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EVIDENCE FOR AN EXPLOSION IN THE CENTER OF THE GALAXY M82

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ABSTRACT

New observations in optical frequencies of the peculiar optical and radio galaxy M82 reveal a massive system of filaments which extends along the minor axis to a height of 3000 pc above and below the fundamental plane. Emission lines typical of low-excitation gaseous nebulae are present The filaments on both sides of the plane appear to be expanding from the center along the minor axis with velocities ranging up to about 1000 km/sec. The data suggest that an expulsion of matter took place from the central regions of M82 about 1 5 $\times 10^6$ years ago. The Hα emission flux from the filaments is estimated to be 1.7×10^{-11} erg cm^{-2} sec^{-1} at the earth's surface, which requires a total emitted power of 2×10^{40} ergs sec^{-1} in Hα if the distance modulus of M82 is $m - M = 27.5$. The ion density in the filaments, estimated from the volume emissivity, is 10 protons cm^{-3}, which then requires the mass of the expanding material to be $5.6 \times 10^6 M_\odot$ as an upper limit An upper limit to the kinetic energy of the moving gas is 2.4×10^{55} ergs.

The filaments form fragments of loops and appear to outline lines of magnetic force. Parts of the filaments appear to radiate weakly in the continuum, as well as in the emission lines, and this suggests that optical synchrotron radiation may be present Polarization measurements of part of the filamentary structure by Elvius and Hall are consistent with this possibility. The radio-flux data are combined with an estimate of the optical synchrotron flux, and a theoretical power spectrum is computed from the synchrotron theory. A high-frequency cutoff between 2×10^{14} and 2×10^{15} cps is derived. The total synchrotron energy radiated in 1.5×10^6 years is 9×10^{55} ergs if the observed power level has been constant over this time interval.

The average magnetic-field strength is estimated to be $H < 2 \times 10^{-6}$ gauss on the basis that the energy stored in the relativistic electron gas has not been replenished in 1 5 $\times 10^6$ years and is sufficient to produce 9×10^{55} ergs of synchrotron radiation. This energy may have been put into the electrons at the time of the explosion. The time for the high-energy optical electrons to lose half their initial energy is longer than 1 5 $\times 10^6$ years for a field strength of 2×10^{-6} gauss. Furthermore, if H is this small, the kinetic energy of the moving gas is sufficient to have pulled the field out of the plane of M82 when the expulsion of the matter began.

Following Woltjer, it is shown that a possible source of the excitation for the low-energy recombination optical spectrum is the synchrotron-radiation field, which extends to frequencies above the Lyman limit, but more accurate measurements of the Hα and the synchrotron flux are needed to establish this possibility.

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I. INTRODUCTION

Although generally classified as an irregular galaxy, M82 is far from being typical of that class of objects. The highly oblong shape of the galaxy suggests a flattened system seen nearly edge-on. However, aside from this, there is little evidence of any regularity of form. On photographs in blue or visual light, the galaxy presents a chaotic mixture of luminous patches and dark lanes (Fig. 1). The integrated spectral type of A5 (Humason, Mayall, and Sandage 1956) contrasts strongly with the color index, $B - V = +0.91$ (de Vaucouleurs 1961). Evidence has been found by Morgan and Mayall (1959) that this discrepancy between spectral type and color index is due to the reddening produced by a large amount of dust in M82. This dust evidently is also responsible for the dark lanes which overlie the face of the galaxy.

One of the most remarkable features of M82 is the system of luminous filaments which extend to about 2 minutes of arc north and south of the galaxy in the direction of the minor axis (see Fig. 1). The National Geographic Society–Palomar Observatory Sky Survey plates show the filaments, as well as the galaxy, to be considerably fainter in the violet than in the red. Previously it might have been supposed that the filaments were subject to the same reddening from dust as the main body of the galaxy, but now it appears most likely, from data reported herein, that a large fraction of the radiation from the filaments is contributed by Hα.

TABLE 1

SPECTRA OF M82

Plate	Exposure Time	Slit P A
ES-92 . . .	15 min.	335°
ES-93 . . .	2 hr.	335°
ES-94 .	2 hr.	322°

Radio observations of M82 (Lynds 1961) have shown that the galaxy is a radio source with a spectral index of approximately 0.2, nearly the same as that found for the Crab Nebula radio source. By analogy with the Crab Nebula, it was suggested that the radio emission from M82 was due to the synchrotron mechanism and that the synchrotron continuum extended into the optical region and was responsible for the optical radiation from the filaments of M82.

After unsuccessful photographic attempts by both Lynds and Sandage to detect optical polarization, Elvius and Hall (1962*a*, *b*) have found polarization by using photoelectric methods. They have measured 10–15 per cent polarization in the filaments and only 2–3 per cent polarization in the main body of the galaxy. The polarization measurements in the filaments show electric vector orientations roughly parallel to the major axis of the galaxy or perpendicular to the radial pattern of the filaments, a point important for our subsequent discussion.

II. NEW OBSERVATIONS

a) *Spectra*

During March, 1962, three spectra of M82 in the Hα region were obtained with the prime-focus nebular spectrograph of the Lick Observatory 120-inch reflector. These plates are listed in Table 1, together with the corresponding exposure times and slit orientations. The emulsion used was Eastman 103*a*-F, and the dispersion is approximately 360 A/mm. All three spectra were obtained with a slit width of 2.7 seconds of arc and a slit length of 5 minutes of arc. The slit of the spectrograph was centered on the galaxy,

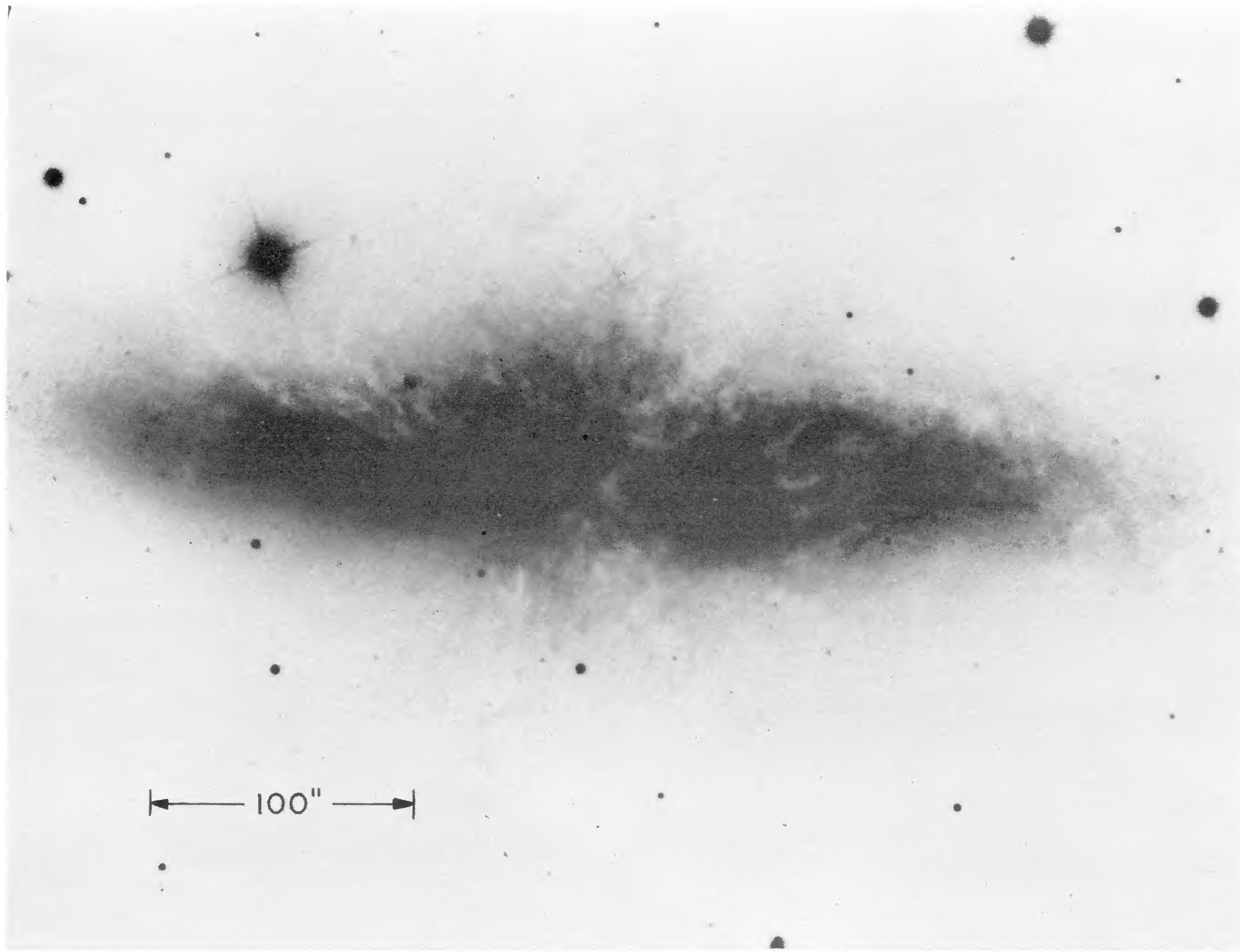

FIG. 1.—Photograph of M82 taken with the 200-inch reflector in blue light on an Eastman 103a-O plate behind a Schott WG2 filter ($\lambda\lambda$ 3600–5000 A). The cardinal directions are skewed on this reproduction, with north pointing down and to the right at about 30° to a vertical line and east pointing up and to the right at about 30° to a horizontal line.

