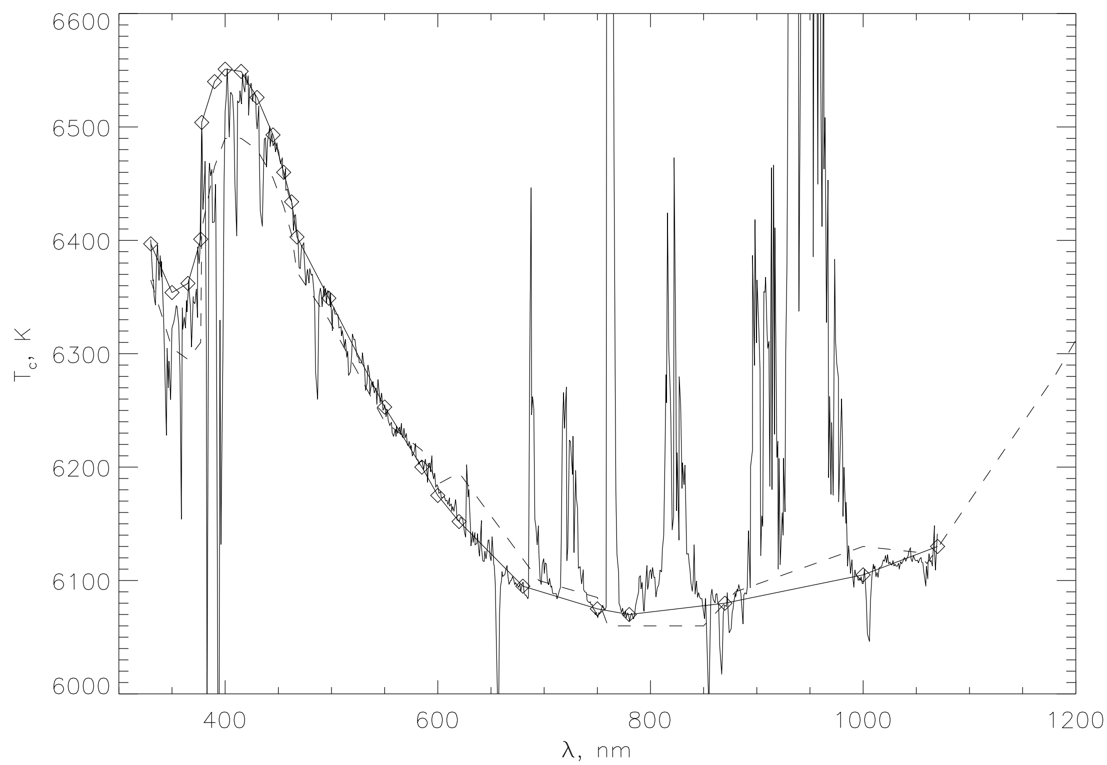


**Figure 2:** Disk-center radiation temperatures for local maxima at 1-nm bands of the calibrated FTS Kitt Peak spectrum, continuum of Neckel and Labs (1984) (dashed line), our results (diamonds). See explanations in **Summary** section.

# 4 Observations

Atmospheric extinction was taken into account by a Bouger's method. Therefore the procedure of measurements represents the repeated scanning of an elected area of a spectrum during a day at various air mass in a direction on the Sun. Usually the air mass were limited by a range 1.2—5.0. The measurements of a solar spectrum were accompanied by parallel measurements of the solar aureole brightness for a control of optical stability of the atmosphere. Before fulfillment the day program of the solar radiation observations the spectrum of the standard lamp in the same area was measured. Thus the image of the ribbon of the standard lamp was formed on the entrance slit of the spectrometer with the help of the spherical collimator mirror.

The two main series of measurements were carryed out: for $\lambda\lambda$ 310—685 nm (1989) and for for $\lambda\lambda$ 645—1070 nm (1992). The result of 1989 was derived from measurements during 7 days in UV region (310—400 nm) and 9 days in visible (400—685 nm) during the period July—August. Totally during 1992 were conducted 3 series of observations (March 24—April 7, August 4—8, September 29—October 1). All together there are 19 days of observations. For final result in IR were used the observations on April 2, 3, 6, 7 and October 1. All the days in March, on April 1 and on September 29, 30 were extracted because of unsatisfactory stability of the atmospheric transparency.

