THE ASTRONOMICAL JOURNAL VOLUME 81, NUMBER 11 NOVEMBER 1976

High-latitude reflection nebulosities illuminated by the galactic plane

Allan Sandage

Hale Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California 91101

(Received 28 June 1976)

Extended regions of faint nebulosity have been found at high galactic latitudes from a survey in progress with the Palomar 1.2-m Schmidt telescope. The surface brightness of some of the nebulosities is as high as $SB_v \simeq 25$ mag/□″ in V, with many more at fainter levels. Some of the nebulosities are diffuse, while others are filamentary with widths on scales of ~30 arcsec that extend in connective patterns over scales of degrees. Photographs of two particulalry bright examples at $l = 187°$, $b = -50°$ and $l = 140°$, $b = +40°$ are given. The second region contains the galaxies M81 and M82. Special plates taken in continuum radiation show the regions to be reflection nebulae. Calculations suggest that the source of the illumination at these high latitudes is the flux of the total galactic plane. This flux at any height h above the plane is equivalent to $m_v = -6.73$ visual magnitudes, independent of h. If the same grains that scatter the galactic light also cause the extinction Δm of the background objects in the line of sight, then a relation exists between observed surface brightness and Δm [Eq. (8)]. Application to the nebulosities in the field near M81 and M82 show agreement between the observations and the prediction that the scattered light is from the galactic disc. If true, observations of faint reflection nebulae in the galactic polar regions hold promise to provide new information on the polar extinction.

INTRODUCTION

A NEW survey of the galactic polar caps made with the 1.2-m Schmidt camera using fine-grain, high-storage-capacity plates is in progress at Palomar. The purpose is to find distant clusters of galaxies with which to extend the Hubble diagram. The exposures have been as long as 4 h on nitrogen-baked Kodak III-aJ plates plus a Wratten-4 filter (λλ 4700–5200 Å), and Kodak 127-04 plates plus a red plexiglass filter (λλ 6200–7000 Å).

In addition to the distant clusters, other new objects appear on the plates, among which are regions of faint nebulosity that occur in some of the high-latitude fields.

The surface brightness (SB) of these nebulosities range from bright enough to be seen on the original Sky Survey Palomar prints ($SB \simeq 25$ mag/□″ in B, near the detection limit on the prints) to the limit of the present new material, which is perhaps 2 mag fainter.

The existence of bright nebulae of this type has been known from earlier work. Lynds (1965), in her study of emission features seen on the Sky Survey prints, noted several high-latitude regions of diffuse radiation. She illustrates (her Fig. 2) a low-SB nebula of the diffuse type near $l^{\mathrm{II}} = 131°$, $b^{\mathrm{II}} = -46°$, and suggested that many more would be found on deeper plates. Her prediction is well confirmed from the new material.

The existence of faint nebulosities at intermediate latitudes was also shown independently by C. R. Lynds in an unpublished study (circa 1968) of the Polaris region ($b \simeq +27°$). He made high-contrast prints from two copy negatives of the north celestial pole from the Palomar Sky Survey, and showed the reality of very faint filaments throughout the area.

It is shown in the next section that two of the new high-latitude nebulosities (at $b = +40°$ and $b = -50°$) are reflection nebulae. This requires the presence of high-latitude dust, and a source of illumination. Calculations of surface brightness set out in Sec. III suggest that the illuminating source is the integrated light from the galactic plane.

The argument is carried further to show that if the galactic plane is, in fact, the source of illumination, then the presence of dust in any high-latitude field must produce reflection nebulosities, and further that the value of the surface brightness permits calculation of the optical extinction through the halo in that direction.

