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Photographic photometry of the Milky Way and the colour of the Scutum cloud

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In November 1919 I proposed to Prof. MAX WOLF, Director of the Heidelberg Observatory, a method for photographic photometry of the Milky Way by extrafocal exposures. Since in ordinary Milky Way photographs the impression of brightness, caused by more or less crowded little starspecks, does not directly and in a simple way correspond to the starlight per unit surface (the discrepancy is strongly shown by starclusters), they cannot be used to deduce numerical values for its photographic brightness. If, however, each starpoint is extended to a circle, the mean surface brightness of the sky over such a circle may be measured by the blackness of the plate; the scale being afforded by the extrafocal images of the bright stars on the plate. Such a picture will bear a much greater resemblance to the visual aspect of the Milky Way than an ordinary photograph. I proposed to make the diameter of the star images ½°; expecting that in that case the stars visible to the naked eye would appear separately. Professor WOLF, obliging as ever, immediately was willing to take the negatives. The first set of plates, taken in 1920, having been by some unknown cause damaged by scratches in the middle parts, he took a second set in 1921. The results of the first plate measured of this second set are the subject of the present communication.

The instrument used was a ZEISS Tessar of 31 mm aperture and 145 mm focal distance. Plate C 542, central star λ Aquilae, was exposed 1921 July 31, 10^h37^m—13^h47^m (190^m) and was developped with 6—7% rodinal. The stars have images of 1.73 mm diameter in the centre; more than 2 cm from the centre they become slightly elongated and at 4 cm distance they are ellipses with axes 1.67 radially, 1.79 tangentially, thus having the same surface as in the centre. They are not equally blackened over the whole surface; a border ring of 0.19 mm breadth, blacker than the rest, is at once visible. The background shows the features of the Milky Way very faintly, much less brilliantly than focal images taken with the same exposure time; evidently the same radiant energy concentrated upon a limited number of small starpoints reduces more silver than if diluted equally over a large surface. The density of the silver deposit (the blackness) in the centres of the stardiscs and on the background was measured with the HARTMANN photometer of the Institute.

Investigation of the microphotometer.

Our microphotometer, constructed by BAMBERG (Berlin) is provided with a wedge made at Potsdam and kindly procured by Professor HERTZSPRUNG. Special measures were made to find the relation between the scale reading x (linear displacement of the wedge) and the blackness s (defined as log I/I_0). This relation is not linear, as is shown by the following results of one series of measures, where the same difference of blackness between two points of the plate was, by putting different shades before the plate, measured at different places of the wedge:

1st reading	6.9	18.9	26.3	36.7	39.8	46.2	51.1	60.4
2d reading	23.1	29.2	34.8	43.0	46.0	52.2	57.9	67.6
Difference	16.2	10.3	8.5	6.3	6.2	6.0	6.8	7.2

The difference between the two readings has a minimum in the middle parts of the wedge; for the denser part it is somewhat and for the thinner part it is much greater. Thus the curve $s = f(x)$ has a point of inflexion in the middle part of the wedge. We will take as unit of blackness a scale unit at this point of inflexion. From a curve representing the differences of the table as a function of the first reading we take that to a value of the first reading

8.0 23.4 32.5 39.5 45.7 51.8 58.4

belongs a value of the difference and thus a second reading

15.4 9.1 7.0 6.2 6.1 6.6 7.2
23.4 32.5 39.5 45.7 51.8 58.4 65.6

Thus the values

8.0 23.4 32.5 39.5 45.7 51.8 58.4 65.6

form a series of readings with equal difference of blackness. Putting this difference 6.0 (the minimum of the curve) and proceeding from 45.7 (lying nearest to the point of inflexion) the values.

21.7 27.7 33.7 39.7 45.7 51.7 57.7 63.7

represent the corresponding blackness in the adopted homogeneous scale. And the corrections, that must be applied to this series of readings, are

+13.7 +4.3 +1.2 +0.2 0.0 −0.1 −0.7 −1.9.

In this way from all series of measures corrections to the scale readings were deduced. These corrections, condensed into means of 5, are found in Table 1.

