THE LAW OF INTERSTELLAR REDDENING

By A. E. WHITFORD
Washburn Observatory

Abstract. A re-examination of the interstellar reddening curve as determined from spectrophotometric comparison of pairs of reddened and unreddened stars shows satisfactory agreement between different observers and different methods. Corrections to Stebbins and Whitford's 6-color filter photometry to give equivalent monochromatic intensities bring these results into better agreement with results by other methods. A new interstellar reddening curve is derived from narrow-band photoelectric photometry with a scanning spectrograph, and from previously unpublished lead sulfide observations through infrared filters. The curve shows two linear portions, with a change in slope at 2.2 μ^{-1} (4500 Å), as opposed to the continuously changing slope previously shown by the 6-color filter observations.

A plot of apparent modulus versus color excess for stars in certain associations confirms the ratio of total absorption to color excess $A_V/E_1 = 6.1 \pm 0.4$ or $A_V/E_{B-V} = 3.0 \pm 0.2$ found by Morgan, Harris, and Johnson. Extrapolation of the new interstellar reddening curve to $\mu^{-1} = 0$ gives the same ratio. Suspected anomalies in the ultraviolet portion of the reddening curve for small regions of the sky do not necessarily affect this ratio. Use of color excesses to get total absorptions is concluded to be a fairly reliable method; since only portions of the interstellar medium near the sun have been tested, however, caution is in order for stars reddened by the dust of other galaxies.

Introduction. Trumpler's original demonstration (1930) that there is a general absorption and reddening of light by finely divided particles in the central plane of the Milky Way came about as the result of an attempt to establish a distance scale for galactic clusters. His use of the method of color excesses to provide the first definitive proof of interstellar reddening has since developed into the standard procedure for correcting photometric distances for the effects of absorption.

It is the purpose of this paper to consider, in the light of present knowledge, the reliability with which the absorption correction can be calculated from a measured color. The importance of this step in establishing the cosmic distance scale is axiomatic; color excesses are as much a proper part of the proper use of distance indicators as are good magnitude scales and the accurate calibration of the luminosity of standard objects.

Trumpler's second test for absorption, that of angular diameters, has been little used, in spite of the fact that it depends only on geometrical considerations. It should be borne in mind as an independent check on photometric methods, particularly in situations where the dispersion in the linear diameter of the standard object or assemblage is not too large. *H*II regions in external galaxies have been suggested as test objects by Gum and de Vaucouleurs (1953). The angular diameters of clusters of galaxies could provide a test for intergalactic absorption.

Before color excesses can be used to determine the amount of interstellar absorption, two important questions must be answered:

1. What is the ratio of total-to-selective absorption, and how accurately can it be determined for a particular color system?
2. Are the properties of the interstellar medium sufficiently uniform in different regions of space so that the same ratio of total-to-selective absorption may be used everywhere?

Since the answers to both questions depend in part on the interstellar reddening curve, a review of the observational data is in order.

Spectrophotometric studies of the reddening law. O and B stars have thus far been the principal test objects for study of absorption by the interstellar medium. Their nearly featureless spectra make them ideal for precise color index measurements, even with the fairly broad filter bands needed to reach faint stars. Their color temperatures are insensitive to luminosity differences within the same spectral type. And existing spectral surveys (Nassau and Morgan 1951; Morgan, Code, and Whitford 1955) have identified a wealth of distant early-type supergiants. Samples chosen for their location in space, or for their degree of reddening effect are available in many regions of the Milky Way.

