ABSORPTION OF LIGHT IN THE GALACTIC SYSTEM

By Robert J. Trumpler

For more than a century astronomers have interested themselves in the question: Is interstellar space perfectly transparent, or does light suffer an appreciable modification or loss of intensity when passing through the enormous spaces which separate us from the more remote celestial objects? Any effect of this kind is generally referred to as "absorption of light in space," whatever the peculiar physical process assumed for its cause. Various hypotheses have been proposed for the latter. The older views attributed such absorbing properties to the hypothetical ether itself; but at present we think rather of a much rarefied invisible material medium and admit that the latter is not necessarily of uniform distribution throughout all space. According to prevailing physical theories, light passing through such a material medium will be affected in various ways: Aside from possible refraction and dispersion effects, light may be absorbed by free atoms or molecules; it may be scattered by free electrons, atoms, or molecules, or by solid particles of extremely small size; and finally light may be obstructed by larger bodies, such as meteorites. The space absorption of light is thus intimately related to the question of the presence, distribution, and constitution of dark matter in the universe.

Let us briefly review the observable phenomena which may give information on this question:

1. *General Absorption.*—By this term we designate the loss of starlight on its passage from the star to the observer. If such loss exists, the apparent brightness of a star will not decrease inversely proportional to the square of its distance, but more rapidly. This will make itself felt in the statistical determination of the space distribution of stars from star counts of successive magnitude intervals. It is further to be noted that a general absorption will affect all photometric distance determinations which are based on a comparison of absolute and apparent magnitudes. Distances derived by such methods (spec-

troscopic parallaxes, variable star parallaxes, etc.) should then differ systematically from the results of other methods not affected by absorption (statistical distances from proper motions, apparent diameters of star clusters or nebulae, etc.).

2. *Selective Absorption.*—If the loss of light is not the same for all colors, but varies with the wave-length, we speak of a selective absorption. Its consequence is that the apparent color of a star changes with its distance from the observer.

3. *Monochromatic Absorption,* or the observation of interstellar absorption lines in stellar spectra.—Evidence that a certain spectral line is not produced in the atmosphere of the star but by atoms contained in the space between star and observer may be gained in two ways:

a) There should be an increase with distance in the intensity of the line for stars of the same spectral type and luminosity.

b) The Doppler shift of such line will generally differ from that of the stellar absorption lines, and it should appear stationary in the case of spectroscopic binaries.

According to the investigations of O. Struve, J. S. Plaskett, Eddington, and others, we have good reason to conclude that the K line of calcium in stars of types O5 to B3 is of interstellar origin and that ionized calcium atoms are scattered through space within our galactic system, taking part in its rotational motion.

4. *Obscuration Effects.*—Among these, we have in the first place to mention the so-called dark nebulae. They are noticed either as well-defined nearly starless patches in the middle of rich Milky Way star fields, or as dark passages apparently projected on bright diffuse nebulae. The view that these formations are caused by local obscuration or absorption of light is rather generally accepted, and some astronomers are even inclined to consider the dark division of the Milky Way between *Scorpio* and *Cygnus* as of a similar origin.

In the second place there is the well-known fact that practically no globular clusters or spiral nebulae are visible near the galactic equator. This suggests that some of these distant objects are obscured by an absorbing medium in our Milky Way system which is strongly concentrated to the galactic plane.

5. *Dispersion of Light,* which means that in a material medium the velocity of light varies with the wave-length. If an effect of this kind is present, the light variation of a distant eclipsing binary should not be observed simultaneously in all colors; there should be a phase difference between the light variations of the various colors. This is known as the Nordmann-Tikhoff phenomenon. Kienle,[1] discussing the observational data relating to it, comes to the conclusion that there is no reliable evidence of a measurable dispersion of light in interstellar space and that we should theoretically not expect it unless accompanied with a large absorption effect.

The study of open star clusters[2] has brought to light new results indicating the existence of a general and selective absorption, and the present paper is mainly concerned with a discussion of these two phenomena.

