Color and Polarization of Reflection Nebulae NGC 2068, NGC 7023, and Merope Nebula in Three Spectral Regions[1]

AINA ELVIUS
Uppsala Observatory
Uppsala, Sweden
AND
JOHN S. HALL
Lowell Observatory
Flagstaff, Arizona

A SURVEY OF THE POLARIZATION OF LIGHT by the nebulosity within 67 regions of the Pleiades cluster was made in early 1962. The survey was made without color filters. On two nights, however, some preliminary polarization measures were made with color filters; the results obtained in this investigation seemed to be promising enough to justify a more thorough study of polarization in three colors. The polarimeter used in 1962 was not suited for observations in the UV, however, because its polaroid analyzer would have absorbed most of the ultraviolet light.

In early 1963 color measures of nebulosity were made within the Pleiades cluster in the blue and yellow spectral regions. Later that year a few more observations of polarization were made in three colors with a polarimeter which contained a Glan-Thompson analyzer. An entirely new polarimeter with a Glan-Foucault prism was built in 1964. With this polarimeter three-color observations of the polarization were obtained in several regions of the nebulae NGC 7023, NGC 2068, and the Merope nebula, and of several other objects not discussed here. The polarization observations described here were mainly obtained in October, November, and December 1964, with the 69-inch Perkins Reflector of the Ohio Wesleyan and the Ohio State Universities at the Lowell Observatory in Flagstaff, Arizona. Colors of NGC 2068 and

[1] The contents of this paper were published previously in the Lowell Obs. Bull. No. 135, vol. VI, No. 16, 1966.

NGC 7023 were obtained from the data which had been secured primarily for the purpose of studying the wavelength dependence of polarization in selected regions of these objects.

EQUIPMENT

The nebulosity involved in these measurements was often fainter than the night sky; consequently, it was necessary to make many measures on the sky background during the course of the observations. Because of this it seemed worthwhile to use two telescopes simultaneously in such a way that both the sky and nebula-plus-sky could be recorded at the same time. This procedure should not only double the rate at which observations could be secured, but also improve the accuracy of the observations, because changes in the intensity of the sky background would be continuously recorded.

Figure 1 shows the arrangement of the equipment as it was intended to be used. A 12-inch telescope was attached to the centerpiece of the 69-inch Perkins telescope in such a way that it could be offset from the position of the 69-inch telescope by as much as 1° either way in the east-west direction and could be moved about half this range either north or south. Unfortunately, despite repeated trials, certain unforeseen technical difficulties made it impossible to take advantage of this dual-telescope arrangement. The main difficulty encountered with the 12-inch sky telescope stemmed from the deviation of the transmitted beam (2 minutes of arc) produced by the rotation of its Glan-Foucault prism, combined with a lack of symmetry in the image on the cathode due to the rapid convergence of an *f*/8 beam. (The 69-inch telescope was used at *f*/18.) This method is mentioned here because the difficulties encountered can be removed and the advantages to be obtained are well worth the additional effort and equipment required.

The two polarimeters were identical, and their analyzers were turned simultaneously and to similar position angles by means of two synchroreceivers coupled to a single sychrotransmitter operated by the observer.

The Glan-Foucault prisms were mounted in hollow cylinders centered on the optical axes. In each series of measures the analyzers were oriented at four predetermined position angles 45° apart, each angle being used twice in a symmetrical sequence. An offset guider, located above the focal plane of the 69-inch telescope, made it possible to determine the center of each observed area to an accuracy of about 1 second of arc.

The signals from the photomultipliers were recorded continuously on a dual-trace Brown Recorder. They were also integrated, usually for 30 seconds; and the integral was automatically printed on a white tape and simultaneously punched into a red tape, which was later used for reduction of the data with an electronic computer, the IBM 1620, in Uppsala, Sweden. After repeated trials, the 12-inch sky data proved

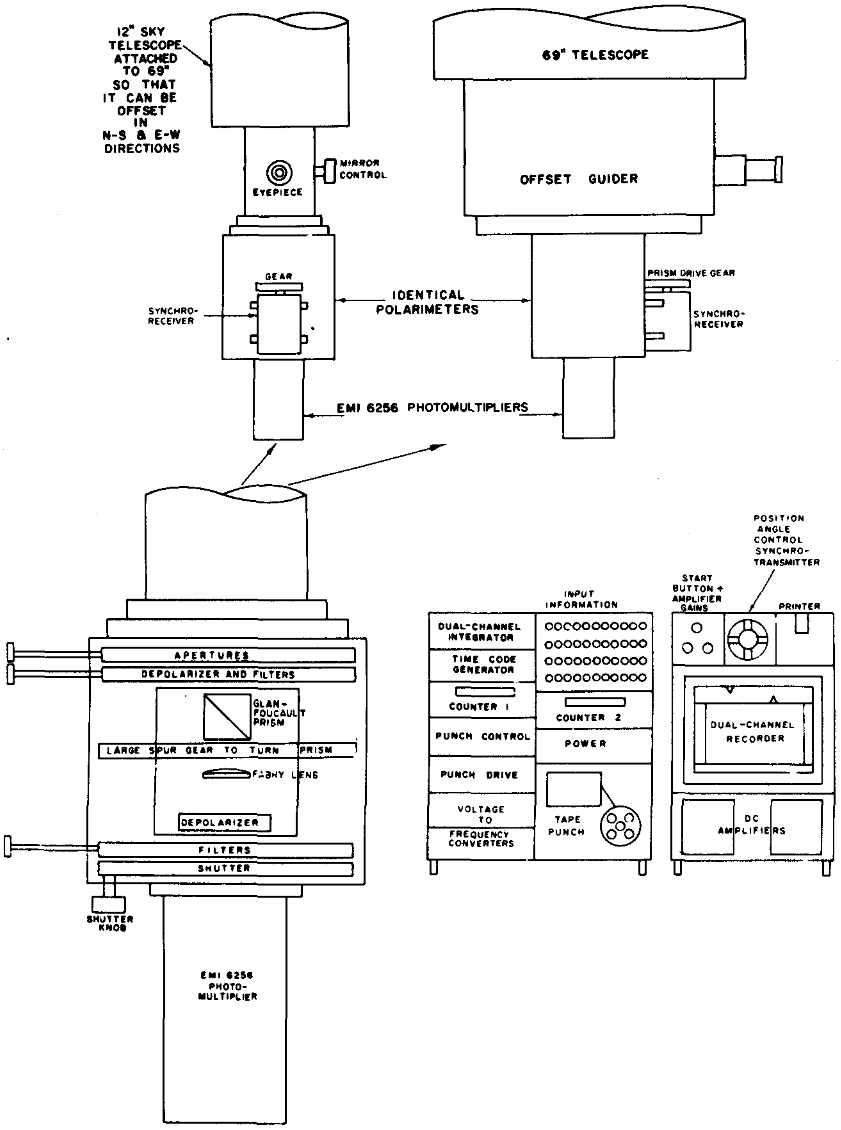


FIGURE 1.—Schematic drawing showing equipment which was intended to be used.

unreliable and only the 69-inch equipment was used for the remainder of the program.

Measures of polarization in three colors required about 20 minutes of observing time. Since a sequence on a nebula field was flanked by two similar sequences on the sky background, or vice versa, a complete set of polarization or color measures occupied about an hour and a half.

https://doi.org/10.1017/S0252921100118378 Published online by Cambridge University Press

Since the color measures were considered to be of secondary importance, as a matter of convenience they were made without removal of the calcite analyzer. In order to be sure that polarized light from different regions did not systematically change the colors, a depolarizer was used together with the analyzer and the color filters. This quartz depolarizer was cemented with Canada balsam, which absorbs in the ultraviolet; consequently, special corrections, determined empirically, were applied.

Figure 2 shows the observed effective energy distribution for the entire light path using Vega as a source when each of the color filters was in position. (See ref. 1.) Energy from Vega was dispersed into focal-plane spectra by means of an objective fine-wire grating. Intensities were measured by accurately offsetting the entrance slit from the central image. The effective wavelengths determined from these data are at 3760 Å, 4460 Å, and 5740 Å. The scale of colors for each of the two systems exceeds that of the $U-B$ system by 5 percent and $B-V$ system by 10 percent. One advantage of this system of filters is that the wavelength bands transmitted by the filters are well separated; a small overlap exists near 4000 Å. Also, very little energy from H beta is transmitted by either the blue or yellow filter; and the response of the photomultiplier to H alpha is almost negligible.