J. Dufay (1953) has reviewed the early spectrophotometric studies by photographic methods. From the very beginning it was apparent that interstellar reddening was not very different from temperature reddening, and therefore must show a wave-length dependence close to a λ^{-1} law. Following the initial photoelectric investigation by J. S. Hall (1937), Stebbins, Huffer, and Whitford (1939) undertook to apply the wide range of the cesium oxide cathode to the spectrophotometric study of reddened B stars. In this early work the analysis was done with a slitless spectrograph which took samples of the spectrum over the range from 3830 Å to 8700 Å. The difficulty of maintaining wave-length calibration led to the adoption of six color filters having effective wave lengths ranging from 3530 Å to 10,300 Å. From the comparison of 69 O and B stars showing various degrees of reddening, Stebbins and Whitford (1943) derived an interstellar reddening curve which showed distinct curvature on a plot of magnitude differences as a function of λ^{-1}. More recently Whitford used the photoelectric scanning spectrograph developed by Code (1954) to compare representative pairs of reddened and unreddened stars that had been measured with the 6-color filters; some of the results are presented later in this report.

Further photographic studies by Schalén (1952), van Rhijn (1953), and Borgman (1954) agreed in showing significant differences from the reddening law derived by Stebbins and Whitford from the 6-color observations. They attributed the difference to incorrect evaluation of the effective inverse wave length at which the magnitude differences observed with the 6-color filters should be plotted. Mlle. L. Divan (1954), on the other hand, found close agreement with the 6-color results. Her extensive study of interstellar reddening by the methods of photographic photometry covered a wide range of the spectrum, measured many points in the spectrum, and reached heavily reddened stars, where small errors become less important in comparison with the absorption effects produced by the interstellar medium.

In the present discussion we shall compare Mlle. Divan's measurements on one pair of stars with those obtained by two photoelectric methods. The stars are:

Reddened: HD 195592, Yerkes spectral type O9.5Ia, color excess $E_1 = +0.56$

Comparison: HD 204172, Yerkes spectral type B0Ib, color excess $E_1 = +0.07$

The color excesses listed are based on the normal C_1 colors derived by Morgan, Harris, and Johnson (1953). The comparison is shown in Figure 1. The scanner points were derived from the author's previously unpublished observations with the first Code scanner on the 100-inch telescope at Mount Wilson. The exit slit gave a resolving power of approximately 0.015 μ^{-1}. Each star was observed on three nights for both the red and the blue portions of the spectrum.

The original 6-color data on the two stars were corrected to give the best representation of monochromatic intensity that could be derived from the wide filter bands used. First, allowance was made for the fact that the reciprocal of the effective wave length is not equal to the effective inverse wave length. A new calculation of the latter quantity was made from the same response curves given in the original paper by Stebbins and Whitford (1943). In this calculation, the energy curve of the star and the transmission of the atmosphere are not included. As recently emphasized by King (1952), the small corrections to get the monochromatic intensity at the effective wave length from an observed integral intensity are easily handled by Strömgren's (1937) method of Taylor expansions; King extended this method to include the atmospheric extinction. The corrections to allow for the stellar energy distribution curve are shown in Table I, along with the new and old effective reciprocal wave lengths. The points have been moved in the abscissa coordinate in the direction found by Schalén (1952) to give agreement with his observations, but the shift is less in amount than he found.

In Figure 1, the run of the mean curve from 2.2 μ^{-1} (4500 Å) to 1.0 μ^{-1} (10,000 Å) is quite linear, in agreement with the earlier work with a slitless spectrograph by Stebbins, Huffer, and Whitford (1939). It is significant that photometric comparisons based on narrow bands agree best with each other and give at least a close approach to a linear relation on each side of the change in slope at 2.2 μ^{-1}. The decreased slope in the ultraviolet is the basis of the *UBV* "reddening line" (Johnson and Morgan 1953; Morgan, Harris, and Johnson 1953). Three-color filter systems with effective wave lengths all on the same linear portion of the reddening curve would

TABLE I. CORRECTIONS TO 6-COLOR OBSERVATIONS TO GET MONOCHROMATIC MAGNITUDES

	U	*V*	*B*	*G*	*R*	*I*
$(1/\lambda_{\rm eff})$, μ^{-1}	2.83	2.37	2.05	1.75	1.39	0.97
$(1/\lambda)_{\rm eff}$, μ^{-1}	2.86	2.40	2.09	1.79	1.43	0.99
HD 195592, Δm	.00	+.03	+.03	+.02	.00	−.01
HD 204172, Δm	.00	.00	.00	.00	.00	.00
Difference, Δm	.00	+.03	+.03	+.02	.00	−.01

