5. THE DISTRIBUTION OF DARK NEBULAE IN LATE-TYPE SPIRALS

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Abstract. Seventeen Sc- galaxies have been studied in order to determine the distribution of dark nebulae within them. Hα plates were used to compare the distribution of obscuring material with the location of H II regions, and it was found that the H II regions are always tangent to or imbedded in regions of high obscuration. Sandage's conclusions are confirmed that strong, regular dust lanes exist in the central regions of these galaxies and wind outward on the inside edge of the two prominent arms. Characteristic dimensions of the dust lanes are noted, and secondary dust characteristics are described.

The most detailed notes on the distribution of interstellar dust in galaxies have been given by Sandage and are to be found in the description of the Hubble classification and in the captions for the illustrations of the Hubble Atlas (Sandage, 1961). In this publication, Sandage points out that the spiral pattern for Sc-galaxies first becomes apparent near the center of such systems as two principal dust lanes; luminous spiral arms appear only at larger distances from the nucleus, at which distances the two principal dust lanes wind out along the inside of the two most luminous outer arms. After winding out for nearly half a revolution, these two principal arms branch into segments which continue to spiral outward to form the multiple-arm structure. Furthermore, Sandage points out that the dust is not confined to these lanes but rather is seen in spiral patterns over the entire face of such systems.

Several detailed studies of individual galaxies have been made in which the distribution of the interstellar dust is discussed, but the emphasis has usually been on the determination of the sense of direction of the motion of spiral arms. Other than the report of Sandage, no detailed studies of the sizes and locations of dark nebulae in galaxies are known to the author. Because of the recent revival of interest in the role played by the dust, a systematic analysis of the sizes and distributions of the dark material in external galaxies should be of interest.

Through the courtesy of the Mount Wilson and Palomar Observatories, the plate collection of 100- and 200-inch photographs of galaxies constitutes the raw material for this study. All galaxies in the Shapley-Ames Catalogue were visually inspected, and a sample of these objects was selected for detailed measurement. The x-, y-coordinate measuring machine of the Mount Wilson Observatory was used to scan across each sample galaxy and to record the positions of the dark and bright spiral features. This report is confined to results obtained from a study of seventeen late-type spirals, classified as Sc- by Holmberg (1958).

Although interstellar dust is most easily detected in spiral systems whose plane of symmetry lies nearly in the line of sight, it is very difficult to determine the exact location of the dust in such systems. Therefore, for this study, the galaxies selected

are those seen nearly face-on for which there is some degree of certainty of identification of the dust clouds. The results given here therefore represent data for those Sc-galaxies in which the dust is readily apparent and relatively easily measured. It is a happy coincidence that such Sc galaxies appear to be the most commonly observed and may reflect average properties of Sc-systems in general in spite of the fact that the sample of 17 studied was in no sense unbiased.

The usual criteria for identification of a dark nebula in any stellar system are firstly, the absence of stars relative to the surrounding area, and secondly, the ability to detect a relatively well-defined boundary of the nebula. In the case of an external spiral galaxy, one can often use these two criteria with as great a certainty as one can in our own Milky Way System. The identification becomes more difficult in the inter-arm regions of spirals and in the outer zones of a galaxy beyond its luminous arms. An effort was made to confine the data to dark regions whose presence would be difficult to interpret other than to say that they are true obscuring clouds.

It was initially hoped that the brightest H II regions of a galaxy would define the spiral pattern against which the positions of the dark nebulae could be compared. Therefore, in this preliminary report, those galaxies (which met the first requirement of containing easily-detected dark clouds) which have available Hα interference-filter photographs in the Mt. Wilson and Palomar plate collection were selected. Perhaps the most interesting result of this study is the confirmation of the oft-quoted statement that there is a 'one-to-one correspondence' between the presence of dust and the presence of young stars. On the basis of the sample studied here, it is concluded that the brightest H II regions of a galaxy are always found either next to or imbedded in regions of high obscuration. The converse of the statement is not true; many regions of equally dense obscuration contain no H II regions. It is also the conclusion of this study that the primary dust lanes of a galaxy better define the spiral pattern than do the H II regions, which often are found on the inside edge of a bright spiral arm but may be found on the outside edge or somewhere within the luminous arm where a 'feather' of a dark lane cuts across the arm. Occasionally, H II regions are even found in heavily-obscured inter-arm areas (if the arms are defined by the regions of relatively uniform luminosity).