TABLE 1. Corrections to scale readings.

x	11.4	20.7	26.7	32.6	37.0	40.9	45.1	48.8	53.0	57.1	62.3	66.9
$s-x$ (obs.)	+11.0	+ 5.7	+ 2.9	+ 1.1	+ 0.3	+ 0.1	0.0	0.0	− 0.2	− 0.6	− 1.3	− 2.2
$s-x$ (form.)	+11.1	+ 5.4	+ 2.8	+ 1.2	+ 0.4	+ 0.1	0.0	0.0	0.0	− 0.2	− 1.1	− 2.6

Now the so called wedge was made from a photographic plate by giving it — by means of a sensitometer — an exposure increasing from one side to the other, in such a way that log t varies proportionally with the linear coordinate. Thus the relation found here between blackness and scale reading must be the same as the relation between blackness and log t. For the relation between the intensity L and the blackness s produced by it HERTZSPRUNG (*Astr. Nachr.* **190** Nr 4543) proposed the formula

$$\log (s - s_0) = a + b \log L - c (\log L)^2$$

where s_0 is the blackness of the non-illuminated part of the plate. Since for these moderate exposures $Lt^p = \text{const.}$ the same formula holds if log L is replaced by log t; thus we have also (with other coefficients)

$$\log (s - s_0) = a + b\,x - c\,x^2.$$

From the data of Table 1 the following numerical values were found

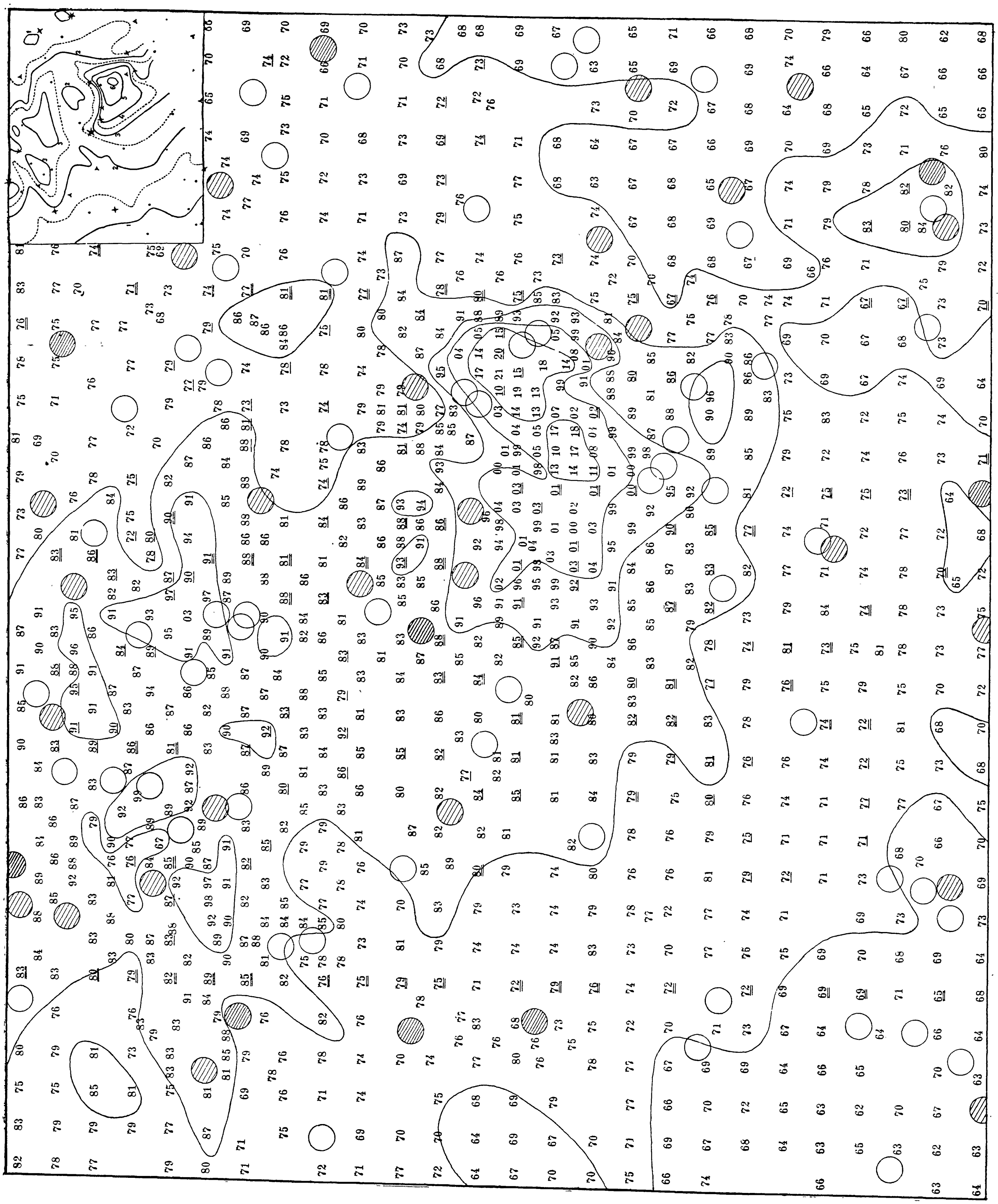
$$\log (s - 18.64) = 0.174 + 0.0390\,x - 0.000251\,x^2.$$