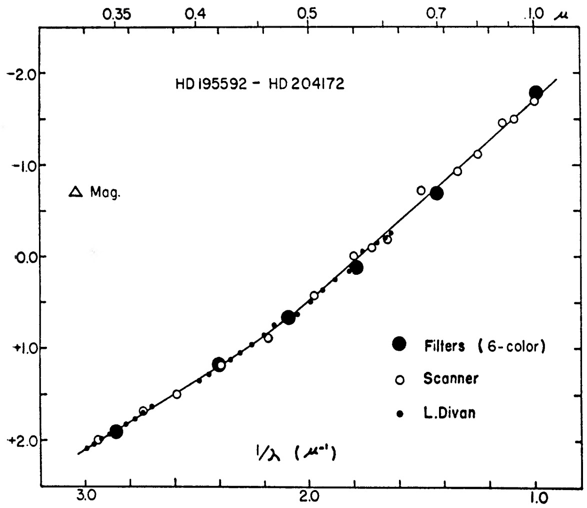

Figure 1. Monochromatic magnitude differences between a reddened and a normal star, as observed by three methods.

not be able to show the sharp separation of reddened stars given by the *UBV* system; for such color systems interstellar reddening and temperature reddening should be indistinguishable.

The remaining discordance of the 6-color points, particularly the green and red points, is probably too large (~0.10 mag.) to be ascribed to observational errors. There may have been systematic errors of the order of 0.02 μ^{-1} (50 Å) in the wave length data upon which the calculation of effective inverse wave length is based.

In summary, it appears that spectrophotometric comparisons of the same pairs of stars by different methods are in satisfactory agreement.

The ratio of total-to-selective absorption. Direct determination of total absorption by star counts would give R, the ratio of total-to-selective absorption, if stars of known color excess can be shown to lie in a clear region behind an absorbing cloud. The accuracy by this method cannot be very high, owing to the low space resolving power of the count method, to variations in the density of absorption over the counted area, and to variations in the luminosity function. Weaver (1949) studied a carefully selected region in Aquila by the count method and obtained a ratio of total photographic absorption to color excess on the International System $R = A_{pg}/E_{int} = 3.4 \pm 0.2$.

A full knowledge of the interstellar reddening curve out to very long wave lengths in the far infrared would establish the zero of the absorption curve. Available intensities and practical detectors preclude this, however. With a lead sulfide photoconductive cell it is possible to close about half of the gap between the last well-observed cesium oxide photoelectric point at 1.0 μ^{-1} and the zero on the wave number scale. The first measures by Whitford (1948) were supplemented by further measures on more heavily reddened stars in 1948 and 1949, previously unreported. These were made with the 100-inch telescope, and the same Cashman lead sulfide cell was used, but refrigeration with dry ice gave better sensitivity. Two of the filters were the same as in the first season's observations. A third filter for the intermediate range was made by crossing a Schott UG-6 (2 mm) glass filter with an alum crystal very kindly furnished by E. Pettit. Data published by Pettit (1927) were used to derive an effective inverse wave length of 0.84 μ^{-1} for this filter.

Since only bright unreddened B stars had enough energy in the 2 μ region to give satisfactory measures, stars which were a close match in type and luminosity for the reddened examples were not available. The stars observed are listed in Table II. The first column gives the star's number in the Henry Draper Catalogue, the second its common designation, the third its Harvard visual magnitude, the fourth its spectral classification on the Yerkes system, the fifth its $V-I$ index from the 6-color measurements of Stebbins and Whitford (1945), and the sixth the color excess with respect to revised normal C_1 colors.