The attention of astronomers was first directed to the possible existence of a general absorption of light in space by statistical investigations on the space distribution of the stars. If we make the assumptions that the stars are uniformly distributed through unlimited space and that light is not subject to a general space absorption, calculation would lead us to the conclusion that the stars counted in every magnitude interval should be 3.98 times as numerous as in the preceding interval, and that the whole night sky should be bright with starlight. Since the latter is not the case and since the observed star numbers increase at a smaller ratio, we are forced to reject either one of the two assumptions or both. The star counts alone cannot tell us which interpretation is correct, but for various other reasons most astronomers now favor the view that the stars are thinning out at greater distances from the Sun. Nevertheless, it is of interest to inquire what amount of general absorption would be necessary to reconcile the observed star counts with a uniform space distribution of the stars. Halm,[3] in his second paper treating the star counts of the whole sky, finds a value of $2^{m}1$ per 1000 parsecs; Schalén,[4] from a study of faint A- and

[1] *Jahrbuch d. Radioaktivität und Elektronik,* **20**, 14, 1923.

[2] *Lick Obs. Bull.,* **14**, 154, 1930.

[3] *M.N.R.A.S.,* **80**, 162, 1919.

[4] *A.N.,* **236**, 249, 1929.

B-type stars in the Milky Way, derives a value of 0^m5 per 1000 parsecs. Halm's figure should rather represent an upper limit, as a general increase in star density at greater distances from the Sun is very unlikely. A local increase in star density in the region of the Milky Way star clouds, however, seems possible, and Schalén's figure may therefore be too small.

While the statistical treatment of star counts can only furnish an upper limit or an estimate for a general absorption, the apparent diameters of open star clusters offer an exceptionally favorable opportunity to test its actual existence and determine its numerical amount.

In *Lick Observatory Bulletin,* **14,** 154, 1930, the writer determined the distances of 100 open clusters by means of the magnitudes and spectral types of their members. These "photometric distances" are based on the inverse square law, and are found in Table 3, column 8, of the paper referred to. In view of the great diversity in cluster formations it seemed *a priori* likely that the real space dimensions are not the same for all of them but that they depend on the constitution of each cluster. The open clusters were therefore classified according to the degree of star concentration toward the center and according to the number of stars contained in them. As expected, the linear diameter in parsecs, computed from the photometric distance and the apparent angular diameter, was found to be correlated with both of these characteristics. Making the assumption that clusters of similar constitution have on an average everywhere the same dimensions, it is possible to determine the distance of a cluster also by comparing its angular diameter with the mean linear diameter of the subclass to which it belongs. The units in which these diameter distances are expressed are, of course, arbitrary; they depend on the values adopted for the mean linear diameters of the subclasses.

A comparison between the diameter distances so obtained and the photometric distances is illustrated in Figure 1 (p. 218). Each cluster is plotted according to its photometric distance as abscissa and its diameter distance as ordinate. The units of the latter are here so chosen that for the mean of all clusters they correspond to the parsec units of the photometric distance scale.

The smaller dots represent clusters for which the photometric distances are less certain and received half weight. The asterisks mark the group means (geometric) formed when the clusters

