VI. A Tentative Determination of the Surface Brightness of Dark Nebulae.[1]

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Absorbing clouds appear on the bright belt of the Milky Way as dark markings. But the dark nebulae doubtlessly possess some surface brightness of their own, because their particles must reflect the starlight. In the following it is attempted to derive a probable value of their surface brightness, and from that to estimate the albedo of interstellar matter.

The total surface brightness of the night sky mainly consists of the following components: the direct starlight, the atmospheric light, the zodiacal light, and the starlight reflected by interstellar matter. Knowing the total amount of the light of an area, and that of the light from other sources, it is possible to determine the amount of the last-mentioned component. On certain assumptions results can be obtained without knowing the amount of terrestrial or zodiacal light. Therefore, it is sufficient to know only the following data: 1. The observed value of the surface brightness of the night sky. 2. For each area the stellar distribution according to apparent magnitude reaching down to the faintest stars recorded.

Photographic photometry is of sufficient exactness for the present purpose. A work belonging here is: Wolf-Pannekoek, "Photographische Photometrie der nördlichen Milchstrasse", Amsterdam Publ. 3, 1932. The data given there are used in the present investigation. The surface brightness given in their photometric charts includes the light from all stars fainter than about $7\overset{m}{.}5$. When calculating the part due to starlight this limit must be taken into account.

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[1] Seminar in Astrophysics 1936/37, conducted by E. Öpik.

For the Selected Areas data exist giving the stellar distribution down to sufficiently faint stars. The material used here is taken from Groningen Publ. **43**, tab. 1, which gives the log of star number per square degree down to apparent magnitude $18\overset{m}{.}5$. Being confined to the Selected Areas it was impossible to pay attention to other known areas with great absorption.

For each Selected Area the stars were divided into groups, by intervals of one magnitude, and the amount of starlight for each group was calculated. The total light of stars fainter than $18\overset{m}{.}5$ was found by extrapolation. The total amount of starlight is set equal to the sum of light from all magnitude groups. The extrapolation may cause a quite considerable error, especially for the areas rich in stars. For this reason it was impossible to find any satisfactory value of the starlight for Selected Areas 64 and 98.

In the Wolf-Pannekoek charts, which are reduced to a common zero point (from plates covering each other), the combined value of atmospheric and zodiacal light appears as a more or less constant correction. This enables us on certain assumptions to determine the quantity of starlight scattered by interstellar matter without knowing the absolute value of the correction.

Subtracting from the mean observed surface brightness, given in the charts, the total light due to the corresponding mean stellar distribution, we obtain a difference which contains the constant correction *plus* a certain mean value of the surface brightness of the absorbing matter for the given area. Table 1 contains mean values of this difference for different galactic latitudes, derived from the entire material of the Wolf-Pannekoek charts.

Table 1.

b	I'	A'	a
0°	136	92	44
5°	132	83	49
10°	112	69	43
15°	97	50	47
		mean	46

b — galactic latitude

I' — mean surface brightness taken from Amst. Publ. **3**

A' — computed mean starlight per square degree

$a = I' - A'$

Unit of surface brightness = the light of a 10^{m} star per square degree

In calculating A', the stellar distribution given in Mount Wilson Contrib. **301** is used, because this and Amst. Publ. **3** refer to the same portion of the sky, namely the northern hemisphere.

Table 2 contains all the material discussed in the present note.

Table 2.

Sel. Area	I	A	H	d	Sel. Area	I	A	H	d
2	107	48	+ 13	+0.5	49	120	75	− 1	+ 1.0
8	160	83	+ 31	+ 1.3	50	130	76	+ 8	+ 1.0
9	111	56	+ 9	+ 2.2	63	120	112	− 38	− 0.1
10	81	36	− 1	+ 1.3	65	140	73	+ 21	+ 0.3
18	118	84	− 12	+ 0.5	73	100	40	+ 14	+ 1.1
19	136	81	+ 9	+ 1.7	74	130	69	+ 15	+ 1.9
22	115	55	+ 14	+ 0.9	75	90	64	− 20	+ 0.9
23	111	55	+ 10	+ 1.1	86	105	70	− 11	− 0.2
24	105	50	+ 9	+ 1.9	87	130	73	+ 11	+ 1.0
25	100	49	+ 5	+ 1.7	88	140	110	− 16	+ 0.1
39	139	127	− 34	− 0.7	97	120	46	+ 28	+ 1.9
40	169	105	+ 18	+ 1.1	109	95	44	+ 5	− 0.1
41	162	119	− 3	+ 0.2	110	95	27	+ 22	+ 3.4
42	115	74	− 5	+ 0.5	111	130	59	+ 25	+ 0.5
48	95	35	+ 14	+ 0.9					