The very good concordance between the $s - x$ deduced from the measures and from the formula shows that, though it does not pretend to be more than an interpolation formula, it is at least an excellent one. A correction table, computed from this formula, has been used throughout to reduce the scale readings of the microphotometer to „measured blackness".

Measures of the Milky-Way negative.

On the λ Aquilae plate the background was measured at regularly distributed points, the corners of squares of 2 mm, sometimes completed by the centres of these squares. Each measure consisted of 3 settings of the wedge. From all stars met in executing these series the centre of the disc was measured. Stars down to 7.5^m are separately visible, a greater number than had been presumed; evidently the discs should have been somewhat greater to cause the 7^m stars to be also dissolved in the background light. Gaps caused by stardiscs covering the regular points were afterwards filled up by other points, at least where this was not made impossible by dense groups of stars. The series of different days were reduced to a common system by a number of common points repeatedly measured. From them the mean error of one measure was found to be 0.23 scale units. The main part of the measures was made by D. KOELBLOED, computer of the Institute.

At first the value s_0, found from the non illuminated borders of the plate, was subtracted from the measured blackness to get the blackness $s - s_0$ caused by the light from the sky. This will be called henceforth s. It must be corrected for distance-error, because the same brightness of the sky produces a blackness greatest in the centre, for perpendicular rays, and decreasing with increasing obliquity of the rays. The areas on the plate corresponding to equal areas of the sky increase with $\sec^3 i$; the transverse section of the incident pencil of light varies with $\cos i$; thus by purely geometrical reasons the light varies as $\cos^4 i$. Since the losses by reflection and absorbtion are also greater for oblique rays, the real reduction of brightness is still greater. It may be determined by a series of plates where the centre of each coincides with the edge of another. I have made a provisional estimate of its amount by using the mean blackness in rings at different distances from the centre; by eliminating as well as possible the influence of real differences in brightness, the distance error was found nearly proportional to $\cos^8 i$. Thus the factor $\sec^8 i$ (for the middle portions of the plate used in this research it does not surpass 1.3)



was adopted to reduce the measured s to the centre.

The values of s reduced in this way are inserted in the accompanying chart (scale $3^1/_2 \times$ original negative); they are given in two figures denoting tenths of scale readings. Where they surpass 100, only the two last figures are put down in order to save space. Values based on two, or on more measures are once or doubly underlined. The brighter stars are indicated by circles somewhat smaller than in the negative. Contour lines or isophotic lines are drawn for every 10 units. The amount of detail visible in this picture is much greater than is shown in the visual representations of the Milky Way; but it is, of course, lesser than in focal photographs, because all sharp boundaries and small features are diffused. The most conspicuous features of these photographs, however, are visible in the lines or the figures of our chart. The bright Scutum cloud clearly stands out in the middle of the chart, abruptly cut off at the *N.* and *W.* side; north following it some less bright patches in the constellation Aquila appear, separated by dark spaces; the dark regions in Serpens between the two branches occupy the *W.* and *NW.* part of the plate;

Reduction to photometric scale.

