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Evidence for the Occurrence of Violent Events in the Nuclei of Galaxies

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I. INTRODUCTION

IT is generally believed that the vast majority of galaxies are massive condensations of matter which reached equilibrium configurations billions of years ago and have essentially remained unchanged ever since. Since they are in equilibrium under gravitational forces (magnetic forces are undoubtedly negligible in the bulk of the matter, which is condensed into stars), no significant departures from this equilibrium can be expected as the galaxy evolves in time, unless gravitational forces comparable in magnitude to the forces exerted in the gravitational potential of the galaxy are encountered. The only situation in which such effects will occur is when galaxies collide, and the most probable place of occurrence of collisions is in clusters.

It is therefore self-evident that unless outside influences come into play, once the equilibrium configuration is reached the distributions of mass and angular momentum do not change in a galaxy in its life history. On the other hand, the form and the distribution of gas and dust in a galaxy may change drastically through the processes of stellar evolution, and through the differential galactic rotation. Since in spiral and irregular galaxies the gas and dust are a very conspicuous feature and play an important role in the classification scheme, it is possible that the outward appearances of galaxies may change drastically as a function of time. Spiral structure is a most important example of this. While the problem of the persistence of spiral structure remains unsolved, the characteristic time scale that must be associated with changes in this structure is the period of rotation at different distances from the center. A reasonable average value for this time is 10^8 yr.

Until recently this time scale has been the shortest which has been thought to be associated with galaxies taken as a whole, as far as structural changes or changes in rate of evolution or energy output are concerned. It is our purpose in this paper to describe a number of phenomena, all associated with the nuclei of galaxies, which may suggest that in these nuclei there may take place violent events manifested by a very large energy output and a time scale as short as 10^6 yr.

Some account of the phenomena described has been given previously in the literature, but we have considered it worthwhile to review all the evidence together.

II. OPTICAL DATA

(1) Nuclei of Seyfert Galaxies

There are nine known galaxies which have nuclei satisfying the following criteria [eight of the twelve originally listed by Seyfert (1943), and a further system described by Burbidge and Burbidge (1962a)]:

(i) They have small, very bright nuclei.

(ii) The spectra of the nuclei may contain emission features not normally seen in the spectra of galaxies, indicating higher excitation than that required to produce [O III] and [Ne III].

(iii) The emission features, or at least the hydrogen emission lines, must be of great width, which if interpreted as Doppler motions, correspond to velocities in the range ±500 to ±4250 km/sec, according to Seyfert (1943).

It is this last criterion which puts these galaxies in a class by themselves.

Since Seyfert's investigation of NGC 1068, 1275, 3516, 4051, 4151, and 7469, further studies using nebular spectrographs and direct photography have been made of NGC 1068, 7469, 1275, 4051 and 4151 (Burbidge, Burbidge, and Prendergast 1959, 1963; Minkowski 1957; Baade and Minkowski, see Woltjer 1959). NGC 1068 is shown in Fig. 1. Investigations of NGC 1275 and NGC 3227 are being made by the authors. If we consider now a composite of all of these investigations the following preliminary model emerges.

The Nucleus

A Seyfert galaxy has a very small bright nucleus in which high-excitation features are seen. Attempts to measure the diameter of the nucleus in, e.g., NGC 4151 show that its size on the photographic plate is set by the seeing. Figure 2 shows a short exposure of NGC 4151 showing the telescope diffraction pattern produced by the nucleus. The true diameter is $< \frac{1}{2}''$ corresponding at a distance of 10 Mpc to < 25 pc. The widths of the emission features, particularly the Balmer series, correspond to Doppler motions in the range given by Seyfert, which we will take to be of the order of 1000–3000 km/sec. These widths are difficult to determine with precision but there is no doubt that the range quoted by Seyfert is approximately correct. However, in all cases the width of the hydrogen lines is significantly greater than the width of the other features, particularly in NGC 3516. In two cases, NGC 4151 and 1068, the nuclei have been observed at larger scale and higher dispersion than that used in normal nebular investigations. This work has been carried out on NGC 4151 by Wilson (1956), on NGC 1068 by Walker (1962), and on both galaxies by Sargent (1963). These results show that there is a very considerable amount of structure in the broad emission bands, showing that the emitting region consists of separate cloud complexes moving about in a disordered fashion with velocities of the order of 1000 km/sec or more with respect to each other. A possible explanation of the broader features which are seen in the hydrogen emission lines is that an outer shell of gas at lower density is expanding outward at somewhat higher velocities than the velocities in the disordered motions of the separate cloud complexes. In any case, the structure in the broadened lines, and the greater widths of the hydrogen lines compared with the other emission lines,