Figures 1–5 contain the distribution of the dark nebulae within those galaxies for which Hα photographs were available. The lightly-shaded areas represent the dust lanes of the galaxy; the heavy black marks are the locations of the brightest H II regions.

When one studies the sketches of Figures 1–5; or, better, when one examines the photographs themselves (see, for example the prints of the Hubble Atlas), certain regular patterns of the distribution of dust become apparent. The two most striking features are those pointed out by Sandage: the existence of very strong dust lanes in the central regions and the presence of dark lanes along the inside edge of the two luminous arms. These latter primary dust lanes can occasionally be traced through more than 360°, that is, through a 'first' and 'second' winding of the arms. In addition to these characteristics, thin dust lanes are also found cutting their way across a bright arm with pitch angles of about 50° relative to the primary lanes.

Once such 'feathers' have been traced across a luminous arm, they are no longer visible against a bright background. There is, however, some evidence that an extensive area beyond a luminous arm also contains dust condensations. Another, smaller scale, characteristic of dark nebulae in these systems is the appearance of nearly
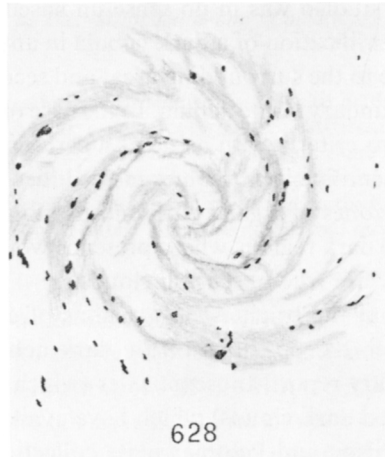

Fig. 1. NGC 628. This is the most regular of the Sc-galaxies studied. The two primary dust arms can be relatively easily traced through a first and second winding. The luminous arms are found sandwiched between the dark nebulae of the sketch.
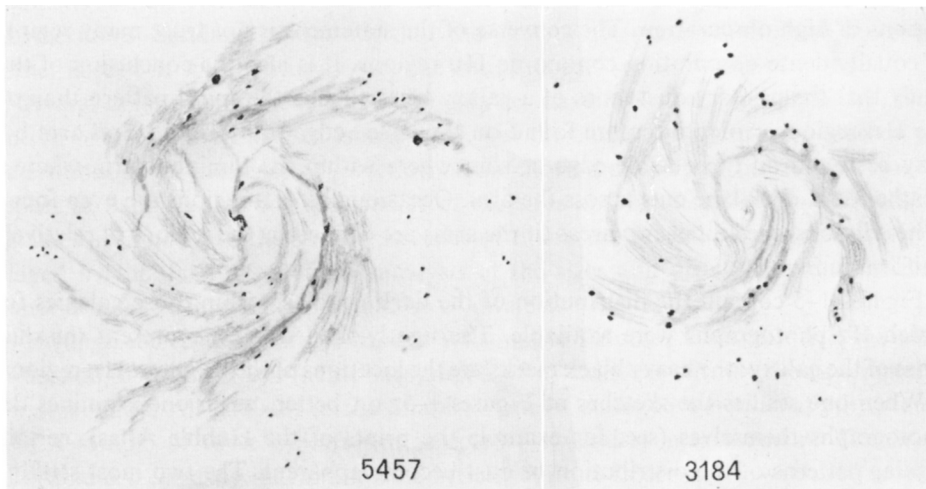

