THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME LXXI | APRIL 1930 | NUMBER 3

SPECTRAL ENERGY-CURVE OF SUN-SPOTS[1]

By EDISON PETTIT and SETH B. NICHOLSON

ABSTRACT

Ratio of the energy in the umbra of the spot to that in the photosphere.—This was measured between λ 0.4 μ and λ 2.2 μ by a thermocouple attached to a monochromator mounted in the focal plane of the 150-foot tower-telescope. That portion to the violet of λ 0.4 μ was determined by photographic photometry with an all-speculum optical system, the image-forming mirror being of 60 feet focal length. The mean curve shows that the spot-photosphere ratio varies in a nearly linear manner from 0.21 at λ 0.3 μ to 0.80 at λ 1.7 μ, after which it is nearly constant.

Sources of error.—Depressions at λ 1.38 μ and λ 1.9 μ may possibly be reflected errors due to the deep water-vapor bands at these points. The color-curve of the objective of the tower-telescope being unknown in the red, no corrections could be made for focus. The great focal ratio of this objective (150/1) probably gave sufficient depth of focus to offset this effect partially. The same argument applies to the stigmatic focus of the concave-grating spectrograph used in the measurements to the violet of λ 0.4 μ.

Spectral energy-curve of sun-spots.—This was obtained by multiplying the solar energy-curve for the center of the disk by the spot-photosphere ratios in different wave-lengths. The resulting spectral energy-curve is much like that for the photosphere and corresponds in total energy to a black body at 4860° K.

Temperature of the sun from the solar constant.—The rate of radiation at the center of the disk is 16 per cent greater than that of integrated sunlight, which makes the rate for this point 2.25 cal cm^{-2} min^{-1} and the corresponding temperature from the fourth-power law 5955° K.

Scattered radiation.—The total scattered radiation from the sky and instrument was measured at a point 15″ off the limb of the sun and found to be 0.037 of the intensity at the limb, or, at the center of the disk, 8 per cent of the photospheric light. If the solar energy-curve is assumed to be that of a black body at 5955° K, the energy-curve of the spot fits that of a black body at 4750° K fairly well except to the violet of λ 0.7 μ, where it is in excess. This amounts to 6 per cent of the area of the curve; hence the measured scattered radiation from the sky and instrument is more than double that necessary to explain this excess.

Total energy in the umbra.—This was measured directly with the thermocouple and found to be 0.471 that of the photosphere. The value computed from the curve of the ratio of spot to photosphere is 0.477.

[1] *Contributions from the Mount Wilson Observatory, Carnegie Institution of Washington*, No. 397.

Distribution of energy over a spot.—A thermocouple was mounted on a moving plate connected with the registering device. This traced the distribution of energy across the spot. In all cases the energy falls continuously from the photosphere to about half-intensity at the umbra and shows no tendency to increase there. Microphotometer runs across spots with connecting bridges show some of this effect however.

Temperature of sun-spots from water-cell measurements.—The water-cell absorption of a spot is 0.50 mag. for average position on the disk, which corresponds to spectral classification dG7 and temperature 4720° K.

An investigation of the spectral energy-curve of sun-spots between 0.4 μ and 2.2 μ was undertaken at the 150-foot tower-telescope in July, 1922, and completed in September, 1922. The apparatus consisted of a Hilger constant-deviation spectroscope arranged as a monochromator with vacuum thermocouple attached and has already been briefly described.[1] The 17-inch solar image was projected horizontally by means of a plane mirror upon a white cardboard screen over the first slit of the monochromator. A pinhole in this screen admitted light to the slit, making it possible to set an image of a sun-spot or a definite point on the photosphere upon the slit with the electric slow motions of the coelostat. For more accurate guiding during an exposure the whole monochromator was mounted on a double slide so that it could be moved in rectangular co-ordinates in the focal plane, by means of two screws, to follow the spot image while an energy-curve was being traced.

The tangent screw of the monochromator prism table was connected through rods and gearing to a photographic recording device[2] which registered a trace from the D'Arsonval galvanometer connected with the thermocouple. The 7×17-inch plate in the registering device was driven at the rate of approximately 1 inch per minute, an entire trace from λ 0.4 μ to λ 2 μ requiring about 15 minutes.