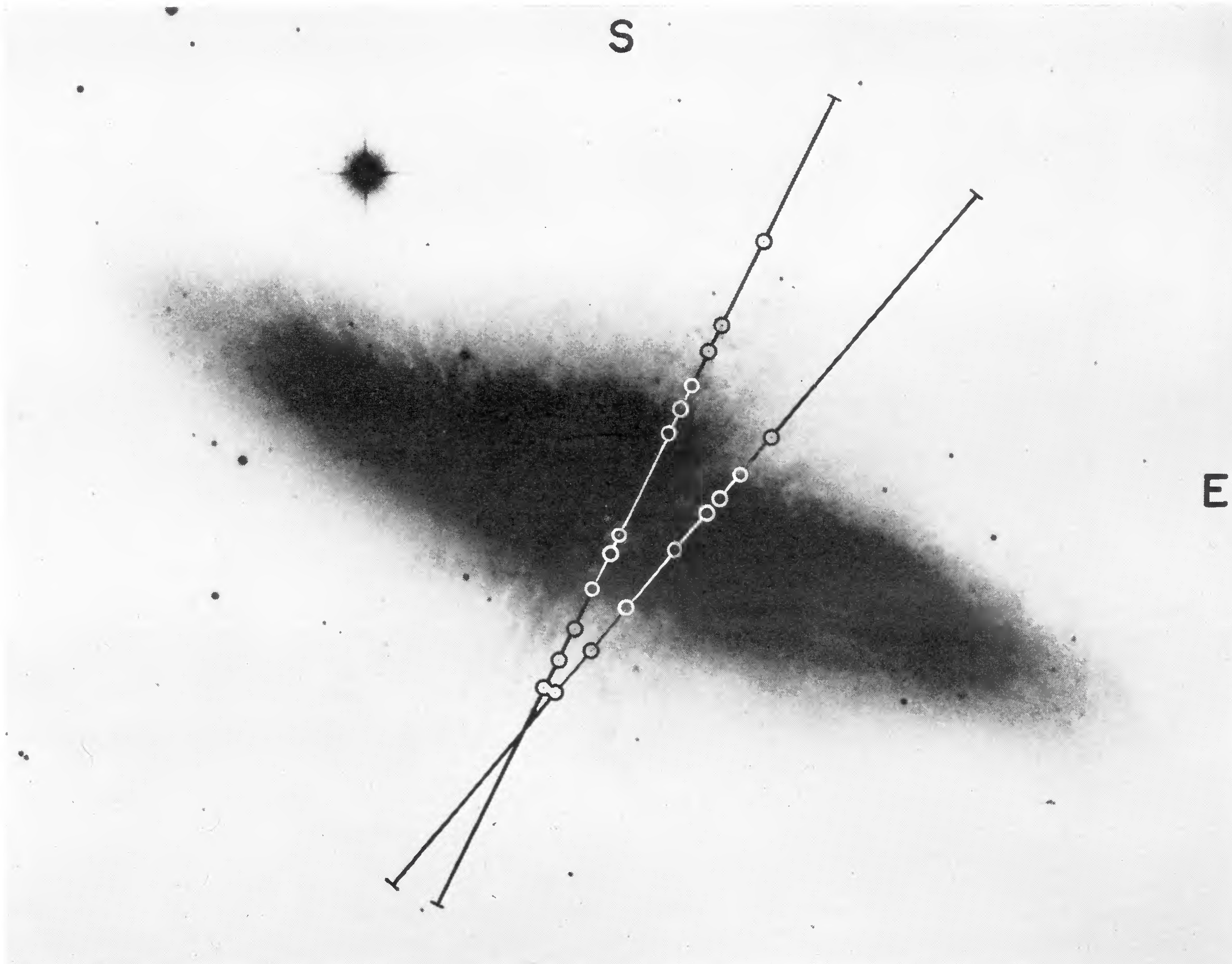

FIG. 2.—Photograph of M82 in red light with lines showing the orientations of the spectrograph slit. The small circles identify the positions at which radial-velocity measurements were made. The reproduction of M82 shown here was made from the same plate as was Fig. 7.

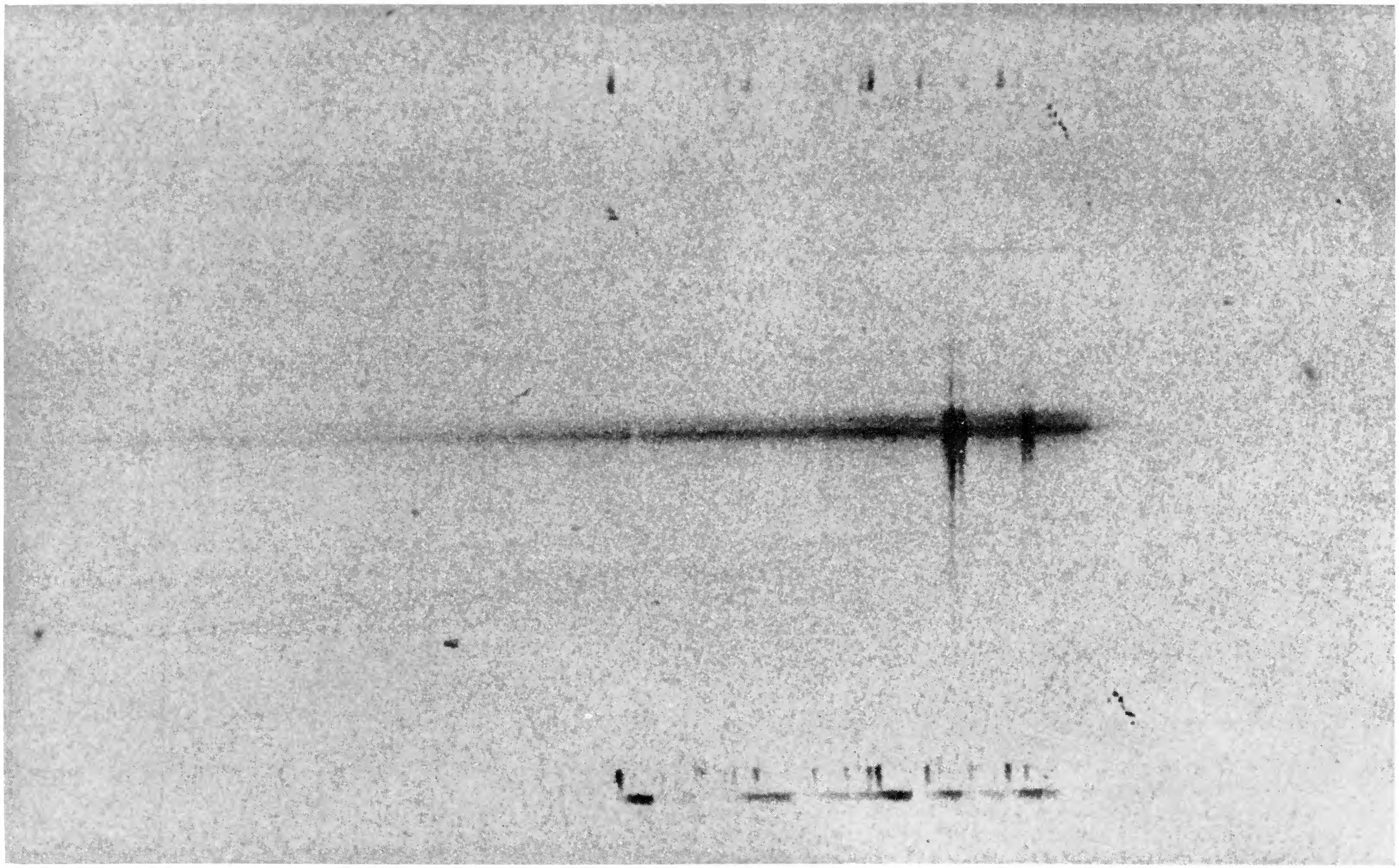

FIG. 3.—The spectrum of M82 in the red ($\lambda\lambda$ 5000–7000 A). The reproduction is from ES-92, a 15-minute exposure with the Lick 120-inch telescope; spectrograph slit oriented at 335° position angle. The comparison spectrum is due to neon.

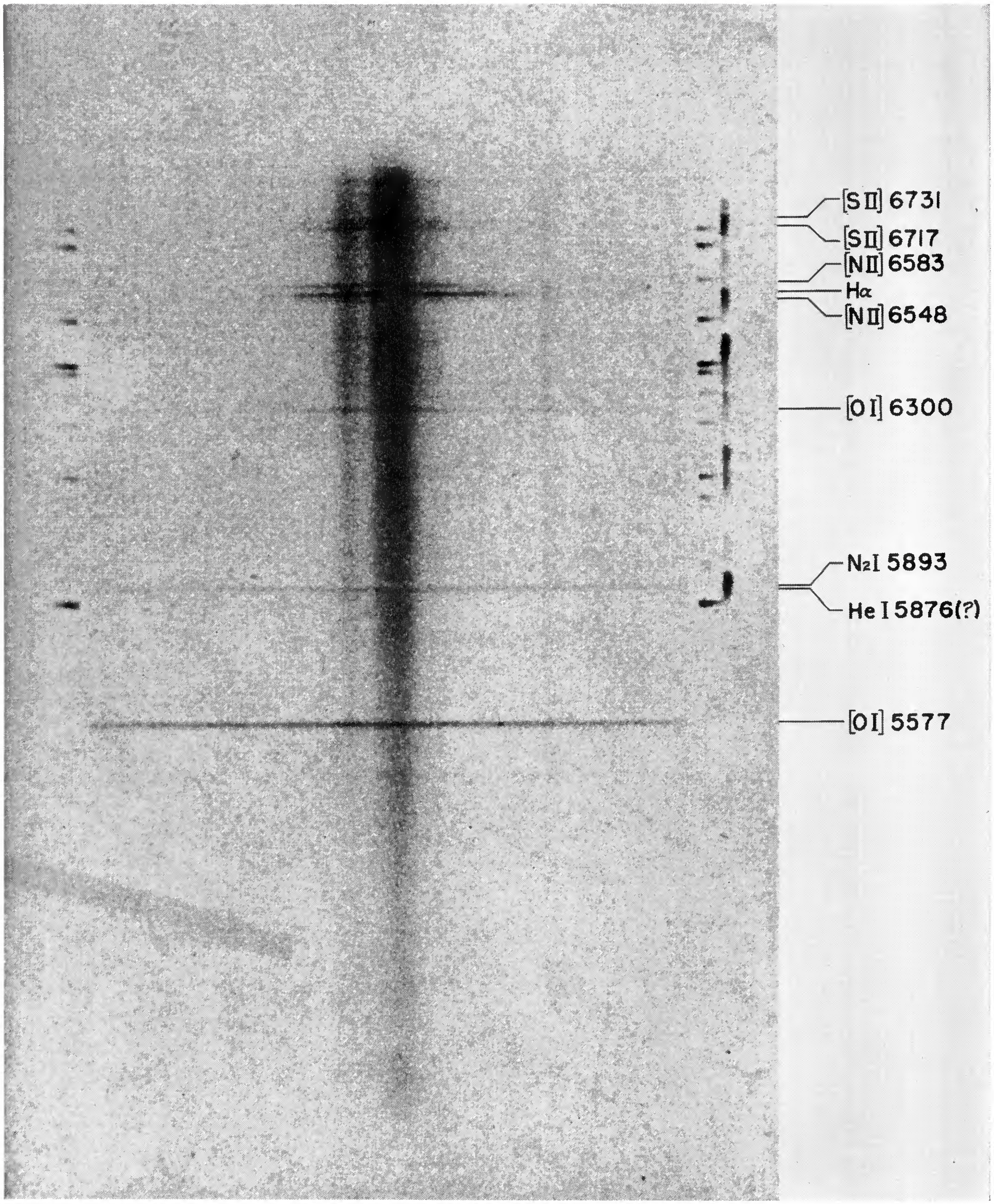

FIG. 4.—The spectrum of M82 and its system of filaments taken with the Lick 120-inch telescope. The reproduction is from ES-93, a 2-hour exposure for which the slit of the spectrograph was oriented at 335° position angle.