I. OBSERVATIONS

The Sky Survey center of the high-latitude region at $-6°$, $3^{\mathrm{h}}12^{\mathrm{m}}$ ($l = 187°$, $b = -50°$) was photographed in the new survey on a 127-04 plate of $4^{\mathrm{h}}15^{\mathrm{m}}$ exposure in October 1975. Bright semifilamentary wisps of diffuse radiation with thin linear structures of width ~5 arcmin were seen over large parts of the plate. The structures are real; their brighter parts can also be seen on the original Sky Survey prints, running north and south the entire length of the print near its central right ascension. A high-contrast reproduction from part of the copy negative of the original Sky Survey E plate is shown in Plate V (p. 1019). (The new 127-04 plate has some nonuniform chemical fog due to excessive baking, and the cleaner print from the Sky Survey E plate is shown here. The fine, hairline criss-cross pattern in parts of Plate V are probably due to the coating device used to lay the original emulsion on the glass of this particular Survey plate.)

A more striking example of high-latitude filaments was found on a plate taken in January 1971 using III-aJ emulsion plus a Wratten-4 filter, baked for 7½ h at 65 °C in dry N_2, with a 2½-h exposure. The field is centered on M81 ($9^{\mathrm{h}}52^{\mathrm{m}}$, $+69°$; $l = 142°$, $b = +42°$).

Again, much of the plate is covered with nebulosities of about the same maximum SB as in the first field. But there are also very many fainter luminosities over the whole of the region.

Plate VI (p. 1020) shows a high-contrast print of part of the area near $\alpha = 9^h48^m$, $\delta = +71° \ 10'$, which is almost due north of M81 and M82. These two galaxies appear as overexposed images near the left-hand, lower-third border. The image of M81 is embedded in the nebulosity, most of which is obviously not connected with the galaxy, while M82 is in a somewhat cleaner region.

The brightest region of the nebulosity begins just below the airplane trail in the upper-left third of the print. It is finely filamented on a scale as small as ~30 arcsec. The region shown in Plate VI is only a small part of a much extensive system of such nebulosities that can be traced into adjacent fields and finally onto the galactic plane. Particularly prominent are the nebulosities in the +72°, 9^h4^m Sky Survey center where the large-scale structure is easily visible on the prints themselves.

The *SB* of the features in Plate VI can be estimated by comparison with the outer filaments in M82 for which photoelectric measurements are available (Sandage and Visvananthan 1969, Table 1; Visvananthan and Sandage 1972, Table 7). The regions in M82 that are useful for this comparison are patches $P(V = 24.6 \text{ mag}/\square'')$, $N(V = 25.0 \text{ mag}/\square'')$, $QV1(V = 25.7 \text{ mag}/\square'')$, and $QV3(V = 25.4 \text{ mag}/\square'')$ which are identified in the quoted reference. Comparison gives $V \simeq 25 \text{ mag}/\square''$ as the "average" *SB* of the prominent filamentary nebulosity at $\alpha = 9^h48^m$, $\delta = +71° \ 10'$ (1950) mentioned earlier.

II. REFLECTION OR EMISSION NEBULAE?

The III-aJ plus Wratten-4 and the 127-04 plus red plexiglass combinations are sensitive to the emission lines of Hβ, N1, N2, Hα, [N II], and [S II]. Hence, the nebulosities could have been either emission patches or reflection nebulae using the evidence to this point.

To test which, the field in Plate VI was photographed again with 103-aD plus a Wratten-16 filter—a combination that is sensitive from λλ5200 to 6000 Å, which is devoid of all emission lines.

The result was that the filaments are equally visible on this plate as on the original III-aJ and the 127-04 plates, showing that the radiation cannot be due to emission lines. Hence, the structures are reflection nebulae. The conclusion is reinforced by noting that the brighter filaments in the +72°, 9^h4^m Survey field mentioned earlier are equally bright on the red and the blue prints.

Such reflection nebulae require the presence of dust in high latitudes, and an illuminating source.