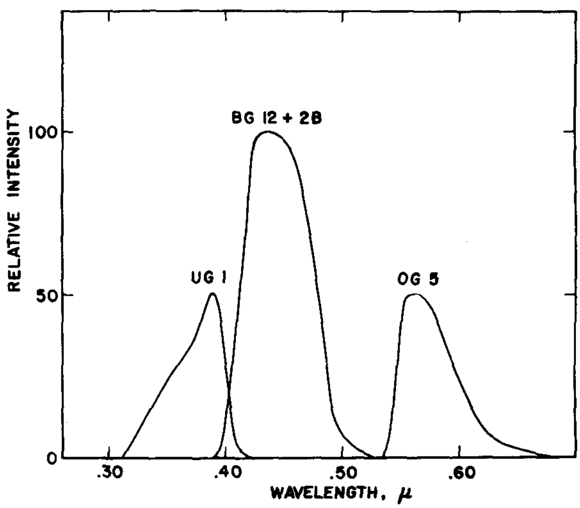


FIGURE 2.—Observed effective energy distribution for each of the three filters when Vega was the light source.

Focal-plane diaphragms with angular apertures corresponding to 29″ and 42″ were usually used. However, in order to obtain measures very close to the stars, special apertures, which are referred to as "baffles," were substituted for the diaphragms. Each baffle consisted of a black central disk mounted on a quartz plate and surrounded by an open annular ring which was used to transmit the nebular energy. When stars were observed, apertures as small as 14″ were often used in order to include as little of the surrounding nebulosity as possible.

In order to eliminate the effects of scattered light from a nearby star, which passes through either the circular aperture or a baffle, special measurements were made in the vicinity of stars which were apparently situated in areas free from nebulosity. Some results obtained for measures of scattered light in each of the three colors using a 29″ circular aperture are presented in figure 3. In this figure, mean curves are shown for measures made through circular apertures equivalent to 29″ with two pairs of Cassegrain mirrors. For the freshly aluminized mirrors in the 72-inch system the scattered light was not only much smaller, but also was only slightly color dependent; the differences, indicated by circles, could only be detected close to the star.

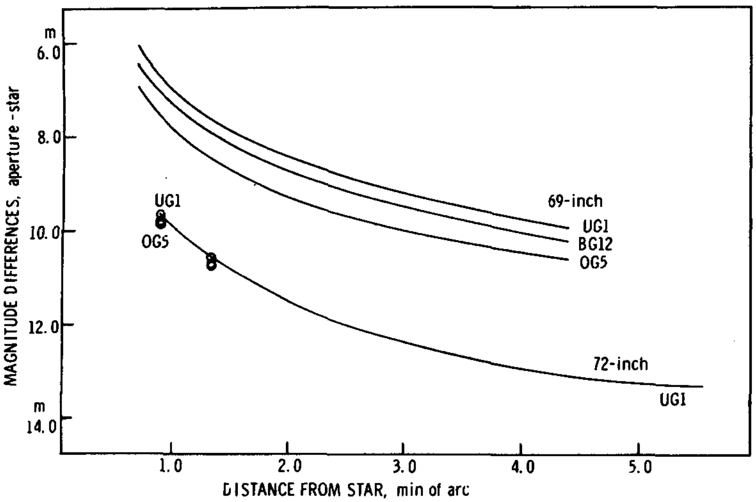


FIGURE 3.—Curves showing amount of scattered light at different distances from a star. Circles indicate areas where noticeable differences for different colors could be detected for the 72-inch system.

As can be seen in figure 3, the scattered light increased substantially toward the shorter wavelengths and varied from night to night. Furthermore, it was 10 or 20 times greater for the 69-inch optics than for the new, freshly aluminized 72-inch mirrors. The 69-inch mirror was last aluminized in 1961. Parts of this mirror had become noticeably etched during resilvering operations since it was polished 34 years ago.

The influence of scattered light on observations of color of the nebulosity south of Merope was found to be so strong for the 69-inch optics that these colors were entirely rejected for this discussion. Special color observations of this region were made in the fall of 1965 by using the new 72-inch optics. Even for these observations, it was found necessary to make calibration runs on each night in order to obtain reasonably consistent results for the nebulosity within a few minutes of arc of Merope. (The analyzer and depolarizer had been removed when these observations were made.)

The colors of NGC 2068 and NGC 7023 presented here were measured with the 69-inch optics only. Because of the much more favorable ratio of nebula-to-star brightness, the scattered light corrections were small or negligible. It is difficult, however, to estimate the effect of the surrounding nebulosity on any observed region (and vice versa)—certainly gradations in color would not be as pronounced as would otherwise be true. Also, because of the wavelength dependence of scattering, the true color of the illuminating star cannot be accurately determined. As a result, the difference in color between star and nebulosity may be systematically in error—perhaps by as much as a tenth of a magnitude.

For the polarization data, the effects of the scattered light (although wavelength dependent) do not influence the results so strongly. The trends, showing wavelength dependence of polarization presented here, are not as reliable for regions close to Merope as for the more distant regions.

Measures with the baffles were less accurate because they are very sensitive, not only to scattering but also to seeing conditions present at the time. For a 29″ occulting disk surrounded by a transparent annular ring 13″ wide, the percentages of scattered light (for the 69-inch optics) were found to be 2½, 2, and 1½ percent for the *UV*, *B*, and *V* regions, respectively. No measures with baffles were obtained with the 72-inch optics.

Extinction corrections were applied to all colors in order to reduce them to unit air mass. The coefficients used were average values obtained during various photometric programs at the Lowell Observatory in recent years and were $0\overset{m}{.}250$ and $0\overset{m}{.}125$ for the $U-B$ and $B-V$ colors, respectively.

All color data presented have been reduced to the *UBV* system. A number of *UBV* standard stars were observed during each dark run. It was found that the same linear transformations for the two sets of colors could be used for each of the three runs made in 1964. The transformation coefficients which were found when the 72-inch system was used to measure colors near Merope were quite similar to those used for the 69-inch optics. The zero points of the observed colors were, however, about $0\overset{m}{.}20$ bluer for the freshly coated mirrors.

OBSERVATIONAL DATA AND RESULTS

The Pleiades

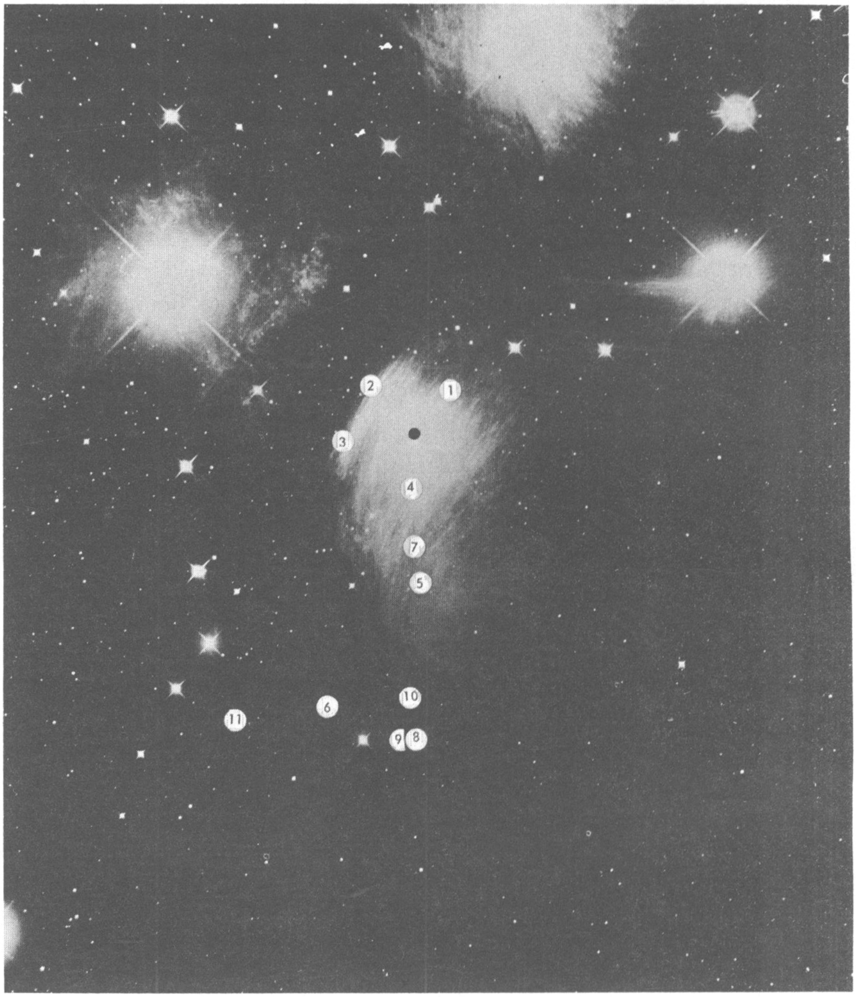
The polarization data in three colors obtained for the Pleiades in the fall of 1964 seem generally to agree well with the data obtained during 1962 and 1963, even though the different techniques were used during the different observing seasons. The polarization survey without filters in 1962 gave a general picture of the polarization of light from the nebulosity near Merope in the Pleiades cluster. This picture of the variation of the polarization with the distance from Merope has been confirmed by later observations. (See ref. 2.) For the regions close to Merope the polarization is small and seems to be of the so-called "radial" type. The data for regions within 5 minutes of arc from Merope are not very accurate, however, because of the strong influence of light from this bright star scattered in our atmosphere and instrument, the scattered light being sometimes as strong as the nebulous region itself.