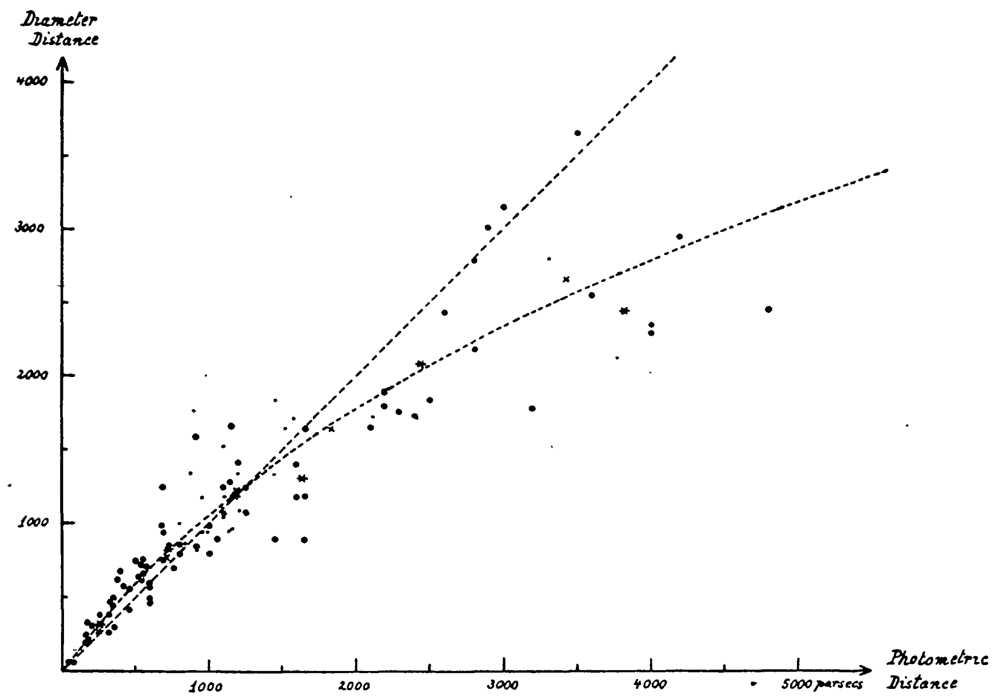

FIG. 1.—Comparison of the distances of 100 open star clusters determined from apparent magnitudes and spectral types (abscissae) with those determined from angular diameters (ordinates). The large dots refer to clusters with well-determined photometric distances, the small dots to clusters with less certain data (half weight). The asterisks and crosses represent group means. If no general space absorption were present, the clusters should fall along the dotted straight line; the dotted curve gives the relation between the two distance measures for a general absorption of $0^m.7$ per 1000 parsecs.

are arranged according to their photometric distances; the crosses mark similar group means obtained by ordering the clusters according to their diameter distances.

If no absorption of light were present, the two distance scales should be in agreement, and the clusters should be scattered along the straight line which divides the angle of the two co-ordinate axes. It is, however, evident that the clusters deviate systematically from this straight line. For the nearer clusters the diameter distances are larger, for the distant clusters they are smaller, than the photometric distances. This discrepancy is not due to a systematic error in the estimates of angular diameters; it persists even if we select only clusters which are nearly of the same angular diameter but at different distances. No error of observation, nor any effect of selection, was found to account for it. Unless we are willing to admit that the dimensions of open clusters depend on their distance from the Sun, we are led to the conclusion that the inverse square law on which the photometric distances are based does not hold and that a general absorption is taking place within our stellar system. Assuming that this absorption is approximately uniform within the region occupied by these clusters, we find its numerical value to be $0^m.7$ per 1000 parsecs. The relation between the diameter distances and the photometric distances which we should expect for an absorption of this amount is shown in Figure 1 by the dotted curve. It represents the observations quite satisfactorily, much better than the straight line.

A close investigation of the distances and diameters of open clusters thus gives good evidence of a general absorption affecting the photographic magnitudes of stars by about $0^m.7$ per 1000 parsecs. This result is quite compatible with the conclusions drawn from star counts. When we compare our figure with the limiting value derived by Halm (p. 216), we see easily that our general absorption will not change the fact that the space density of stars decreases in general for greater distances from the Sun, although the decrease will be somewhat slower. A comparison with Schalén's value, on the other hand, would indicate a slight local increase in star density in the region of the Milky Way star clouds. Unfortunately, neither trigonometric or dynamical parallaxes nor statistical parallaxes derived from proper motions are at present sufficiently accurate to detect so small an absorption by comparison with spectroscopic parallaxes.

Studies of the diameters of globular clusters and spiral nebulae, and of the surface brightness of the latter, have been made by Shapley,[5] van Rhijn,[6] and Lundmark. Notwithstanding the great distance of these objects, no appreciable space absorption was found. This suggests that the general absorp-

[5] *Harv. Bull.*, **864**, 1929.

[6] *B.A.N.*, **4**, 123.

tion which affects the open clusters is not operating throughout the Universe, but appears to be confined to the Milky Way system, while extragalactic space is of much greater transparency.

We have now to take up the question whether this absorption is selective, that is, whether it varies with the wave-length. If this is the case, the color of a star should change with its distance. The fact that the fainter stars on an average are more reddish and have larger color indices was at first taken for an indication of selective absorption. Since spectral types of fainter stars became available, however, it was recognized that this is due to an increasing percentage of low-temperature dwarf stars.