III. THE SOURCE OF ILLUMINATION

Both the large angular extent of the nebulosities (in many cases, connective patterns can be traced over several Sky Survey fields that are each 7° on a side), and

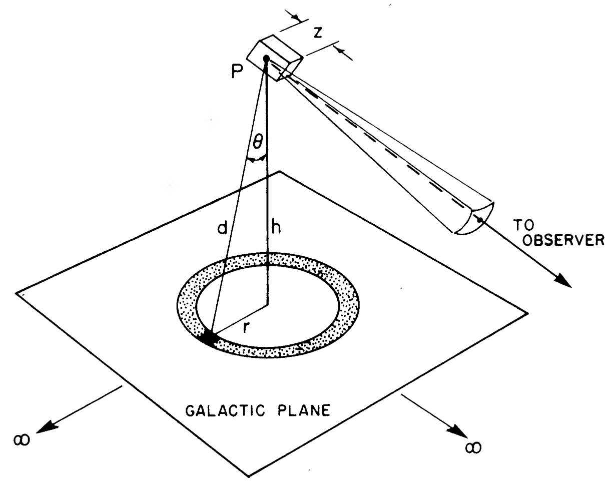

FIG. 1 Geometry of the illumination of point *P* by the galactic plane, and the subsequent scattering of the incident flux toward the observer.

their high latitudes eliminate a single star as the source of illumination, which applies for most low-latitude reflection nebulae (Hubble 1922). In this section we ask whether the integrated light of the galactic plane is sufficient to produce the observed surface brightness of the nebulosities, as previously suggested by van den Bergh (1966). If so, these two points would not stand as objections.

Consider an arbitrary point P at height h above the galactic plane, such that h is small compared with the diameter of the galaxy. The plane can then be considered to extend to infinity in both directions. We require the apparent flux at P due to the entire sheet. Let the plane have a uniform brightness of absolute magnitude S per unit area. (Throughout the remainder of this paper we assume that h is small enough that the part of the plane which contributes most of the light is quite local, and hence that the gradient of S with increased distance from the center can be neglected.)

From Fig. 1 it follows that an areal element of the plane dA at a constant distance d from P contributes a flux df at P that is proportional to

$$df \equiv 10^{-0.4S} d^{-2} dA = 10^{-0.4S} 2\pi r d^{-2} dr. \qquad (1)$$

The most important aspect of Eq. (1) is that the flux is independent of the height h as seen by substituting $r = h \tan\theta$, and $d = h \sec\theta$ to obtain

$$df(\theta) = 10^{-0.4S} 2\pi \tan\theta \, d\theta. \qquad (2)$$

That this must be so follows from the usual considerations concerning surface brightness effects, i.e., as the height is increased, the elemental area included between θ and $\theta + d\theta$ increases as d^2, hence the flux at P due to the plane between these angles remains constant.

The total flux at P due to the plane between $\theta = 0$ and θ_{max} is then

$$f(\theta_{max}) = 10^{-0.4S} 2\pi(-\ln\cos\theta_{max}), \qquad (3)$$

found by integrating Eq. (2).

It is useful to express this flux in terms of an apparent magnitude on the conventional zero point. Suppose, then, that the surface brightness of the plane is given in units of absolute magnitude M per square parsec. Because the absolute magnitude is the apparent magnitude of an object at a unit distance of 10 pc, the apparent magnitude at P can be obtained from Eq. (3) only if S is the surface brightness in the same units, i.e., in a unit area 10 pc on a side, or 100 pc^2. Hence, $S = M - 5$.

It then follows that the apparent magnitude of the galactic plane as seen from P is

$$m_v = -2.5 \log(-2\pi \ln \cos\theta_{\max}) + M_v - 5. \quad (4)$$

[Equation (4) has a very mild divergence at $\theta = 90°$, which is unphysical because the plane is not infinite in extent for any nonzero value of h. Hence, $\theta_{\max}$ is always less than 90°. We arbitrarily adopt $\theta_{\max} = 89°$.]