The general procedure consisted in taking a trace with the slit of the monochromator set on a point of the photosphere just north of the penumbra of the spot, a second trace on the umbra, and a third on a point just south of the penumbra, all curves being recorded on the same plate. In other cases two traces were made on the umbra of the spot and one on the photosphere. Figure 1 illustrates such a record.

The plate was then placed on a comparator and the ordinates were

[1] *Mt. Wilson Contr.*, No. 336; *Astrophysical Journal*, **66**, 43, 1927.

[2] *Journal of the Optical Society of America*, **10**, 267, 1925.

measured in steps of 0.05 μ, and the ratio of the ordinates of the spot-curve to the average of the corresponding ordinates of the two curves from the photosphere or the average of the ordinates of the two spot-curves to that of the curve from the photosphere, as the case might be, was formed for each wave-length. Figure 2 is a plot of these ratios of spot umbra to photosphere for six plates on two spots thus obtained in September, 1922, under good conditions of seeing. The open circles are observations made by Abbot with the bolometer in the Snow telescope in August, 1905.[1] His method consisted in setting the spectrobolometer for a given wave-length and causing the spot to drift across the slit with the lunar gears of the coelostat. The ratios for five wave-lengths were determined from drift-curves traced in this way.

That part of Figure 2 to the violet of λ 0.4 μ was determined by photographic photometry[2] with a 1-meter concave-grating spectrograph mounted Eagle fashion. A 6-inch concave speculum mirror of 60 feet focal length formed the image for this spectrograph and was fed by one reflection from a speculum-mirror coelostat. The 6-inch solar image fell upon a card in front of the slit, light being admitted to the latter through a pinhole. In some cases a quartz enlarging lens which gave an

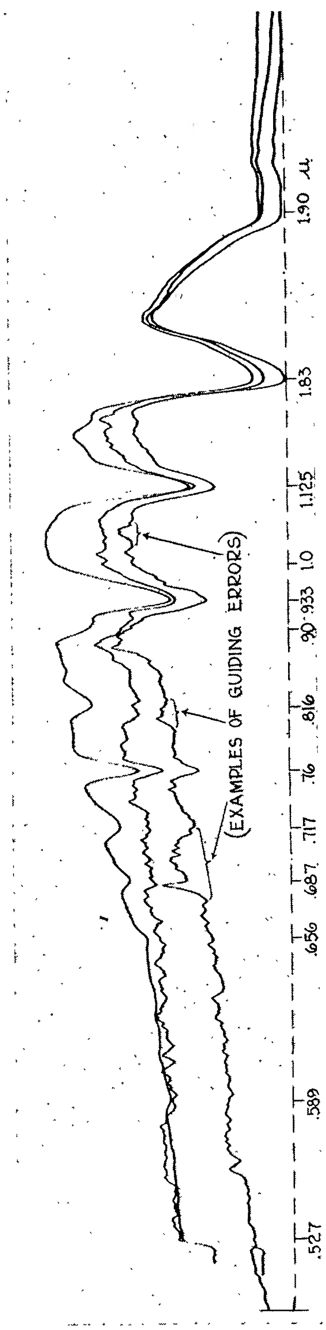

FIG. 1

[1] *Annals of the Astrophysical Observatory, Smithsonian Institution*, **2**, 233, 1908.

[2] *Mt. Wilson Contr.*, No. 336; *Astrophysical Journal*, **66**, 43, 1927.