Since the color of a star depends mainly on its surface temperature, a change of color by selective absorption can only be detected if the surface temperature can be determined independently of the color, e.g., from the spectral types. As far as the latter are based on the relative intensities of spectral lines they are not much affected by a space absorption and measure the temperature by means of the ionization and excitation in the stellar atmosphere. A selective absorption would then be noticed by an increase with distance of the mean color index corresponding to a given spectral type. Investigations of this problem were made in 1909 by Kapteyn[7] for the stars of the *Harvard Revised Photometry* and later by van Rhijn[8] and Jones[9] for the stars of the *Yerkes Aktinometry*. Taking into account also the change of color with absolute magnitude and the existence of possible systematic errors in the visual and photographic magnitude scales, the results were the following:

	Increase in Color Index per 1000 Parsecs
Kapteyn	$+0^{m}.31 \pm 0^{m}.09$
Jones	$+0.47 \pm 0.05$
van Rhijn	$+0.15 \pm 0.05$
Mean	$+0^{m}.3$

Although the stars investigated were relatively near and al-

[7] *Contr. Mt. W. No. 42; Ap. J.*, **30**, 284 and 398, 1909.

[8] Dissertation, Groningen, 1915.

[9] *M.N.R.A.S.*, 75, 4, 1914.

though the separation of the unknowns was uncertain, these results suggested a selective absorption of $0^m\!.3$ per 1000 parsecs.

A few years later Shapley began his brilliant researches on the globular clusters. The fact that he found many small color indices in globular clusters more than 10,000 parsecs distant seemed to disprove the existence of any appreciable selective absorption and discouraged further work on the subject.

When observing the spectral types of faint stars in open star clusters, the writer was struck by the consistent discrepancy between his spectral-type estimates and the color indices determined by other observers. Since the average relationship between color index and spectral type for the nearer stars is now well known, we can predict for any giant or dwarf star of known spectral type its "normal color index." The difference between this normal color index and the one actually observed is called the color excess. Table I gives for eight of

TABLE I

COLOR EXCESS IN OPEN STAR CLUSTERS

Cluster N.G.C.	Cluster Messier	Distance in Parsecs	Mean Color Excess	No. of Stars	Observer of Color—I
1647	..	610	$+0^m\!.17$	33	Hertzsprung[10]
			.19	6	Seares[11]
2682	67	740	.27	81	Shapley[12]
2099	37	820	.05	25	Von Zeipel and Lindgren[13]
2168	35	840	.14	98	Wallenquist[14]
1960	36	980	.05	40	Wallenquist[15]
6705	11	1340	.65	46	Shapley[16]
7654	52	1360	.49	43	Wallenquist[17]
663	..	2170	+0.71	41	Wallenquist[17]

the more distant clusters the mean color excess (col. 4) derived by combining the writer's spectral types with the color indices

[10] *Contr. Mt. W. No. 100; Ap. J.*, **42**, 92, 1915.
[11] *Contr. Mt. W. No. 102; Ap. J.*, **42**, 120, 1915.
[12] *Contr. Mt. W. No. 117.*
[13] *Kgl. Svenska Vet. Akad. Handlingar*, **61**, No. 15, 1921.
[14] *Ann. Bosscha-Sterrenwacht, Lembang* (Java), **3**, No. 2, 1929.
[15] *Meddel. Upsala*, No. 32, 1927.
[16] *Contr. Mt. W. No. 126; Ap. J.*, **45**, 164, 1917.
[17] *Meddel. Upsala*, No. 42, 1929.

measured by the observer listed in the sixth column. The clusters are arranged according to their distance from the Sun (corrected for general absorption), and the table clearly brings out the fact that the color excess is always positive and that it increases with the distance. For the three most distant clusters the excess is so large that B- and A-type stars were found to have color indices normally associated with F- or G-type stars. As all the color index determinations, with the exception of the first, are based on comparisons with the North Polar Sequence, it is out of the question to trace all these figures to observational errors. There seems to be no alternative but to interpret the observed color excess as being due to a selective absorption of light in space; this will explain not only why the color excess is always positive but also why we find its largest values in the most distant clusters. If we assume the absorption to be uniform, the color excess γ should be proportional to the distance, and we obtain by least squares solution for its value:

$$\gamma = +0\overset{m}{.}31 \pm 0\overset{m}{.}03 \text{ per 1000 parsecs}$$

This result is in good agreement with the mean of the earlier determinations of Kapteyn, Jones, and van Rhijn; it is further confirmed by two recent unpublished investigations which show that it applies not only to clusters but to the fainter Milky Way stars in general.