Measurements of the polarization of light from this part of the Merope nebula have been published in reference 3. The data in that reference for three regions around Merope were obtained with a 12-inch telescope under poor observing conditions and they differ widely from our results.

In the fainter regions of the nebula south of Merope the polarization seems to be systematically higher than near the star; and the direction of the polarization does not depend so strongly on the direction to the illuminating star, but seems to be related to the direction of nebulous filaments in this area. This fact indicates that the light is scattered by nonspherical particles oriented in a magnetic field associated with the filaments. Hall (ref. 4) pointed out that the starlight transmitted through this system of filaments shows polarization parallel to the filaments, an indication that magnetic fields are present along the filaments. More extensive polarization measurements of stars in the Pleiades reported in reference 5 and some made by us more recently tend to confirm this conclusion, although there is not always a complete correspondence, presumably because of the complexity of the nebular structure in many areas.

A similar relationship between the directions of polarization and bright filaments in several other reflection nebulae has been pointed out in the comprehensive study of the polarization of light from reflection nebulae reported in reference 6.

The polarization vectors for scattered nebular light south of Merope were found to be nearly perpendicular to those of the starlight transmitted by the nebula. This evidence seems to strengthen the arguments given in references 7 and 8 that the polarization of scattered light is in some cases strongly correlated with the polarization of transmitted starlight, the two processes being complementary. It should be noted, how-



ever, that the schematic model used in these references is oversimplified and needs revision as soon as enough data are obtained to make a more elaborate model meaningful.

Preliminary results of polarization measurements in three colors are indicated in figure 4, which also shows the regions on a photograph where the measures were made. The degree of polarization has been plotted as a function of λ^{-1} with the effective inverse wavelengths: 2.66 for UG, 1, 2.24 for BG+2 B, and 1.74 for OG 5, which were obtained from the data of figure 2.

Figure 5 shows a plot of the degree of polarization (measured with the yellow and the blue filter) as a function of distance from Merope. There is a fairly strong correlation between polarization and distance.

https://doi.org/10.1017/S0252921100118378 Published online by Cambridge University Press

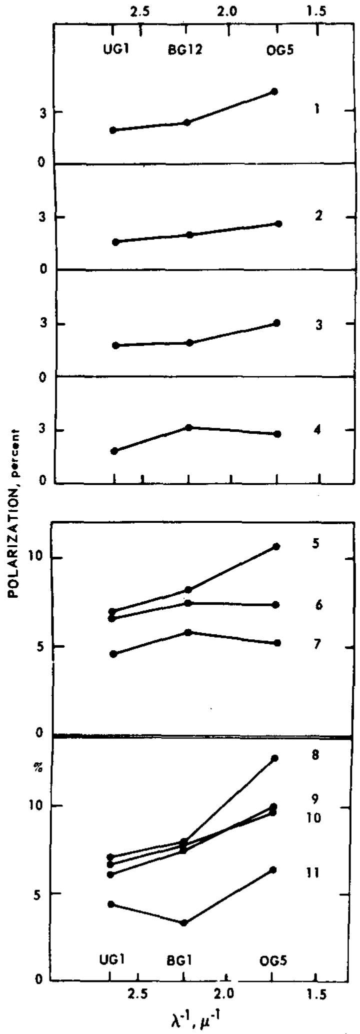


FIGURE 4.—Photograph of Merope nebula and polarization observed at different wavelengths in selected areas. The white disks with identification numbers have twice the diameter of the largest areas measured. The diagrams at the right show the increase of polarization found at three effective wavelengths with increasing distance from Merope (represented by black disk). Official U.S. Navy photograph obtained by E. Roemer with the 40-inch Ritchey-Chrétien telescope.

The degree of polarization increases with distance to a maximum, and then seems to decrease again at greater distances. The curves are drawn in a tentative way to illustrate this general relation. Data obtained in the ultraviolet would result in a similar curve with a lower maximum and are omitted from the diagram to avoid overcrowding.

The degree of polarization probably depends strongly on the scattering angle so that the relation between polarization and distance mainly reflects this dependence on scattering angle. Since the nebula are not expected to be entirely symmetrical, the scattering angles cannot be expected to vary smoothly with distance; thus, it is not surprising that the points in the diagram deviate more or less from the mean curve.

As must be expected from the close correlation between polarization

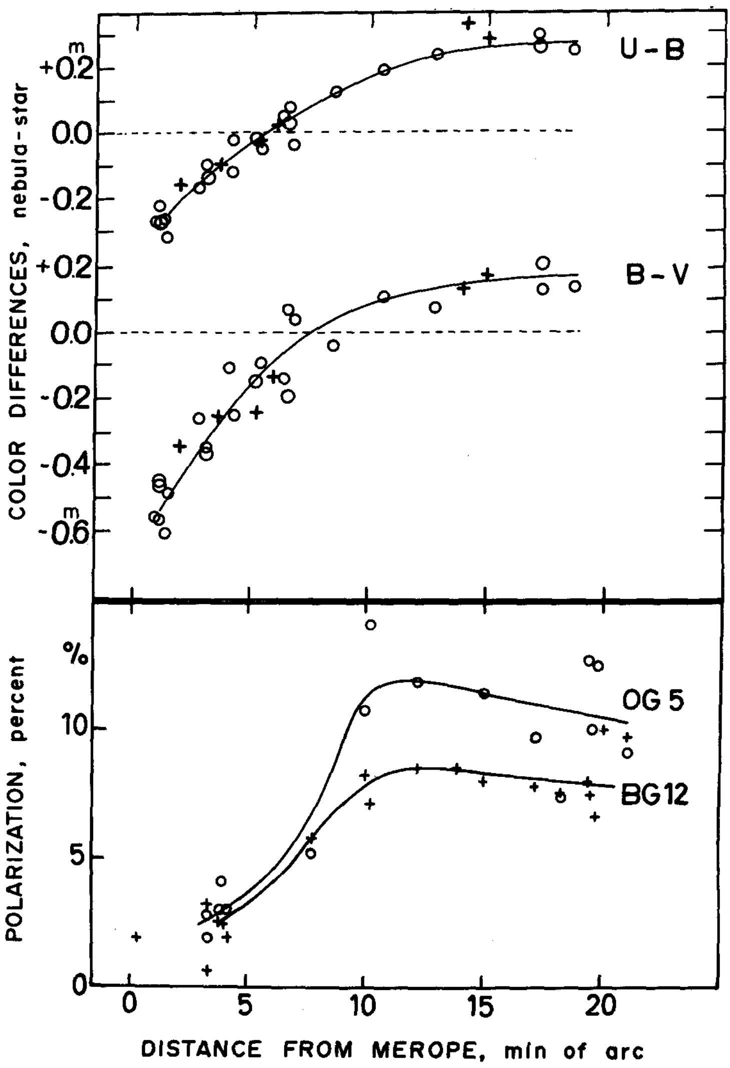


FIGURE 5.—Variation of color and polarization with distance from Merope. The data plotted in the upper part of the figure pertain to areas south of Merope; the crosses (upper plot only) represent data from reference 12. Polarization data for UG 1 are not shown but indicate the same trends as the data for OG 5 and BG 12.

and distance and the even closer correlation between color and distance, there is also a fairly close relation between polarization and color. This correlation is not considered important, however, as it seems to be quite different for different objects.