The sky light producing the blackness of the plate is composed of:

1. a part A, not coming directly from the stars (scattered light, auroral earth light, zodiacal light) that may be assumed constant over the region covered by a single plate;

2. the starlight B, the varying intensity of which, expressing the phenomenon of the Milky Way, is the quantity that we wish to determine.

In the stardiscs this is still increased by an amount C caused by the light of the star. This will enable us to reduce the measures to an absolute scale. Putting the magnitude of the star m, its light expressed in stars 0.0^m L, the radius of the stardisc (in degrees) r, we have for the surface brightness C (unit one star 0.0^m pro square degree):

$$C = (k/\pi r^2)\, L\,; \quad L = 10^{-0.4m},$$

where the factor k is necessary because the starlight is not wholly equally distributed over the disc. From measures at a great number of points on the disc of the brightest star (λ Aquilae) I found $\log k = \log 1.033 = 0.014$. Though a narrow dark outer ring surrounds the fainter inner part, the blackness again increases towards the centre somewhat above the average of the whole disc. From the diameter of a stardisc 1.73 mm and the value of 1 degree in the centre 2.66 mm, deduced from the measured coordinates, we find $r = 0°.325$, $\log(k/\pi r^2) = 0.493$, $C = 3.11\, L$.

The blackness s' in the centre of the stardisc is caused by the light $A + B + C$, the blackness s in its immediate surroundings by $A + B$. Comparing $s' - s$ with C we find a relation which, if $A + B$ were constant $= L_0$, would be the relation between s and L, only referred to other zeros, viz: L_0 and s_0. If $s = f(L)$ has been found we may by a second approximation reduce the stardiscs projected upon the darkest background ($A + B$ and s greater than for the rest of the plate) to a constant s_0.

The relation $s' - s = f(C)$, applied to the fluctuations of the background: $s_2 - s_1 = f(B_2 - B_1)$, may then be used to deduce from the fluctuations in s the fluctuations in the skylight $A + B$.

The photographic magnitudes of the stars were taken from the Draper Catalogue (*Harvard Annals* **97**; for 19^h *RA* advance sheets were kindly provided by Director HARLOW SHAPLEY). The stars were at first separated into four rings (by circles of 14, 24, 30 mm radius); but no difference indicating a distance error could be found between them. *) Thus they were all combined in a single series and arranged according to the sum of the variables (taken after reduction to the same unit). The means are shown in the following table ($s' - s$ expressed in tenths of a scale unit, just as on the chart; n is the number of stars).

TABLE 2. Blackness of stardiscs.

$10^4 L$	$s' - s$	n	$O - C$	$10^4 L$	$s' - s$	n	$O - C$
9.0	4.7	23	−0.3	56.0	30.3	6	− 0.7
10.9	7.4	28	+1.3	79.7	40.2	6	− 3.8
16.0	9.1	26	+0.2	91.7	53.7	3	+ 3.2
20.7	11.9	13	+0.4	117.0	62.8	4	− 1.3
24.9	14.6	8	+0.7	176	107	1	+11
33.5	16.2	8	−2.4	225	121	1	0
39.0	21.5	10	+0.2	377	182	1	−15
48.0	24.2	5	−2.4	413	212	1	− 2.