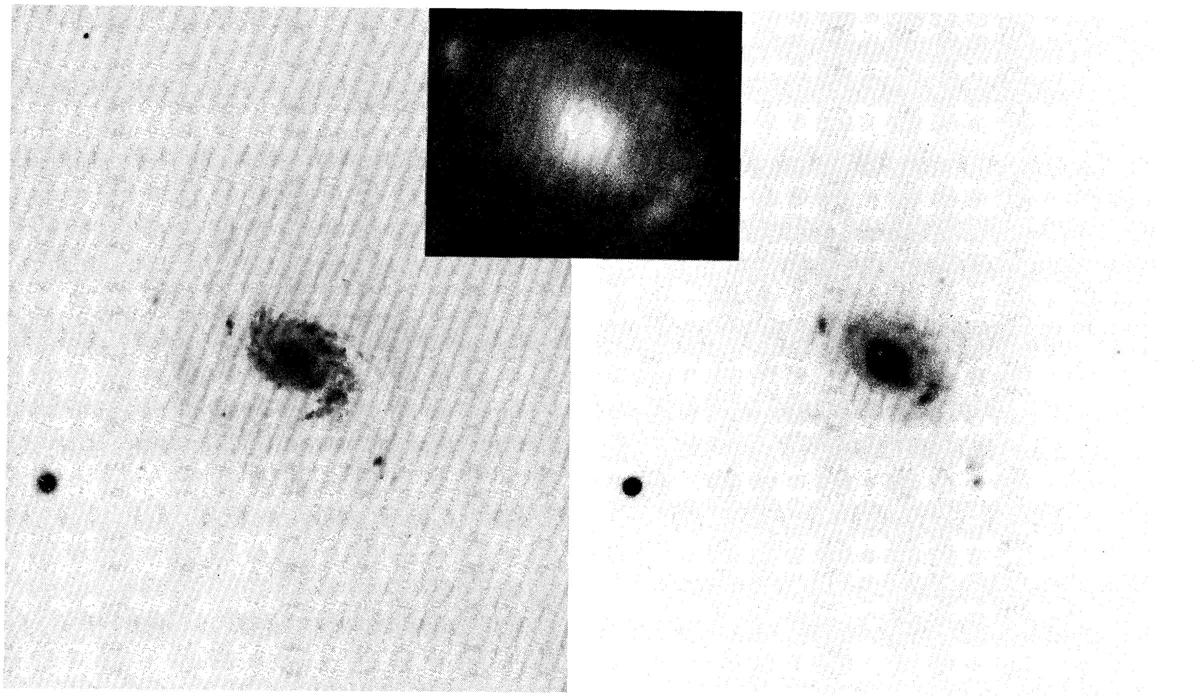

FIG. 1. NGC 1068. The inner parts of this Seyfert galaxy have an abnormally high surface brightness. The nucleus itself, burned out in these photographs, is exceedingly small and bright. The left photograph, taken with the 200-in. telescope, is a 1-min exposure on a 103*a*–O plate behind a GG 13 filter. The right photograph is a 30-min exposure on a 103*a*–E plate behind an Hα interference filter of 80 Å total half-width. The insert is an enlarged portion of the Hα plate. There is some suggestion of an Hα filament coming from the central region.

all strongly support the idea that the broadening seen is Doppler broadening.

Conditions Outside the Nuclei

In the cases of NGC 1068, 7469, 3227, and 1275, spectra taken in good seeing show that, immediately outside the regions where the broad emissions are seen, only the emission lines characteristic of more quiescent ionized gas are seen, i.e., Hα, [N II] λ6583, and [O II] λ3727. These features are narrow and tilted. While there are some deviations from symmetry in these cases, and these may well be due to the gas moving in noncircular motions in the nuclei, for NGC 1068 and 7469, the systems studied in the most detail so far, it appears that the inclinations of these narrow emission components are predominantly due to the rotations of the galaxies. They appear to be consistent with the normal rotation curves for spiral galaxies in as far as they have been observed (measurements have been made out as far as 3.5 kpc from the nucleus in the case of NGC 7469). It is possible, however, that this simple explanation does not hold for NGC 1275. The masses that are derived for these inner parts based on the rudimentary rotation curves are of the order of several times $10^{10} M_{\odot}$. It seems clear therefore that the disordered motions seen in the nuclear regions are far in excess of the escape velocities in the centers. A photograph of NGC 1068 taken through an Hα filter shows a curious double flare coming from one side of the nucleus (Fig. 1), which may represent the escape of gas from the nuclear region.