TABLE II. STARS OBSERVED WITH LEAD SULFIDE PHOTOCONDUCTIVE CELL

HD	Name	m_v	Yerkes class	$V-I$	E_1
886	γ Peg	2.87	B2IV	−2.53	+0.04
24398	ζ Per	2.91	B1Ib	−1.58	+ .20
24760	ε Per	2.96	B0.5V	−2.46	+ .05
37128	ε Ori	1.75	B0Ia	−2.38	+ .06
116658	α Vir	1.21	B1V	−2.51	+ .01
120315	η UMa	1.91	B3V	−2.39	− .01
169034	—	8.6	B5Ia	+2.01	+ .64
190603	—	5.69	B1.5Ia+?	—	+ .37
194279	—	7.05	B1.5Ia	+1.28	+ .57
198478	55 Cyg	4.89	B3Ia	−0.66	+ .27
206165	9 Cep	4.87	B2Ib	−1.06	+0.25

In order to combine the observations, the difference between the colors observed and the mean color of the unreddened star was normalized to the case of a color excess $V-I = 1.00$ mag. For the remainder of the curve through the visible and ultraviolet, three well-observed pairs selected from the scanner data were used. The

TABLE III. PAIRS OF STARS OBSERVED WITH PHOTOELECTRIC SCANNING SPECTROGRAPH

HD	Name	m_v	Yerkes class	$V-I$	E_1
195592	—	7.15	O9.5Ia	+0.75	+0.56
204172	69 Cyg	5.84	BoIb	−2.18	+ .07
169454	—	6.84	B1Ia+	+1.04	+ .53
204172	69 Cyg	5.84	BoIb	−2.18	+ .07
190603	—	5.69	B1.5Ia+?	—	+ .37
2905	κ Cas	4.24	B1Ia	−1.50	+0.15

stars observed are listed in Table III, which has the same arrangement as Table II. The color differences were likewise normalized to a standard color excess of $V-I = 1.00$. The combined scanner and lead sulfide data are shown in Figure 2. The rounding off in the infrared is still unmistakable, but is less than in the mean curve drawn through the discordant I_2 points in the earlier results and less than that predicted by Oort and van de Hulst (1946). The star ζ Persei seems definitely to be anomalous, and is plotted separately. Although the internal probable error of the point representing the other five stars is ±0.01 mag., the reliability of the measures is not as high as in other types of photoelectric photometry.

Observations of this type can only narrow the uncertainty about the remaining absorption in the extrapolated portion beyond the last plotted point and zero on the abscissa scale. The heavy bar on the ordinate axis in Figure 2 shows the range of probable error given by Morgan, Harris, and Johnson (1953) in their derivation of the result that $A_V/E_{B-V} = 3.0 \pm 0.2$. The $B-V$

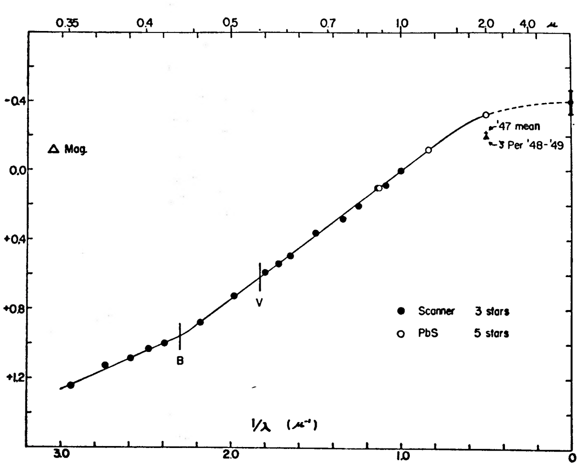

Figure 2. Normalized interstellar reddening curve derived from photoelectric scanner observations, and from infrared filter observations with a lead sulfide photoconductive cell.

excess is read off the reddening curve at the points marked. These effective inverse wave lengths were calculated from the response data given by Johnson (1951) in the same way as was done in this paper for the 6-color filters.