Two photographic investigations of the color of the nebulosity in the Pleiades conducted about 30 years ago are reported in references 9 and

10. The net result of these investigations was that the nebulosity was bluer than the illuminating star. Another photographic study of the Merope nebula (ref. 11) was made later. The results clearly indicated that the color of the Merope nebula increased with increasing distance south of Merope. The zero point of the colors in this investigation was not determined accurately, an indication that the nebula was always redder than Merope.

The color observations of reference 3 were made with an aperture corresponding to 12 times the area included by the largest diaphragm of the present investigation. There is little correlation between the color data of reference 3 and those of the present investigation, which were obtained for much smaller regions.

The colors of six selected regions near Merope are presented in reference 12. Interference filters were used to make measurements at four wavelength regions between 3400 Å and 5620 Å. Their equivalent widths were not greater than 250 Å. These photoelectric observations were obtained at the 82-inch telescope at the McDonald Observatory in Texas with a 63″ focal-plane diaphragm. The six regions were generally south of Merope at distances between 127″ and 885″.

The $U-B$ and $B-V$ color differences observed on four nights with the new 72-inch optics in the Perkins telescope (circles) are compared with those differences obtained in reference 12 (crosses) in the upper part of figure 5. Despite the difference in aperture size and in the positions of the areas measured, the agreement with the data of the present investigation is excellent. Shifts of only 80 Å in effective wavelength could explain the discrepancies.

The observations plotted in figure 5 show that at a distance of 1′ from Merope the nebulosity in $U-B$ and $B-V$ is about 0.3 and 0.6 magnitude bluer, respectively, than the star. In $U-B$ the color of the nebula becomes about equal to the color of Merope at 5′ south of the star; in $B-V$ the corresponding separation is 7.5.

NGC 7023

The NGC 7023 reflection nebula, shown in figure 6, subtends a much smaller angle in the sky than does the Merope nebula. The illuminating star is 7.3 magnitudes and has a color excess of 0.6 magnitude, indicating a total absorption of two magnitudes.

The polarization of light from NGC 7023 has been studied by several astronomers; however, in reference 13 is published the only data indicating the wavelength dependence of polarization for this object. These were obtained in three wavelength bands in a single region of the nebula.

Figure 6 gives a general picture of the direction of the electric vectors and the degree of polarization found for the areas that have been observed.

TABLE I.—*Color and Polarization*

Observed area offset from star	Aperture, mm	Colors		Polarization data			
				UG 1			BG 12 +2 B
		$U-B$	$B-V$	Region, sky	Polarization, percent	Position angle θ, deg	Region, sky
Star HD 200 775	....	$-0^m.41$	$+0^m.40$	....	0.7	85	....
Around star	....	−0.34	+0.20	8.1	1.5	175	11.7
5 mm S	4	−0.72:	+0.19:	4.1	4.2	91	4.3
10 mm S	4	−0.68	+0.16	2.5	11.2	92	3.9
20 mm S	4	−0.53	+0.02	0.9	3.5	90	1.2
20 mm S, 11 mm E	6	−0.68	−0.06:	0.9	9.9	62	1.0
10 mm E	6	−0.74	−0.12	1.1	4.3	5	1.1
20 mm E	6	−0.77	−0.13	0.6	6.5	162	0.45
25 mm E	6	−0.72	−0.03	0.7	7.1	172	0.9
28 mm E	6	−0.56	−0.30	0.7	8.1	178	0.7
38 mm E	6	−0.80	−0.22	....	....	....	....
10 mm N	4	−0.46	+0.38	1.5	11.8	81	2.3
4 mm N, 4 mm E	4	−0.56	+0.16	5.5	7.4	126	5.7
5 mm N, 5 mm E	4	−0.42	....	1.8	9.5	129	2.5
6 mm N, 6 mm E	6	−0.62	−0.04	1.7	6.4	125	2.2
10 mm N, 10 mm E	6	$-0^m.72$	+0.04	1.1	4.1	125	1.1
30 mm W	6	....	$-0^m.21$	....	....	....	0.27

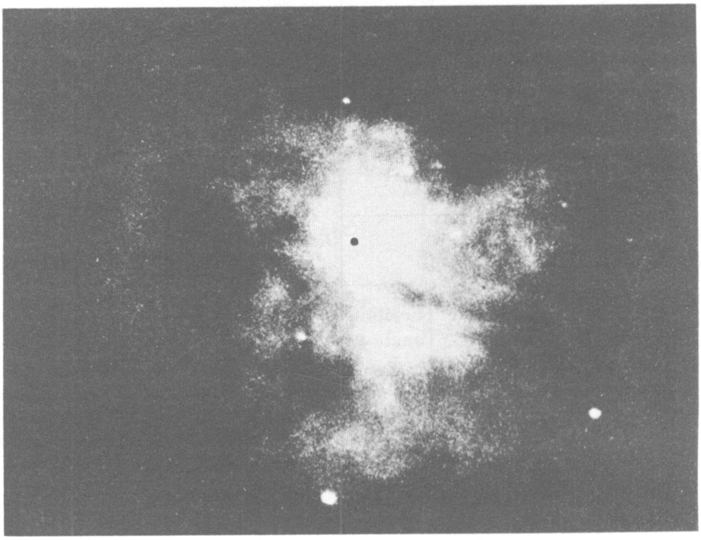
a Colons denote unconfirmed data.
b 6 mm = 42 sec of arc.

https://doi.org/10.1017/S0252921100118378 Published online by Cambridge University Press

Data for NGC 7023 [a]

Polarization data – Continued					Distance from star, sec of arc	Remarks
BG 12 +2 B – Con.		OG 5				
Polarization, percent	Position angle θ, deg	Region, sky	Polarization, percent	Position angle θ, deg		
1.4	85	....	1.3	85:	....	Data are mean values of observations with 2-, 4-, and 6-mm apertures [b]
1.0	175	3.9	1.5	1	20	Observed with baffle aperture, 8-mm opening with 4-mm black disk in center; two observations with BG 12 and OG 5 filters
8.2	88	1.3	12.9	87	33	
15.8	92	1.5	19.1	91	67	Two observations with BG 12 and OG 5 filters
9.0	92	0.45	13.3:	81	133	Two observations with each filter
8.9	68	0.35	10.1	57	152	Two observations with each filter
6.3	174	0.35	11.0	1	67	Two observations with BG 12 filter
3.0	154	(0.12:	13:	20:)	133	
9.5	178	0.26	14.4	173	166	Two observations with each filter
13.1	179	0.18	20.3	179	186	Two observations with OG 5 filter
....	....	....	....	....	253	
13.4	86	1.2	18.1	85	67	
9.5	126	2.1	12.6	125	38	Two observations with each filter
10.0	122	0.9	14.0	122	47	
7.5	123	0.6	12.6	126	57	Mean of two observations with each filter; one series with aperture of 6-mm opening with black disk of 2-mm diameter in center (by mistake)
3.9	121	0.35	5.8	131	94	
7:	171	0.07	(35:	174:)	200	

271-992 O-67—7



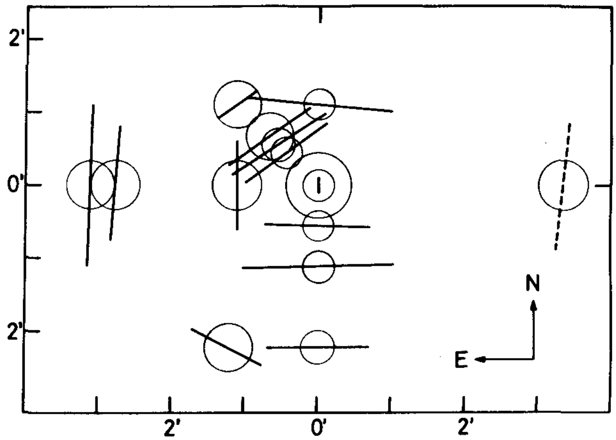


FIGURE 6.—Photograph of NGC 7023 and diagram, printed to same scale, showing polarization found in different regions. The illuminating star, HD 200775, is represented by a black disk on the photograph. The polarization of the nebulosity surrounding the star, corresponding to the area within the annular ring, is represented by the vector at the center of this ring. The open circles represent areas observed, and the length and direction of the electric vectors represent degree and direction of observed polarization. These vectors are consistently perpendicular to the direction to the star. Photograph obtained using Crossley Reflector, Lick Observatory.