Miss L. Slocum, comparing the spectral types observed by A. Maxwell[18] for stars of magnitudes 11–14 in five selected areas near the galactic circle with her color index determinations of the same stars, found:

$$\gamma = +0\overset{m}{.}34 \text{ per 1000 parsecs.}$$

Dr. P. van de Kamp, investigating the color indices of B- and A-type stars of about 10^m, obtained the following values for the selective absorption (communicated by letter):

$$\begin{array}{lll} \gamma = & +0\overset{m}{.}38 \pm 0\overset{m}{.}03 & \text{Galactic lat. } 1^\circ\text{–}3^\circ \\ & +0.23 \pm 0.04 & 4^\circ\text{–}6^\circ \\ & +0.22 \pm 0.05 & 7^\circ\text{–}12^\circ \end{array}$$

[18] *Lick Obs. Bull.*, 13, 68, 1927.

Although much further research on the change of color with distance is desirable, we have in the various results quoted quite definite evidence of a selective absorption of about $0^{m}_{\cdot}32$ per 1000 parsecs in low galactic latitudes.

Only a brief reference can here be made to some other observational facts which may also find their explanation as effects of selective absorption. Concerning the colors of O-type stars the textbook of Russell-Dugan-Stewart[19] makes the following statement: "The stars of class O (which, from the character of the lines that appear in their spectra, must be the hottest of all) are slightly yellower than those of class B." In consequence of their high luminosity (absolute magnitude –4), even the brighter stars (4–6^{m}) are at distances of 400–800 parsecs, and, since they lie close to the galactic plane, their color index will be increased by $0^{m}_{\cdot}15$ to $0^{m}_{\cdot}25$ through selective absorption in space. B-type stars of the same apparent magnitude are nearer and therefore less affected by such absorption. It is, however, possible that the small change in color between types B5 and B0 is also due to the same effect.

Another case is that of B- and A-type stars which are abnormally yellowish for their spectral class. Two lists compiled by Hertzsprung[20] contain 41 such objects and show that they are nearly all situated in low galactic latitudes, while their small proper motions indicate great distance. This is exactly what we should expect if their abnormal color is due to selective absorption. The most bluish stars listed by Hertzsprung, on the other hand, are mostly found in higher galactic latitudes.

The existence of a selective absorption in low galactic latitudes should make itself felt in the statistical study of the magnitudes and color indices of faint stars in Milky Way regions. With decreasing apparent brightness the lower and upper limits of observed color indices should gradually shift toward the red. In other words, among the fainter stars we should find none of blue-white color, but on the other hand a number of unusually large color indices ($>2^{m}_{\cdot}0$). A phenomenon of this kind is

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[19] P. 735.

[20] *B.A.N.*, 1, 204 and 217, 1923.

indeed noticeable in the majority of observations so far made,[21] but this subject will be taken up more fully in a later paper.

There remains the task of reconciling our results on selective absorption with Shapley's observations of small color indices in distant globular clusters and with similar observations of Hubble in spiral nebulae. To avoid any contradiction we must again draw the conclusion that the medium responsible for the observed general and selective absorption is limited to our stellar system and does not extend through extragalactic space. Moreover, it must be highly concentrated to the galactic plane, as most of the observed absorption effects are found in low galactic latitudes, and van de Kamp's figures in fact indicate a rapid decrease in selective absorption for higher galactic latitudes. When we consider that two-thirds of all open star clusters lie within 100 parsecs of their plane of concentration, it does not seem unreasonable to assume that the absorbing medium has a similar distribution, forming a relatively thin disk or sheet extending along the galactic plane but thinning out very rapidly at greater distances from this plane. Since the globular clusters and spiral nebulae observed for color are situated in higher galactic latitudes, their light in reaching us passes only the short distance of a few hundred parsecs through the absorbing medium and will not be much affected. Whether this medium should be thought of as a continuum or whether it is composed of local aggregations of which we observe the statistical effect, cannot be decided at present.