The method used by Morgan, Harris, and Johnson in obtaining their value for the ratio of total-to-selective absorption has not been reported in detail. The most satisfactory method at present depends on observations of stars in a cluster or OB-association which shows a considerable range of reddening among its members. If m_0 is the apparent magnitude m corrected for absorption, then in any chosen system of magnitudes and colors

$$m_0 = m - A = m - RE$$

and the usual expression for the distance modulus becomes

$$m - M = RE + 5 \log D - 5.$$

A plot of the apparent modulus of a group of stars assumed to be at a common distance should then show a linear dependence on E, with the slope of the line equal to R.

Figure 3 shows four examples of such plots for well-known associations, selected to exhibit determinations of low and high weight. The data for II Cygni came from Morgan, Whitford, and Code's catalogue (1953) of blue-giant stars, and show all stars on that list for which $42^\circ.0 < l < 45^\circ.3$ and $-1^\circ.0 < b < 2^\circ.0$. Johnson and Morgan's data (1955) were used for I Persei, with additional data from the catalog of blue-giant stars, the color excesses in the latter case being converted to the $B-V$ system by the factor given by Morgan, Harris, and Johnson (1953). The study of the I Gemini association by Crawford *et al.* (1955) gave data for the plot in the upper left of Figure 3. The material for the Orion association was taken from Sharpless' extensive study (1952); only stars with Yerkes MK classification are used. In all cases the apparent modulus is based on the absolute magnitudes given by Keenan and Morgan (1951).

It is apparent that both a fairly large number of stars and a good range of color excesses are required for a significant determination of the slope. The scatter does not arise from errors in magnitudes or color excesses, nor from distance dispersion in the members of an association; rather it comes from an uncertainty of about ±0.5 magnitude in determining the absolute magnitude of supergiants from spectroscopic

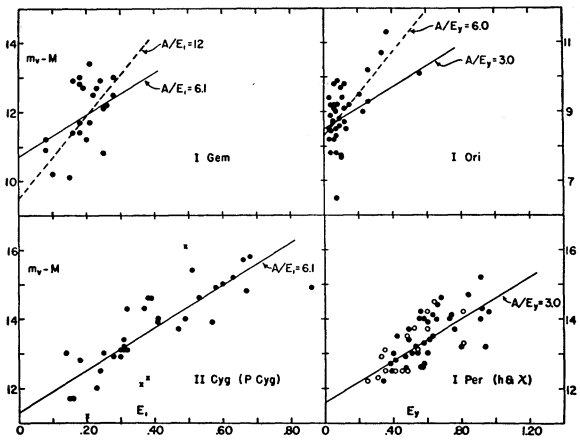

Figure 3. Relation between apparent modulus and color excess for 4 associations. The E_y of the right-hand panels is the same as the E_{B-V} of the text. Open circles represent stars whose color excess on the E_{B-V} system was calculated from C_1 observations. Crosses represent doubtful members of an association.

luminosity criteria. Another association in the catalogue of blue-giant stars, I Cephei, gives a determination of good weight in agreement with II Cygni. T. E. Houck (1956) found $A_V/E_1 = 6.3 \pm 0.2$ for the association I Crucis. Studies of other associations may bring further determinations of high weight. At present there seems to be no reason to revise the ratios given by Morgan, Harris, and Johnson (1953), and recently confirmed by Hiltner and Johnson (1956):

$$A_V/E_1 = 6.1 \pm 0.4$$
$$A_V/E_{B-V} = 3.0 \pm 0.2.$$

The close agreement of the latter value with the extrapolation for the reddening curve given in Figure 2 is reassuring. To the extent that this curve may be regarded as a universal curve applicable to all interstellar material, it may be used to compare reddening in various color systems and to calculate the total absorption in a magnitude system centered at any given effective inverse wave length.

Uniformity of the law of reddening. A wide-range spectrophotometric study like that given in Figure 2 is not practical for a large number of reddened stars in various regions of space. Many would be too faint for available detectors; and in any case there would be a residual uncertainty about extrapolation in the unobserved infrared portion. Two other tests can give information regarding uniformity: (a) correlation plots between color systems; and (b) color-excess plots of groups of stars at a common distance (as discussed in the previous section).