The results of observations on NGC 7023 are demonstrated in table I. The data given in this table have been corrected for scattered light from the central star HD 200775 by means of the upper curves shown in figure

https://doi.org/10.1017/S0252921100118378 Published online by Cambridge University Press

3 as described in the text. Because of the unknown variations of atmospheric and instrumental scattering from one night to the other, the values in table I may have been slightly overcorrected or more probably undercorrected by an amount of about the same order of magnitude as the corrections already applied. In order to make it possible for the reader to estimate the uncertainty due to variations in scattering, the values obtained for the same regions without any corrections for scattered light are given in table II.

TABLE II.—*Color and Polarization Data for NGC 7023 Uncorrected for Scattered Light* [a]

Observed area offset from star	Colors		Degree of polarization, percent		
	$U-B$	$B-V$	UG 1	BG 12+2B	OG 5
Star HD 200 775	$-0^m.41$	$+0^m.40$	0.7	1.4	1.3
Around star	−0.48	+0.16	0.6	0.1	0.4
5 mm S	−0.73	+0.07	3.8	7.3	11.5
10 mm S	−0.54	+0.15	10.3	14.8	17.9
20 mm S	−0.62	+0.06	3.2	8.4	12.5
20 mm S, 11 mm E	−0.69	−0.05	9.3	8.4	9.6
10 mm E	−0.75	−0.12	3.4	5.1	8.9
20 mm E	−0.86	−0.22	6.0	2.2:	11:
25 mm E	−0.71	−0.05	6.6	9.0	13.5
28 mm E	−0.60	−0.26	7.8	12.5	19.2
38 mm E	−0.77	−0.28			
10 mm N	−0.40	+0.33	10.4	12.2	16.9
4 mm N, 4 mm E	−0.58	+0.13	6.9	8.7	11.5
5 mm N, 5 mm E	−0.43	+0.06	8.3	8.7	12.4
6 mm N, 6 mm E	−0.60	−0.04	5.5	6.5	10.9
10 mm N, 10 mm E	−0.74	−0.02	3.6	3.4	5.1
30 mm W		$-0^m.24$		6.4:	31:

[a] Colons denote unconfirmed data.

In table III a comparison is made of the data of the present investigation with those of references 6, 14, and 15. The overall agreement is good. However, in the present tests, none of the very faint areas where the authors of reference 14 reported extremely high polarization have been observed. It may be of interest to point out that yellow-sensitive plates were used in the tests of reference 14 and the effective wavelength was estimated to be 5800 Å. The work of reference 14 was criticized by the author of reference 16, who found the polarization to be much smaller. Unfortunately, he did not mention the effective wavelength at which his measures were made. If he used ordinary blue-sensitive plates without any filter, his measures were made at much shorter wavelengths than those of reference 14; and thus

TABLE III.—*Comparison of Polarization Data Given in Table I With Those of References 6, 14, and 15 for Adjacent Areas in NGC 7023*[a]

Source	Area	Color	Polarization, percent	Position angle, deg
Present paper	25 mm E mean	Blue	11	179
	28 mm E mean	Yellow	17	176
Refs. 6 and 15	A	Blue	11±9	0±25
	XVI	Yellow	12	
Ref. 14	3	Yellow	14±5	
	4	Yellow	8±6	
Present paper	10 mm N	Blue	13	86
		Yellow	18	85
Refs. 6 and 15	F	Blue	8±4	90±11
	I	Yellow	19	
Present paper	10 mm S	Blue	16	92
		Yellow	19	91
Refs. 6 and 15	S	Blue	16±5	95±6
	VIII	Yellow	17	
Present paper	20 mm S	Blue	9	92
		Yellow	13	81:
Refs. 6 and 15	IX	Yellow	25:	
Ref. 14	16	Yellow	13±3	
Present paper	20 mm S, 11 m E[b]	Blue	9	68
		Yellow	10	57
Refs. 6 and 15	P	Blue	36±8	45±6
Ref. 14	9	Yellow	21±7	
	10	Yellow	21±4	

[a] Colon denotes unconfirmed data.
[b] This is a faint region surrounded by much brighter regions.

the polarization naturally would come out smaller. This point is clearly illustrated by the data presented in figure 7, showing how the observed polarization changed with the ratio λ^{-1} in different parts of NGC 7023. In any given direction, the polarization for each wavelength region seems to increase with distance and then decrease again, as was found for the Merope nebula. The maximum polarization, however, in different directions occurs at widely different distances from the illuminating star.

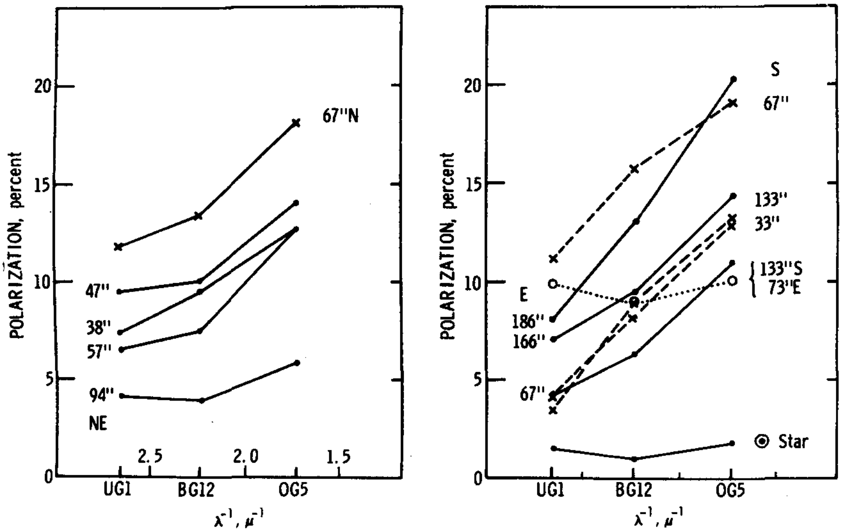


FIGURE 7.—Polarization observations obtained in various areas of NGC 7023 in three different wavelength regions.

The single region previously observed by the author of reference 13 is situated about 38″ NE of the star HD 200775, which illuminates the nebula. The present results show almost exactly the same slope of the line joining the points in UV and yellow as those reported in reference 13 for the same region, but the degree of polarization is systematically smaller in the present observations.

In NGC 7023 there is not such a simple relationship between polarization and distance as in the Merope nebula. It is true that when one starts out in any one direction from the star in NGC 7023 the polarization seems to increase, reach a maximum, and then decrease again, as was found for the Merope nebula. But the maximum polarization will be reached at widely different distances from the star in different directions. This is probably because of the very complicated three-dimensional structure of NGC 7023. No correlation between polarization and $B-V$ colors was detected for this object.

Photographic measures of the color of the nebula in eight regions were reported in reference 17. Some areas were found to be bluer and some were found to be redder than the illuminating star.

Photoelectric color measures were made by Mme. Martel in six regions situated 0'.8 and 1'.6 from the star. The present color measures were made at a dozen points, with that farthest from the star centered in a faint filament on the eastern edge of the nebula. The agreement between the two sets of data is quite satisfactory. She concluded that the nebula is bluer than the star and that the color index increases with increasing distance from the object. Her conclusion that the nebula is bluer than the star does not necessarily contradict that of reference 17, because the regions studied were not the same.

More recently photoelectric colors obtained during three scans across the nebula in an east-west direction have been published in reference 18. These data show a general increase in color as one scans away from the star, with maximum negative color excess to the southeast.