What then is the surface brightness M_v of the plane? From Seares' (1920) discussion, updated with modern star-count data in the poles (cf. Roach and Gordon 1973, p. 23, Table 2-IV), it follows that $M_v = 1.78$ visual absolute magnitude per square parsec in the solar neighborhood. (The SB in the galactic poles due to stars is 30, 10th V-mag stars per square degree, or 6.3 mag/□°. This is half the light through the entire halo. Hence, the SB is 23.35 mag/□″ at the Sun's position in the galaxy, from which it follows that M_v is the value given.)

With this value of M_v, Eq. (4) using $\theta_{\max} = 89°$ gives $m_v = -6.73$ as the apparent magnitude of the galactic plane as seen from any point P. (This value could, if desired, be changed into the flux in units of ergs/sec cm^2 over the V passband by using the known conversion of apparent V magnitude to these absolute units.)

Consider now the scattering effects of interstellar grains at P. Let there be N grains/cm^3, each with geometrical cross section $\sigma = \pi a^2$, scattering isotropically with an albedo γ. Let the depth of the filament in the line of sight to the observer be z. Hence, the total scattering cross section due to 1 cm^2 of the filament is $\gamma N\sigma z$.

To find the surface brightness of the reflection nebula at P that is seen by the observer, consider the following geometry. Let the distance of P from the observer be R. A fraction $\gamma N\sigma z/4\pi R^2$ of the power (erg/sec) that crosses every square centimeter at P is scattered across each square centimeter of a detector at the observer. But the number of square centimeters for each square second of arc of the nebula at P is $R^2/(206\,265)^2$. Hence, the flux (i.e., power per square centimeter) at the observer from each square second of arc of the nebulosity is

$$f_0 = 10^{-0.4m}(\gamma N\sigma z)/4\pi(206\,265)^2. \quad (5)$$

Note again that this flux is independent of the distance R, as it must be because it is a surface brightness.

From Eq. (5) it follows that the surface brightness of the nebula at P is

$$SB_v = m_v - 2.5 \log[\gamma N\sigma z/4\pi(206\,265)^2],$$

which, by substituting $m_v = -6.73$, gives

$$SB_v = 22.6 - 2.5 \log \gamma N\sigma z, \quad (6)$$

in units of visual magnitude per square second of arc.

What is the optical depth $N\sigma z$ of the nebula? Suppose, that the same grains that scatter the galactic light cause extinction of objects in the line of sight from behind P. Let the optical depth for extinction be τ. In the usual notation, $\tau = N\sigma Qz$, where Q is the efficiency factor of the grains (about a factor of 2 in the wavelength realm where $a > \lambda$). Hence, the extinction in the line of sight is $\Delta m = 1.086 N\sigma Qz$, and the second term in Eq. (6) becomes $2.5 \log(0.921\gamma\Delta m/Q)$, giving

$$SB_v = 22.7 - 2.5 \log(\gamma\Delta m/Q) \quad (7)$$

visual magnitudes per square sec of arc. This solves the problem, providing that Δm can be found by classical means, and if γ and Q are known. Remember again that the assumptions here are (1) the source of illumination is the galactic plane, (2) the particles at P scatter isotropically, and (3) the same particles that scatter at P cause the extinction Δm of background objects. Assumption (2) is likely to be wrong due to a probable forward throwing scattering function, but this refinement is neglected here.

IV. APPLICATION TO THE FIELD NEAR M81

We now apply Eq. (7) to the nebulosities of Plate VI to see if the observed value of $\langle SB\rangle_v \simeq 25$ mag/□″ can be understood in this way. What is Δm?

Inspection of the plates for galaxy counts on and off the nebulosities suggests that $\langle\Delta m\rangle$ is less than 0.5 mag, and more like 0.3 mag, but the estimate is not accurate.

