A STUDY OF DARK NEBULAE

by

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Table 1
PREAMBLE:

For many years dark nebulae were not considered to be clouds of cosmic grains, but they were rather thought of as "holes in the sky". This idea was discarded in the late 19th century, when Barnard began his photography of the Milky Way. Photographs made with high resolution telescopes showed bright nebulose structure in many of the obscured areas. It is now realized, of course, that gas and dust constitute a substantial mass component of our Galaxy.

Dark nebulae seem very likely to be closely linked with star formation, and it is of increasing importance to discover the physical processes taking place in these areas to further our understanding of pre-protostar conditions. Radio observations of molecular lines are revealing some of the chemical constituents of dark clouds, as well as indicating temperatures. Optical studies furnish data on absorptions and distances of nebulae, which in turn yield minimum values of densities and masses provided we can make some fundamental assumptions concerning grain characteristics. The combining of radio and optical data, combined with theoretical interpretation, are leading to reasonably definite conclusions regarding early star formation.

The section that follows gives a brief summary of different types of dark nebulae together with representative properties for each variety we discuss. Later sections discuss the methods for finding approximate absorptions and distances of dark clouds through the use of star count data and from results obtained with modern color techniques.
Finally, a summary of available catalogues and photographic atlases of dark nebulae is given.

I. VARIETIES OF DARK NEBULAE

A basic characteristic of the interstellar medium is its clumpiness. The dust is formed into clouds and lanes of dark nebulae; and, although many areas of the sky show filaments of absorption, there are also many unit clouds with well-defined dimensions. These single structures can be roughly categorized into three types, according to size.

The smallest unit clouds that we can observe directly are seen in relief against bright emission nebulae. These clouds are the small Bok globules, first postulated as regions of star formation by Bok and Reilly (1947). They are frequently observed in clumps or chains; see for example, photographs of NGC 2244 (the Rosette nebula) and IC 2944. These globules appear as opaque specks, with shapes varying from extremely round, compact spheres, as seen in NGC 2244, to more windswept filaments such as those seen in Messier 8. Bok, Cordwell and Cromwell (1971) indicate that diameters for these objects range between 0.01 to 0.1 parsec, and masses are somewhere between 0.1 and 1.0 solar mass.

The second category of dark nebulae includes isolated large globules with angular sizes between about 5' and 20', which are seen as voids against rich star fields. Many of the nebulae catalogued by Barnard (1927) fall in this category, hence these globules are sometimes referred to as "Barnard objects".

Two large, semi-transparent globules, Barnard 361 and Barnard 34, were found by Bok et al (1971) to have photographic absorptions of about 2.5 mag., masses around 60 solar masses, and radii in the neighborhood of 1 pc. Many of the large
globules appear opaque to the limit of the plate, and only minimum absorptions can be assigned to them. Examples of these are Barnard 227 and Barnard 335. Unlike the tiny Bok globules, which appear in turbulent surroundings, the Barnard objects seem to be very quiescent and isolated.

The third category of dark nebulae encompasses large dark complexes of dust, such as the ρ Ophiuchi nebula, several clouds in Taurus, and the Southern Coalsack. The ρ Ophiuchi nebula and three regions in Taurus were extensively studied by Bok (1956). Star counts were made from the original Palomar Sky Survey plates, and absorptions were mapped for each region. The ρ Ophiuchi complex shows a distinct radial density gradient, with a total absorption amounting to 8 mag. in the center, and decreasing to about 3 mag. near the edge. This cloud has a radius of about 4 pc., and a mass of the order of 2100 solar masses. It is of interest that Heiles (1969) finds a temperature for this cloud near 10° K or less, as indicated by OH absorption lines.

The Taurus region displays several large dark lanes, with absorptions running as high as 7 magnitudes. Young T Tauri stars have been found in this area, and radio astronomers are searching these clouds for interstellar molecules.

The Southern Coalsack, as seen in the older atlases, appears as a large unit cloud, but upon closer inspection of higher resolution plates, it looks as though it is divided into many knots of absorption. It is possible that fragmentation is taking place in this cloud, leading to the formation of a star cluster. Rodgers (1960) finds absorptions ranging from 0.7 to 2.4 mag.

Each category of dark nebulae is studied in a somewhat different manner. The following sections summarize the current methods of analysis which lead to values of absorptions and distances for these objects. A final section lists various catalogues and photographic atlases of dark nebulae.
II. STAR COUNTS

Most determinations of distances and absorptions of dark nebula involve a statistical analysis of star counts. Star counting is still a laborious process, but through the application of modern techniques it is becoming both simpler and more accurate. If a major project were undertaken, it would pay to develop now a fully automatic star counting machine.