Fig. 2. NGC 5457. M 101 is the prototype of the special subgroup of Sc-galaxies which shows the most regular dust patterns. The luminous arms are thinner than those of NGC 628, which belongs to the same subgroup. Sandage has pointed out that in M 101 the dust lanes appear as separate segments which combine to form a spiral pattern. NGC 3184: No Hα interference filter photograph was available for this galaxy, but the H II regions listed by Hodge (1969) were identified on the 100-inch 103aO photograph. Hodge's data were based on 48-inch Schmidt photograph, so that the central regions are incomplete in the H II identifications. The dust in this galaxy is more difficult to detect.

circular clouds which often contain a very bright central knot. These bright knots are frequently not H II regions but may be one or more bright blue stars.

Table I lists the representative sizes of the characteristic interstellar features. The distances $(m-M)$ and radii (R) were taken from Holmberg (1964). The galaxies are
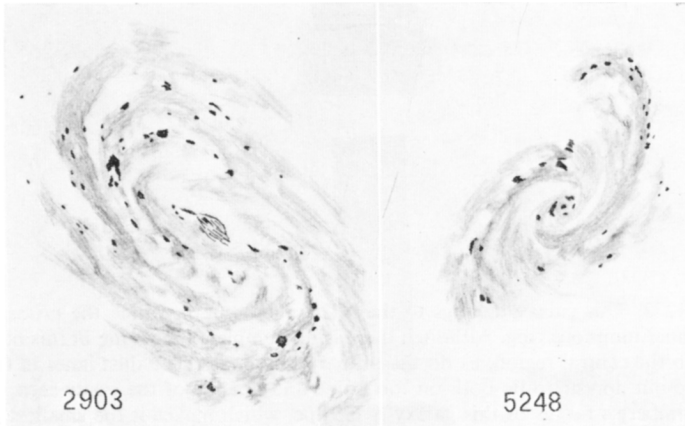

Fig. 3. NGC 2903. These two galaxies are viewed more highly inclined to the line of sight. NGC 2903 belongs to the NGC 253 subgroup of Sc-galaxies which has ill-defined spiral arms and more chaotic dust. For the subgroup, spiraling dark lanes are still quite apparent over the entire galaxy. – NGC 5248. This galaxy is of the NGC 1637 type, whose luminous arms are not as well-defined as those of M 101 subgroup. Nevertheless, this subgroup shows the same characteristic dust pattern as does the M 101 type.
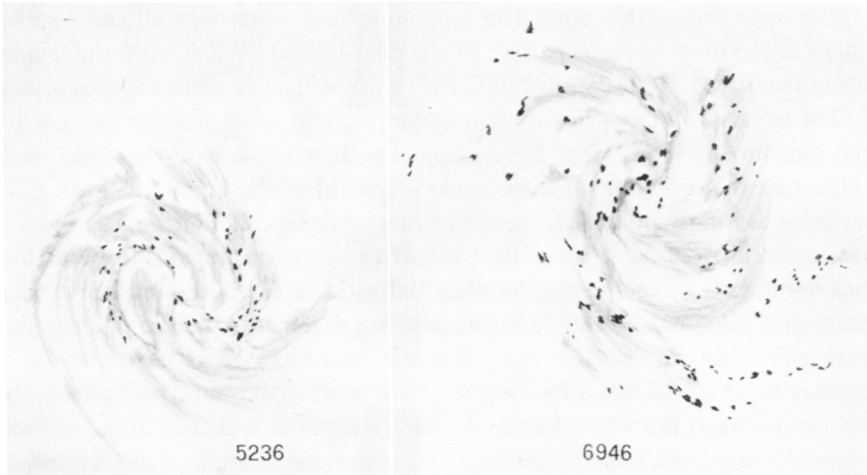