Our observed color differences on the $B-V$ system in the sense, region-minus-star, are shown in figure 8. When a baffle was used to eliminate the direct light from the illuminating star, the observed color

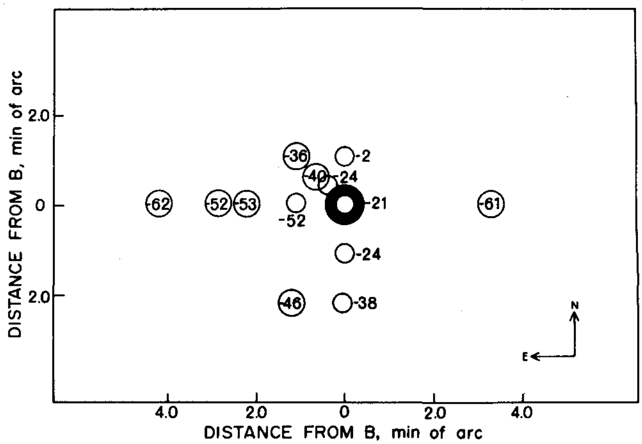
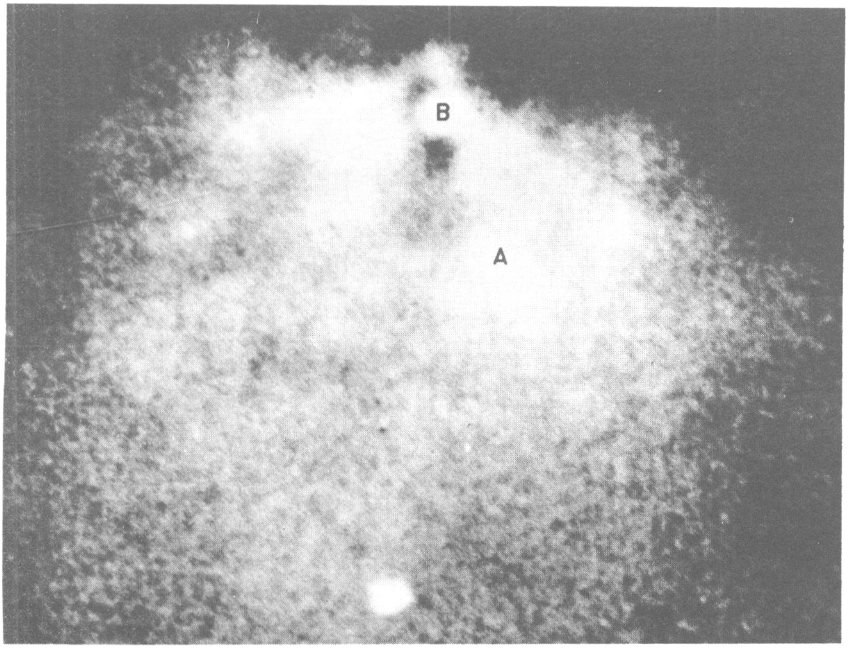


FIGURE 8.—Color differences (nebula minus star) found for NGC 7023 in different areas. Size and position of circles represent areas observed. The color of the nebulosity found for the annular ring surrounding the illuminating star is $0^m.21$ bluer than the star itself. Unit, $0^m.01$.

of the nebulosity immediately around the star was found to be $0^m.21$ bluer than the star. The degree of bluing in the east-west direction is about 0.6 magnitude in $B-V$ at a distance of 4′ from the central star. However, the color 1 minute of arc north of the object is only slightly bluer than the star, a result which agrees with the color observed near this region by Mme. Martel. Much farther to the north, Keenan (ref. 17)



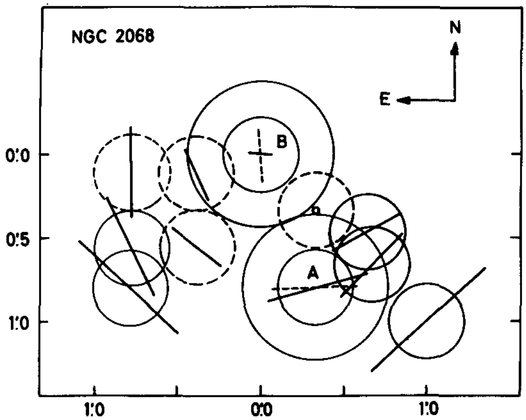


FIGURE 9.—Photograph of NGC 2068 and diagram showing observed polarization found for different areas. The positions of stars B and A are indicated together with the observed electric vectors. These correspond to yellow light and are represented by straight lines which pass through the centers of circles outlining the observed areas. The polarization found within the annular rings surrounding the two stars is similarly represented by vectors. The dotted lines describe the polarization found for the stars A and B themselves. The data clearly show that star B illuminates the nebulosity—even in the area "surrounding" A. Photograph obtained using Crossley Reflector, Lick Observatory.

https://doi.org/10.1017/S0252921100118378 Published online by Cambridge University Press

TABLE IV.—*Color and Polarization*

Object or area offset from B	Colors		Polarization data			
			UG 1			BG 12 +2 B
	$U-B$	$B-V$	Region, sky	Polarization, percent	Position angle θ, deg	Region, sky
Star A	$-0^m.06$	$+0^m.65$	....	3.4	92	....
Star B	+0.20	+1.26	1.4	0.5:	....	3.5
Around star B	−0.45	+0.37	2.3	0.9	81	3.5
3 mm S, 3 mm W	....	....	....	....	....	....
4.2 S, 5.7 W	−0.44	+0.28	2.1	3.5	116	3.1
6.0 S, 6.0 W	−0.39	+0.24	2.6	3.6	129	2.8
9.0 S, 9.0 W	−0.53	+0.13	2.1	4.6	134	2.5
7.2 S, 7.1 E	−0.47	+0.25	1.9	2.5	76:	2.7
5.0 S, 7.0 E	−0.54	+0.25	1.8	4.5	34	2.2
1.0 S, 7.0 E	....	....	....	....	....	....
5.0 S, 3.5 E	....	....	....	....	....	....
1.0 S, 3.5 E	....	....	....	....	....	....
Around star A	$-0^m.54$	$+0^m.21$	4.5	4.9	96	5.2

[a] Colons denote unconfirmed data.

NOTE: When not otherwise stated the aperture used was 4 mm (29″) in diameter and the area was observed only once with each filter.

https://doi.org/10.1017/S0252921100118378 Published online by Cambridge University Press

Data for NGC 2068 [a]

Polarization data—Continued					Distance from star B, sec of arc	Remarks
BG 12+2 B—Continued		OG 5				
Polarization, percent	Position angle θ, deg	Region, sky	Polarization, percent	Position angle θ, deg		
4.0	90	....	4.3	96	52	Color observation with 2-mm aperture. Polarization measures with 2-mm and with 4-mm aperture.
1.3	175:	7.8	2.4	179:	0	Color observation with 2-mm aperture. Polarization measures with 2-mm and with 4-mm aperture.
0.6:	....	1.8	0.9	81	20	Mean values of three observations with baffle; 8-mm opening with 4-mm black dot in center.
....	....	2.3	0.2	....	28	
3.4	119	1.3	4.2	118	47	
4.4	144	1.6	4.9	137	57	
5.5	132	1.0	8.3	133	85	Mean of three observations.
5.5	47	1.5	7.5	36	67	Polarization in BG 12 and OG 5 mean of two observations.
4.8	11:	1.5	6.1	29	57	Polarization in OG 5 mean of two observations.
....	....	1.8	5.5	1	47	Polarization in OG 5 mean of two observations.
....	....	1.8	3.5:	52:	41	
....	....	2.2	3.1	24	24	
4.4	106	2.8	5.6	107	52	8–4 mm baffle.

https://doi.org/10.1017/S0252921100118378 Published online by Cambridge University Press

found the nebulosity to be redder than the star. Consequently, the presently available data indicate that this object does not have the same nearly symmetrical properties which characterize the Merope nebula. Because of differences in the regions observed, apertures used, and possible differing influence of emission lines, it is not possible to make close comparison of present results with those of reference 18.