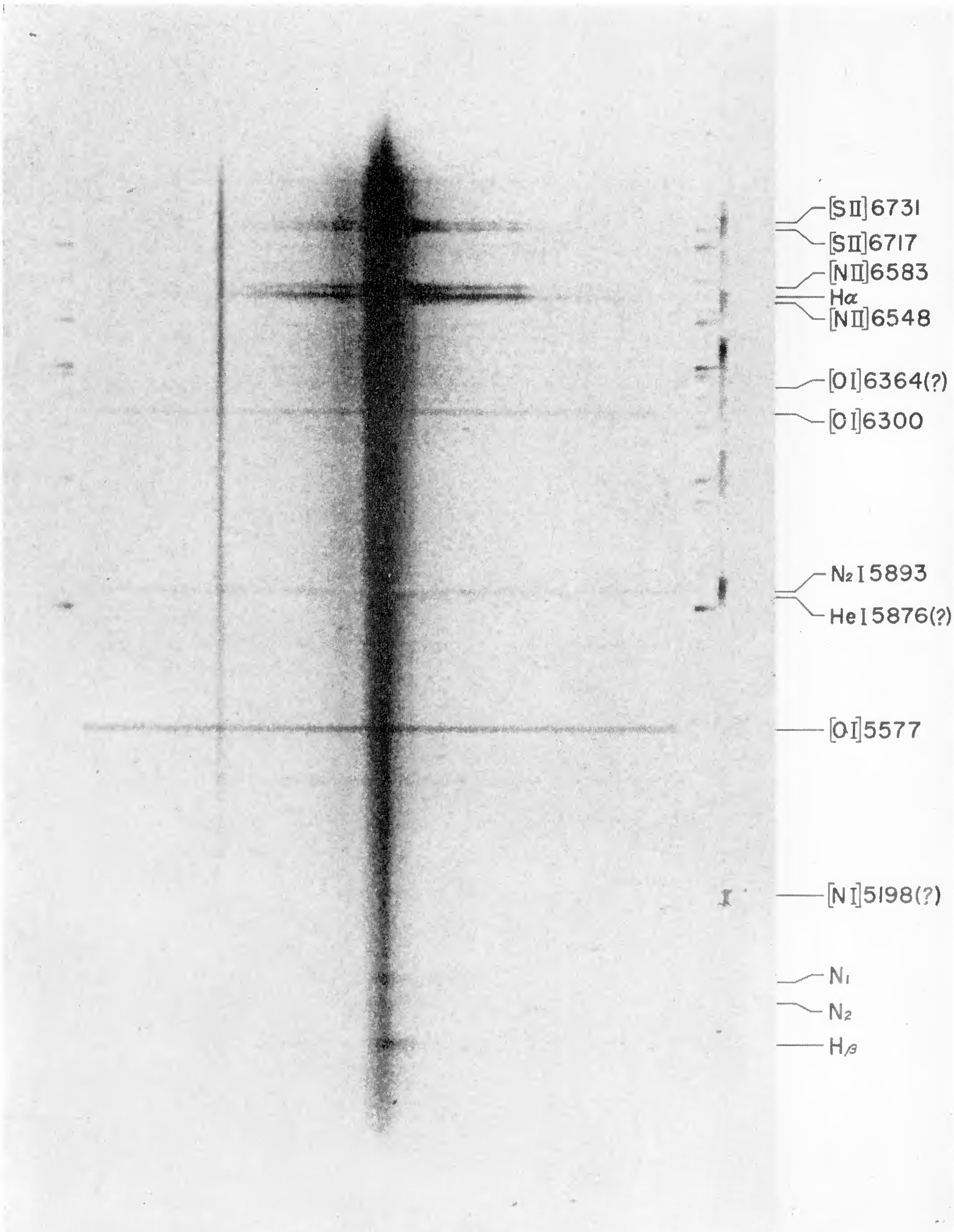

FIG. 5.—The spectrum of M82 and its system of filaments taken with the Lick 120-inch telescope. The reproduction is from ES-94, a 2-hour exposure for which the slit of the spectrograph was oriented at 322° position angle.

with orientations roughly perpendicular to the major axis of the galaxy. For all three spectra the slit passed over the prominent star approximately 1.2 minutes of arc north preceding the nucleus of M82 and had position angles as given in the third column of Table 1. The spectrograph was rotated through approximately 180° between exposures ES-93 and ES-94. The slit positions on M82 are shown on Figure 2.

The three spectra of M82 are reproduced in Figures 3, 4, and 5. In addition to the usual night-sky lines, [O I] 5577, 6300 (and possibly 6364), and Na I 5893, the spectra show Hα, [N II] 6548, 6583, and [S II] 6717, 6731 in emission, and Na I 5893 in absorption. There is some evidence for the presence of [O I] 6300 and He I 5876. Weak [O I] 6364 is present, but it is impossible to determine whether it arises from the galaxy or from the night sky. On the original of ES-92 it is possible to see evidence of strong Hα absorption underlying the emission, thus tending to confirm an early integrated spectral type for the stellar content of M82. On ES-93, in the out-of-focus 5000 A region, Hβ and N1, N2 of [O III] appear in emission. On this plate there is also a faint indication of [N I] 5198 in emission. For ES-93 the slit of the spectrograph crosses the most intense emitting region of M82, located just west of the main dark band crossing the galaxy. Judging from the relative intensities of Hβ and N1, the excitation class (Aller 1956) of this part of M82 is between 2 and 3. It will be noticed that the region of strongest Hβ is not coextensive with the region showing the strongest continuous spectrum.

Referring to Figures 4 and 5, it is seen that, in general, little or no continuum was recorded outside the fairly well-defined main body of the galaxy. On the other hand, the emission lines of [N II] and [S II] and Hα are seen to extend well beyond the main boundary of M82. In fact, Hα and λ 6583 can be traced to nearly 2 minutes of arc from the center of the galaxy. This is almost the maximum extent of the system of filaments shown on the Sky Survey "E" plate. It now appears that the relatively great strength of the filaments as shown on red-sensitive plates is due largely to the Hα and λ 6583 emission lines.

The relative intensities of the emission lines are somewhat abnormal when compared with the spectra of typical planetary nebulae (Wyse 1942). Compared with Hα, the emission lines of [S II] and [N II] are stronger than average. In addition, there is an interesting variation in the intensity ratio Hα:[N II]6583. This ratio varies from about 3:1 in some regions just north of the galaxy to approximately 1:1 in the faint filaments south of the galaxy—a variation which is shown in Figure 6, taken from a microphotometer tracing of plate ES-94 made along Hα and λ 6583. The curves represent opacity (reciprocal transmission) as the microphotometer slit was scanned along the emission lines. The abscissa is angular distance from the foreground star located about 80 seconds of arc north of the center of M82. Figure 6 shows that Hα is substantially stronger than λ 6583 from 20 seconds to 80 seconds north of the galaxy center, but to the south the lines are of nearly equal intensity. Furthermore, the original plates show that the ratio Hα:λ 6583 is noticeably greater for the intense emission region crossed by the slit of ES-92 and ES-93 than it is for the relatively low surface-brightness region of the galaxy crossed by the slit of ES-94. Similar variations in the relative intensity of Hα and λ 6583 have been found by Burbidge and Burbidge (1962) in certain types of spiral galaxies.

It will be noticed that there are numerous condensations in the Hα line and the lines of [N II] and [S II]. These features may be identified with corresponding areas of emission in Figure 2. However, most of the detail of the direct plates remains unresolved on the spectra because of the small scale in the focal plane of the spectrograph camera (approximately 1.3 minutes of arc per mm). There appears to be some irregularity of the position in wavelength of the various knots in the emission lines, indicating differential velocities of the order of 50 km/sec. A possible dispersion in the radial velocity of the fine structure included within the knots is difficult to detect at the dispersion of the present spectra.

One characteristic feature of the filament spectra that can be seen upon careful inspection of Figures 4 and 5 is the pronounced inclination of the emission lines relative to the comparison lines.[1] The inclination of the lines is in the sense that the material in the filaments north of the galaxy is receding and the material sourh of the galaxy is approaching. Velocity measurements relating to this effect will be treated in Section III.

b) Direct Photographs

Figure 7 is a reproduction from a plate taken in December, 1955, with the Palomar 200-inch reflector on 103*a*-E emulsion behind a Schott RG1 filter—a plate and filter combination which passes radiation between λ 6100 and λ 6700 A. The delicate filamentary structure perpendicular to the major axis is clearly seen extending to at least 2 minutes of arc on either side of the M82 major axis, which, when compared with the spectra, leaves no doubt that the filaments are due to a localized emission of radiation rather than to an irregular absorption of a continuous background of radiation.

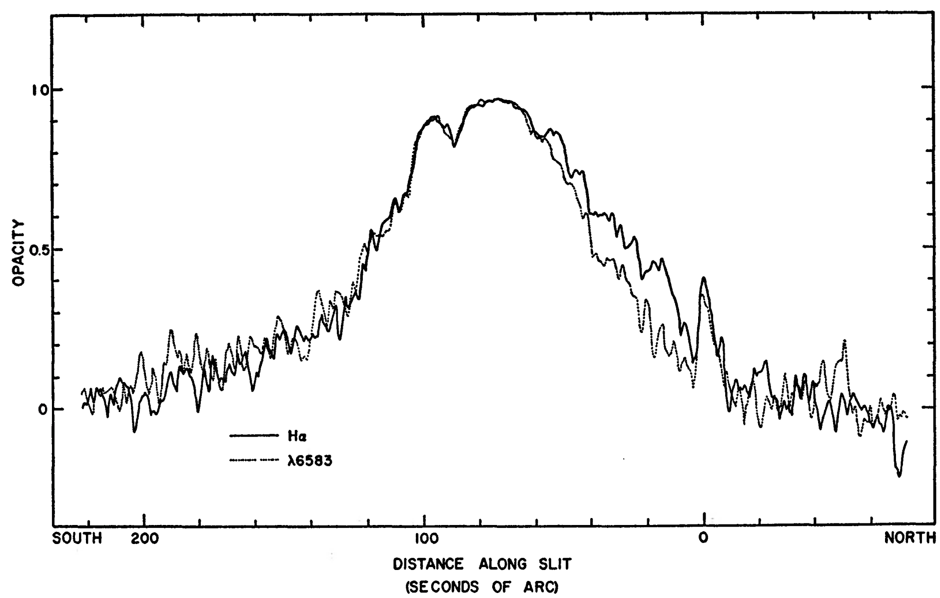

FIG. 6.—Microphotometer tracings showing the variation in the relative intensity of Hα and λ 6583 on the spectrogram ES-94. The scanning slit of the microphotometer was made very short and was scanned along the lines individually in a direction perpendicular to the dispersion.

To increase the contrast between the filaments and the background of sky, additional plates were taken with the 200-inch in March, 1962, using an Hα interference filter of 80 A total half-width (transmits the [N II] lines in addition to Hα). Figure 8 is a reproduction from a 3-hour interference-filter exposure made with a 103*a*-E emulsion. The filamentary structure is massive and lies perpendicular to the major axis of the galaxy. Figure 8 has been automatically dodged to increase the latitude of the paper print, but otherwise shows faithfully the structure. The dodging technique, developed by W. C. Miller, consists of making a low-density printing negative from a printing positive made from the original plate, then superimposing exactly this negative with the glass positive in the photographic enlarger and printing through the combination. Without this procedure, the denser regions of the original plate are lost. We are much indebted to Mr. Miller for using his characteristic skill in making this and other reproductions of the direct plates shown herein.

[1] In view of the rather remote possibility of a systematic instrumental effect, it is reassuring to note that the spectrograph orientation was reversed between ES-93 and ES-94.