The object of star counts is generally to find the numbers of stars per magnitude interval to as faint a limit as possible. Stellar images of different sizes are counted, and their sizes are then converted to magnitudes by means of a standard magnitude sequence. For the study of a dark nebula, star counts are made both in the obscured region of interest, and in one or two comparison fields. The selection of comparison fields is a matter of careful choice, since they should be selected from areas relatively free from absorption, yet close to the nebula.

An iris photometer provides the most accurate means of measuring image sizes. The aperture readings are converted into magnitudes by means of a standard photoelectric sequence. The stars can then be counted in magnitude intervals.

As an illustration, consider B and V stellar plates which have photoelectrically determined standard sequences on them. By utilizing the method of photographic photometry, we can obtain B and V magnitudes for any stars on our photographic plates, and then we can find the photographic and visual absorptions of the dark nebula by methods to be outlined later in this paper.

Effective methods of counting were developed by Lindsay and Bok (1936) and by Miller (1936). A magnitude sequence of image sizes is imprinted at the top and bottom of a transparent reseau, which is then placed on the plate to be counted.
A specific scale image is selected, and all stars which have sizes less than or equal to this calibration image are counted column by column in the manner shown in figure 1. The process is repeated for successive scale images.

If no sequence of standard magnitudes is available, then one can get a rough total photographic absorption by counting stars to the limiting magnitude on a blue plate. The areas counted are reduced to an area of one square degree, and the counts are compared directly with van Rhijn's (1929) tabulation of log $N(m)$ versus $m$ for old galactic latitude and longitude. Here, $N(m)$ is the number of stars per square degree of magnitude $m$ or brighter.

As an example, suppose the counts in the comparison field give a log $N(m)$ which corresponds to $m = 18$ in van Rhijn's table, and that the star counts in the dark nebula correspond to van Rhijn's counts to $m = 15$. We can then conclude that the nebula absorbs about 3 magnitudes. For this method to be applicable, we require that the counts must reach sufficiently faint limits so that most of the counted stars lie beyond the dark nebula.

There are no tables such as van Rhijn's for star counts in red colors. To get an approximate red absorption for the nebula one can look at the ratio of numbers of red to blue counts in the comparison fields, and use this ratio as a multiplying constant to go from red to equivalent blue counts in the dark nebula. Van Rhijn's tables can then be used as before.

This technique for finding blue and red absorption was used by Bok (1956) to map absorption for regions in Taurus and Ophiuchus.

Van Rhijn's star count tables were made many years ago, under less than perfect conditions, and the accuracy of his counts has long been in question. Consequently, absorptions should be found in this manner only when no magnitude sequences are available. The application of the van Rhijn
Tables to visual or red counts is even more dubious, since we should really use basic tables (not available) prepared for red or visual log N(m)'s. The only safe procedure is really to proceed via a sequence of standard magnitudes in B, V, and R established for the purpose.

III. ABSORPTIONS AND DISTANCES OF DARK NEBULAE

A. Wolf Diagrams

A fairly easy way to find the absorption of a dark nebula is through the use of a Wolf Diagram. Star Counts yield values of A(m), the number of stars in the magnitude interval m - \(\frac{1}{2}\) to m + \(\frac{1}{2}\). A graph of log A(m) versus m (Wolf Diagram) is made for both the comparison region and the obscured field. At a distance less than that of the nebula the curves are parallel. At the point where the nebula begins to affect the counts in the obscured region, say at \(m_1\), the curve for the obscured region has the lesser slope and separates from the curve for the comparison field, until some magnitude, \(m_2\), where the curves again run parallel. The difference in magnitudes, \(m_2 - m_1\), is the absorption of the nebula.

It is generally not possible to use the Wolf curves derived from general star counts for a derivation of the approximate distance to a dark nebula. To find this distance, one should use one of the methods described in the sections that follow.

As spectral data for faint stars becomes more plentiful, one should not hesitate to represent the basic material through Wolf curves applicable to narrow intervals in spectral, class, B8 to A3 for example. The Wolf curves continue to be the most effective way to illustrate the results that are obtained from counts in obscured fields and comparison regions.

An example of a pair of Wolf curves is shown in Figure 2.
B. The \((m, \log \pi)\) Table

Distances to dark nebulae can be found in a straightforward way through the use of \((m, \log \pi)\) tables. Kapteyn, prior to 1918, first set up the \((m, \log \pi)\) table for teaching purposes. The potential of this type of presentation was later recognized by B. J. Bok who applied \((m, \log \pi)\) tables to finding absorptions and distances to dark nebulae. The details of this method can be found in the original paper by Bok, (1932), with further ramifications in The Distribution of Stars in Space, pp. 27-30 and 46-47.