More definite information comes from the neutral hydrogen column density $N_{\mathrm{H\,I}}$ (integrated over all velocities) as determined by Heiles (1975). His value is $N_{\mathrm{H\,I}} = 5 \times 10^{20}$ atoms/cm^2 in the direction of the nebulosities in Plate VI, averaged over a spatial resolution of 0°.6, which is the radio beamwidth. If the ratio of dust to gas in these high latitudes is the same as in the plane, then $E(B-V) = N_{\mathrm{H\,I}}/5 \times 10^{21}$ atoms/cm^2 mag from Knapp and Kerr (1974), following an earlier suggestion by van den Bergh and Heidman (1969) that the reddening and hydrogen column densities are related. Sturch (1969) demonstrated the effect with RR Lyrae stars, and the idea had its antecedent in the original demonstration by Lilley (1955).

Hence, if $N_{\mathrm{H\,I}} = 5 \times 10^{20}$ atoms/cm^2, then $E(B-V) = 0.10$ mag and $\Delta m_v = 0.3$ mag. Similar results hold for the region shown in Plate V.

Finally we need γQ^{-1}. Previous studies (cf. Greenstein 1951) have suggested $\gamma \simeq 0.5$. Hence, with $Q = 2$, and $\Delta m = 0.3$, Eq. (7) requires the surface brightness to be $SB_v = 25.5$ mag/□″. The remarkable agreement of this prediction with the observations supports the hypothesis that the high-latitude reflection nebulae, which can now be found almost at will, are illuminated by the galactic plane.

V. CONSEQUENCES

The galactic plane is everywhere, all the time. Because it provides the same flux density at every height (providing that h is small compared with the scale over which gradients in S are important), the presence or absence of detectible reflection nebulosities to given SB limits betrays the presence or absence of optical extinction of strength Δm.

The limits on Δm are quite useful. If $\gamma = 1/2$ and $Q = 2$, Eq. (7) becomes

$$SB_v = 24.2 - 2.5 \log (\Delta m) \text{ mag}/\square''. \quad (8)$$

Therefore, if nebulosities as faint as $SB = 27$ mag/$\square''$ can be detected, then $\Delta m \simeq 0.08$ mag. This is small enough to be interesting, and the method is expected to be useful as an auxiliary tool with which to measure the transparency of the halo. [Its drawback is that only differences (contrasts) in SB can be found this way. A uniform dust sheet would add a uniform SB to the night sky, and hence would not be detected.]

The question where the dust comes from is of interest. There is much prior evidence for matter in high galactic latitudes, principally from the polarization map of Mathewson and Ford (1970) and from the work by Heiles and collaborators of the H I column densities for $|b| > 10°$ (Heiles 1974a, 1974b; Heiles and Habing 1974; Heiles 1975; Heiles and Jenkins 1976; Heiles 1976a). From their correlations of galaxy counts, H I column densities, polarization vectors, and the well-known nonthermal radio loops, it is clear that dust must be present in the same region as the neutral hydrogen, the magnetic fields, and the relativistic electrons of the synchrotron loops.

Heiles (1976b) has also presented evidence that the H I loops are expanding, and he suggests supernovae explosions for their origin. Hence, there may be a natural way via these events for dust to reach the high latitudes from the plane. The heights are probably modest. We suppose that the order of distance to the reflection nebulae studied here is ~100 pc.

If the proportionality between dust density and H I column density is the same at high latitudes as in the plane, then regions of high $N_{\mathrm{H\,I}}$ should be regions of strong reflection nebulosities. Our two areas discussed here are consistent with this view because for both directions ($l = 187°$, $b = -50°$; $l = 140°$, $b = +40°$) the neutral hydrogen maps show great H I density. The M81/M82 area is particularly interesting because it is on a well-defined loop of high H I intensity, plainly visible on the maps (Heiles and Jenkins 1976, Figs. 1 and 2; Weaver 1976).