W. Becker's (1948) color difference method, or the *UBV* plot introduced by Johnson and Morgan (1953), or indeed any comparison of color systems that involves wave lengths on both sides of the break in the reddening curve near 2.2 μ^{-1} (4500 Å) is a test of the uniform shape of that part of the curve. The close linear relation between the C_1 colors and the $B-V$ system (Morgan, Harris, and Johnson 1953) is an example; a more extensive comparison of about 100 widely scattered OB stars by Code and Houck (1956b) gave an equally close relation. The *UBV* plot is more sensitive because it covers a wider baseline. Johnson and Morgan (1955) noted a small but distinct difference in the *UBV* plot of the heavily reddened association VI Cygni, when compared with stars in the sector from Cepheus to Monoceros. Very recently Hiltner and Johnson (1956) have used extensive observations of O stars to show that the curvature of the reddening line predicted by Blanco (1956) as a consequence of heterochromatic photometry with broad-band filters cannot be the reason for the discrepancy, though the effect is present. They found that all O stars affected by the Great Rift Cloud show a reddening line which is slightly anomalous when compared with O stars in all other parts of the Milky Way. The difference lies in the direction of greater absorption in the ultraviolet for stars in the Rift, and the change in slope of the reddening line at about 2.2 μ^{-1} would be less for these stars. All of the stars used in plotting this portion of Figure 2 were Rift stars.

Miss E. A. Müller (1956) has reported an anomaly in the opposite direction for the cluster NGC 654, in the Perseus arm. Other nearby clusters are normal. This type of variation is in the direction first reported for the Trapezium stars of the Orion nebula by Baade and Minkowski (1937) and confirmed in 6-color measures by Stebbins and Whitford (1945). On the other hand, Mlle. L. Divan (1954) found that the four stars of the Trapezium, measured separately, showed the normal reddening law found by her to hold elsewhere. Stebbins and Kron (1956) pointed out that the abnormal 6-color values for the composite light could be approximately explained by a combination of normal reddening and the contribution of later-type binary companions. All four components seem to be spectroscopic binaries. Further photoelectric observations, possibly with a scanning spectrograph, are desirable.

Variations in the reddening curve which affect only the slope of the ultraviolet part relative to the visual portion need not affect the ratio of total-to-selective absorption if the excess is derived from, say, the $B-V$ index. This ratio is determined mainly by the red and infrared portions of the curve, and the best test is the color excess plot of association as in Figure 3. Thus far there is no strong evidence of variation in the ratio. Sharpless (1952) suggested a ratio $R = 6E_{B-V}$ for the whole Orion region; but when, as in Figure 3, the data are restricted to accurately classified stars, the evidence is not strong. Certain stars are suspicious, but the reddest star, HD 37061, is in agreement with Mlle. Divan's finding. Sharpless (1954) later found a normal *UBV* plot for the Orion region; but conversely this is not an argument against abnormalities in the infrared part of the reddening curve.

In summary, the evidence points to a very close approach to uniformity of the reddening law over the range of moderate color excesses likely to be used in reaching out to any considerable distances; Mlle. Divan's results (1954) on stars well distributed over the Milky Way give strong support to this view. There are a few clear anomalies, and others suspected. These may involve mainly the ultraviolet portion of the curve. All such cases should be given a careful spectrophotometric study over the widest possible spectral range. Wherever suitable material can be gathered, modulus-color excess diagrams should be plotted to test the total absorption.

Detailed investigations of the law of reddening using stars in various directions are necessarily heavily weighted in favor of the properties of the interstellar medium in our own immediate neighborhood. The structure of the interstellar calcium line may enable us to isolate absorbing clouds in the Sagittarius or Perseus arm, but this is still a part of our general region of the Milky Way. We must therefore guard against the possibility of wrongly interpreting the reddening that standard distance indicators suffer from immersion in the dust of other galaxies.