Up to $L = 0.01$ and $s' - s = 60$ these values are quite well represented by a linear relation $s' - s = 0.55 . 10^4 L = 5500\, L$. Only the brighter stars show a distinct curvature, with smaller blackness, such as, according to HERTZSPRUNG's formula, occurs beyond the point of inflexion; the whole of the data may be represented by

$$s' - s = 5600\, L - 10000\, L^2$$

leaving the residuals $O - C$ (in s). For the fluctuations

*) This does not contradict the former result on the distance error in the background blackness. Since the surface of the stardiscs does not increase far from the centre the distance error must be much smaller here.

in blackness actually occurring in the background the deviation from a linear course is not perceptible; thus a second approximation for the stars on the most blackened regions is not necessary. Since $C = 3.11\, L$ we obtain from the linear formula $C = {}^{3.11}/_{5500}\,(s' - s) = 0.00057\,(s' - s)$. Written in the form

$$\Delta B = 0.00057\,\Delta s$$

this relation will serve us to convert the scale of numbers of our chart into an absolute scale of brightness with unit one star 0.0^m pro square degree. Thus the largest range of blackness on the chart, between 120 (the brightest part of the Scutum cloud) and 65 (at the following border of the eastern branch), corresponds to a difference in brightness 0.032. It is not allowed, of course, to write $A + B = 0.00057\, s$ and to compute in this way from the blackness itself the total brightness of the sky; for the linear formula certainly does not hold down to $s = 0$. *)

Comparison with visual results.

We are not able to separate the portions of the total blackness caused by A and B without making use of other data. It does not seem impossible to find the true galactic brightness B by suitable simultaneous photographs of galactic and extragalactic regions combined with theoretical deductions on the brightness caused by the stars in the last named parts. But it will be easier to attain this aim by making use of visual determinations. From his Mt. Wilson measures VAN RHIJN has deduced (*Groningen Public.* **31**) the visual brightness, caused by the stars alone for different parts of the Galaxy. This scale of absolute values I have transferred (*Astr. Nachr.* **214**, 392) to the stepvalues expressing the minutest details observed all along the Milky Way by visual observers. Thus a comparison of the photographic values with the visual results will afford a means to free the first named ones from the earthlight. At the same time this comparison may give us some information about the colour index and thus about the mean spectrum of the cloud stars.

At the upper right hand corner of our chart a small chart is given, showing the same region with visual isophotic lines, copied from Chart VII in „Die nördliche Milchstrasse" (*Annalen Leiden* XI 3) which represents the average of four observers. Though there are many differences in detail, the same chief objects may be traced in both. In order to compare the scales we may follow the course of the visual isophotic lines on the great chart, see what values they meet and take their average. The results are:

Line	1	$1\frac{1}{2}$	2	$2\frac{1}{2}$	3	4	5	6
Av. s	70	74	79	82	86	94	107	117
Vis. B	171	203	236	273	309	390	480	579.

The third line contains the visual brightness (in 0.0001) corresponding to the step values of these lines, expressed in stars 0.0^m pro square degree. Between these quantities the relation is found

$$\text{Vis. } B = 0.00088\,(s - 51).$$

Before making use of it, however, a correction should be applied. The photographic brightness expressed by the values s is caused by stars below $7.5 - 8^m$, the visual brightness by all stars from 6.5 downward. To take into account this difference in the origin of the light, I have computed how much the photographic brightness would be increased if the light of all the stars separately measured below 6.5 were evenly distributed over the background. It was found that on the average s would increase by only 1 unit; for the portions < 2, $2 - 3$, > 3 the increase would be 0.6, 1.0, 1.6 unit, so that the variation in the values of s becomes slightly greater and the coefficient is lowered to 0.00085.

Comparing it with the relation between s and the photographic brightness

$$\Delta B = 0.00057\,\Delta s,$$

we see at once that the photographic brightness is smaller than the visual one in the proportion ${}^{57}/_{85} = 0.67$. This corresponds to a difference of 0.43 magnitudes; *thus the colour index of these galactic clouds* (i. e. especially the Scutum cloud, though the fainter patches in Aquila do not deviate sensibly) *is* 0.43, *corresponding to a mean spectral class F* 5.

In 1912 the integrated spectrum of some bright galactic clouds (Sagittarius-, Scutum-, Cygnuscloud) was photographed by E. A. FATH at Mount Wilson (*Aph. J.* **36**. 362) with exposures of 30, 67 and 74 hours. It was found „approximately of solar type". Afterwards some doubts were raised, whether the spectrum photographed might have been caused by the zodiacal light. As according to the researches of VAN RHIJN the zodiacal light causes the chief part of the non-galactic skylight, this question can only be settled by a method allowing to compare bright and faint or non-galactic starlight. Our result on the colour index indicates a mean spectral class of somewhat less advanced type than was found by FATH; thus it is probable that in his integrated spectrum zodiacal light was mixed with galactic light.