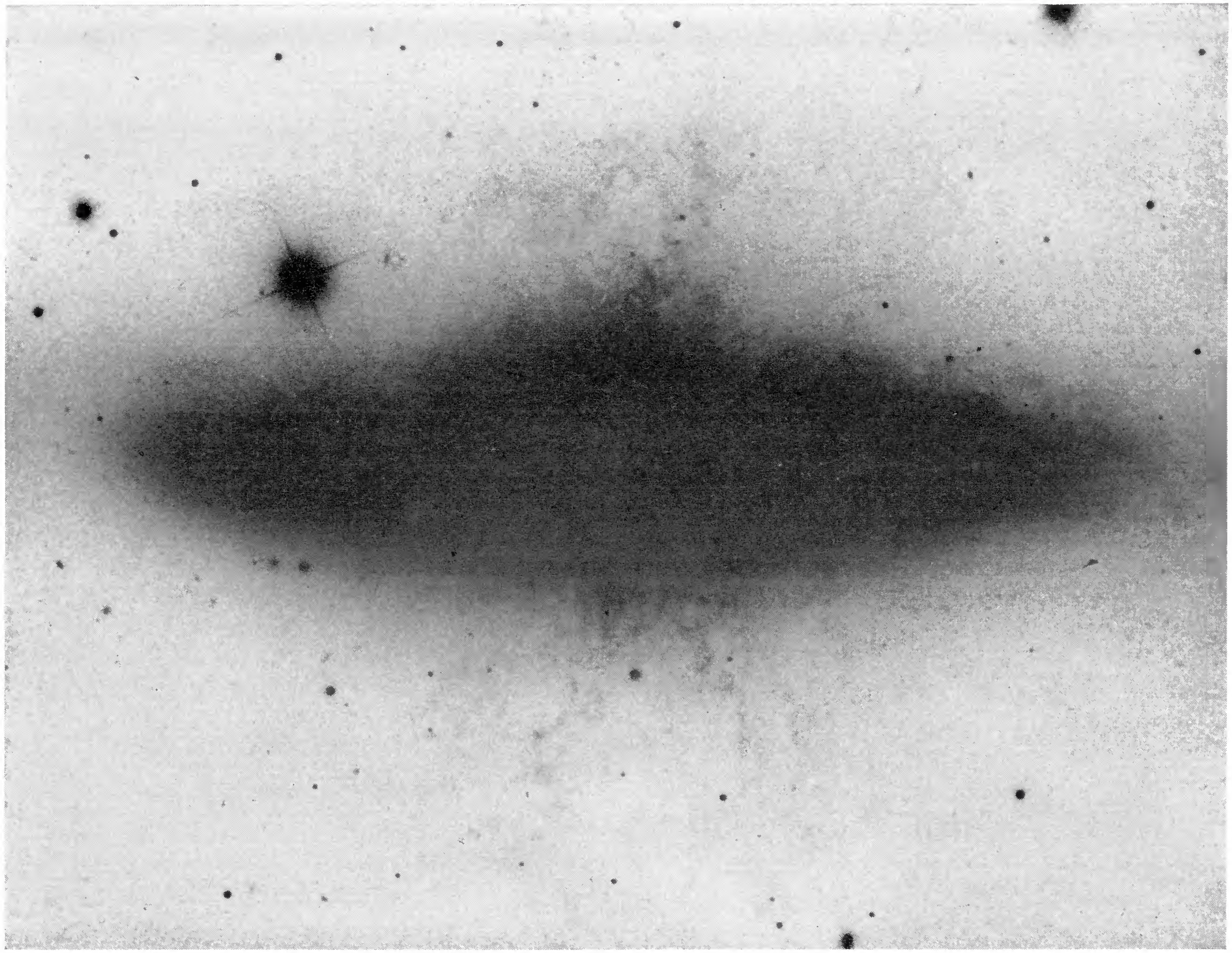

FIG. 7.—Photograph of M82 taken with the 200-inch telescope in red light with a 103a-E plate behind an RG1 filter ($\lambda\lambda$ 6100–6700 A). The scale and orientation are the same as in Fig. 1.

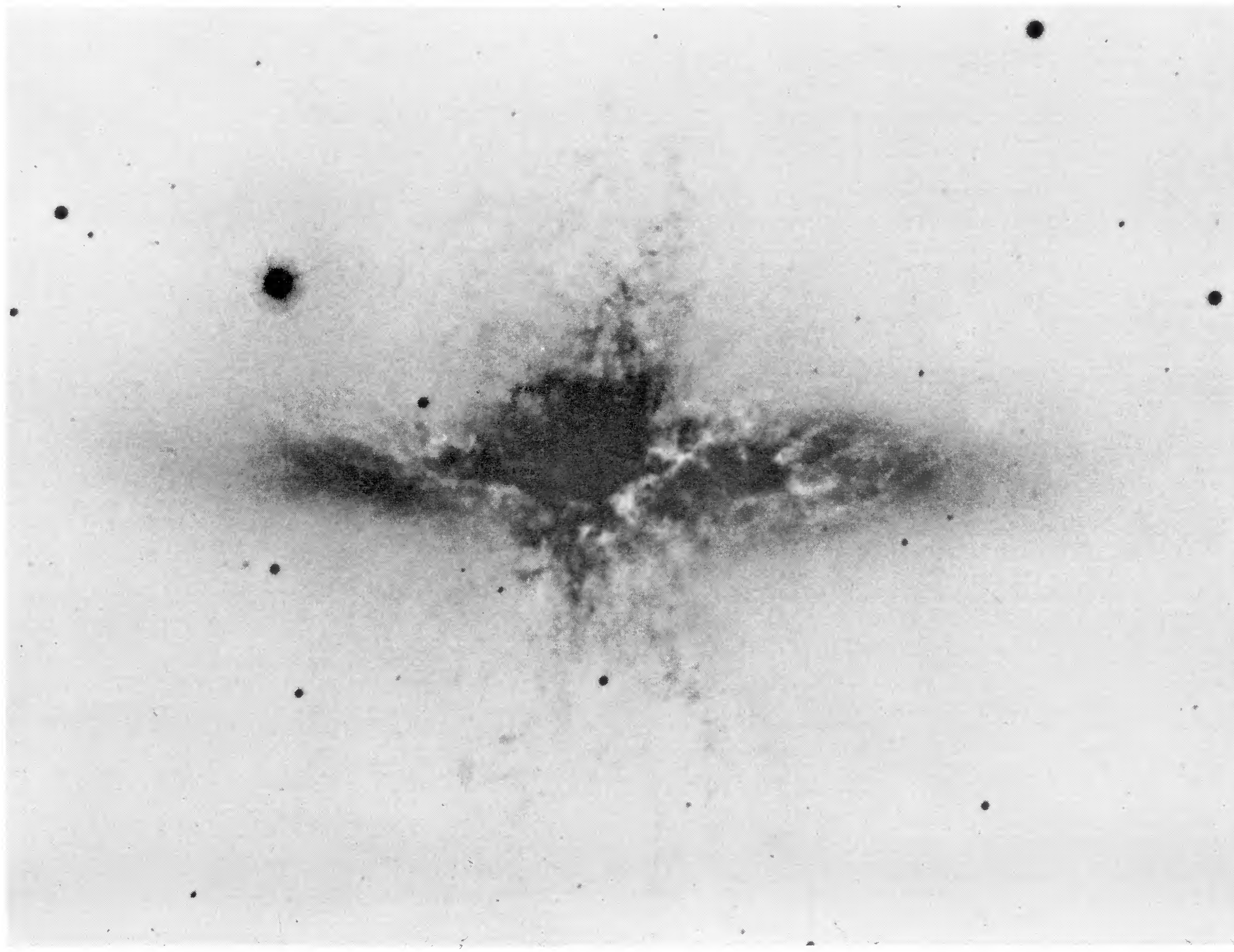

FIG. 8.—Photograph of M82 taken with the 200-inch telescope in Hα light with an interference filter of total half-width 80 A. The scale and orientation are the same as in Fig. 1. The print has been automatically dodged to increase the latitude of the photographic paper, as explained in the text. We conclude from the asymmetry of the dust pattern that the northwest (lower) edge of M82 is the near side.

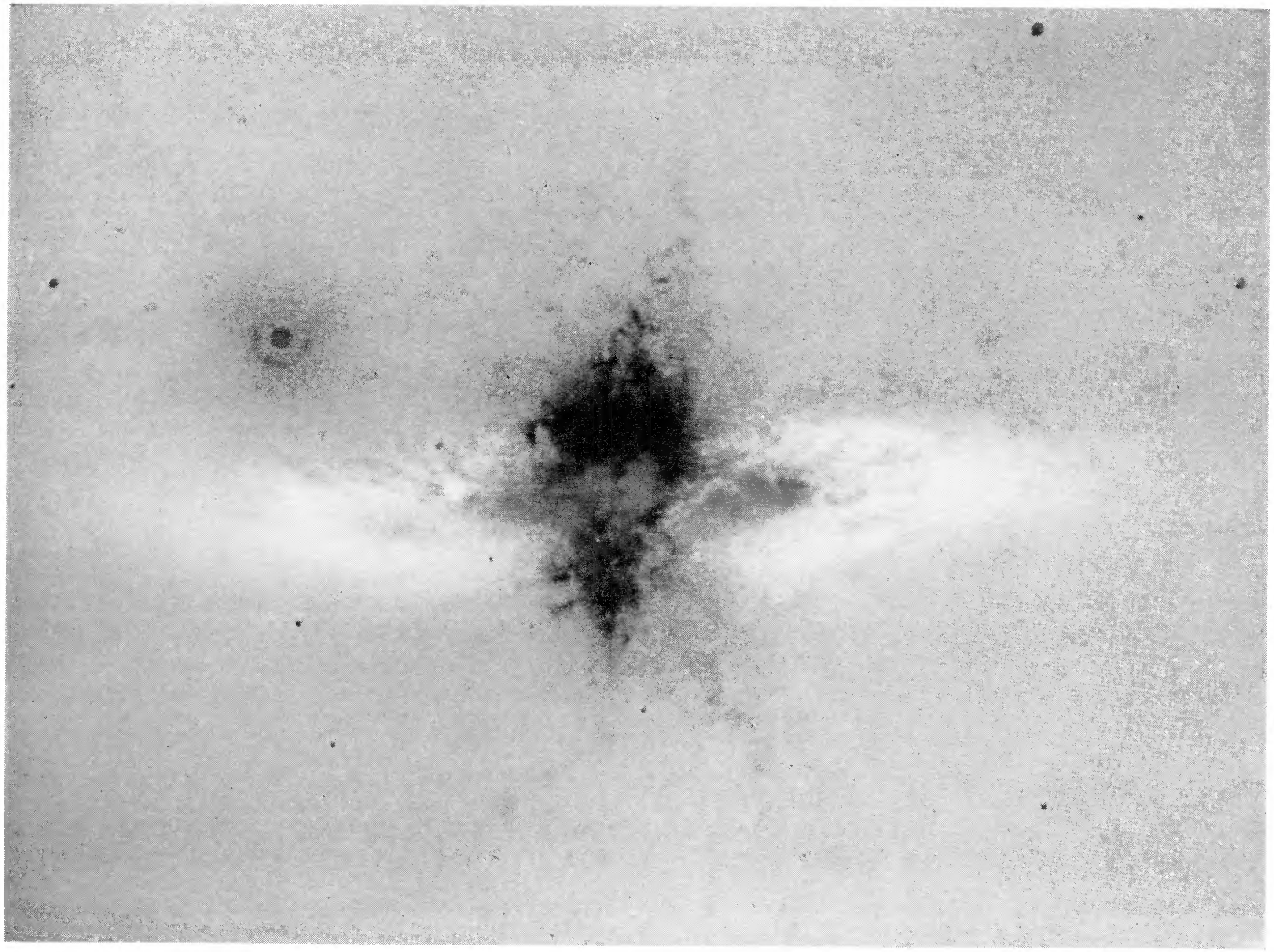

FIG. 9.—A composite photograph of M82 obtained by "subtracting" a photovisual plate (Fig. 10) from the Hα plate of Fig. 8