We consider space to be divided into shells concentric with the sun, with radii corresponding to the following values of the logarithms of the parallax:

\[
\log \pi = -0.1, -0.3, -0.5, \ldots \quad (1)
\]

The inner boundary of a shell \(k\) is given by

\[
\log \pi_k = -\frac{2k - 1}{10} \quad (2)
\]

and that of the outer boundary by

\[
\log \pi_k = \frac{2k + 1}{10} \quad (3)
\]

Without appreciable error we can take the average of these boundaries to give radii corresponding to

\[
\log \pi_k = -\frac{2k}{10} \quad (4)
\]

so that the relation between absolute and apparent magnitudes may, in the absence of interstellar absorption, be written as:

\[
M = m + 5 - k \quad (5)
\]
An example of an \((m, \log \mathcal{T})\) table is shown in Figure 3. Each row of the table represents a certain shell; each column, a given apparent magnitude. The entries in the table, denoted by \(a_{mk}\), are the products of \(\phi(M)\), the luminosity function, and \(V\), the volume of that part of the shell which covers one square degree of the sky. If the density in the space cone were uniform, and if general absorption is ignored, then the entries, \(a_{mk}\), are the numbers of stars in shell \(k\) between magnitudes \(m - \frac{1}{2}\) to \(m + \frac{1}{2}\), per square degree. The total number of stars per square degree in this magnitude interval, \(A(m)\), would then be equal to the sum of the \(a_{mk}\)'s in column \(m\).

The basic \((m, \log \mathcal{T})\) table is corrected for local density and general absorption, so that in the new table the \(a_{mk}\)'s at each \(m\) add up to the corrected \(A(m)\) values.

Let \(\Delta_k\) represent the unknown density in shell \(k\) so that

\[
A(m) = \sum_{k=-\infty}^{\infty} \Delta_k a_{mk} .
\]  

By trial and error, the density values which best fit the observed \(A(m)'s\) are found, and the new entries in the table are given by \(\Delta_k a_{mk}\) for each square. A simplification can be made by assuming \(\Delta_k = 1.0\) for \(k \leq 10\) and \(\Delta_k = 0.0\) for \(k \geq 21\). This is valid since stars within 100 parsecs of the sun contribute little to the total number of stars with \(m = 9.0\) to \(10.0\) and fainter near the galactic plane. At large distances stars are not seen due to absorption and there is a decrease in star density, so that we may safely ignore the shells with \(k \geq 21\). McCuskey (1956) was successful in using computers to calculate density functions.

To correct for general absorption in the comparison field (which is assumed known), the entries for each shell \(k\)
are shifted to fainter magnitudes by an amount corresponding to the absorption for that shell. The addition of the entries in each column should give the observed values of the \( A(m) \)'s for the comparison field.

The basic \( (m, \log \Pi) \) table that is obtained through the procedure just described is presumably a table applicable to the comparison field. We note that it may be necessary to correct the table further for effects of general interstellar absorption, which -- if basic information is available at all -- should be applied.

Turning to the field of the dark nebula, we have for it available values of \( \log A(m) \) reduced to the same area of the sky that was used in the analysis for the comparison field. We now make the simplifying assumption that the only difference between the comparison field and the dark nebula is that the region of the dark nebula is affected by an absorbing sheet, absorbing \( \epsilon \) magnitudes and located at a distance \( r \) from the sun. Our problem is to attempt to find the values of \( \epsilon \) and \( r \) which will best represent the \( A(m) \) counts in the obscured region.

Suppose that the distance \( r \) corresponds to the inner boundary of some shell \( k_1 \). Then for \( k \leq k_1 \) the entries of the \( (m, \log \Pi) \) table for the comparison region and the nebula should be the same, and for shells with \( k > k_1 \) the entries should be shifted towards fainter magnitudes by the amount the nebula absorbs, \( \epsilon \). One chooses several values of \( r \) and \( \epsilon \) until the entries in the \( (m, \log \Pi) \) table best represent the observed counts for the dark nebula. In this way we arrive at a distance and absorption of the dark nebula.

Distances are more accurately determined if stars in a narrow spectral interval are considered. In this case, the mean value of the absolute magnitude and dispersion
around the mean are well known, so that the entries in the 
(m, log \( \tau \)) table are accurately determined. Smaller 
magnitude and parallax intervals can be chosen—for 
example, intervals of \( \frac{1}{2} \) in magnitude and 0.1 in log \( \tau \) —
to obtain higher resolution in the analysis. For stars 
with a narrow range of absolute magnitudes the entries in 
the (m, log \( \tau \)) table should cluster along diagonal lines, 
which facilitates the calculation of space densities and 
the making of corrections for general absorption.

Care must be exercised in choosing a spectral interval 
so that enough stars are in the comparison and obscured 
fields to permit statistical analysis.

C. Pannekoek's Method

The first statistically sound method for determining 
the absorption and distance of a dark nebula was developed 
by Pannekoek in 1921. The principles behind this method 
are fundamental for all dark nebulae investigations.