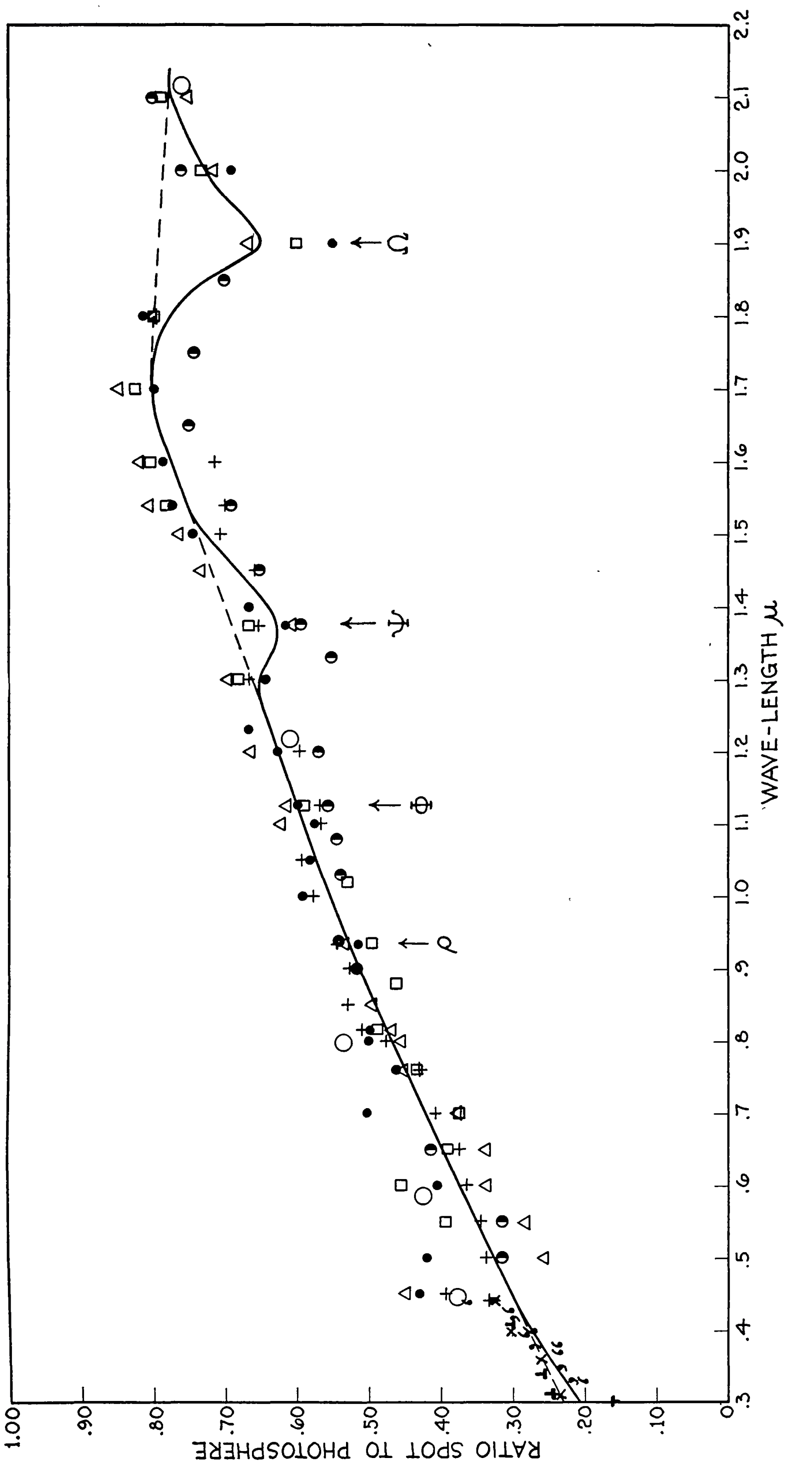
RATIO SPOT TO PHOTOSPHERE
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
0
WAVE-LENGTH μ
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2.1
2.2

FIG. 2

equivalent focal length of 150 feet was used. The spectrograph was mounted on a stand which permitted slow motion in rectangular co-ordinates in the focal plane for guiding on the spot during the exposure. The method of timed exposures was used with plates and development as already described.[1] When the spectrograph is used in the ultra-violet of the first order the stigmatic focus of the solar image is about 5 cm in front of the slit, but since the ratio of focal length to aperture of the image-forming mirrors is 120 to 300, only a small area about 1 cm in diameter on the grating was used; hence the great depth of focus of the spectrograph made this stigmatic effect practically ineffective. The points shown in Figure 2 to the violet of λ 0.4 μ were obtained on a spot in August, 1927.

The curve in Figure 2 is nearly linear, being slightly convex between λ 0.3 μ and λ 1.7 μ; for greater wave-lengths the ratio, spot to photosphere, appears to be nearly constant. The positions of the atmospheric water-vapor absorption bands are indicated by their symbols. Rather marked drops in the curve will be seen at Ψ and Ω, although none show for the other bands. Whether these are real or merely reflected effects of these deep bands on the measurement of the relatively small quantities is difficult to decide until additional data are available.