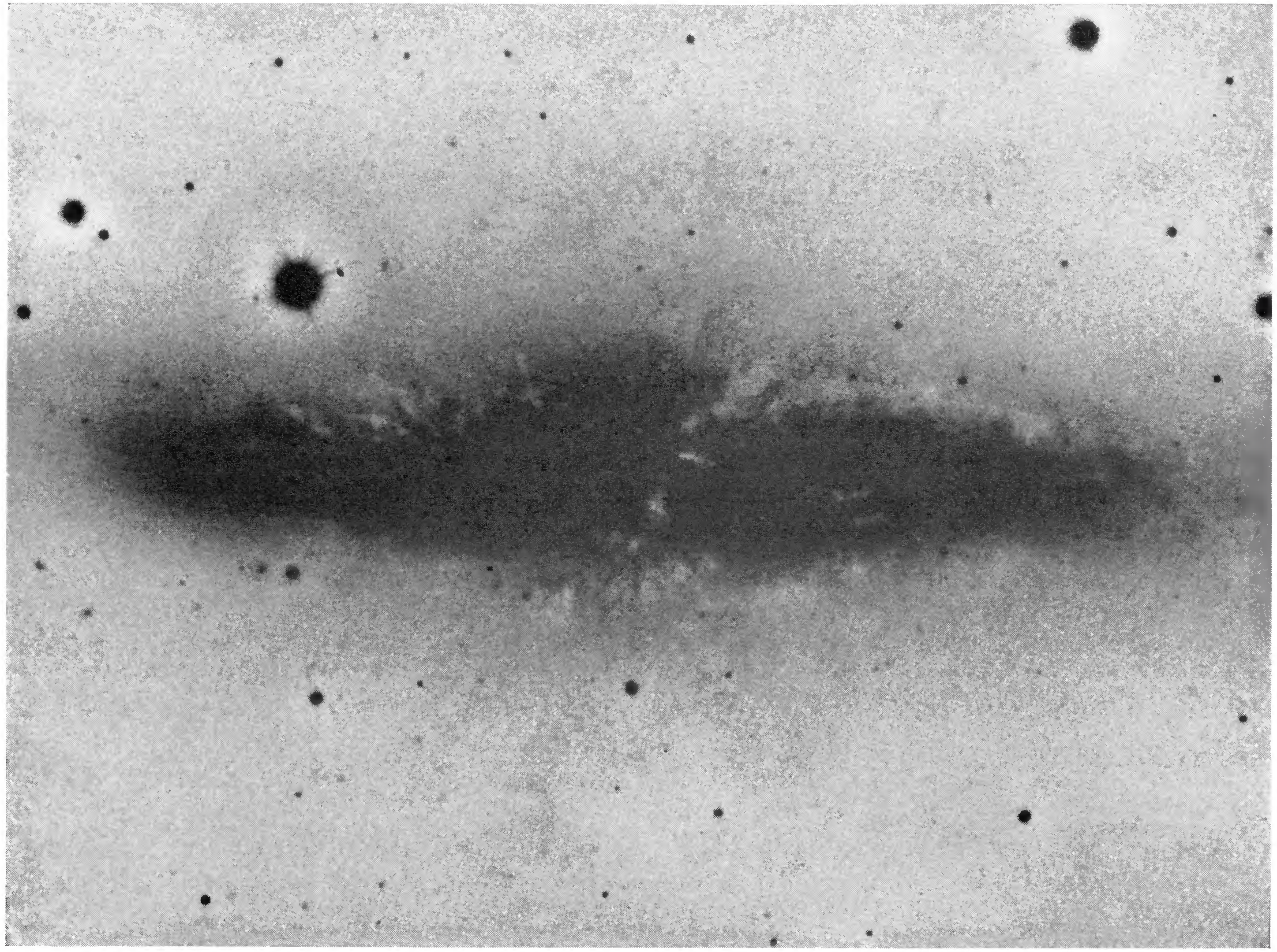

FIG. 10.—Photograph of M82 in yellow light obtained on 103a-D emulsion behind a GG14 filter ($\lambda\lambda$ 5100–6500 A). This plate-filter combination covers a spectral region devoid of emission lines from M82 (see Figs. 3, 4, and 5) and therefore shows only continuum radiation. It is seen that some of the filaments radiate in the continuum as well as in Hα. The illustration has been printed very dark, in order to show this effect.

The filaments in Figure 8 show some regularity. The more extended part of the structure on the south-following part of the minor axis displays segments of two closed loops, one of which is bright and the other faint and somewhat fragmentary. These loops lie slightly to the east of the minor axis on the south side and reach at least 120 seconds of arc into the halo. On the original plate they can be seen to attach onto the main body of the galaxy through two intense Hα emission spikes. At least four other loops of smaller extension can be traced on the south side, and these terminate in the halo at a point 40 seconds of arc from the major axis on the boundary which separates a high-intensity region from the two low-intensity filaments. The filamentary structure on the north side of the major axis is not nearly so regular, but faint extensions can be traced to 190 seconds of arc from the major axis on this side. The general appearance of Figure 8 as regards the loops is that of a solar prominence photographed in Hα.

Figure 9 gives another representation of the filamentary system and was made by photographically "subtracting" the image of the galaxy in yellow light (103*a*-D plus GG14) from the Hα plate of Figure 8. A positive film was made from the original Hα plate, which was then superimposed with the original 103*a*-D negative, and the two were printed together. The resulting photograph clearly shows that the Hα filaments are predominantly perpendicular to the major axis of the galaxy.

The linear extent of the filamentary system is enormous. Here and in the following sections, we adopt a distance modulus $m - M = 27.5$, or a distance of 9.76×10^{24} cm, based on the membership of M82 in the M81 group (Sandage 1962). At this distance, a projected length of 190 seconds of arc on the sky corresponds to approximately 3000 pc. Hence we are dealing with a heretofore unknown but major element in the description of M82.

Figure 10 is a reproduction of a long-exposure plate taken on an Eastman 103*a*-D plate behind 2 mm of GG14 filter—a combination which accepts radiation from λ 5050 to just shortward of Hα. Although there are no strong emission lines in this wavelength interval (see Figs. 3, 4, and 5), some of the filaments are visible on the reproduction, in particular the faint streamer on the northwest side of the minor axis and parts of the brightest extended loop on the south minor axis. We do not believe this is to be due to Hα radiation leaked to the plate because a special series of red-leak tests showed that the 103*a*-D emulsion is 220 times less sensitive at λ 6563 A than the 103*a*-E emulsion. This factor is so large relative to the intensity ratio of the filaments shown between Figure 8 and Figure 10 that we conclude that some of the filaments *radiate weakly in the continuum as well as in Hα*. If the filaments outline lines of magnetic flux as in solar prominences, then we conclude that continuum radiation of these filaments is connected with the magnetic field, and this is the basis for our later calculation of the synchrotron emission. In addition to these filaments, the original plate of Figure 10 shows a faint, semi-uniform surface emission over the entire volume of the halo, which we also later attribute to synchrotron emission from electrons moving in a magnetic field threading this entire volume. Figure 10 has been deliberately overprinted in an attempt to show this feature.

III. MOTIONS OF THE FILAMENTS

The three spectra, ES-92, 93, and 94, have been measured for radial velocity. Corrections have been made for the effects of slit curvature, the earth's motion, and the motion of the sun with respect to the local group. The solar-motion correction was made following the procedure of Humason *et al.* (1956).

The measurements of the main body of the galaxy yielded radial velocities of 300 km/sec for ES-92, 350 km/sec for ES-93, and 400 km/sec for ES-94. The difference in velocity given by ES-93 and ES-94 may possibly be due to real differential motion between the parts of the galaxy covered by the two slit positions. However, the difference between the velocities shown by ES-92 is believed to be an exposure-time effect arising from differential motions along the slit. The measurements have an estimated internal precision of about 25 km/sec; however, the absolute accuracy of the measurements is not known, since the spectrograph has been in operation only a short time and its velocity system has not as yet been well established. It is felt that little significance can be attached to any differences between the present velocity measurements of M82 and those published by Humason *et al.* (1956), which gave +400 km/sec from the Mount Wilson data and +410 km/sec from the Lick material.

The positions at which velocity measurements were made along Hα and λ 6583 are indicated by the circles in Figure 2. The corrected velocities for these positions have been plotted in Figure 11. The abscissa is the same as that in Figure 6 and is the distance in seconds of arc south from the reference star located approximately 75 seconds north of M82. The arrow in the upper part of the figure indicates the approximate center of

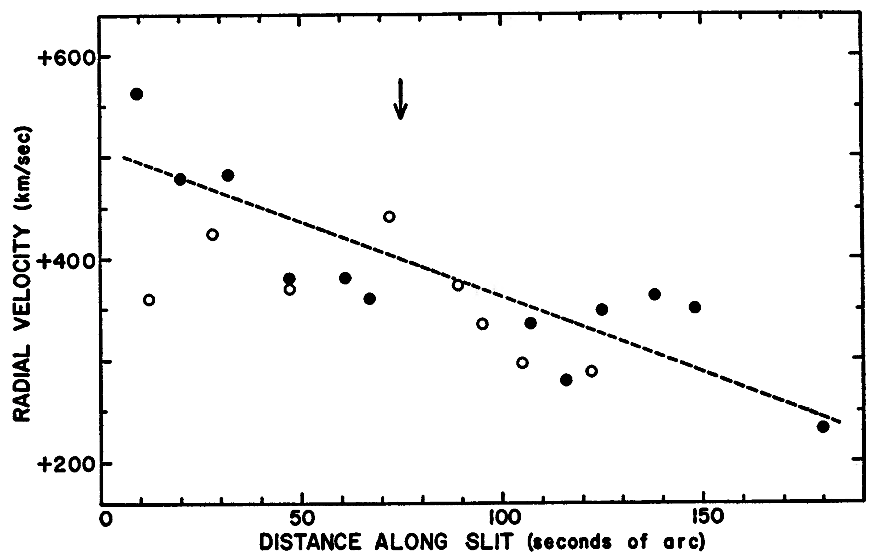

FIG. 11.—Measurements of the radial velocity of the filaments at various positions along the slit of the spectrograph. The filled circles and open circles represent velocities obtained from ES-93 and ES-94, respectively. The dashed curve is a least-squares straight line fitted to the observations from ES-93. The arrow in the upper part of the figure indicates the approximate center of the galaxy.

the galaxy. The filled circles represent the velocities obtained from ES-93, for which the slit was oriented perpendicular to the major axis of the main outline of the galaxy. It is seen that the tilt of the emission lines, mentioned in Section II, is well represented by the measurements. A linear velocity relation, established by a least-squares fitting to the observed velocities, is shown as a dashed line in Figure 11. The measured velocities are not of sufficient weight to warrant the determination of a velocity relation of higher than the first order in the angular distance from the center of the galaxy. The linear velocity relation has a slope of 1.5 km/sec per second of arc and crosses the plane of the galaxy at about 400 km/sec. However, the quoted velocity at the crossover point may be of little significance for the reasons mentioned above.

The open circles in Figure 11 represent the radial velocities obtained from ES-94, for which the slit made an angle of approximately 13° with respect to that for ES-93. The abscissa is the same as before, that is, angular distance along the slit; however, depending on the interpretation given to the observed velocities, account should be taken of the projection angle between the two slit orientations. Aside from the discrepancy at about 65 seconds north of the galaxy, there is general agreement between the velocity relationships shown by the two spectra. Although measurements were not actually made as far south on ES-94 as on ES-93, visual inspection of the spectra confirms a general decrease in radial velocity to the south for both spectra.

Mayall's observations (1960) show that the spectrum of M82 has inclined lines when a spectrographic slit is placed along the major axis. These data suggest that the galaxy is rotating about its minor axis as in normal systems, with an average gradient of 1.4 km/sec per second of arc, which gives a minimum total mass of 2.7×10^{10} solar masses, using an adopted distance of 9.76×10^{24} cm. The interpretation of Mayall's data as rotation seems highly likely, even though we have observed radial velocities of the filaments with the slit placed 90° to Mayall's direction. It is, of course, possible that the total angular momentum vector is not along one of the principal axes of inertia, in which case there would be components of the rotational velocity along *both* the major and minor axes of the projected image and inclined lines would then be produced, as observed, when the slit is placed along *either* of these axes. But this seems so unlikely that we, for the moment, reject such a possibility and suggest that Mayall's data give the rotational curve for the galaxy and, therefore, that our data show that the filaments are in systematic motion perpendicular to the fundamental plane.