By combining the numerical data of general and selective absorption, we derive the absorption coefficients for the photographic and visual region of the spectrum:

	Absorption Coefficients per 1000 Parsecs		
	Observed	Rayleigh Scattering	Non-selective Residual
Photographic ($\lambda = 4300$)	$\varkappa_p = 0^{m}.7$	$0^{m}.51$	$0^{m}.19$
Visual ($\lambda = 5500$)	$\varkappa_v = 0.38$	0.19	0.19
Selective absorption	$\varkappa_p - \varkappa_v = 0.32$	0.32	

[21] See, e.g., *Lick Obs. Bull.*, **14**, 122, 1929. Dr. Krieger's color indices, however, need a zero correction of about $+0^{m}.2$ because they were calibrated by means of spectral types of faint stars before any selective absorption effect was suspected.

The space absorption decreases rapidly with increasing wave-length, similar to the extinction in the Earth's atmosphere. This suggests its interpretation as Rayleigh scattering, i.e., scattering of light by particles which are small compared with the wave-length of light. According to Rayleigh such scattering is inversely proportional to the fourth power of the wave-length. This law, however, is not exactly fulfilled by our figures. If we determine its numerical coefficient so as to fit the selective absorption, which is the more accurate of the two, we have a small non-selective residual effect left which, if real, must be explained by other causes (electron scattering, obstruction by larger meteoric particles). It will be of great interest to test by spectrophotometric measures whether the selective absorption actually follows the inverse fourth-power law. If we admit it tentatively, we can use Rayleigh's formula to draw some conclusions on the constitution of our scattering medium. We shall first calculate its space density, making an assumption about the mass of the individual particles. It is natural that we should try free atoms with an average atomic weight of 40 (like calcium atoms). In this case about 1800 atoms per cubic centimeter are required to produce the observed effect; this corresponds to a space density of 1700 times the Sun's mass per cubic parsec. Such a figure is quite inadmissible; it would lead to an enormous mass for our stellar system, and this in turn would by its gravitational action produce much greater stellar velocities than those actually observed. In fact, we can say that the latter do not admit a greater space density than about half a Sun's mass per cubic parsec. If we adopt this limiting value for the density, we can proceed in the reverse order and find that the average mass of the particles would have to be of the order of 2×10^{-19} grams (3400 calcium atoms). Such extremely fine solid dust particles with a diameter of about one-hundredth of the wave-length of visual light would still be small enough to produce Rayleigh scattering. We see, thus, that our numerical results for the selective absorption cannot be traced to Rayleigh scattering by free atoms in interstellar space; they admit, however, interpretation as scattering by fine cosmic dust.

It seems very probable that there is some relation between the medium causing our general and selective absorption on the one hand, and interstellar calcium and obscuration effects on the other hand. Although we have so far made only a beginning in the study of space absorption and interstellar matter, it may be helpful for future research to formulate a tentative working hypothesis which attempts to incorporate and co-ordinate the various observational data available, and utilizes the interesting theoretical studies by Eddington.[22]

Our Milky Way system seems to contain a considerable amount of finely divided matter, noticeable by its absorption of light. This matter appears to be made up mainly of:

1. Free atoms (*Ca, Na,* and probably others) causing interstellar (stationary) absorption lines observable in the spectra of distant stars. Eddington estimates their space density of the order of 10^{-24} grams per cubic centimeter (one H atom per cubic centimeter) and shows that this is not sufficient to originate an observable amount of Rayleigh scattering.

2. Free electrons are likely to be included, since the observed interstellar calcium atoms are ionized.

3. Fine cosmic dust particles of various sizes (average mass of particle 10^{-19} grams or larger, space density of the order of 10^{-23} grams per cubic centimeter) maintained in space by light pressure of the stars and producing the observed selective absorption by Rayleigh scattering.

4. Perhaps we should add also larger meteoric bodies, obstructing light of all wave-lengths equally, which may be responsible for a small part of the general absorption (residual effect).

This absorbing medium is limited to our galactic system, forming an essential feature of it; it is much concentrated to the galactic plane extending along the latter like a thin disk probably not more than a few hundred parsecs thick. While its distribution follows the Milky Way in general, it is not necessarily uniform. The observed obscuration of globular clusters and spiral nebulae near the galactic circle then follows as a natural consequence of the great depth of the medium in

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[22] Bakerian Lecture, *Proc. Roy. Soc.*, 111, 1926.

this direction. The so-called dark nebulae or obscuring clouds seem to be of incomparably greater opacity, and it is as yet uncertain whether their absorption is selective or not. As they are also most prominent in the Milky Way, they may represent strong local condensations of the general absorbing medium or of some of its above-mentioned constituents.

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July 19, 1930