The investigated spectral area was divided into few areas, each of which was measured at a certain position of the diffraction grating. The adjacent areas were overlapped among themselves on 1/2 length.

## 5 Calibration

The absolute scale was supported with the help of two tungsten lamps (type TRU 1100-2350 #359 and #92) with 2×1 mm calibrated area on the ribbon. They were calibrated as radiance standards at the State Institute of Optical and Physical Measurements (Moscow, Russia). The accuracy of calibration was stated as 2.5% at $\lambda = 300$ nm and 1% at $\lambda = 1100$ nm.

During 1989—1990 years we had conducted numerous comparisons of our lamps with the standards of some other laboratories of former Soviet Union and with the standard of the PMOD/WRC (Davos, Switzerland). These measurements showed that during this period of several years (namely from the moment of the first calibration in 1988) the lamps saved the brightness within the limits of a parts of a percent.

The lamps were calibrated in 1988, 1989 and 1990. The differences between calibrations were within the accuracy bar stated above. During measurements of a the solar spectrum the lamps were used in different modes. The lamp #359 was used for calibration daily. The lamp #92 was used not so often – only for mutual comparisons with the lamp #359 in the very beginning and at the end of a series of observations. In result the time of burning of a lamp #92 is less in factor 10 than for a lamp #359. We believe that in this case the constancy of the ratio of two lamps brightness can be a criterion of preservation of an internal laboratory scale of measurements. It is very difficult to assume that both lamps will in coordination change the brightness at so different modes of use.

The measurements 1992 and result of calibration 1990 differ not more, than on 1%. We believe, that the scale of our measurements was constant within that limit.

## 6 Sources of Uncertainty

We have paid attention to the following possible sources of the measurements uncertainty:

- **Uncertainty of the lamp's collimator reflectivity.**

  For the forming of the image of a calibrated area of a lamp ribbon was used the spherical collimator mirror. Factor of reflection of the mirror was defined experimentally. Uncertainty of these measurement equals to 1% at $\lambda = 300$ nm, 0.3—0.5% at $\lambda\lambda$400—700 nm, and 1% at $\lambda = 1200$ nm.

- **Transmittance changes of the optical system.**

  The telescope transmittance changes during the day due to reflectivity changes of the coelostat mirror with the angle of incidence of the solar beam. Moreover, the light reflected by the coelostat is partially polarized, and the amount and character of polarization depends on the incidence angle. All of the following optical elements are sensitive to polarization. Thus their transmittance changes during measurements. It should be noted that the mirror reflectivity is influenced by dust: the decrease of reflectivity with an increase of incidence angle becomes more steep. The results of the special investigation can be summarized follows:

1. degree of linear polarization after the coelostat mirrors may change by 1—5% during the day
2. polarization properties of the whole spectrometer are mainly due to the grating
3. absorption caused by dust increases by 0.5% with increasing angle of incidence from $0^o$ to $40^o$, but influence of the dust upon the polarization properties is almost zero.

The maximum error caused by variation of the optical system transmittance can amount to 3%. But this error can be reduced substantially by choosing the coelostat position and time interval. By this means and with the use of grating with a small polarization effect, the uncertainty can be reduced to 0.1—0.2%.

- **Detector's stability between calibrations.**

  It was monitored by radioluminiscent emitters. Trend did not exceed 0.1—0.2% during several hours and the reproducibility is within the errors of measurements (about 0.2%).

- **Detector's linearity.**

  Because of differences of solar and lamp brightness, which is up to 4 order near $\lambda = 300$ nm, detector must have a high linearity. That is why we used silicon photodiode (spectral sensitivity ranges from 190 to 1100 nm).It was investigated with a set of neutral density filters calibrated at the State Optical Institute (St. Peterburg, Russia). Results demonstrated a high linearity over four orders of magnitude.