Our data can be reproduced if the fundamental plane is tilted slightly to the line of sight so that a component of the filament motion along the minor axis appears as a radial velocity. Such a geometry seems plausible because the observed axial ratio of the best-fitting ellipse to Figure 10 is $\beta/a = 0.175$. Most of the flattened galaxies of the S0–Sc type have true axial ratios of $b/a \simeq 0.10$ (see Pl. 8 of NGC 4762 and Pl. 25 of six nearly edge-on galaxies in the *Hubble Atlas* ["Carnegie Institution of Washington Publications," No. 618]).

The inclination angle of the fundamental plane of M82 to the line of sight can be computed from Hubble's formula (1926)

$$\cos^2 i = \frac{1 - (\beta/a)^2}{1 - (b/a)^2}, \tag{1}$$

which gives $i = 8°23'$ if $b/a = 0.10$, or $i = 9°56'$ if $b/a = 0$ (the flat-disk assumption). In all subsequent calculations, we adopt $i = 8°23'$.

Having established the possibility of systematic motions of the filaments, we now inquire as to the direction of the velocity field—a problem which is solved only if identification of the near side of the galaxy can be made. Following Hubble (1943), we have adopted the asymmetry of absorption lanes across the galaxy face as the primary tilt criterion, a point well taken by the established small dispersion in the height of the distribution of dust in the principal planes of other galaxies. Figure 8 then requires that the northwest side of M82 be nearest to the observer. The radial-velocity curve of Figure 11 shows that the filaments on this side of the projected image are receding, which then requires that the matter on both sides of the major axis be *moving away from the fundamental plane. The filaments appear to be expanding from the center of the galaxy!*

This expansion is approximately linear (see Fig. 11) and of the form $\rho(\theta) = \mu\theta$, where $\rho(\theta)$ is the radial velocity of a particular segment of a filament at an angular distance θ from the center of M82 and $\mu = 1.5$ km/sec per second of arc, a value found earlier in this section. If $v(r)$ is taken to be the true velocity of expansion at a true distance r from the center of M82 along the minor axis, then $\mu = 0.664$ km sec^{-1} pc^{-1} or 2.15×10^{-14} cm sec^{-1} cm^{-1}, where the inclination angle has been taken into account.

In the absence of deceleration, a linear velocity-distance relation has the unique property that the time for every element to travel along its path from a common point of origin to its presently observed position is a constant for all segments of the filaments. This time is μ^{-1}, which in our case is 1.47×10^6 years. It is the interval from the present epoch to that time in the past when all matter in the filaments was near the center of the galaxy. Deceleration has undoubtedly occurred but will be neglected in our following exploratory calculations because of lack of precise data. When more extensive radial-velocity measurements are available and when the mass distribution of M82 is known, a more complete description can be made, taking deceleration into account.

IV. THE PROPOSED MODEL

Data from the last section require that an expulsion of material has occurred from the nuclear regions of the galaxy in what appears to have been an explosion. It looks as if the filamentary material in the halo is partially confined to loops which are assumed to outline magnetic field lines [as, for example, in the case of the Crab Nebula (Baade 1956)] carried from the disk by the matter in its outward motion. Although the initial explosion may have been isotropic, the debris cannot move freely in the fundamental plane because of the magnetic pressure built up by compression or, perhaps more importantly, because of the high probability of inelastic collisions with gas which may be associated with the abundant dust which covers the plane. Most of the expanding matter will move poleward in the directions of least constraint. If this material is to carry the magnetic field, then the kinetic energy of the filaments must be greater than the total magnetic energy carried with it. Estimates in Section VI of the magnetic-field strength (computed from the synchrotron theory) and of the mass of the filaments (computed from the observed Hα flux) indeed suggest that this may be the case.

By some mechanism, not understood, a large fraction of the explosion energy may be put into relativistic electrons which spiral in the magnetic field, producing the observed radio emission and the continuous optical emission in the halo. The polarization observed by Elvius and Hall (1962*a*, *b*) midway in the halo can be explained in this way because the polarization plane is perpendicular to the predominant orientation of the filaments, as required by theory.

The remaining problem is to find the source of excitation of the emission lines in the optical spectrum. The observed recombination spectrum resembles that of planetary and gaseous nebulae of low excitation. Forbidden emission lines of N II, S II, and possibly O III are present in addition to the emission lines of hydrogen. The relativistic electrons cannot be the excitation source because they pass through the cold gas with no appreciable interaction. The character of the line spectrum requires that the recombining electrons have average energies of only a few electron volts ($T \simeq 10000°$ K). Consequently, two energy systems coexist in the filaments of M82: a high-energy electron component, giving rise to the synchrotron emission, and the low-energy electrons, which produce the recombination emissions and excitation for the forbidden lines. Following Woltjer's (1958) discussion of a similar situation in the Crab Nebula, we postulate in Section VII that the ionization of the hydrogen is produced by the optical synchrotron radiation below the Lyman limit—a radiation source which substitutes for the more usual hot-star radiation in emission nebulae in our own Galaxy.

The plan of the remainder of this paper is to carry through calculations based on this model so as to estimate the magnitude of the relevant parameters.

V. THE FILAMENTS: ELECTRON DENSITY, MASS, AND KINETIC ENERGY

The electron density in the filaments can be determined by standard methods, once the volume emissivity E is known in absolute units (ergs cm^{-3} sec^{-1}) for any of the Balmer lines. We can determine E from M82, provided that (1) the apparent Hα flux received at the earth (ergs cm^{-2} sec^{-1}) is known, (2) the distance of the galaxy is known, and (3) the volume occupied by the filaments can be estimated. Unfortunately, we have no direct measurement of the apparent Hα flux but have resorted to an estimate of the intensity of the filaments on the Hα interference filter plate relative to the sky brightness at λ 6563, whose absolute surface brightness can be determined approximately. Photoelectric measurement of the sky brightness at λ 6260 A was made by Lynds with the

20-inch reflector at Palomar on a night when the aurora was active, with the result that $S(\lambda\ 6260\ \text{A})_{\text{sky}} = 5.3 \times 10^{-31}$ w m^{-2} cps^{-1} per square second of arc. The absolute calibration of the photometer was made by observing several stars of known apparent magnitude and then using the sun as a standard in the normal way. This flux density can be compared with Allen's tabulation (1955), which gives $S(\lambda\ 6500\ \text{A})_{\text{sky}} = 2.0 \times 10^{-31}$ w m^{-2} cps^{-1} per square second of arc. As a compromise, we adopt the specific sky brightness to be $S(\text{H}\alpha)_{\text{sky}} = 2.5 \times 10^{-31}$ w m^{-2} cps^{-1} per square second of arc.

It is estimated by visual inspection of the Hα plate that the radiation flux in Hα from the entire filament system is equivalent to the flux from the sky over an area of 1.2×10^4 square seconds of arc. The total band width of the Hα interference filter is 80 A to half-power points (or $\Delta\nu = 5.57 \times 10^{12}$ cps), which, after calculation, gives the observed Hα flux density as 1.7×10^{-11} erg cm^{-2} sec^{-1} (or 5.6 Hα photons cm^{-2} sec^{-1}) at the earth's surface. This is admittedly a crude estimate; but, as the electron density varies as the square root of this number, we can obtain the electron density N_e to within a factor of 10 (provided that we know the volume-filling factor) even if the value of $S(\text{H}\alpha)$ is in error by a factor of 100. Such accuracy for N_e is adequate for our purpose. The observed Hα flux requires that the total power radiated by the filaments of M82 in Hα be $4\pi D^2 S(\text{H}\alpha) = 2.0 \times 10^{40}$ ergs sec^{-1} if $D = 9.76 \times 10^{24}$ cm is the distance to M82.

We now require the volume emissivity of the filaments of M82. This quantity can be found, once the geometry of the system has been specified. (In this discussion it should be recognized that, to some extent, the geometry of the system of filaments was implicitly involved in the foregoing estimate of the Hα flux density.) For this it is assumed that the filaments are contained in the volume common to a sphere of radius $R = 1550$ pc (100 seconds of arc) centered on the nucleus of M82 and a cone (extending symmetrically to either side of the nucleus) of apex half-angle 60° whose axis of symmetry coincides with the minor axis of the galaxy. This geometry gives the total volume containing the filaments as $V = 2\pi R^3/3 = 2.29 \times 10^{65}$ cm^3. The Hα emission is not uniformly distributed throughout the volume but is concentrated in the filaments. Inspection of the Hα plate suggests a volume-filling factor of approximately $7^3 = 343$, which is a guess based on our simple geometry and the observed dimensions of the filaments. The volume contained within the filaments is $V_f = V/343 = 6.68 \times 10^{62}$ cm^3. Therefore, the average volume emissivity of the filaments is 3×10^{-23} erg cm^{-3} sec^{-1}.

The well-known theory of the hydrogen recombination spectrum, due principally to Menzel and his co-workers,[2] gives the volume emissivity in Hα as

$$E_{\text{H}\alpha} = \frac{6.54 \times 10^{-19} b_3 g_{32} N_i N_e}{T_e^{3/2}} \exp\left(\frac{1.75 \times 10^4}{T_e}\right) \tag{2}$$

in erg cm^{-3} sec^{-1}, where N_i and N_e are the proton and electron densities in particles per cm^3, T_e is the electron temperature, b_3 measures the departure of the population of the third quantum level from what it would be in thermodynamic equilibrium, and g_{32} is the Gaunt factor which Baker and Menzel (1938) tabulate as 0.757. The quantity b_3 depends on the physical conditions of the radiation field and has a value near 0.1 for a situation where the filaments are optically thick in the Lyman continuum (Baker and Menzel, case B). Adopting $b_3 = 0.1$, $T_e = 10^4$ ° K, and $N_i = N_e$ requires that

$$E_{\text{H}\alpha} = 2.85 \times 10^{-25} N_e^2 \tag{3}$$

in erg cm^{-3} sec^{-1}. Our observed emissivity of 3×10^{-23} erg cm^{-3} sec^{-1} then requires $\langle N_e \rangle = 10.3$ particles per cm^3 for the average density in the filaments.

The total amount of material responsible for the recombination radiation is evidently

[2] Contained in a series of articles in this *Journal* beginning with Vol. **85**.

$\langle N_e \rangle V_f = 7 \times 10^{63}$ protons $= 1.2 \times 10^{40}$ gm or 5.8×10^6 solar masses, which is very high, representing as it does 2×10^{-4} of the total mass of the galaxy.[3]

In computing the kinetic energy of the hydrogen in the filaments, we shall adopt the geometry of the system outlined above. For the distribution of the material in the filaments, we shall consider two cases: (*a*) the electron density in the filaments is a constant for all distances r from the center of M82, $N_e(r) = \langle N_e \rangle$, and (*b*) the electron density is given by

$$N_e(r) = \frac{\langle N_e \rangle}{26}\left(53 - 40\frac{r}{R}\right). \tag{4}$$

For both cases the velocity relation adopted is that determined in Section III, namely,

$$v(r) = \mu r, \tag{5}$$

where $\mu = 2.15 \times 10^{-14}$ cm sec^{-1} cm^{-1}. In addition, the fraction of space occupied by the filaments, $\Lambda(r)$, is assumed to be of the form

$$\Lambda(r) = \frac{\Lambda}{2}\left(5 - 4\frac{r}{R}\right), \tag{6}$$

where Λ is the reciprocal of the volume-filling factor adopted earlier in this section. Equation (6) has the properties that $\Lambda(R) = \Lambda/2$ and that the average value of $\Lambda(r)$ taken over the whole volume of space is equal to Λ, i.e.,

$$\langle \Lambda(r) \rangle = \frac{3}{R^3}\int_0^R \Lambda(r)\, r^2 dr = \Lambda. \tag{7}$$

Equation (4) has the property that $N_e(R) = \langle N_e \rangle/2$ and that the total mass of the system is conserved, that is,

$$2\pi m_{\rm H}\int_0^R \Lambda(r)\, N_e(r)\, r^2 dr = \tfrac{2}{3}\pi R^3 \Lambda \langle N_e \rangle m_{\rm H}. \tag{8}$$

It is obvious that case *a* will exactly reproduce the value of the Hα flux from which the average electron density was originally determined. This is not true for case *b;* a computation of the Hα flux gives a value about 10 per cent too large, indicating that the adopted value of $\langle N_e \rangle$ should be reduced by about 5 per cent to be appropriate for this particular electron-density distribution.