The brightest stars of the Scutum cloud have been

*) The total brightness $A + B$ may be deduced from s by standardizing the plate, before developping, by light of different intensities, whose relation is known, e. g. by a sensitometer.

found by KREIKEN (*Dissertation*, Groningen, 1922) to belong to class B and A. Thus the mean colour found here shows that the main part of its fainter stars must be second type stars, just as is the case with the stars surrounding our sun. As furthermore the relative number of dwarf stars in this cloud agrees with the conditions prevailing in our surroundings (*B. A. N.* **42**. 11), it appears that in every respect the structure and composition of this cloud is similar to the nearer parts of the local galactic system.

If we try to make an estimate of the uncertainty of our result on the colour index, its chief cause must be sought for in the visual observations. The values for the photographic brightness are sufficiently accurate, the mean error of each figure on the chart being 2 units while the difference between the lines 2 and 5 is 28 units. Since the faint galactic regions chiefly occupy the border parts of the plate, an error in the reduction to centre may cause a systematic error in the colour index; but its amount is small, as may be inferred from the result that by neglecting the reduction to centre entirely the colour index would be found 0.36 instead of 0.43. The visual brightness, however, may be considerably in error, because for the Scutum cloud it is found by extrapolation. The brightest parts of the galactic zone measured by VAN RHIJN and used in deriving the reduction of step values to the photometric scale are $3^1/_2 - 5$; we have no guarantee that the step scale is homogeneous up to 6; and if e.g. 6 should be read 5.5 or 6.5 on a homogeneous scale, the difference between the lines 2 and 6 and the coefficient 0.00085 would be changed about 15°/₀, causing an error of 0.17 in the colour index. The extreme limits of uncertainty thus may be estimated $F0 - G0$; direct accurate measures of the visual brightness of these bright patches will be necessary to get a greater precision.

Corrections for atmospheric extinction have not been applied, because for southern declinations not only the star light B decreases, but also the earthlight A increases with zenith distance after a law not exactly known. We see the effect on the lower part of the chart in the lack of contrast between the bright triangular patch around 2 Hev. Scuti and the dark lane separating it from the Scutum cloud; but we are not able to correct it quantitatively.

A remark on the non-stellar skylight may still be added. For the brightness of the sky outside of the Milky Way contradictory results have been found, the high values of YNTEMA and VAN RHIJN (viz: 0.056 and 0.052 stars 0.0^m per square degree) standing against the low values of NEWCOMB, BURNS and ABBOT (0.012, 0.020, 0.030) (*Gron. Public.* **31**, 73) Now the Heidelberg plates cannot give a value for this brightness itself, because we cannot compute the total $A + B$ from s. We may, however, deduce a minimum value. Since the coefficient of variation of s with L decreases when L decreases below the mean brightness corresponding to the point of inflexion of $s = f(L)$, we have $s/(A+B) < \Delta s/\Delta B$, or $A + B > 0.00057\,s$. From the comparison with visual brightness the blackness s_0 corresponding to the non-stellar skylight was found 51; thus we get $A > 0.00057 \times 51$ or > 0.029 (photographic). If this non-stellar light is chiefly zodiacal light its colour must be yellow, as has been found actually by Lord RAYLEIGH. (The colour of the Light from the Night Sky; *Proc. Royal Soc. A* **99**. 10. 1921). Taking the mean colour $F5$ or $G0$ we have for the corresponding visual brightness $A > 0.044$ or > 0.049. This result, though it affords no actual value itself, tends to confirm the larger values found by the Groningen observers.

Errata in B. A. N. 19.

Page 107, first formula, for $+6.49$ read -6.49

„ 113, near bottom, „ $Ca+ \begin{cases} 3933 \\ 3933 \end{cases}$ „ $Ca+ \begin{cases} 3968 \\ 3933 \end{cases}$