Since the color-curve of the objective of the tower-telescope is unknown in the infra-red, it is possible that the curve in Figure 2 to the red of λ 0.8 μ is somewhat too high owing to a mixture of partial pencils of photospheric light in this region with that from the umbra of the spot. No attempt was made to correct the focus, but the great focal-length aperture ratio, 150, of the objective in the tower-telescope probably gave a depth of focus sufficient to offset this effect somewhat. On the other hand, the observations in the infra-red agree well with those of Abbot made with a mirror telescope, and in the visual region run even somewhat less than those of Abbot. The photographic measures in the ultra-violet, which were made with a mirror telescope, show no pronounced discontinuity and check the overlapping radiometric measures between λ 0.4 μ and λ 0.45 μ fairly well. It is hoped that further work may be done with an all-mirror system.

[1] *Ibid.*

Energy-curve of sun-spots.—Curve A in Figure 3 is Abbot's solar energy-curve[1] for the center of the disk to which our spot measurements refer. Curve C is obtained by multiplying the ordinates of curve A by the ratio of the energy in the umbra of the spot to that in the photosphere read from Figure 2 for the corresponding wave-lengths.

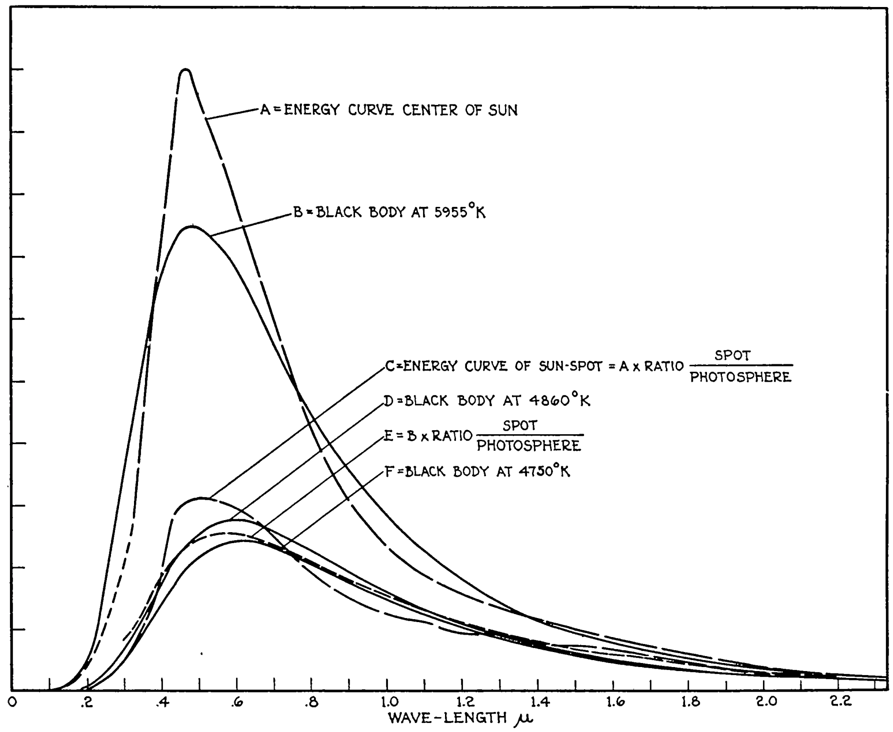

FIG. 3

That the energy-curve C of a sun-spot is not that of a black body is seen by the following argument. The ratio of the area of curve C to curve A should be the ratio of their total energies and is 0.445. The total energy of integrated sunlight is the solar constant, 1.94 cal cm^{-2} min^{-1}. The rate of radiation from the center of the disk where the sun-spot measurements were made is 1.16 times this quantity,[2] or 2.25 cal cm^{-2} min^{-1}, which corresponds to a black-body temperature of 5955° K. This is the temperature of the photosphere given by total radiation measurements and would appear to

[1] *The Sun* (1929), p. 107; *Annals of the Astrophysical Observatory, Smithsonian Institution*, **3**, 159, 1913.