We denote the luminosity function for the stars in 
question by \( \phi(M) \), and define \( D(r) \) as the number of stars 
per unit volume of space at distance \( r \). The number of 
stars per unit volume with absolute magnitudes between \( M \) 
and \( M + dM \) at distance \( r \) is given by:

\[
D(r) \phi(M)dM
\]

The number of stars per square degree between apparent 
magnitudes \( m \) and \( m + dm \), falling inside a spherical shell 
with inner radius \( r \) and thickness \( dr \), may be written as:

\[
a(m,r)dm\,dr = \omega \, r^2 D(r) \phi(m+5-5\log r)\,dm\,dr \tag{7}
\]

where

\[
\omega = \frac{4\pi}{41.253} \quad \tag{8}
\]
As before, we denote by $A(m)$ the number of stars per square degree of the sky between apparent magnitudes $m$ and $m + dm$. $A(m)$ and $a(m, r)$ are then related by the equation:

$$A(m)dm = dm \int_0^\infty a(m, r)dr$$  \hspace{1cm} (9)

and the fundamental equation for $A(m)$ in the absence of general interstellar absorption is:

$$A(m) = \omega \int_0^\infty r^2D(r) \phi (m + 5 - 5\log r)dr.$$ \hspace{1cm} (10)

If we have a sheet absorbing $\epsilon$ magnitudes at a distance $r_1$, then the fundamental equation for the representation of the counts in the obscured region will be:

$$A'(m) = \omega \int_0^{r_1} r^2D(r) \phi (m + 5 - 5\log r)dr$$

$$+ \omega \int_{r_1}^{\infty} r^2D(r) \phi (m + 5 - 5\log r - \epsilon)dr.$$ \hspace{1cm} (11)

We may write:

$$A'(m) = \gamma_1 A(m) + \gamma_2 A(m - \epsilon)$$ \hspace{1cm} (12)

where

$$\gamma_1 = \frac{\omega \int_0^{r_1} r^2D(r) \phi (m + 5 - 5\log r)dr}{A(m)}$$

and

$$\gamma_2 = \frac{\int_{r_1}^{\infty} r^2D(r) \phi (m + 5 - 5\log r - \epsilon)dr}{A(m - \epsilon)}.$$ \hspace{1cm} (13)
From star counts we get values of $A'(m)$ and $A(m)$ for the obscured and clear regions respectively. If we may assume a luminosity function $\Phi(M)$, and have obtained a density function $D(r)$ for the comparison field, then we can proceed by trial and error to find the best $r_1$ and $\epsilon$ which represent the observations, very much in the manner of the $(m, \log \tau)$ method described above. Several values of $r_1$ and $\epsilon$ are tried in the computation of $\gamma_1'$ and $\gamma_2'$, and the derived numbers are then compared with the observed $A'(m)$ until the combination of best fit is found.

In a way the method developed by Bok is really the same as Pannekoek's method developed ten years earlier. The principal difference is that Bok's method is basically a numerical one, and need not be tied to analytical expressions for the density and luminosity functions. General absorption of light in space can readily be taken into account in the Bok approach; it was not considered in Pannekoek's early studies.

D. Malmquist's Method

In Pannekoek's work general space absorption was ignored. Malmquist (1939) has developed a method by which distances and absorptions can be found which are corrected for general space absorption.

Let $N(r)$ be the number of stars up to a distance $r$ for the comparison field. Then,

$$N(r) = \omega \int_0^r r^2 D(r) dr \quad \text{(14)}$$

$D(r)$ is again the density distribution function, and $\omega$ is a solid angle. Let $a(r)$ be the general space absorption in magnitudes, assumed to be known for the comparison field, at distance $r$. Define a fictitious $r_0$ such that
In other words,
\[ r_0 = r \times 10^{0.2a(r)} \]  \hspace{1cm} (16)

From these relations we find
\[ N_0(r_0) = \int_0^{r_0} D_0(r_0) dr_0 = N_0(r \times 10^{0.2a(r)}) \]  \hspace{1cm} (17)
or
\[ N(r) = N_0(r_0) \]  \hspace{1cm} (18)

It is convenient to introduce a new variable
\[ y = 5 \log r \]  \hspace{1cm} (19)

so that
\[ N(y) = N_0(y + a(y)) \]  \hspace{1cm} (20)

In this fundamental equation \( N_0(y) \) is the number of stars within a space cone considered up to distance \( r = 10^{0.2y} \), computed without regard to any space absorption; \( N(y) \), the real number of stars up to the same distance.