The total kinetic energy of the system of filaments is

$$\epsilon_k = \pi m_{\rm H}\int_0^R \Lambda(r)\, N_e(r)[v(r)]^2 r^2 dr, \tag{9}$$

which, when integrated, gives $\epsilon_k \simeq 2.4 \times 10^{55}$ ergs to within about 20 per cent for both cases *a* and *b*, showing that the kinetic energy is relatively insensitive to the exact distribution of matter within the system. This estimate is an upper limit to ϵ_k because, as previously mentioned, we may have overestimated the total mass of the filaments.

If the magnetic field is assumed to be constant throughout the volume, the total magnetic energy will be

$$\epsilon_M = \tfrac{1}{12}R^3 H^2 = 9.1 \times 10^{63} H^2 \text{ ergs}, \tag{10}$$

[3] It should be pointed out that this may be an upper limit to the mass of the visible matter because the volume-filling factor may be larger than we have estimated. If the angular diameters of the filaments are smaller than they appear on our plates ($\sim 2''$ of arc) due to seeing difficulties, then V_f is decreased, N_e is increased, but the product $V_f N_e$ is decreased by $V_f^{1/2}$, which gives a smaller total mass than computed above. Of course there may be a large additional mass of invisible neutral hydrogen.

where H is the field strength in gauss. For a field strength of 2×10^{-6} gauss, obtained in Section VI, equation (13) gives a magnetic energy of 3.6×10^{52} ergs, which is about three orders of magnitude smaller than the kinetic energy of the moving filaments. This insures that the material ejected from the central region of M82 was sufficiently energetic to carry a substantial magnetic field from the galaxy.

VI. THE SYNCHROTRON RADIATION

The available radio-frequency observations of the M82 radio source are given in Table 2. The first column gives the frequency in kilomegacycles; the second column, the flux density in units of 10^{-26} w m^{-2} cps^{-1}; and the third column is the reference. On the basis of the presence of optical polarization of the filaments found by Elvius and Hall (1962*a*, *b*), we suggest that some or all of the radiation from the filaments, as well as from the background halo recorded on the photovisual plate, arises from the optical synchrotron continuum. We have attempted to estimate this synchrotron flux using the 103*a*-D + GG14 photograph (Fig. 10) in the same way that we previously used for the Hα flux. However, there is a question of the degree to which the discrete emission lines contribute to the photographic image of the filaments on this plate. The emission lines of interest

TABLE 2

RADIO OBSERVATIONS OF M82

Frequency (kMc)	$S(\nu) \times 10^{26}$ (w m^{-2} cps^{-1})	Reference
0 158	12	Brown and Hazard (1953); Edge, Shakeshaft, McAdam, Baldwin, and Archer (1959)
0 71	10 7	California Institute of Technology Radio Observatory, unpublished
0 75	8	Lynds (1961)
1 423	8 6	Goldstein (1962)
3 0	6 15	Lynds (1961)
3 2	6 5	California Institute of Technology Radio Observatory, unpublished

are Hα and N1. The test already described in Section II shows that the 103*a*-D emulsion is down by a factor of 220 relative to the 103*a*-E emulsion at the wavelength of Hα and, therefore, that the effect of Hα radiation on the photovisual plate is negligible. Furthermore, the GG14 filter transmits only 20 per cent of the radiation at the N1 line (determined by measurement of the actual filter used), which suggests, by comparison of the intensities of the emission lines in the spectra of the filaments of M82, that the effect of N1 on the photovisual plate can also be neglected.

The photographic density of the filaments and of the semiuniform halo which fills the conical volume was compared with the density due to the night sky, for which we have adopted a surface brightness of 7×10^{-32} w m^{-2} cps^{-1} per square second of arc. In this manner the flux density of the visual synchrotron emission of the entire source is estimated to be 8.5×10^{-28} w m^{-2} cps^{-1} at the effective wavelength of 5550 A ($\nu = 5.4 \times 10^{14}$ cps).

If we now make the assumption that the flux at radio frequencies is generated in the same volume of M82 as is the optical synchrotron radiation, we can determine the power spectrum of the source over the range $\nu = 1.6 \times 10^{8}$ cps to 5.4×10^{14} cps. The radio-frequency flux densities given in Table 2 and the above estimate of the optical flux density (with an estimated error of ± 1.5 mag.) are plotted in Figure 12. The indicated spectral index is about 0.23, and the cutoff frequency would seem to be between 10^{14} and 10^{15} cps. The three curves represent the theoretical synchrotron spectra having cutoff frequencies of 3×10^{14}, 6×10^{14}, and 10^{15} cps, as determined later in this section.

A general development of the theory of synchrotron radiation has been given in a well-known article by Schwinger (1949). The theory has been put in a form useful for astronomical problems by Oort and Walraven (1956), by Woltjer (1958), and by Burbidge in a series of articles (cf. 1956). The results of interest for us are that an assemblage of electrons with an energy distribution

$$N(E)dE = kE^{-\beta}dE \tag{11}$$

moving in a magnetic field H will radiate at frequency ν with a flux density

$$P(\nu) = 1.171 \times 10^{-22} k L^{(\beta-1)/2} (H \sin \theta)^{(\beta+1)/2} \nu^{-(\beta-1)/2} \times \int_{a_m}^{\infty} a^{(\beta-3)/2} F(a)\, da \text{ erg sec}^{-1} \text{ cps}^{-1}, \tag{12}$$

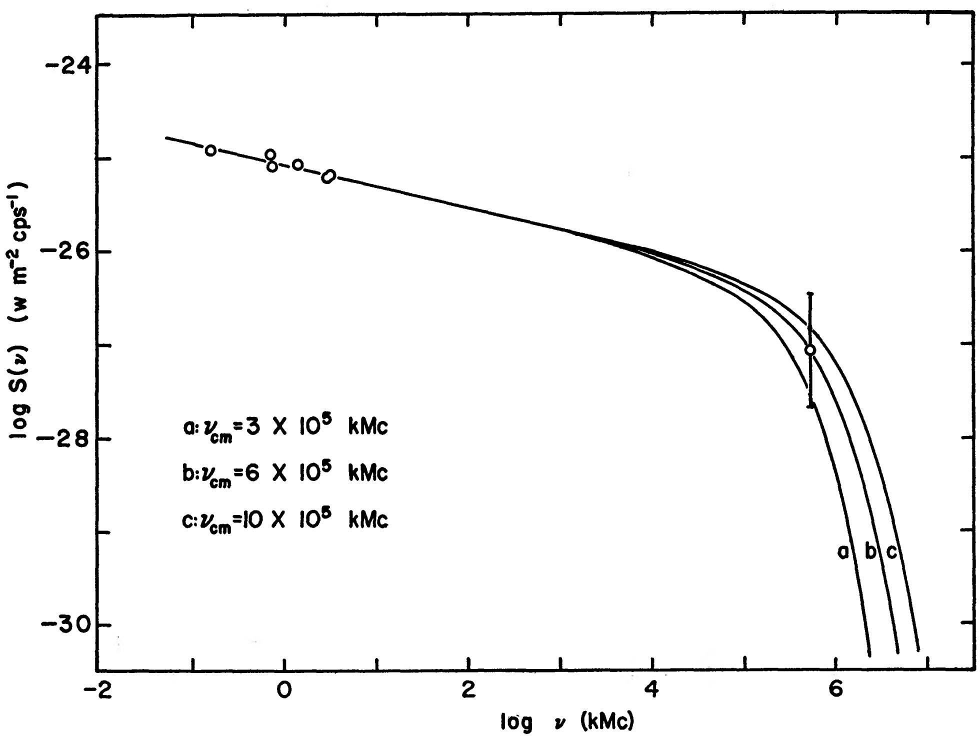

FIG. 12 —The syncrotron spectrum of the M82 filaments. The circles represent the observed spectrum, and the curves give theoretical spectra for different values for the cutoff frequency (the frequency corresponding to the high-energy cutoff of the electron energy distribution).

where $L = 1.608 \times 10^{13}$, θ is the pitch angle of the electron orbits, a_m is the ratio of ν to the frequency radiated by electrons at the high-energy cutoff E_m, and $F(a)$ is a function tabulated by Oort and Walraven (1956) and by others. The high-frequency cutoff is given by

$$\nu_{cm} = LH \sin \theta E_m^2 , \tag{13}$$

where E_m denotes the maximum energy reached by the electron distribution (E_m in 10^9 ev if ν is in cps). In our calculations we have adopted $\langle \sin \theta \rangle = \pi/4$ and $\langle \sin \theta^{(\beta+1)/2} \rangle = \frac{3}{4}$, corresponding to an isotropic velocity distribution and a uniform magnetic field.

From the observed radio-frequency spectral index of 0.23, we deduce from equation (12) that $\beta = 1.46$. Also, from the radio data the flux density at 3 kMc is $S(3 \text{ kMc}) = 6.4 \times 10^{-26}$ w m^{-2} cps^{-1} $= 6.4 \times 10^{-23}$ erg sec^{-1} cm^{-2} cps^{-1}, which gives, for the total power emitted at $\nu = 3$ kMc in a bandwidth of 1 cps,

$$P(3 \text{ kMc}) = 4\pi D^2 S(3 \text{ kMc}) = 7.66 \times 10^{28} \text{ ergs sec}^{-1} \text{ cps}^{-1}, \qquad (14)$$

where we have again adopted a distance modulus for M82 of 27.5. Upon substitution of equation (14) in equation (12), we find that

$$k = 4.0 \times 10^{49} \, H^{-(\beta+1)/2}, \qquad (15)$$

where the integral has been evaluated numerically, using the $F(a)$ tables and the asymptotic form $F(a) = 2.15 \, a^{1/3}$ for $a = \leq 0.001$.

By combining the relation for k (eq. [15]) with equation (12), we have the theoretical synchrotron spectrum,

$$S(\nu) = 3.2 \times 10^{-24} \, \nu^{-0.23} \, G(\nu) \qquad (16)$$

in w m^{-2} cps^{-1}, where

$$G(\nu) = \int_{a_m = \nu/\nu_{\text{cm}}}^{\infty} a^{(\beta-3)/2} F(a) \, da, \qquad (17)$$

which is the function only of ν, once ν_{cm} is specified.