I — total surface brightness taken from Amst. Publ. **3**

A — computed starlight per square degree

$H = I - A - a \ldots\ldots$ — residual surface brightness

$d = 18.^{m}5 - m_N$; m_N — effective limiting magnitude found from starnumber $N_{18.^{m}5}$ of the area, and from the mean stellar distribution in the corresponding galactic latitude as given in Groningen Publ. **43**, tab. 6; thus d is a measure of the excess (—) or defect (+) of starnumber in the given individual area expressed in magnitudes

The relative diminution of light in an absorbing layer of optical depth x equals $1 - e^{-x}$. A part of this quantity is reflected (or diffused) by the absorbing matter. For the purpose of our estimates the amount of reflected light can be assumed to be proportional to the total diminution of light. On this account the surface brightness $K = K_0\ (1 - e^{-x})$. In the simplest case the albedo is proportional to the surface brightness, $a = a_0\ (1 - e^{-x})$; K_0 and a_0 are surface brightness and albedo of a layer with infinite optical depth. Further, denoting $r = \frac{a}{a_0} = 1 - e^{-x}$, we have $K = K_0\, r$.

On the assumption that the interstellar matter is illuminated more or less uniformly by stars, it is possible to use the preceding formulae. Denoting the total absorption in stellar magnitudes by Δm, the following equation is obtained: $2.512^{-\Delta m} = e^{-x}$. Thus the relative albedo $r = 1 - 2.512^{-\Delta m}$ (1).

Supposing that H given in Table 2 includes besides K only a constant term Δ, we have $H = K_0\, r + \Delta$ (2).

Knowing the values of H with the corresponding total absorption Δm [which determines r by (1)], it is possible to derive the correlation (2). For our purposes, it is only important to find K_0 and a_0.

It is impossible to obtain the amount of total absorption of starlight in interstellar space for each area separately. In Table 2 the values of d denote only the excess of starnumber of the area over the mean starnumber in the given galactic latitude. Thus d contains the effect of interstellar absorption together with local irregularities of stellar distribution. Taking the mean value of d from several areas, the effect of local irregularities in starnumber must be partly compensated. However, the accidental error of H seems to be quite considerable. On this account it is necessary to combine the available data into normal groups, and to find the corresponding mean values for each group separately. The whole material we choose to subdivide into four groups according to the value of d.

Further, the mean d represents only a deviation of the local absorption from the mean absorption. Therefore the total absorption is $\Delta m = d + \mu$, μ being a mean value of total absorption for the given galactic latitude. It is possible to obtain minimum values of the surface brightness and albedo of a dark nebula by taking $\mu = 0$ and $\Delta m = d$.

From the distribution of the extragalactic nebulae, Hubble (Mt. W. Contrib. 485) estimates the total absorption in the direction of the galactic pole to be $0^{m}25$. In other directions it varies approximately with the cosecant of galactic latitude. On the assumption that this law holds in low galactic latitudes, it is possible to compute the value of μ.

This was found for each group separately by using the mean galactic latitude of each group. In such a manner another set of values of the surface brightness and albedo is obtained.

In Table 3 are given the results for the two cases.

Table 3.