The computation of \( N(r) = N(y) \) is generally less complicated than the determination of a density function \( D(r) \). In most cases we derive \( D(r) \) by dividing the computed number of stars between consecutive limits of distance by the corresponding elements of volume. That is, if \( n(r_1) \) is the number of stars between distances 0 and \( r_1 \); \( n(r_2) \), the number between distances \( r_1 \) and \( r_2 \) etc., and \( v(r_1), v(r_2) \) ... are the corresponding elements of volume, then the density
at distances between \( r_{i-1} \) and \( r_i \) is given by:

\[
D(r_i) = \frac{n(r_i)}{v(r_i)}.
\]

On the other hand, the function \( N(r) \) is obtained from

\[
N(r_i) = \sum_j n(r_j).
\]

From star counts we find \( N_0(y) \). If we plot \( \log N_0(y) \) against \( y \), we can obtain the \( \log N(y) \) curve by simple geometrical construction if the amount of space absorption for different distances is known. For example, the ordinate \( \log N_0(y + a(y_1)) \), where \( a(y_1) \) is the absorption at distance \( r_1 = 10^{0.2 \, y_1} \), is equal to the ordinate \( \log N(y) \) at the point \( y = y_1 \). In this way, the \( \log N(y) \) curve is constructed, as seen in Figure 4.

Analogously, we can determine the distance and amount of absorption of a dark nebula. From star counts in the obscured region we derive the function \( \log N_0(y) \), and from clear neighboring regions, \( \log N(y) \). In order to find the absorption at the distance \( r = 10^{0.2 \, y} \), the value of \( \log N(y) \) is found from the curve and the horizontal line from this point to the \( \log N_0(y) \) curve gives directly the amount of absorption at this distance. The assumptions are that the real distribution in space is the same in the obscured region as in the neighboring unobscured regions, and that the distribution of the absolute magnitudes is known. Malmquist's method can be applied most effectively when counts made with reference to small spectral subdivisions are available.
E. Becker's Color-Difference Method

Three-color UBV photometry may be used in a manner proposed by W. Becker (1938) and applied by Rodgers (1960) to find the absorption and distance of a dark nebula. The basis of this method is the color-difference diagram, a plot of (U-B) - (B-V) against (B-V). The intrinsic color-difference diagram for bright, nearby photoelectric standards is shown in Figure 5, with spectral types designated for different positions in the diagram. This diagram for unreddened stars is used as a reference standard.

For slightly reddened stars,

\[ \frac{E_{U-B}}{E_{B-V}} = 0.76 \]

so that the slope of the reddening line in the color-difference diagram is given by

\[ \frac{E(U-B) - (B-V)}{E(B-V)} = -0.24 \]  \hspace{1cm} (23)

This implies that if a star is reddened, its intrinsic colors \( [(U-B) - (B-V)]_o \) and \( (B-V)_o \) may be found by extrapolating along the reddening slope (-0.24) to the standard curve from the point given by its observed colors, \( (U-B) - (B-V) \) and \( (B-V) \).

The Becker-Rodgers method has certain obvious weaknesses. The supposedly constant and known slope for the reddening line involves a rather restrictive assumption for the properties and dimensions of the particles that make up the dark nebula—we assume basically that the same distribution functions apply to particles in the dark nebula and those of the interstellar absorbing medium close to the galactic plane. We note also that the curve for the early-type stars in Figure 5 is for luminosity
class V. Without luminosity classification, we naturally assume that all observed stars are of class V and we assign absolute magnitudes accordingly. Dispersion in absolute magnitudes may cause difficulties in analysis.

When the color-difference diagram is used for studying dark nebulae, it is assumed that the nebula acts as a thin absorbing sheet, and not as an extended dust cloud. In the former case, nearby stars in front of the nebula lie along the standard color-difference curve, whereas stars behind the nebula are displaced along reddening lines. If the dark nebula is at several hundred parsecs from the sun, then the foreground stars may become affected by general space reddening. The dark nebula will then stand out as a discontinuity in the diagram of $A_V$ versus $m - M$, which is discussed in this section.

If the cloud were extended, the observed color-difference curve would be distorted as well as displaced, and it would then be very difficult to analyze the situation from colors alone.

Rodgers applied Becker's method to several uniformly obscured regions in the Southern Coalsack. The methods of photoelectric calibration followed by photographic photometry were applied to find UBV colors for all the stars. (Note that observations of a comparison field are not required.) Relatively few stars brighter than $V = 14.4$ mag. were found in the regions of the dark nebula. Rodgers chose apparent magnitude intervals of $V < 9, 9 - 9.99, 10 - 10.99, \text{ etc.}$, for separate analyses. For each interval, color-difference diagrams are plotted, and intrinsic colors are found for each star by following from observed positions along parallel reddening lines to the standard curve. These intrinsic colors yield absolute magnitudes, so that distance moduli are known. An example of an observed color-difference diagram is shown in Figure 6.
The color excess, $E_{B-V}$, is equal to the component of the reddening shift along the $(B-V)$ axis. From this color excess, an absorption is found by assuming a standard extinction ratio of $A_V/E_{B-V} = 3.0$. Plots of $A_V$ against $m - M$ are then made for each region, and from these the absorption and distance of the obscuration are found. Figure 7 gives an example of the drawing of the final curve, absorption against distance. The conclusion is that the dark nebula is at a distance corresponding to $m - M = 6.0$ and that general absorption becomes appreciable beyond $m - M = 8.0$, with $A_V = 2.6$ for $m - M = 12$.