- **Lamp adjustment and feeding.**

  The transfer of the lamp calibration to the spectrometer is influenced by the following factors: accuracy of the lamp adjustment inhomogeneity across the ribbon surface, stability of the power supply, anisotropy of the radiation and possible temperature effects. Our measurements have shown that the resulting uncertainty is about 0.5% at $\lambda = 300$ nm and 0.2% at $\lambda = 1100$ nm.

# 7 Extrapolation to Zero Air Mass

Reduction to zero air mass was fulfilled by the Bouger's method with the independent monitoring of the atmosphere optical stability (with the help of the halo photometer and pressure control). For the "best" day the formal uncertainty of the extrapolated to zero air mass solar disk-center intensity $I_{\lambda,0}$ is about 0.3% (outside the molecular absorption bands). For the "worst" day adopted for the data evaluation this value is 1.5%. We have considered the following restrictions of the Bouger's method:

- **Monochromatic radiation.**

  In UV region the observations were performed with a resolution of 0.5 nm, and 0.1 nm in visible and IR. The error of the extrapolation to zero air mass because of nonmonochromatic radiation observed in UV and visible for these cases is less then 0.2%, but in some narrow regions of the strong oxygen and water vapour telluric bands in IR it can be extremely large: $\lambda\lambda$ 890—990 nm ($H_2O$) - up to 30% (for real water abundance at Peak Terskol); $\lambda\lambda$ 759—771 nm ($O_2$) - 75%! In the regions with the strong telluric bands we had to do the added reduction which was derived from the synthetic atmospheric absorption spectra computed on the basis of HITRAN molecular parameters data and standard model of the atmosphere. The uncertainty of these reductions needed in a few narrow bands is about few percent.

- **Accuracy of the air mass computation.**

  Usually the air mass of Bemporad is used. Straightforward analysis shows that Bemporad's air mass at some wavelength in UV (with telluric ozone bands) and IR (water vapour bands) even for observations with zenith distances less then $75^o$ may cause a relative error in the atmosphere transparency coefficient of about 3%. We performed a more elaborate calculation of air mass using real model of atmosphere over Peak Terskol and taken into account the dependence of air mass on $\lambda$ because of different contribution of Rayleigh scattering, telluric bands and aerosol extinction to air mass value at different $\lambda$. Obtained values is valid to within 0.1% for zenith distance less $80^o$.

- **Stable optical atmospheric conditions.**

  Instability of atmospheric extinction in wide wavelength range is mainly due to variations of the aerosol portion of the atmosphere. Moreover, special investigation fulfilled for Peak Terskol show that the atmospheric water vapour abundance is correlated with abundance of the *scattering* aerosol while the *absorbing* aerosole over Peak Terskol is mostly absent at all. For monitoring of the *scattering* aerosol stability we used atmosphere halo brightness measurements, which let us to find time with stable atmospheric transparency. As a rule it was only from sunrise to 10-11$^h$ of local time.

- **Absence of the scattered atmospheric radiation.**

  Multiple scattering of the light in the atmosphere would affect on the results obtained with Bouger's method at the high values of the atmospheric optical thickness (in strong telluric bands only at high air masses). We have carryed out the model computations to avoid the observations at these conditions.

# 8 Results

For each spectral record observed the dispersion function was founded with the accuracy of 0.1 nm. Then the records of relative solar spectral intensity $I^{\rm r}_{\lambda,m}$ obtained with different air mass $m$ for each day of the observations was evaluated to derived the extrapolated to zero air mass spectrum $I^{\rm r}_{\lambda,0}$. The absolute value of the disk-center intensity, $I_{\lambda,0}$, then was derived separately for each day of the observations as

$$I_{\lambda,0} = (I^{\rm r}_{\lambda,0}/I_{{\rm k},\lambda}) \cdot R_\lambda \cdot I_{{\rm tab},\lambda}$$

where $I_{{\rm k},\lambda}$ is the averaged record of the standard lamp spectrum obtained in the same instrumental scale as the solar spectrum record, $R_\lambda$ – reflectivity coefficient of the lamp's collimator mirror, $I_{{\rm tab},\lambda}$ – table values of the standard lamp absolute spectral intensity. Averaged result is