NGC 2068

The NGC 2068 reflecting nebula is interesting from several points of view. Two tenth-magnitude stars, situated within the nebulosity A and B, are only 50″ apart, yet show polarization of almost "opposite" direction, as has been pointed out in reference 19. The electric vector has a po-

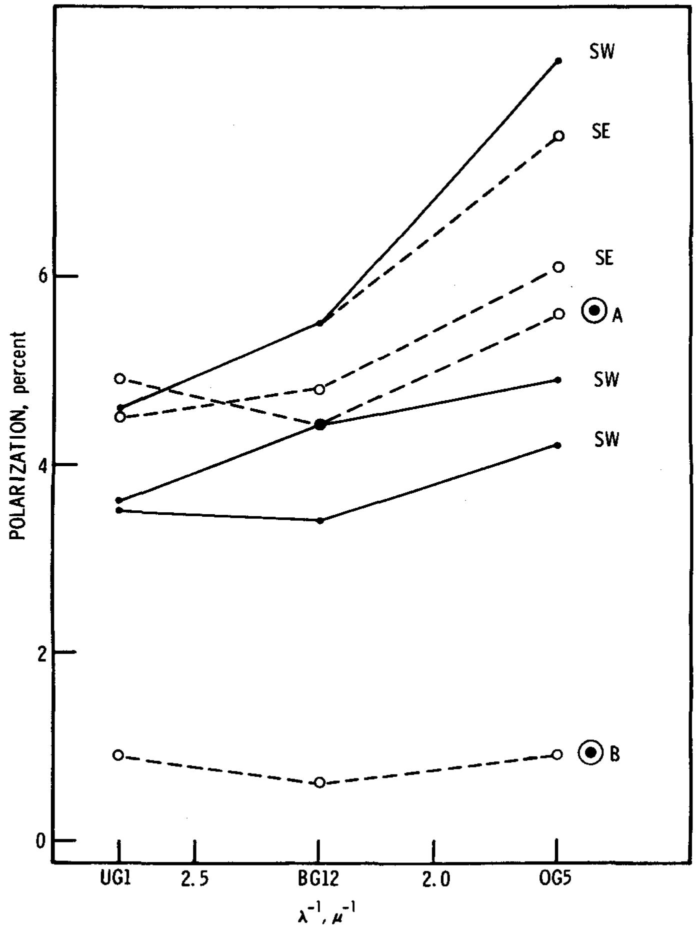


FIGURE 10.—Polarization observed in NGC 2068 at three different wavelength regions in different directions from star B.

https://doi.org/10.1017/S0252921100118378 Published online by Cambridge University Press

sition angle close to 90° for star A and close to 0° for star B. It has been suggested in reference 20 that the nebula is being illuminated by the star B, which is seen in figure 9 to be very close to the northern edge of the visible nebula.

This assumption of reference 20 is verified by present polarization measures which indicate a strong correlation between the polarization vectors and position relative to star B. Even the nebulosity "around" star A seems to be illuminated mainly by the star B. It is not clear how much of the dark matter which causes the sudden change in brightness just north of star B also influences the polarization of the two stars and the nebulosity. Perhaps the dark patch close to star B, which is elongated in a north-south direction, may contribute both to the obscuration of star B and to the change in polarization relative to star A.

The polarization found for NGC 2068 is shown in table IV as a function of the ratio λ^{-1} in figure 10. The degree of polarization seems to be related to distance, as shown in figure 11, in much the same way as was found for the Merope nebula. It should be noted that the distances are small and the apertures relatively large. The relation between polarization and $B-V$ color seems to be almost opposite to that found for the Merope nebula, if there is any significant correlation at all.

In reference 20 the illuminating star is classified as B1 and its color excess is found to be 1.5 magnitude in the $B-V$ system. Since the position of the object in the Orion association places it 15° from the galactic plane, it is reasonable to assume that most of the heavy absorption is in some way associated with the nebula.

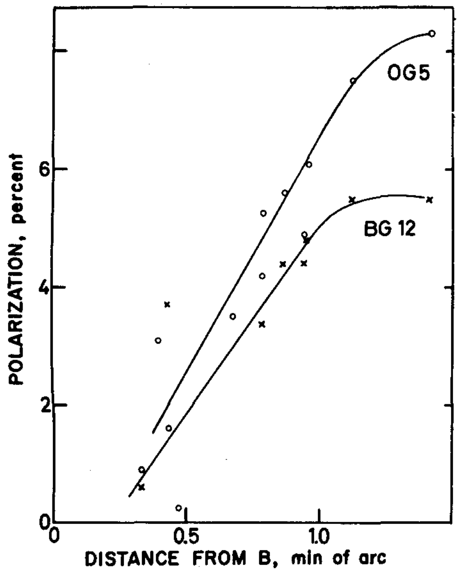


FIGURE 11.—Increase of polarization for blue and yellow regions, with increasing distance from star B in NGC 2068.

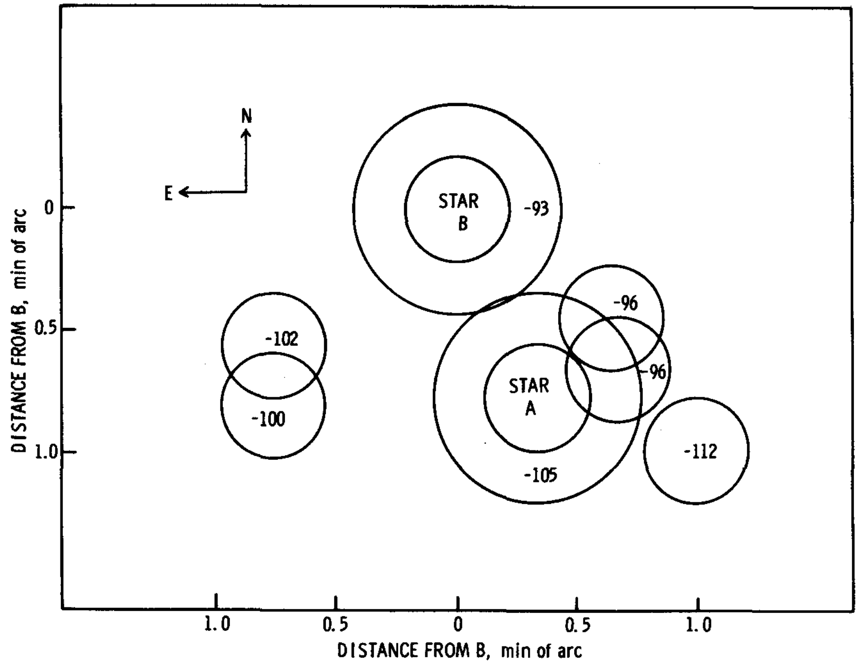


FIGURE 12.—The $B-V$ color differences (nebula minus star) found for NGC 2068. Unit, $0^m.01$.

The $B-V$ color differences (nebula minus star) found for this object are shown in figure 12. The nebulosity appears to become bluer with increasing distance from star B. These color differences are much more pronounced in NGC 2068 than in the Merope nebula and in NGC 7023; it is near 1.0 magnitude, rather than 0.6 magnitude. This larger difference must be due at least in part to very strong reddening of star B within the nebula.

TABLE V.—*Color Excesses, Spectra, and Magnitudes of Illuminating Stars*

Nebula	Data for illuminating star			
	E_{B-V}	Spectrum	V	Ref.
Merope Nebula	$+0^m.08$	B6 IV nn	$4^m.2$	21, 22
NGC 7023	+0 .6	B3 ne (V)	7 .3	6, 18, 23, 24
NGC 2068	$+1^m.5$	B1 V	$10^m.7$	20

https://doi.org/10.1017/S0252921100118378 Published online by Cambridge University Press

Pertinent data concerning the color excesses and spectra of the illuminating stars for the three objects discussed in this paper are outlined in table V.

CONCLUSIONS

1. The data obtained in three colors indicate that the polarization varies with wavelength in approximately the same way for the three objects studied, although small variations which might be significant do occur from one region to the other within each object.

2. The polarization data show that the fainter (northern) of the two tenth-magnitude stars in NGC 2068 is the illuminating star.

3. No general correlation between the degree of polarization and the $B-V$ color of the nebulosity seems to exist.

4. The expected change in polarization with scattering angle is observed as a systematic change in polarization with distance from the illuminating star, at least in areas where the structure of the nebula is not too complicated. The shape of the curve relating polarization and angular distance, and especially the position of maximum polarization, may be helpful in solving the geometrical problems concerning the arrangement of various parts of the nebulosity relative to the position of the star.

5. It is highly probable that Merope is near the front side of the nebula and there is a rather uniform increase in color index with angular distance southward from the star. One minute of arc south of Merope the nebulosity is 0.3 and 0.6 magnitude bluer than Merope in $U-B$ and $B-V$, respectively. The angular distances at which the $U-B$ and $B-V$ colors are equal to those of the star are, respectively, $5'$ and $7'.5$.