Fig. 4. NGC 5236. The spiraling dust segments in this very open galaxy are its most dominant feature. The arms appear to be exceptionally rich in H II regions and are quite obviously closely associated with the dust. – NGC 6946. The dust pattern in this galaxy is similar to NGC 5236 but more difficult to measure and the luminous arms are more difficult to trace. The 48-inch Schmidt print of this galaxy strongly suggests that obscuration exists in the outer regions beyond the luminous primary lanes, as sketched in the figure.
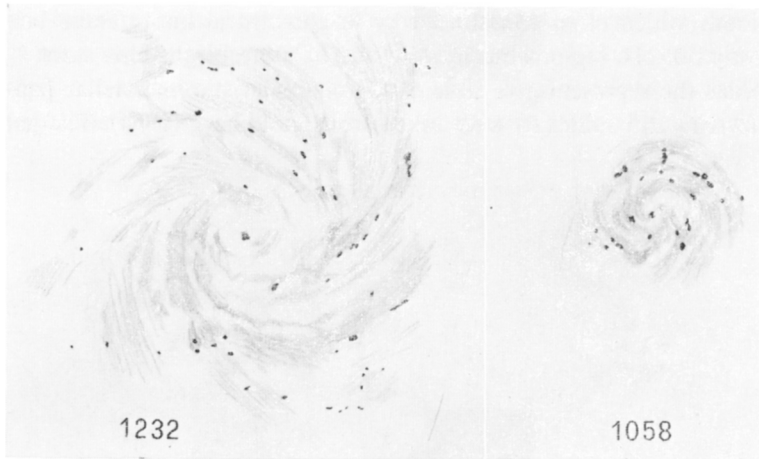
Fig. 5.   NGC 1232. This galaxy belongs to the NGC 5364 type in which the primary arms begin
tangent to an inner luminous ring. Although there is no complete inner ring in this object, the arms
begin tangent to the central region, as do the primary dust lanes. The dust lanes in this galaxy are
difficult to trace but appear to lie both on the inside and outside of the easily-seen bright arms. –
NGC 1058. Holmberg's radius of this galaxy is 6.6 kpc, which makes it the smallest galaxy in this
study. The primary dust lanes produce the spiral appearance of this galaxy.

divided into the Sc subgroups defined by Sandage (1961). Five of his six major
subgroups are represented in the table; only the NGC 4395-type (having very chaotic
and ill-defined spiral arms) is not included. NGC 2403, like M 33, has obvious dust
patches, but the dominant spiraling dark lanes of the other types of Sc systems are
not readily apparent in this type. The remaining four subgroups all show spiraling
dark lanes as the most obvious pattern of the distribution of dust, with the regularity
increasing from type NGC 253 to NGC 1637 to M 101. The sixth subgroup, having
NGC 5364 as its prototype, has its two primary spiral arms starting tangent to an
external circular luminous ring. Here again, the dust appears in the form of dark
lanes either on the inside or on the outside (or both) of the luminous arms, but the
dark nebulae are more difficult to detect in these galaxies. Columns 4, 5, and 7 give
the measured widths of the primary dust lanes for the nuclear regions (n), 1st winding
and 2nd winding distances, respectively; columns 6 and 8 give the respective nuclear
distances (d). Columns 8, 9, and 10 list the widths (w), lengths (l), and pitch angles (i)
of the dark feathers.

  Ten galaxies of the M 101 subgroup were included in this study. Figure 6 shows
the relation between the width of the primary dust lane and its distance from the
nucleus for these galaxies. Both quantities are expressed in units of the radius of the
galaxy. It appears that there is a general increase in thickness of the primary dust lane
as it winds its way out from the nucleus; the overlapping of the points representing
first (filled circles) and second (open circles) winding positions indicates that the width
depends more on the nuclear distance than on the tightness of the winding of the arms.
The lower portion of Figure 6 shows that the measurements of the width of the primary