Finally, the measured column density in the polar caps ($|b| > 60°$) of order $N_{\mathrm{H\,I}} = 2 \times 10^{20}$ atoms/cm^2 (Heiles 1975, Figs. 3 and 4) suggests, from the Knapp–Kerr correlation (Sec. IV), that the optical extinction may be as high as $\Delta V \simeq 0.15$ mag in many parts of the polar caps, again providing that the dust-to-gas ratio at these heights is the same as in the plane. The H I maps show the distribution to be somewhat patchy, which, as previously mentioned, provides the density contrasts needed to detect the nebulosities optically. Equation (8) predicts $SB_v \simeq 26.3$ mag/$\square''$ for such nebulosities.

Although detection of contrasts in surface brightness at this level is a difficult technical problem, the test is possible and, if made, holds promise to provide new information on the polar extinction.

ACKNOWLEDGMENTS

It is a pleasure to thank J. Bedke, photographer of the Hale Observatories, for the excellent and difficult reproductions in Plates V and VI. It is also a pleasure to thank C. Heiles and H. Weaver for discussion of the nature of the high-latitude H I distribution, and C. R. Lynds for discussions of his remarkable photographs of the Polaris region.

REFERENCES

Greenstein, J. L. (1951). *Astrophysics,* edited by J. A. Hynek (McGraw-Hill, New York), Ch. 13, p. 544.
Heiles, C. (1974a). Astron. Astrophys. Suppl. **14,** 557.
Heiles, C. (1974b). *Galactic Radio Astronomy,* IAU Symp. No. 60, edited by F. J. Kerr and S. C. Simoson (Reidel, Dordrecht), p. 13.
Heiles, C. (1975). Astron. Astrophys. Suppl. **20,** 37.
Heiles, C. (1976a). Astrophys. J. **204,** 379.
Heiles, C. (1976b). Discussion at the June 1976 Berkeley Meeting of the Astronomical Society of the Pacific.
Heiles, C., and Habing, H. J. (1974). Astron. Astrophys. Suppl. **14,** 1.
Heiles, C., and Jenkins, E. B. (1976). Astron. Astrophys. **46,** 333.
Hubble, E. (1922). Astrophys. J. **56,** 400.
Knapp, G. R., and Kerr, F. J. (1974). Astron. Astrophys. **35,** 361.
Lilley, A. E. (1955). Astrophys. J. **121,** 559.
Lynds, B. T. (1965). Astrophys. J. Suppl. **12,** 163.
Mathewson, D. S., and Ford, V. K. (1970). Mem. R. Astron. Soc. **74,** 139.
Roach, F. E., and Gordon, J. L. (1973). *The Light of the Night Sky* (Reidel, Dordrecht), p. 23.
Sandage, A., and Visvanathan, N. (1969). Astrophys. J. **157,** 1065.
Seares, F. H. (1920). Astrophys. J. **52,** 162.
Sturch, C. (1969). Astron. J. **74,** 82.
van den Bergh, S., (1966). Astron. J. **71,** 990.
van den Bergh, S., and Heidman, J. (1969). Unpublished preprint.
Visvanathan, N., and Sandage, A. (1972). Astrophys. J. **176,** 57.
Weaver, H. L. (1976). Private communication.

PLATE V (Sandage, p. 954). A high-contrast print from the original Palomar Sky Survey E plate of a part of the field labeled survey 3^h12^m, $-6°$ ($l = 187°$, $b = -50°$). The scale can be found by noting that the width of the photograph is 3° 12′ and the length is 4° 4′.