F. Observational Aspects

A word should be said about the kinds of basic observations which can be made with existing equipment. A first requirement is that a faint magnitude sequence be established in or near the section of the sky under investigation. The photoelectric magnitude limit of a telescope depends on its aperture size, seeing conditions and, of course, on the experience of the observer. With the 36-inch reflector at Cerro Tololo Interamerican Observatory, visual magnitudes from $V = 9$ to 16 can be obtained when the seeing is of the order of 1 second of arc. With the 60-inch, under similar conditions, one is able to go (without offsetting) as faint as 17th magnitude. With the Steward Observatory 90-inch telescope, direct photoelectric observations to $V = 18$ are possible on good nights. Sometimes even fainter magnitudes can be reached by offsetting, which, however, is a difficult technique for use in rich Milky Way fields. Claims have been made that by offsetting, $V = 20$ can be reached with a 50-inch reflector even in fairly crowded fields, but this is far from simple. No matter which telescope is used, obtaining photoelectric magnitude sequences is a laborious task and it would be very beneficial to have such sequences already established for selected plates of the Palomar Sky Survey.
Spectral counts are especially valuable for distance determinations of dark nebulae. McCuskey and Houk (1971) give a good example of spectral counting in the interval B8 - A3. They classify these stars from objective prism plates, and count down to $V = 13$ for regions near the galactic plane between galactic longitudes $l = 50^\circ$ to $l = 150^\circ$. The mean absolute magnitude and dispersion (per unit volume of space) adopted for the B8 - A3 stars are $M_0 = +0.9$ and $\sigma_0 = 0.7$, respectively. These have been taken from the tabulation by Blaauw (1963). For future reference, we list in Table 1 mean absolute magnitudes and dispersions per unit volume of space for several spectral intervals. Average corrections for interstellar absorption can be taken from the catalogue by Neckel (1967), and the paper by FitzGerald (1968). These references give diagrams and charts showing $E_{B-V}$ and/or $A_V$ as functions of distance.

Stars in the spectral interval B8 - A3 are both bright and plentiful enough to be used for spectral counts in large dark nebulae complexes. These stars are fairly easy to classify from objective prism Schmidt photographs.

Besides objective prism spectra, a useful way of obtaining spectral classifications is through UBV photometric colors. However, these colors give only a rough classification and luminosity classes are needed if spectral counts are to be done. The color-difference method of Becker and Rodgers is a useful special application of UBV photometry.

For spectral-luminosity classification the limiting magnitude is about 12, but for straight spectral classification, stars to $V = 13$ can be reached with modern Schmidt telescopes. Color studies permit one to go about 3 magnitudes fainter with a good Schmidt telescope.
G. Practical Applications

Different types of dark nebulae lend themselves to different analyses. The large nearby complexes cover enough area so that stars in narrow spectral ranges can be counted. Since we shall want to penetrate through the absorbing screen, we need to choose intrinsically bright stars, such as B8 - A3, which are present in large numbers. In a narrow spectral interval the mean absolute magnitude and the dispersion around the mean are known, and an \((m, \log T)\) analysis can easily be applied to find the distance to the absorbing cloud.

Absorptions are best found by counting stars to faint magnitudes in the colors desired, and by then applying a Wolf curve analysis. If no magnitude sequence is available for calibration, then, as a last resort, one can count all stars down to the magnitude limit of the plate and obtain a rough photographic absorption by use of van Rhijn's tables.

Large dark clouds can also be analyzed by the color-difference method of Becker and Rodgers to find distances and absorptions. UBV magnitudes are required for a plot of \((U-B) - (B-V)\) against \((B-V)\). By noticing at which spectral type a shift along reddening lines occurs, one can find the absorption and distance of an obscured region.

An alternate color method is discussed by Karlsson (1971), in his analysis of a large dark complex in Monoceros. Certain spectro-photometric quantities were derived from objective prism plates. The observed quantities used by Karlsson are:

- \(m_{4400}\) monochromatic magnitude at 4400 Å,
- \(H\gamma\delta\) weighted mean of apparent depths of \(H\gamma\) and \(H\delta\),
- \(K\) apparent depth of K line,
- \(C_1\) color equivalent equal to \(m_{4030} - m_{4600}\).
Calibration with stars of known MK types gives absolute magnitudes, \( M_{4400} \), and intrinsic colors \( (C_1)_0 \) from the observed quantities \( H \gamma \delta \) and \( K \), the procedure being equivalent to a one-dimensional classification. Then, using \( m_{4400} \) and \( C_1 \), distance moduli and color excesses are derived, and the interstellar extinction and space distribution of stars are studied as a function of distance.