Equations (16) and (17) have been used to compute theoretical spectra for three different assumed values of the high-frequency cutoff ν_{cm}. Equation (17) was integrated numerically over the range of $F(a)$ covered by the tables of Oort and Walraven (1956) and was extended to the limits analytically, using the well-known asymptotic forms of $F(a)$. For small a_m, the analytical extension is trivial. For $a_m > 10$, the asymptotic form of $F(a)$ requires that

$$G(\nu) = 1.26 \int_{a_m = \nu/\nu_{\text{cm}}}^{\infty} a^{-0.27} e^{-a} da \qquad (18)$$

(with $\beta = 1.46$), which can be integrated by parts to give an asymptotic series where only the first term need be kept, giving

$$G(\nu) = 1.26 \left(\frac{\nu}{\nu_{\text{cm}}}\right)^{-0.27} e^{-\nu/\nu_{\text{cm}}}, \qquad \text{for } \frac{\nu}{\nu_{\text{cm}}} > 10. \qquad (19)$$

Three theoretical spectra computed from equation (16) in this manner are shown in Figure 12, where the values of ν_{cm} are 3×10^{14}, 6×10^{14}, and 10^{15} cps. For $\nu < 10^{13}$ cps, a_m is nearly zero, and $G(\nu)$ is a definite integral with effective limits between 0 and ∞ and is therefore a constant. Hence, in this frequency range, the three spectra are nearly identical and follow a power law, as is observed at radio frequencies. However, the differences between the spectra in the optical region are substantial, and the importance of an accurate value of the observed optical flux density is apparent if ν_{cm} is to be well determined. Figure 12 shows that ν_{cm} could be as low as 2×10^{14} cps or as high as 2×10^{15} cps and still fit the one optical observation. We adopt $\nu_{\text{cm}} = 6 \times 10^{14}$ cps in subsequent calculations.

Making use of equation (11) and our determination of k (eq. [15]), we find that the total energy in relativistic electrons is

$$\epsilon_R = k\int_0^{E_m} E N(E)\, dE$$

$$= \frac{4\times 10^{49}}{2-\beta}\left(\frac{4\nu_{\rm cm}}{\pi L}\right)^{(2-\beta)/2} H^{-3/2} \tag{20}$$

$$= 2.1\times 10^{50} H^{-3/2}\ \text{Bev}\ ,$$

$$\epsilon_R = 3.36\times 10^{47} H^{-3/2}\ \text{ergs}\ , \tag{21}$$

where any error introduced by assuming the lower limit of the integral to be zero will be negligible. Although the quantity $\nu_{\rm cm}$ is not well determined, the total energy is seen to be relatively insensitive to its precise value. Even if $\nu_{\rm cm}$ is in error by a factor of 10, the error in ϵ_R will be less than a factor of 2.

In previous considerations of the energy balance in radio sources (see, e.g., Burbidge 1956), it has been customary to introduce here an assumption of equality between the energy stored in the relativistic electrons (eq. [21]) and the energy ϵ_M stored in the magnetic field [eq. [10]). Doing this would give $H = 2 \times 10^{-5}$ gauss for M82, but this leads to some problems in the time scale and the total energy by the following argument. Equation (21) shows that this value of H requires $\epsilon_R = 3.7 \times 10^{54}$ ergs for the energy now stored in the electrons, which should be compared with the total energy radiated by the synchroton process in the past 1.5×10^6 years. Integration of the power spectrum of equation (16) over the entire frequency range from 10^8 cps to 6×10^{14} cps gives 1.64×10^{-9} erg cm^{-2} sec^{-1} for the apparent synchrotron flux. Multiplication by $4\pi D^2$ and by the time of 1.5×10^6 years gives 9×10^{55} ergs radiated in the lifetime of the M82 source, a number which is large compared with the 3.7×10^{54} ergs now stored in the electron reservoir. Therefore, electrons would have to be continuously injected into the system from an unseen energy reservoir to maintain the present rate of radiation for 1.5×10^6 years. And it would appear that a Fermi-type acceleration mechanism which transfers part of the energy contained in the magnetic field to the particles cannot be the replenishment source because, on the foregoing assumptions, the total energy in the field is only 3.7×10^{54} ergs, which is small compared with the 9×10^{55} ergs required. Therefore, the field cannot be pumped for 9×10^{55} ergs unless the field itself is periodically regenerated.

The need for continuous injection of high-energy electrons can be seen in another way by considering the time for the optical electrons to lose one-half of their initial energy, which is

$$T_{1/2} = \frac{8.35\times 10^{-3}}{(H\sin\theta)^2 E_0}\ \text{years}\,. \tag{22}$$

This gives $T_{1/2}(\text{optical}) = 2.5 \times 10^4$ years (using $E_0 = 1.5 \times 10^3$ Bev obtained from eq. [13] with $\nu_{\rm cm} = 6 \times 10^{14}$ cps and $H = 2 \times 10^{-5}$ gauss). This time is much smaller than the lifetime of radio M82.

Following Burbidge (1956), we had originally supposed that the unseen energy reservoir might be high-energy protons which collided with the quiescent cool protons in the filaments, producing mesons which would subsequently decay into the required electrons. Burbidge (1956) estimates that 10 per cent of the collision energy of the bombarding protons finally appears in the relativistic electron gas. This means that, if each bombarding proton were to make one collision in the lifetime of the system, at least 9×10^{56} ergs must reside in the high-energy protons. But the probability of a single bombarding proton colliding with the quiescent hydrogen in the halo and the filaments in time t is not 1.0 but $c\sigma Nt$, where σ is the collision cross-section ($\simeq 4 \times 10^{-26}$ cm^2/proton), c is the velocity of light, and N is the number of target protons per cm^3. Spitzer has pointed out to us that the high energy protons, if they exist, cannot be confined in the filaments because their energy density is much higher than the magnetic-field energy density; hence N must be much smaller than 10, which applied only in the filaments. Even if we take the average density over the halo to be as high as 0.1, the number of collisions per bombarding proton in 1.5×10^6 years will be 6×10^{-3}, and the energy store in these protons must then be $9 \times 10^{56}/6 \times 10^{-3} = 1.5 \times 10^{59}$ ergs, which is very high. Consequently, unless the total energy of the system is as high as 10^{59} ergs, the assumption of equipartition between ϵ_R and ϵ_M may not apply to M82.

Spitzer has suggested that a way to reduce the total energy of the problem is to require that ϵ_R be equal to, or greater than, the energy radiated over the lifetime of the M82 radio source. This assumption is equivalent to saying that the energy put initially into the electron gas was high enough to maintain the observed radiation for at least 1.5×10^6 years. Equation (21) then requires that $3.36 \times 10^{47}\ H^{-3/2} > 9 \times 10^{55}$ ergs, which gives $H < 2.5 \times 10^{-6}$ gauss. We have adopted this point of view, which eliminates the necessity of a continuous injection or reacceleration of electrons to maintain the observed synchrotron flux. We then require that the initial "explosion" put at least $\sim 10^{56}$ ergs into the high energy electrons. But we wish to emphasize that we have discussed only two of the many possibilities of the energetics of the system. Until we have an independent way of estimating H, the problem has no unique solution, although it may be fair to say that the total energy must be at least as high as 10^{56} ergs and is probably less than 10^{60} ergs.

As in other radio source problems, these energy levels are extremely high. An energy of 10^{56} ergs is equivalent to the total emission of about 10^6 supernovae. This result seems inescapable. We observe radio emission from an expanding filament system whose expansion time is 1.5×10^6 years, and this requires that at least 10^{56} ergs have been emitted if the synchrotron emission extends into the optical region. Arguments in the next section, which are in addition to those already given, suggest that the electron radiation probably does extend below the Lyman limit and, therefore, that these minimum power levels obtain.

The nature of the initial explosion in the central regions of M82 is an enigma. But M82 may be the first recognized case of a high energy explosion originating in the central regions of a galaxy, and as such may provide features required for a general explanation of many extragalactic radio sources. In passing, it is interesting to note that Hoyle and Fowler (1963) have recently postulated an explosion mechanism involving the gravitational collapse of a massive ensemble of gas which can generate as much as 10^{62} ergs. Also, Ambartsumian (1961) for many years has considered similar problems concerned with energies in the nuclei of galaxies.

VII. EXCITATION OF THE EMISSION LINES

The problem of the radiation source for the low excitation emission lines observed in the filaments was outlined in Section IV. Some source other than stellar must be found because of the lack of any evidence for stars in the halo of M82. Furthermore, the high energy particles can play no direct role in the problem. Following Woltjer's discussion (1958) of the Crab Nebula, we have calculated the number N_L of photons below the Lyman limit for two of the theoretical synchrotron spectra of Figure 12. If the optical synchrotron radiation below the Lyman limit is the ionization source for the hydrogen recombination spectrum, then N_L must be about 3.3 times larger than the number of Hα photons emitted (see, e.g., Zanstra 1961), provided that the filaments are optically thick to Lyman continuum radiation.

One can determine N_L by dividing equation (16) by $h\nu$ and integrating over all $\nu > 3.29 \times 10^{15}$ cps ($\lambda = 912$ A). For values of ν_{cm} in the optical region, the main contribution from $F(\alpha)$ (in eq. [17]) occurs within the range of the $F(\alpha)$ tables, and numerical techniques yield a good determination of N_L. The resultant photon flux at the earth is 0.09 photon cm^{-2} sec^{-1} for $\nu_{cm} = 6 \times 10^{14}$ cps and 1.2 photons cm^{-2} sec^{-1} for $\nu_{cm} = 10^{15}$

cps. These values correspond to the upper two spectra represented in Figure 12. N_L is evidently extremely sensitive to ν_{cm}. We estimated in Section V that the observed Hα photon flux from M82 was 5.6 photons cm^{-2} sec^{-1}, with a possible error of a factor of 10–100. Adopting this estimate as correct requires N_L to be approximately 18 for the excitation mechanism to work, a condition not met even for $\nu_{cm} = 10^{15}$ cps. There are two ways out of the difficulty: (1) the estimated Hα flux must be reduced by a factor of about 16, in which case our calculated electron density of the filaments would be decreased by a factor of 4, decreasing in like fashion the mass and the kinetic energy in the filaments; or (2), the value of ν_{cm} must be put to about 2×10^{15} cps ($N_L = 12$ photons cm^{-2} sec^{-1}), which is quite possible if our estimate of the synchroton flux at λ 5550 A is only a little too low. Obviously, the problem cannot be solved without accurate photometric measurements of the Hα and optical continuum flux from the filaments, but we can conclude that, to within the accuracy of our present data, the far ultraviolet synchrotron emission could be the excitation mechanism producing the low-energy recombination spectrum observed in the filaments.

VIII. CONCLUSIONS

In conclusion, it may be well to summarize our tentative knowledge of M82 and point out certain striking similarities between phenomena observed in the filaments of M82 and those observed in the Crab Nebula. First of all, the radio-frequency spectra of M82 and the Crab Nebula are very similar and are among the "flattest" known. Both objects show a strong optical emission-line spectrum, requiring a source of excitation other than that which is normally provided by ultraviolet stellar radiation. In both the Crab Nebula and M82 we find a filamentary structure emitting polarized continuum radiation with electric vector orientations roughly perpendicular to the filament orientations. Expansion velocities of about 1000 km/sec are indicated in both systems.

We have proposed that approximately 1.5 million years ago there took place an extremely energetic expulsion of material from the central regions of M82. The expulsion was confined to regions near the minor axis of the galaxy, because of pressure in the disk, and was sufficiently energetic to dominate the magnetic field existing in the disk of the galaxy. By some unknown mechanism, relativistic electrons reaching energies of about 5×10^{12} ev were created in the "explosion," and these have radiated radio and optical noise by the synchrotron process for the lifetime of the system. If the magnetic field is lower than 2×10^{-6} gauss, the decay time for the most energetic electrons is longer than the lifetime, and no replenishment is necessary. Calculations indicate that it may be possible to account for the excitation of the observed optical emission lines by means of the synchrotron radiation shortward of the Lyman limit.

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