TABLE I

Dust measurements in Sc-galaxies

NGC	m–M	R	Primary dust lanes					Feathers			Plates[a]
		kpc	n pc	1st pc	d kpc	2nd pc	d kpc	w pc	l kpc	i	
M 101-Type											
157	31.7	18	–	350	2.8	900	7	160	1.0	75°	103aO
628	29.7	15	60	100	1.1	530	3	60	0.5	50	103aO, D, E; Hα
2532	34.0	35	–	300	2.0	–	–	–	–	–	103aO
3184	29.3	10	–	80	0.4	190	2	–	–	–	103aO (100-inch)
4254	30.5	13	–	250	1.2	320	2	80	0.8	45	103aE
4303	30.5	20	130	100	2.4	–	–	–	–	–	103aO
4321	30.5	18	120	270	2.4	270	5	130	0.9	45	103aO, D, E
5236	28.2	8	70	200	1.4	300	3	40	0.5	–	E40 (100-inch), Hα
5457	27.7	14	30	50	0.6	200	2	40	0.2	60	103aD, E; Hα
6946	28.4[b]	9	40	150	1.2	540	3	50	0.4	–	103aO (100-inch), 103aE; Hα
NGC 1637-Type											
1637	29.5	9		100	0.8	130	1.3				103aO
5248	30.9	18				210	4			55	103aO, Hα
1058	29.4	7		80	0.2	240	0.5				103aO, D, E; Hα
NGC 5364-Type											
864	31.5	13		560	2.	1000	4				103aO
1232	30.7	19				640	2			40	103aO, Hα
5364	30.1	12		330	1.9	550	4				103aO
NGC 253-Type											
2903	29.5	16		~100	3						103aO, Hα
M 33-Type											
2403	27.6	14	dust patches ~100 pc segments of lanes of width ~30 pc								103aO, D, E

[a] Plates are 200-inch photographs unless otherwise stated.
[b] Distance from redshift; diameter measured by Lynds.

dust lane are not distance-dependent for this sample. Most of the plates measured were 200-inch direct photographs, with a scale of 11.06″ per mm. It is possible to be fairly certain in the identification and measurement of a dark lane which has a thickness equal to or greater than 0.1 mm on the plate; the observational lower limit to the detection of a dark lane thus corresponds to about one second of arc. The measured thicknesses of the thin feathers of dark nebulae branching from the primary lanes do show a distance effect, as illustrated in Figure 7. The width of the feathers appears to be about one-half that of the primary lane, if only the upper part of Figure 7 is considered. However, the lower part of the figure suggests that although the measured feather widths appear to be greater than the observational lower limit for galaxies whose distance moduli are less than 30, beyond this distance of 10 Mpc the measurements represent only the selected wider lanes. The dashed line in the lower part of
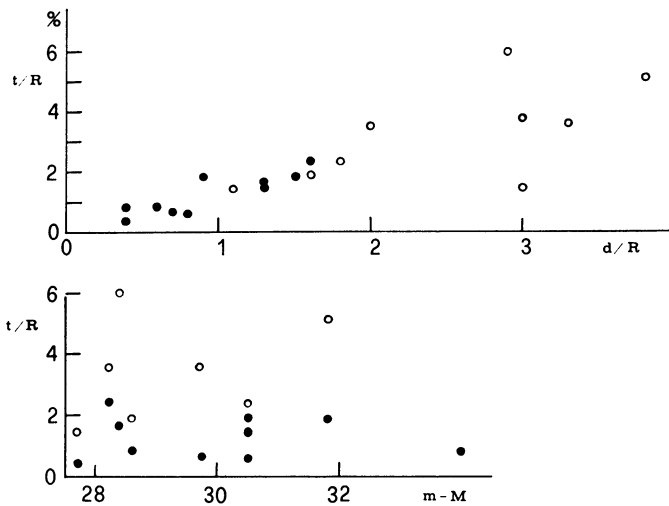
Fig. 6.   Variation in width of primary dust lanes with distance from the nucleus (upper) and with distance modulus (lower). The units are in terms of the radius of the galaxy. The ordinate is the percentage width of the primary lane; the upper abscissa is the fractional distance from the center of the galaxy. The lower array of points shows that the measurements are independent of distance for the ten M 101 galaxies studied. The filled circles are measurements of the first winding thicknesses; the open circles are the second winding measurements.
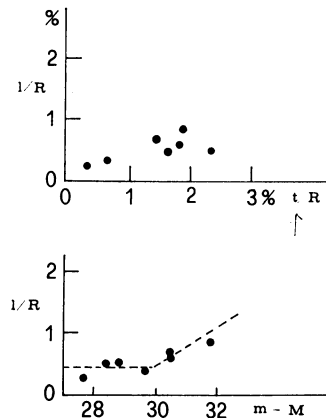
Fig. 7.   Variation in width of dust feathers with width of primary lanes (upper) and with distance (lower). The Units are percentage of radius of the galaxy. The dashed curve of the lower diagram represents the expected variation in the measured feather widths if a galaxy of 11 kpc had dark feathers of widths 50 pc and greater.