[2] *Mt. Wilson Contr.*, No. 299; *Astrophysical Journal*, **62**, 210, 1925.

be the best value of the temperature of the sun derived from the solar constant. If the spot radiates like a black body, its temperature is therefore

$$T = 5955^\circ \text{ K} \times \sqrt[4]{0.445} = 4860^\circ \text{ K} .$$

Curve D in Figure 3 is a black-body energy-curve for this temperature having the same area as the sun-spot energy-curve C. It appears from curves D and C that, generally speaking, the sun-spot has more energy than the black-body curve for wave-lengths to the violet of $\lambda\, 0.7\ \mu$, and correspondingly less for wave-lengths to the red. A considerable part of the deviation of the sun-spot energy-curve C from a black-body curve such as D is due to the deviation of the solar energy-curve A from the black-body curve. To demonstrate this the black-body curve B for 5955° K has been drawn with the same area as the solar energy-curve A, and from it the energy-curve E has been drawn by multiplying B by the ratio, spot to photosphere, as was done to obtain curve C. It will be seen that this curve lies for the most part between the black-body curve F for 4750° K and D for 4860° K, agreeing to some extent with the former in wave-lengths greater than about $0.7\ \mu$.

Scattered photospheric light.—A comparison of the spectra of photospheric light with those of sun-spots used to obtain the ultra-violet portion of the curve in Figure 2 shows little difference between the two in the region below the calcium lines H and K. This suggests that the spot spectrum has superposed upon it a considerable amount of photospheric light which would in turn explain the deviation of the energy-curve E of the spot spectrum (computed from the black-body curve B) in the visual and ultra-violet region from the energy-curve F of a black body at 4750° K. The area between these two curves to the violet of $\lambda\, 0.7\ \mu$ is only 0.06 of the area of curve E; hence it might be thought that this represents the order of magnitude of the total scattered photospheric radiation. This scattered photospheric light may be from the sky, the instruments, and from the spot itself, where the photospheric light projected into the spot is scattered by the gases there to the observer along with the intrinsic light of the spot.

The total scattered radiation in the instrument and sky was measured at the limb of the sun with the thermocouple behind a pinhole diaphragm as described below. The radiation from the sky and the instrument 15″ outside the limb of the sun was found to be 0.037 of that 15″ inside the limb of the sun. In order to approximate the conditions of scattering in a spot we may imagine another sun placed on the other side of the point, 15″ away, so that it would be practically surrounded by the two solar disks, whence the scattered light would have been 0.074 of the intensity 15″ inside the limb. After allowing for the increase in scattered light toward the center of the disk it appears from this rough estimate that scattering in the earth's atmosphere and the telescope will amount to fully 8 per cent or more of the photospheric radiation or 16 per cent of the total radiation received from the spot, which is approximately half that of the photosphere, as will be shown shortly. The radiation scattered by the sky and instrument is therefore more than twice as much as that necessary to explain the deviation of curve E from curve F.

Total energy in the umbra.—We may measure the whole radiation in the spot directly with the thermocouple and compare the result with that obtained from spectral distribution of energy. For this purpose the thermocouple was placed directly behind a pinhole in a card and mounted in the focal plane of the 150-foot tower-telescope. With this arrangement the ratio of the whole radiation received from a small area of the photosphere on each side of the spot was compared with the same area of the umbra. From twenty measures on six different spots in October, 1921, this ratio was found to be 0.471. The greatest value was 0.521 and the least 0.428. The solar energy-curve at the earth's surface on Mount Wilson was then multiplied by the transmission of the objective and the reflecting power of the silvered mirrors of the tower-telescope, ordinate by ordinate, and the resulting area compared with that obtained by multiplying this same curve by the ordinates of the curve in Figure 2. The ratio of the latter to the former, which should be the ratio of the total energies in the spot and the photosphere, is 0.477, which agrees quite well with that (0.471) determined above from direct measurement. The very small pinhole, approximately 0.01 mm in diameter, which could be used in these measurements made the check the more rigorous, since the aperture used over the slit of the monochromator was approximately 0.5 mm in diameter, which gave a usable slit about 0.5×0.1 mm.