6. For NGC 7023 the color excess of the nebulosity seems to decrease slightly with angular distance from the illumination star in the east-west direction. However, much more extensive color data, free from possible influence by hydrogen emission lines, should be secured before a clear picture can be obtained.

7. For NGC 2068 (M78), where the illuminating star has a color excess of 1.5 magnitude and therefore is behind heavy absorption, the color of the nebulosity decreases very slowly with increasing distance.

8. This color and polarization survey of parts of three objects suggests that for NGC 2068 and NGC 7023 the interpretation of the data is far more complicated than for the nebulosity south of Merope. The proximity and the relative symmetry of the Merope nebula suggest that it is a favorable object for intense study by several different observational techniques. The region also offers one of the best possibilities to study the relationship between the polarization due to extinction of transmitted starlight and that due to scattering of light in the same clouds.

REFERENCES

1. HALL, J. S.: Spectrophotometry of 67 Bright Stars with a Photoelectric Cell. Astrophys. J., vol. 94, 1941, p. 72.

2. ELVIUS, A.; and HALL, J. S.: Three-Color Observations of Polarization in the Light From the Reflection Nebulae NGC 2068, 7023, and IC 349, the Crab Nebula and the Galaxies NGC 1068, 3034, and 7814. Astron. J., vol. 70, 1965, p. 138.

3. JOHNSON, H. M.: Photoelectric Photometry of Diffuse Galactic Nebulae and Comet Arend-Roland. Astron. Soc. Pacific, Pub., vol. 72, 1960, p. 10.

4. HALL, J. S.: The Polarization of Light From Stars Behind Filamentary Structure. Mem. in 8° Soc. Roy. Sci. Liège, ser. 4, vol. 15, 1955, p. 543.

5. VAN DEN BURGH, S.: Polarisation des Sternlichtes im Gebiet der Plejaden. Zs. Astrophys., vol. 40, 1956, p. 249.

6. MARTEL, T. M.: Polarisation de la Nébuleuse du Crabe. Polarisation et Couleur des Nébuleuses Diffusantes. Pub. Obs. Haute-Provence, vol. 4, no. 20, 1958.

7. ELVIUS, A.: Polarization of Light in the Spiral Galaxy NGC 7331 and the Interpretation of Interstellar Polarization. Stockholm Obs. Ann., vol. 19, no. 1, 1956.

8. ANON.: On the Polarization of Light in Reflection Nebulae with Filamentary Structure. Uppsala Astron. Obs. Medd., 1959, p. 121.

9. STRUVE, O.; ELVEY, C. T.; and KEENAN, P. C.: On the Colors of Diffuse Nebulae Having Continuous Spectra. Astrophys. J., vol. 77, 1933, p. 274.

10. GREENSTEIN, J. L.; and HENYEY, L. G.: The Spectra of Two Reflection Nebulae. Astrophys. J., vol. 89, 1939, p. 647.

11. SCHALÉN, C.: The Colour Distribution in the Nebula Surrounding the Star Merope in the Pleiades. Uppsala Astron. Obs. Ann., vol. 2, no. 5, 1948.

12. O'DELL, C. R.: Photoelectric Spectrophotometry of Gaseous Nebulae II. The Reflection Nebula Around Merope. Astrophys. J., vol. 142, 1965, p. 604.

13. GEHRELS, T.: Measurements of the Wavelength Dependence of Polarization. Lowell Obs. Bull., vol. 4, 1960, pp. 105, 300.

14. GLIESE, W.; and WALKER, K.: Polarisationsuntersuchungen am Reflexionsnebel NGC 7023. Zs. Astrophys., vol. 29, 1951, p. 94.

15. MARTEL, T. M.: Polarisation de la Lumière Diffusée de NGC 7023. Pub. Obs. Haute-Provence, vol. 2, no. 17, 1951.

16. WESTON, E. B.: Polarization of the Reflection Nebula NGC 7023. Astrophys. J., vol. 57, 1952, p. 28.

17. KEENAN, P. C.: Photometry of the Diffuse Nebula NGC 7023. Astrophys. J., vol. 84, 1936, p. 600.

18. VANÝSEK, V.; and SVATOŠ, J.: Solid Particles in Reflection Nebulae I. Acta Univ. Carolinae-Math. and Phys., no. 1, 1964, p. 1.

19. HALL, J. S.: Polarization of Starlight in the Galaxy. Pub. U.S. Nav. Obs., vol. 17, 1958, p. 275.

20. SHARPLESS, S.: A Study of the Orion Aggregate of Early-Type Stars. Astrophys. J., vol. 116, 1952, p. 251.

21. JOHNSON, H. L.; and MORGAN, W. W.: Fundamental Stellar Photometry for Standards of Spectral Type on the Revised System of the Yerkes Spectral *Atlas*. Astrophys. J., vol. 117, 1953, p. 313.

22. MENDOZA, E. E.: A Spectroscopic Study of the Pleiades. Astrophys. J., vol. 123, 1956, p. 54.

23. GREENSTEIN, J. L.; and ALLER, L. H.: Spectra of Stars in Diffuse Nebulae. Astron. Soc. Pacific, Pub., vol. 59, 1947, p. 139.

24. MENDOZA, E. E.: A Spectroscopic and Photometric Study of the B Stars. Astrophys. J., vol. 128, 1958, p. 207.

DISCUSSION

O'Dell: I have obtained results that indicate that the regions at distances of about 15′ from Merope observed through narrower filters show a sharper decrease; that is, the nebula becomes even redder than the authors have indicated. This trend might be explained by the rather wide band-pass filter employed for the ultraviolet measurement of your tests. However, in general the results are the same.

Wickramasinghe: Isn't it true in general that the total color of a nebula tends to be bluer than that of the exciting star?

Elvius: I think that the integrated color of the nebula was bluer than the star. We did not measure the very faint regions far away from the star, however. You may remember that the color of the Merope nebula becomes redder with increasing distance from the star (fig. 4). Thus, the integrated color of this complete nebula may not differ much from that of the star.

Wickramasinghe. It seems this should tell us something about the nature of the grains.

Greenberg: I think that when Mr. Roark talks he will be able to point out that the color is strongly dependent on the geometry.

Wickramasinghe: The total integrated color?

Greenberg: Yes. The total color is a function of the geometry of the nebula.

Nandy: Did you study whether bluing or reddening depends upon the spectral type of the exciting star?

Elvius: The spectral types were rather similar in the cases we observed from B1 to B6.

Nandy: Are the illuminating stars of these nebulae all of the same spectral type?

Elvius: They are almost the same types; they are usually B stars.

Greenberg: Mr. Roark has noted a significant difference to be expected for the total intensity of the light for different grain models. This is another feature by which one can investigate the character of the grains. This is all, of course, a function of the albedo.

Elvius: I think we should clarify our definition of "bluing." With what do you compare the color of the nebula? The starlight we observe is often reddened. Do you compare the color of the nebula with the original color of the star?

Wickramasinghe: Yes.

Elvius: Then you get quite a bit of reddening if the light of the illuminating star is very reddened, as in NGC 2068.

Wickramasinghe: You get both bluing and reddening.

Elvius: Yes; it depends on the geometry.

Serkowski: Is the plane of polarization of the Merope nebula perpendicular to the plane for the transmitted starlight?

Elvius: Yes, the polarization vectors for the scattered light are perpendicular to those of the transmitted starlight except close to Merope, where the direction to the star is more important. We have not yet used the data to determine the albedo or to construct any models. I think the geometry problem is important, particularly in cases with nonisotropic scattering.

Greenberg: The geometry here is simplest in Merope. This seems to be the prevailing opinion.

Hall: But I don't see how you can deduce the albedos without making half a dozen assumptions.

Wickramasinghe: Yes, the situation is very difficult here. Very special models must be made before the albedos can be computed.

O'Dell: It might be important to put an error on the albedos, considering, possibly, the role of second-order scattering. If an attempt is made to fit this nebula, which becomes much redder in the outer regions, to an optically thick nebula, the fact that second-order scattering is important becomes obvious. This constitutes one more term of complication in addition to considering the geometry in obtaining a meaningful albedo.

Strömgren: I believe Dr. Hall emphasized that the Merope is the simplest case, not only because of the geometry but also because we can be fairly certain that there is no foreground absorption.

Dressler: Are there any other similar cases?

Hall: Several stars other than Merope in the Pleiades are unreddened. It looks as if the nebulosity is mostly behind the stars.