Limits of d	$\bar{H}$	e	$\bar{d}$	n	r_1	$\|\bar{b}\|$	μ	r_2
≤ 0.5	-5.0	± 4.1	$+0.14$	11	0.12	$11^0.1$	1.30	0.73
$0.6-1.2$	$+7.6$	± 2.6	$+1.00$	9	0.60	$9^0.1$	1.51	0.90
$1.3-2.0$	$+12.3$	± 3.0	$+1.67$	7	0.78	$5^0.7$	2.5	0.98
$2.1 \leq$	$+15.5$	± 4.3	$+2.8$	2	0.92	2^0	—	1.0

$\bar{H}$ — mean H

e — probable error of $\bar{H}$ derived from the dispersion of individual H

$\bar{d}$ — mean value of d

n — number of Selected Areas in the group

r_1 — relative albedo $\frac{a}{a_0}$ (minimum) computed on the assumption $\mu = 0$

$|\bar{b}|$ — mean absolute galactic latitude

$\mu = 0.25 \operatorname{cosec} |\bar{b}|$ = assumed mean total absorption

r_2 — relative albedo corresponding to the above value of μ

In fig. 1 the values of H and r are represented graphically. According to formula (2), the correlation obtained should be linear; in the figure, I corresponds to the hypothesis $\mu = 0$ (r_1); II — to $\mu = 0.25 \operatorname{cosec} |\bar{b}|$ (r_2).

As it turns out, in both cases all the four points fall close to a straight line. The agreement is closer than required by the probable errors of the data, thus the good correlation is evidently accidental.

The total amount of starlight according to Seares, Van Rhijn, Joyner, and Richmond, Ap. J. **62**, 373, 1925, equals the light of 577 first magnitude stars or fifty-six 10^m stars per square degree. Assuming the mean surface brightness of the sky due to the starlight in interstellar space to be the same as observed from the earth, it is possible to estimate the albedo.

The correlation I of fig. 1 furnishes a lower limit of surface brightness $K_0 = 25$ and $a_0 = 0.5$, which refers to the albedo of a cloud of infinite optical thickness.

Using Hubble's data for the total absorption of starlight in the Galactic System, i. e., the correlation II of fig. 1, the surface brightness is estimated at $K_0 = 70$ units, and the albedo appears to be unreasonably great, namely, $a_0 > 1$. This second solution is especially uncertain. A deviation from the cosecant law, and a small error in the absorption coefficient given by Hubble may cause very different results. Taking into account the possible deviation from the cosecant law in low galactic latitudes, the value of K_0 here found may be regarded as a maximum value.

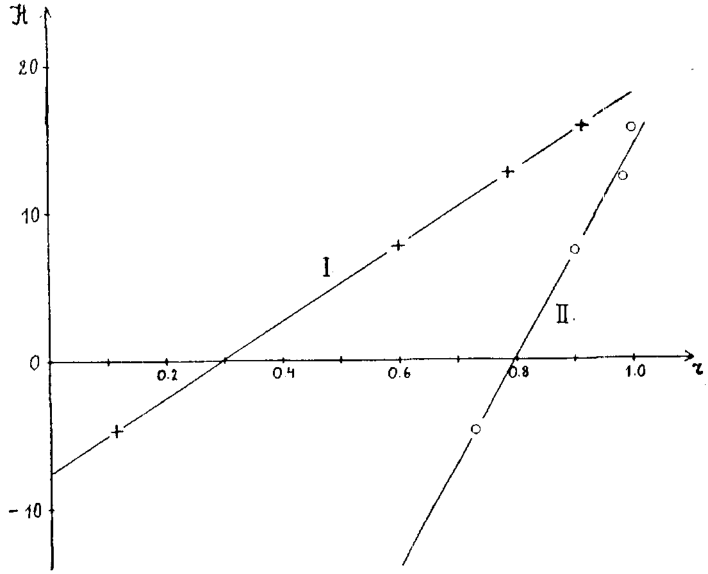

Fig. 1.

From our results it seems to be certain that the albedo of interstellar matter is comparatively high. It is known that clouds consisting of dielectric particles (water, ice, etc.) have much higher an albedo than mettallic dust. The results obtained seem to indicate that dielectric particles (mineral dust?) are more abundant than absorbing particles (metals) in interstellar space.

Taking into account the provisional nature of the present paper, the results obtained may indicate only the order of magnitude of the effect which we wanted to determine. The uncertainties in the limited observational data and in the hypotheses used are sufficiently great to cover the tiny effect of the surface brightness of dark nebulae.

After this paper had been finished, the author found in Ap. J. 85, 213, 1937 the same problem treated by C. T. Elvey and F. E. Roach. Remarkably enough, the conclusions reached by these authors coincide entirely with those of the present investigation, though the method and observational data are quite different.

Tartu, June 4, 1937.