Figure 7 illustrates this resolution effect and defines the locus of observational points to be expected if a galaxy of radius 11 kpc had feathers of widths 50 pc and greater.

Table I also lists the emulsion sensitivities of the plates measured in this study. For some spirals, scans across the galaxy were made on O, D, and E plates. The

accuracy of positional registration of these plates for intercomparison is about 30 microns, and to this accuracy no difference was found in the sizes of the dark nebulae over the wavelength regions represented by the red and the blue plates. This must mean that the nebulae selected to be measured are of very large optical thickness. Furthermore, in many regions of these galaxies, dark lanes can be seen occulting a luminous spiral arm which itself is several magnitudes above the plate limit. It is therefore concluded that the extinction through the dark clouds whose characteristic sizes are listed in Table I must be greater than about 3 magnitudes.

If 3 magnitudes is adopted as the lower limit to the optical extinction through the dark nebulae and if Holmberg's distances are assumed, then the actual physical sizes of the nebulae may be estimated. If we adopt 15 kpc as an average radius of a M 101-type Sc-galaxy, then Figure 7 may be used to estimate the width of the primary dust lanes. Near the nucleus the lane has a thickness of about 50 pc; the width of the lane gradually increases, reaching a value of about 240 pc at a distance of 2 kpc from the center. Unfortunately, we have no means of estimating the z thickness of the cloud, which is the pathlength needed to correspond to the 3 magnitude extinction estimate. If we use the simple model in which the lane is as 'thick' as it is wide, the pathlength may be set equal to the measured width of the lane. In this case we can estimate the lower limit to the grain density within the primary lane. According to Solomon (1969), the grain density of a cloud of 3 magnitudes absorption is given by

$$\varrho_g = 10^{-4}/L \text{ g cm}^{-3},$$

where L is the pathlength in cm through the cloud. For our model lane the grain densities must be greater than 7×10^{-25} g cm^{-3} for the nuclear regions and 4×10^{-25} g cm^{-3} at a distance of 2 kpc from the center. This assumes that the extinction is produced by the same type of particle which exists in our galaxy. If we further assume the usual 100:1 ratio of gas to dust, we find an interstellar density greater than about 10^{-23} g cm^{-3} throughout the winding of the primary dust lane. In an analogous manner, the mass of a typical feather of obscuration must be greater than 10^6 solar masses. Such a lane of dark nebulosity crossing a luminous arm meets the requirements of Spitzer and Schwarzschild (1953) who predicted similar interstellar clouds on dynamical arguments related to stellar velocity dispersions.

In summary, the seventeen Sc-galaxies studied here indicate that the spiral pattern of these galaxies is revealed by the distribution of the interstellar dust. The dominant lanes of obscuration evident in most of these systems probably have densities comparable to those of the luminous arms themselves. Although each galaxy on close inspection has many individual features peculiar to itself, the overall pattern of dust as defined in this study seems to be characteristic of such systems.

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