Thus far there have been only a few programs which attempted to determine accurate colors of individual objects in external systems. Kron and Mayall (1955) have a photoelectric study of globular clusters in progress; objects in several members of the local group are included. Arp (1956) monitored the colors of novae in M31. These Type II objects avoid the dusty regions of external galaxies and are generally not seriously reddened. Stebbins (1950) found that the surface color of M31 was redder along the nearer side of the minor axis where absorption lanes obscure the bright central portion.

For Type I distance indicators in other galaxies, heavy obscuration is common, as was found by Baade and Swope (1955) in their study of Cepheids in M31. Here it was reasonable to assume that the brightest stars of a given period are the unreddened ones. For non-variable stars a study of color and the law of reddening is necessary. Code and Houck (1956a) have made a start on this problem. They found that the OB supergiants in M31 have normal colors, and that there is therefore no galactic absorption at $\beta = -20°$. The cosecant law predicts about 0.7 magnitude. Normal colors were also found for the bluest supergiants in the Magellanic Clouds, where a cosecant correction of 0.3 to 0.4 magnitudes has normally been applied. In the Magellanic Clouds individual spectra of stars could be obtained. A *UBV* plot of stars in the Large Cloud shows a normal reddening law. In the Small Cloud, however, the reddening line appears to lie close to the intrinsic line for cooler early-type stars. This implies that the interstellar medium in the Small Cloud is abnormal in the sense that the reddening curve is straight and does not begin to level off in the ultraviolet.

An extension of this work to all members of the local group containing blue supergiants would be of great interest. NGC 205, as an elliptical with a trace of dust, and NGC 6822 and IC 1613, as low-density irregulars, might offer examples of an interstellar medium unlike that in spiral galaxies. It should not be assumed, however, that all spirals will have a normal law of reddening.

NOTE ADDED JANUARY 6, 1957

Code and Houck now feel that the suspected abnormal reddening by the interstellar medium in the Small Magellanic Cloud should be viewed with reserve until the possibility of an intrinsic difference between the blue supergiants of the Small Cloud and those in the Galaxy has been further investigated.

DISCUSSION

Blaauw pointed out that no strong evidence is left in favor of an abnormal reddening law in Orion. In Sharpless' original paper abnormal reddening seemed to be indicated when the color excesses of the stars of a narrow range of spectral type were plotted against their apparent visual magnitudes, uncorrected for absorption. However, in Orion the most heavily absorbed region is also the most concentrated one, with probably the youngest stars of the association, and we know now that in such a subgroup the stars tend to be intrinsically fainter than the stars in the more dispersed regions.

SCHWARZSCHILD asked whether it is not somewhat puzzling to find so much lower interstellar absorption within our own galaxy than would be expected from the cosecant law, in the direction of at least two of the three extragalactic systems discussed by Whitford.

BAADE pointed out that there are indeed large deviations from the cosecant law. For instance, star counts by Shane in the neighborhood of the directions toward the Andromeda nebula would indicate an interpolated absorption of about one magnitude for this system. On the other hand, Code's photoelectric measures of stars in the south preceding part of the nebula show little absorption. With regard to the Small Magellanic Cloud, Baade mentioned that one wonders whether there is any absorption at all in this system, though there is plenty of gas according to the emission nebulae and the 21 cm measures. Hasn't grain formation started yet in this system?

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PROBLEMS IN THE DETERMINATION OF THE DISTANCES OF GALAXIES

By W. BAADE
Mount Wilson and Palomar Observatories

Abstract. Galactic distance scales are no more accurate than the apparent and absolute magnitudes on which they rest. Whereas the old apparent magnitudes, based on photographic sequences in Selected Areas, were far off at the fainter end, recent photoelectric work has established reliable standards to the 23rd mag. Absolute magnitudes still depend primarily on variable stars, with the cluster-type and classical Cepheid zero-points remaining the most essential references on which to base other criteria.

The determination of the distances of the nearest galaxies is based on objects in these systems with well-defined absolute magnitude. From the apparent magnitudes of these objects, and by the application of the inverse square law, one derives the distance, taking into account the interstellar absorption.

In the application of this method various diffities have to be overcome. Hubble encountered one in determining the apparent magnitudes; the