$$\overline{I_{\lambda,0}} = \frac{1}{\sum\limits_i \frac{1}{\sigma_i^2}} \sum_i \frac{I_{\lambda,0}}{\sigma_i^2},$$

where $\sigma_i$ is the standard r.m.s. error of $I_{\lambda,0}$ for every day of the observations. To obtain 1-nm integrals we considered the effect of the influence of the apparatus profile of the spectrometer on the the obtained spectrum $\overline{I_{\lambda,0}}$ ($\sim$0.1 nm wide). The result is shown in Figure 1. The uncertainty of the data is under 2% (except mentioned above regions of strong telluric absorption $\lambda\lambda$ 890—990 nm and $\lambda\lambda$ 759—771 nm, where uncertainty is estimated with value of 3% and 7% correspondingly).

To find out the absolute position of the solar "continuum" we used Fourier high-resolution spectrum obtained by Broult at Kitt-Peak calibrated by our absolute data. The spectrum was divided into 1-nm intervals and each piece was then independently calibrated by correspondent integrals. After that the local maxima of each peace was mark out. As the Fourier spectrum contains telluric bands which are absent in our data, telluric lines deviate up the local maxima while the solar lines deviate down these maxima from the smooth curve of the continuum. In Figure 2 we marked out points of the continuum chosen in the regions free from solar end telluric lines.

To find the solar irradiance (disk-averaged radiation) we used the ratio of disk/center intensities given by Neckel and Labs for integral spectrum ($\lambda < 685$ nm) and continuum. In Figure 3 is shown our and some other irradiance data as the ratio to the correspondent integrals by Neckel and Labs.

Irradiance data as the ratio to the correspondent integrals by Neckel and Labs:

——— present work,

◇◇◇ Shaw and Fröhlich (1979), Shaw (1982),

△△△ Wehrli (1992),

– – – – Lockwood, Tüg, and White (1992),

· · · · · Makarova, Kharitonov, and Kazachevskaya (1991),

– · · · – Arvesen et al. (1969).