Under certain special conditions, there are simple ways to find the distance to a dark nebula. If a star is observed as being associated with the dark nebula, then the distance to the star may be taken as the distance to the nebula. A spectral-luminosity classification plus color measurements for the star will yield an absolute magnitude and approximate photographic absorption, hence a true distance modulus for the star. One must of course have good reason for supposing that the star is truly associated with the dark nebula. The best proof comes in the case where a small reflection nebula is found close to the star.

Large globules (about 5' to 20' in diameter) cannot be as accurately analyzed as the large dark complexes. Usually, very few stars are seen through them, so that star counts in a narrow spectral range are impossible. We can obtain a rough total photographic absorption with the aid of van Rhijn's tables, if we see any stars shining through the dark nebula. A guess at red absorption may be made by noting the ratio of red to blue stars in the comparison field and applying this ratio to the dark region.

Distance estimates are hazardous at best, but some postulation can be made by noticing the number of foreground stars in the obscured region. If there are as many blue stars as red stars seen in the globule, then these stars are most likely unreddened foreground stars. Using the general luminosity function one can determine the distance at which
the number of stars predicted from the luminosity function matches the number of counted foreground stars.

If the red stars seen in the globule far outnumber the blue stars, then these stars are probably background stars for which the light has been reddened by dust in the globule, and an estimate of the number of foreground stars cannot be made. However, a good total absorption value can be found if many stars lie behind the nebula.

The third category of dark nebulae includes tiny globules seen against emission nebulae. These are usually less than 2 minutes of arc in size and no detailed absorption studies are possible. Apparently these globules are usually totally opaque to the limiting magnitude of the plate. The distance to these globules is taken to be the distance to the emission feature.

IV. CATALOGUES AND ATLASES OF DARK NEBULAE

Several photographic atlases of the sky are available for searches of dark nebulae. E. E. Barnard (1927) has published a series of 50 positive photographs in blue light of various regions of the Northern Milky Way. Each print covers an area of approximately 7° by 7° and has a scale of about 2.7 '/mm. Barnard has drawn contours for the dark nebulae on his photographs, which are published in a separate volume. He list coordinates, apparent dimensions and individual characteristics of each dark nebula. His listing includes a total of 349 dark nebulae.

In the early 1900's J. Franklin-Adams undertook a photographic survey of the whole sky. The Royal Astronomical Society has published the 206 blue photographs, each of
which covers an area of $15^\circ \times 15^\circ$ and has a scale of $3'/\text{mm}$. To date this is the only photographic survey of the entire sky and, although some of the prints are not of the best quality, the uniformity of the atlas is valuable for searches of both northern and southern dark clouds. Lundmark (1926) graphically displays the sizes and distribution of the 1550 dark nebulae which he and P.J. Melotte discovered using the original Franklin-Adams plates.

The Ross-Calvert Atlas (1934), which also is in blue light, covers a large section of the Northern Milky Way. The atlas contains forty positive prints $21^\circ$ on a side with a scale of $3.8 ' / \text{mm}$. Schoenberg (1964) prepared a catalogue of 1456 dark clouds based on these prints. Khavtassii (1955) used the Ross-Calvert Atlas and others to catalogue 797 dark nebulae over the whole sky between latitudes $-20^\circ \leq b \leq +20^\circ$. He lists old galactic coordinates, equatorial coordinates, the value of the visible surface area in square degrees, the position angle and individual comments for each nebula. In addition, Khavtassii (1960) has drawn in three different shade, colored contour maps of these nebulae. The different shades correspond to apparent obscuration.

The National Geographic Society - Palomar Observatory Sky Survey prints are very well suited for the study of dark nebulae. The prints are $6^\circ$ on a side and have a relatively open scale of $1.11 ' / \text{mm}$. The two colors, red and blue, yield a contrast that the single prints from the other atlases cannot accomplish. The resolution is very good, and stars of $20^{th}$ magnitude can readily be seen on the blue prints. This limit is about 3 magnitudes fainter than that reached by the atlases previously mentioned. Lynds (1962) compiled a list of dark nebulae from studies
of the Palomar prints. Positions, areas and relative visually estimated opacities on a scale from 1 to 6 are given for each nebula.

The minimum size of the dark nebulae listed in the catalogue of Lynds and others described earlier in this paper is 2 square minutes of arc, which excludes the tiny globules. However, Sim (1968) has published a detailed catalogue of globules observed in and near 66 OB clusters and associations which were investigated by Reddish (1967) for dust-embedded stars. She finds 63 certain and 63 probable globules using the Palomar Sky Survey prints. The positions, shapes, orientations and angular sizes of the globules are tabulated.