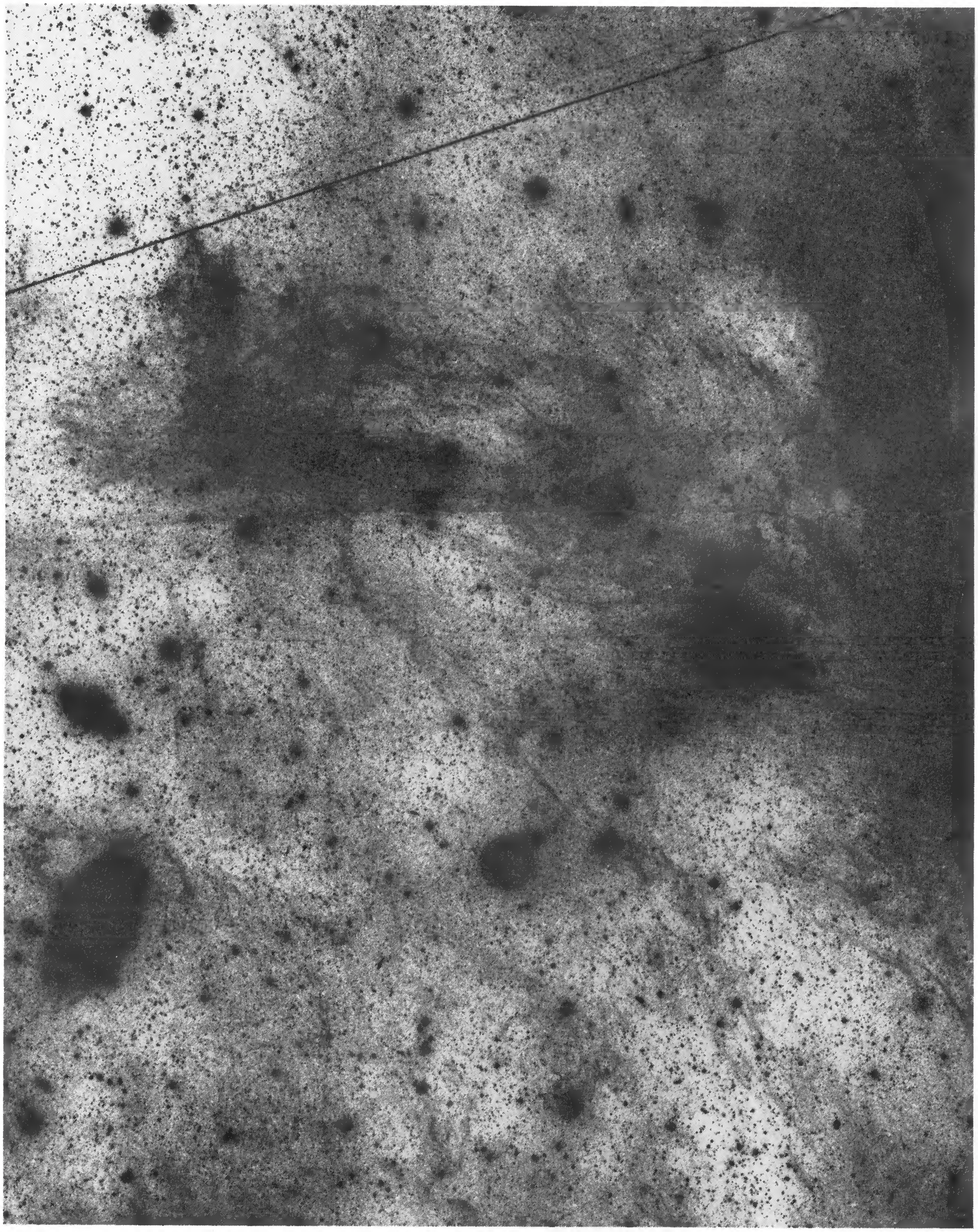

PLATE VI (Sandage, p. 954). A high-contrast print from a new III-aJ plate plus Wratten-4 filter of a region near the galaxies M81 and M82. The bright filamentary nebulosity in the upper-left third of the print, just below the airplane trail, is at $\alpha_{1950} = 9^h48^m$, $\delta_{1950} = +70°$ 10′; $l = 140°$, $b = +40°$. The scale can be found by noting that the width of the photograph is 2° 45′ and the length is 3° 32′.