In order to study the distribution of total energy over the spot, the thermocouple with its pinhole diaphragm as used above was mounted on a screw-driven plate which was connected with the photographic registering device by a rod and gears, as in the case of observations of the spectral energy-curve. In this manner the thermocouple with its pinhole diaphragm was made to move across the spot

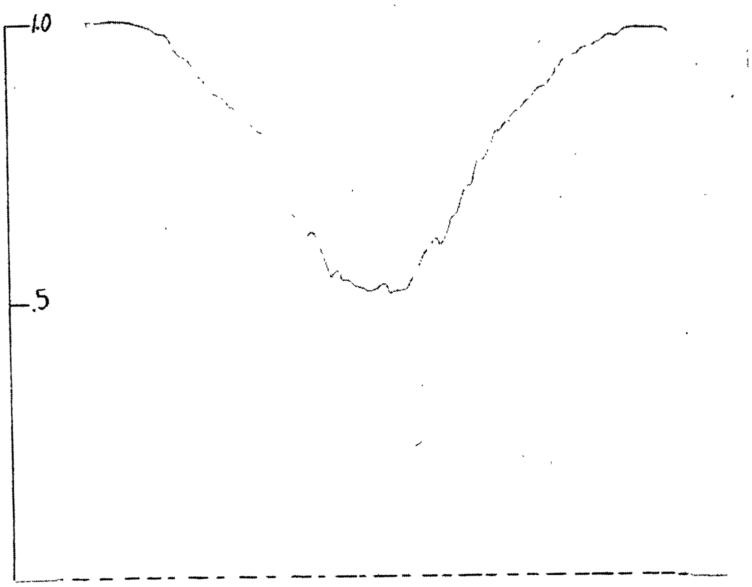

FIG. 4

while the galvanometer traced the corresponding distribution-curve in the registering device. Figure 4 is a reproduction of such a trace.

It will be noted that in Figure 4 the total energy falls continuously from the photosphere throughout the penumbra to the umbra, where it remains fairly constant at about half the photospheric intensity, as was found from the deflections described above. It will be recalled that Secchi[1] believed that the penumbra actually became brighter toward the periphery of the umbra, which his drawings strongly represent, and explained it by the convergence of the penumbral filaments toward the umbra.[2] None of our curves shows

[1] *Le soleil*, 1, 81, 1875.

[2] Russell, Dugan, and Stewart, *Astronomy*, 1, 200, 1926; Young, *The Sun* (1910), p. 116.

this effect, and considerable experience in drawing the daily polarity charts at the 150-foot tower gives visual confirmation of this result. Secchi's observation is possibly an effect of contrast. Some microphotometer runs made on a photograph of spots crossed by penumbral bridges show, however, something of the effect along the bridge. How much photographic contrast is involved is difficult to estimate.

The temperature of a sun-spot from water-cell measurements.—The water-cell absorption of the umbra of a spot near the center of the disk measured at the 150-foot tower-telescope is 0.47 mag., while the photosphere at the center of the disk gives 0.38 mag. The water-cell absorption for integrated sunlight[1] with two reflections from silver, but without the lens of the tower-telescope, is 0.41 mag. The difference of 0.03 mag. is probably due to the difference between the center of the disk and integrated sunlight. This would make the water-cell absorption for spots in an average position on the sun 0.50 mag., the corresponding spectral classification[2] dG7, and the temperature 4720° K. That the water-cell absorption of a spot should be affected in this manner by its position on the solar disk is indicated by measurements made on a spot in solar longitude 75° west of the central meridian and 8° north latitude, which gave a water-cell absorption of 0.7 mag. Such measurements are difficult, however, on account of the steep energy distribution-curve of the photosphere at the limb of the sun, and further observations will be necessary to determine accurately the water-cell absorption of a spot so near the limb.

We have finally the following comparative temperature data:

Temperature of the photosphere at center of disk	5955° K
Temperature of sun-spot umbra from spectral distribution of energy	4860°
Temperature of sun-spot umbra from spectral distribution of energy corrected for scattered light	4750°
Temperature of sun-spot umbra from water-cell absorption	4720°

From these data it appears that the temperature of the umbra of a sun-spot is probably near 4800° K, or possibly a little less.

Carnegie Institution of Washington
Mount Wilson Observatory
January 1930

[1] *Mt. Wilson Contr.*, No. 369; *Astrophysical Journal*, **68**, 289, 1928.

[2] *Ibid.*, p. 297, Table V.