Several photographic surveys of the southern hemisphere have been published. Rodgers et al (1960) present a mosaic in $\text{H} \alpha$ light of the southern sky on a large scale. Haffner and Nowak (1969) have edited the Würzburg atlas which covers the Southern Milky Way from $-15^\circ$ to $-70^\circ$ declination. The prints reach as faint as $B = 16$, and have a scale of about $2.8'$/mm. The original plates were not intended for general publication, hence the quality of the prints is not, in many cases, as fine as the Franklin-Adams charts, which have nearly the same scale.

Wray and Westerlund (1971) have prepared an atlas based on a series of 159 103aD plates with GG 14 filters taken with the Uppsala Schmidt telescope at Mount Stromlo Observatory. The area covered extends from $l = 237^\circ$ through $360^\circ$ to $7^\circ$ within the band $-3^\circ \leq b \leq +3^\circ$ (new galactic coordinates). The original plates have been enlarged onto a dimensionally stable Gravare film, to a scale matching the Palomar Observatory Sky Survey. The Palomar Survey coordinate grids may be used directly with these prints. The Wray-Westerlund Atlas provides very promising basic material for dark nebulae searches.
In addition to the more extensive catalogues of dark nebulae, selected lists have been published. Bok (1937) gives a brief survey of major dark features seen in our Galaxy. Becker (1942) lists 18 large dark complexes of area 1 square degree or greater for which approximate distances and absorptions are available from star counts. Lynds (1968) has updated Becker's list and added to it.

Bok, Cordwell and Cromwell (1971) have catalogued a few representative dark nebulae of various kinds and have given approximate absorptions, distances and masses for some of these. This work is being extended by Bok and Cordwell. They plan to catalogue the more representative dark nebulae, and list their principal properties. In particular, attention will be drawn to southern areas, where there is great potential for dark nebulae studies, both in the optical and radio regions.
EPILOGUE:

Dark nebulae studies are becoming increasingly more important as sophisticated star formation theories are advanced. If accurate observational data can be made available, greater insight into pre-protostar conditions can be achieved and theories of star formation can be developed on the basis of well established initial conditions. With high resolution telescopes we can make good progress toward finding absorptions and distances, especially through the proper use of assorted star count techniques. Progress is being made in the study of interstellar grains, although the question as to whether grains in dark clouds are the same as grains in the diffuse interstellar matter is still unanswered. Estimates of total masses and densities for dark nebulae depend in part on assumptions of grain characteristics, so that work on interstellar grains appears vital to those who study dark nebulae. The total mass and density of a dark cloud are heavily dependent on the amount of gas present. The ratio of gas to dust by mass has usually been assumed to be 100 for the interstellar medium. 21-centimeter studies of neutral hydrogen confirm the strong presence of the gas between the stars. However, no neutral hydrogen concentration has been detected in dense dark nebulae. Because of the low temperatures involved, it has been postulated that the gas in these nebulae is in the form of molecular hydrogen, or possibly in the form of very cold HI. It may be that higher resolution radio telescopes will still detect the 21-cm. line of H I, but as of now little is known about the amount of gas in dense dark nebulae or what form that gas has taken.
The extremely low temperatures of dense dark nebulae, which are at approximately 10^6K or less, provide excellent conditions for molecule formation. OH has already been found in the densest region of the \( \rho \) Ophiuchi complex (Heiles, 1969), and most certainly other molecules will be discovered which will give an indication of the chemical constituents and internal conditions in the interiors of dark clouds. An obvious and real need exists for extensive, high-caliber optical and radio studies of dark nebulae.

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Illustration of a reseau which may be used for star counts. The star magnitudes are shown at the top and bottom of the reseau. The observer mentally fixes a particular image size, and counts down a column at a time in the order shown. He can refer to either image set when necessary. After the total area has been counted down to a particular image size, he goes to the next image, and counts all stars with sizes greater than or equal to that size considered. This gives a series of $N(m)$ values.
Example of a Wolf diagram. A total absorption of 1.0 magnitude is shown here.
Figure 3

(m, log $\Pi$) table for van Rhijn's general luminosity curve for photographic magnitudes. (After Bok, 1932)
Malmquist curves of log $N(y)$ and log $N_0(y)$ versus $y$. At the distance $r_1 = 10^{0.2y_1}$ the absorption is $a(y_1)$.
The intrinsic color difference diagram for stars on the UBV system.

**Figure 5**
Figure 6

Observed color-difference diagram for a region in the Southern Coalsack (after Rodgers, 1960). The magnitude range is $10.00 < V < 10.99$. Spectral types (for illustration only) are from the H. D. Catalogue and Extension. Part of the intrinsic curve is shown, for BOV to AOV stars, as a solid line.
Example of one of Rodger's curves for the Southern Coalsack. This plot of absorption against distance shows a nebula at a distance of 174 parsecs, corresponding to $m - M = 6$, with an absorption of 1.0 magnitude. Beyond this nebula, there is a clear region extending to 800 pc. At greater distances, absorption again sets in.
Mean absolute visual magnitudes and dispersions per unit volume of space. (After McCuskey, 1956)