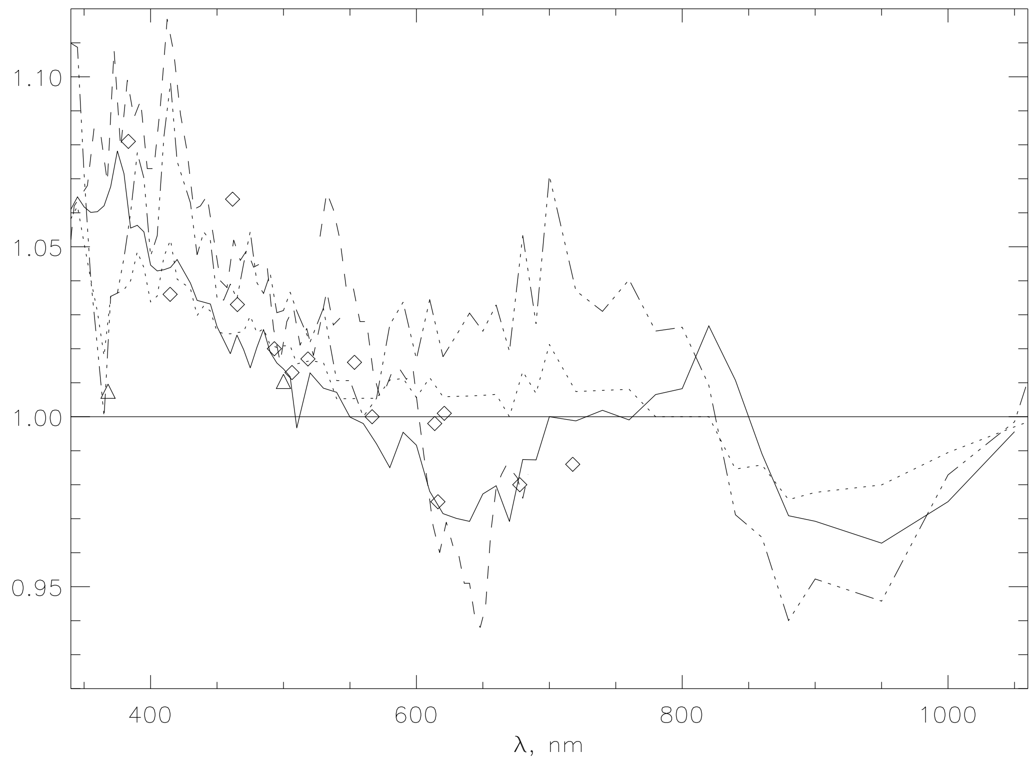


**Figure 3:** Disk-center radiation temperatures for local maxima at 1-nm bands of the calibrated FTS Kitt Peak spectrum, continuum of Neckel and Labs (1984) (dashed line), our results (diamonds). See explanations in **Summary** section.

# 9 Synthetic UBV

As the solar spectral irradiance data are available for the near UV, visible and IR range, we can compute the solar color-indices. Here we presents the results for $UBV$ system.

Different determinations give the value of 0.14—0.20 for $(U-B)_\odot$, and 0.63—0.69 for $(B-V)_\odot$ (Makarova et al. (1991)). The values $(U-B)_\odot = 0.18$ and $(B-V)_\odot = 0.67$ are adopted. These values differ from the standard meanings for G2V star (0.10 and 0.62 respectively) and are more close G5V (0.20 and 0.68). The absolute magnitude of the Sun $V_\odot = -26.70$ now is commonly used.

To compute the solar color-indices and absolute magnitude we used the relative reaction curves for $UBV$ system, given by Buser (1978), calibrated by the spectral energy distribution for Vega. We consider here the following data sets for Vega: by Hayes (1985), Archarov et al. (1989), Terez (1983), Knyazeva and Kharitonov (1988). In the case of necessary the absent data at 300 nm was added.

| $U-B$ | | | Sun | | |
|---|---|---|---|---|
| Vega | Neckel and Labs | Makarova et al. | Present work | Thekaekara |
| Knyazeva & Kharitonov | 0.1608 | 0.1770 | 0.1454 | 0.0944 |
| Terez | 0.0798 | 0.0961 | 0.0645 | 0.0134 |
| Archarov et al. | 0.1204 | 0.1367 | 0.1051 | 0.0540 |
| Hayes | 0.1024 | 0.1187 | 0.0871 | 0.0360 |
| $B-V$ | | Sun | | |
| Vega | Neckel and Labs | Makarova et al. | Present work | Thekaekara |
| Knyazeva & Kharitonov | 0.6318 | 0.5893 | 0.6008 | 0.5645 |
| Terez | 0.6583 | 0.6158 | 0.6273 | 0.5911 |
| Archarov et al. | 0.6461 | 0.6036 | 0.6151 | 0.5789 |
| Hayes | 0.6767 | 0.6342 | 0.6457 | 0.6095 |
| $V$ | | Sun | | |
| Vega | Neckel and Labs | Makarova et al. | Present work | Thekaekara |
| Knyazeva & Kharitonov | -26.7453 | -26.7291 | -26.7483 | -26.6787 |
| Terez | -26.7469 | -26.7307 | -26.7499 | -26.6803 |
| Archarov et al. | -26.6710 | -26.6548 | -26.6740 | -26.6044 |
| Hayes | -26.7462 | -26.7300 | -26.7491 | -26.6795 |

One can see that the values of the color-indices more close to G5V star are in the contradiction with the solar and star absolute spectrophotometry. Moreover, as the both of the color-indices are not independent, they *must* lie on the normal stars Main Sequence in the twocolors $UBV$ diagram. We could find two close pairs of the spectrophotometer curves for the Sun and Vega, respectively present work — Archarov *et al.*, and Makarova et al. — Terez, which satisfy to this requirement. In both cases solar color-indices are typical for G2V star. The solar absolute magnitude $V_\odot$ obtained from spectrophotometry is close to commonly used.

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