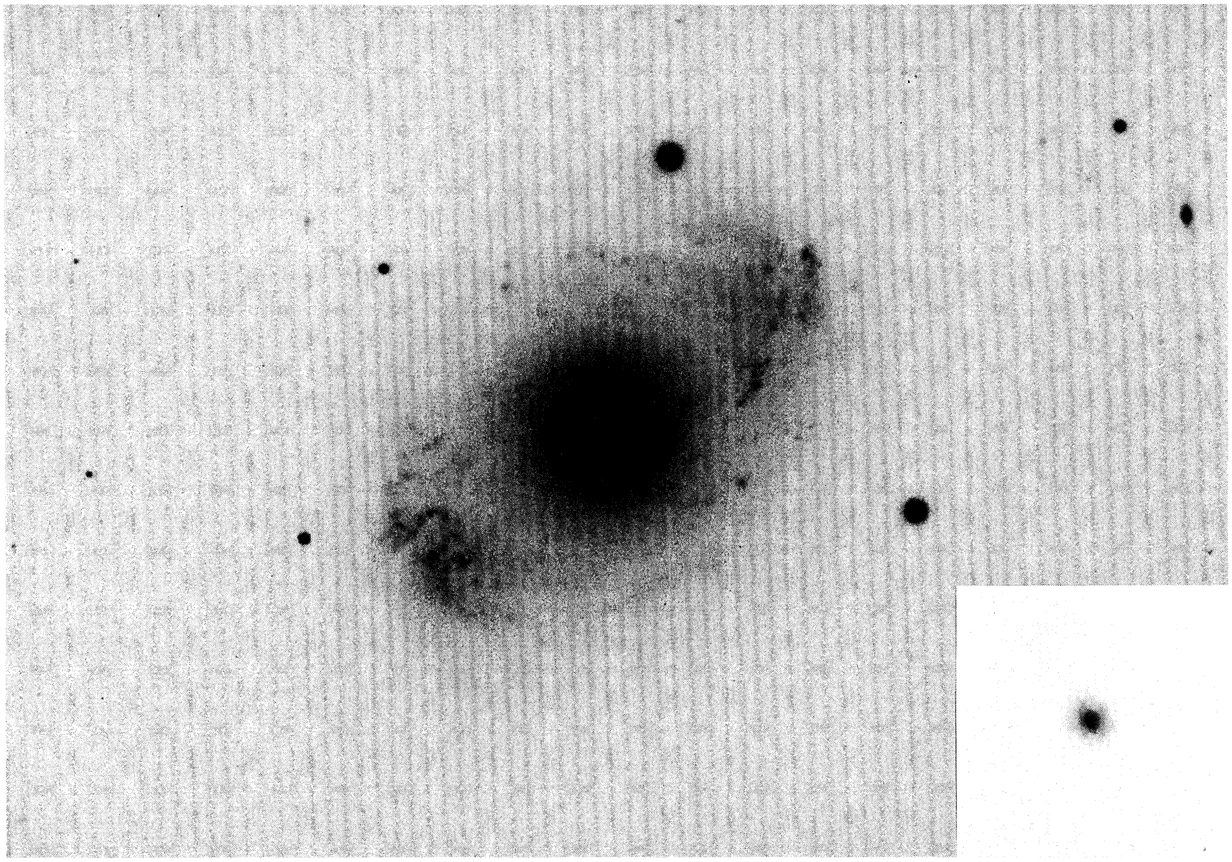

FIG. 2. The Seyfert galaxy NGC 4151 from a 30-min 200-inch photograph taken on 103*a*–O emulsion behind a GG 13 filter. Very faint outer arms exist. They are not visible on this reproduction, but can be seen on the Palomar Sky Survey prints. The nucleus appears stellar on visual inspection in the telescope. Short-exposure photographs show diffraction spikes on the nuclear image, which shows that the nucleus is of very small angular size. The insert is greatly enlarged from a short-exposure blue plate taken with the 100-inch, where the diffraction spikes are easily seen on the original.

NGC 1068 and 7469 both have outer rings of low luminosity with diameters of the order of 30 kpc. NGC 4151 also has faint outer spiral arms, with a pitch different from that of the inner arms, and NGC 3227 has two broad rather smooth outer structures; these may be seen in Fig. 3.

NGC 1275 is still being studied, and discussion of it is more tentative. Figures 4 and 5 show various features of this galaxy, including many small patches of luminosity surrounding it which appear to be connected with it, and radially directed streaks which show strongest on the photograph taken in mainly Hα light. However, the nucleus of this galaxy shows the Seyfert characteristics, and immediately outside this region narrow tilted lines are seen. This galaxy was first investigated by Minkowski (1959). He showed that an outer mass of gas is present whose spectrum has a separate and discrete set of emission lines, indicating a velocity of 3000 km/sec with respect to the nucleus. This result has been confirmed by spectra obtained more recently. Since NGC 1275 is in the center of the Perseus cluster of galaxies, Minkowski's argument that this should be interpreted as a collision between two galaxies is still, on the basis of the spectroscopic evidence, an entirely reasonable one, and cannot be directly discounted. However, the background to the interpretation at the time it was made was that strong radio sources were produced by collisions between galaxies, and of course, NGC 1275 is such a strong source. It appears now that the concept of collisions being responsible for radio sources must be abandoned (for a summary of the reasons for this see, for example, Burbidge 1961). Consequently, if we continue to argue that NGC 1275 is a collision on the basis of the spectroscopic evidence, then we have to suppose that in this galaxy an event has taken place which has led it to become a strong radio source, while at the same time it is by chance in collision with another system. The alternative explanation is that the material which is seen to have a velocity of 3000 km/sec with respect to the nucleus of NGC 1275 has been driven out of the central part of this galaxy. This material is present in a broad structure extending over a distance of the order of 10–20 kpc from the center.

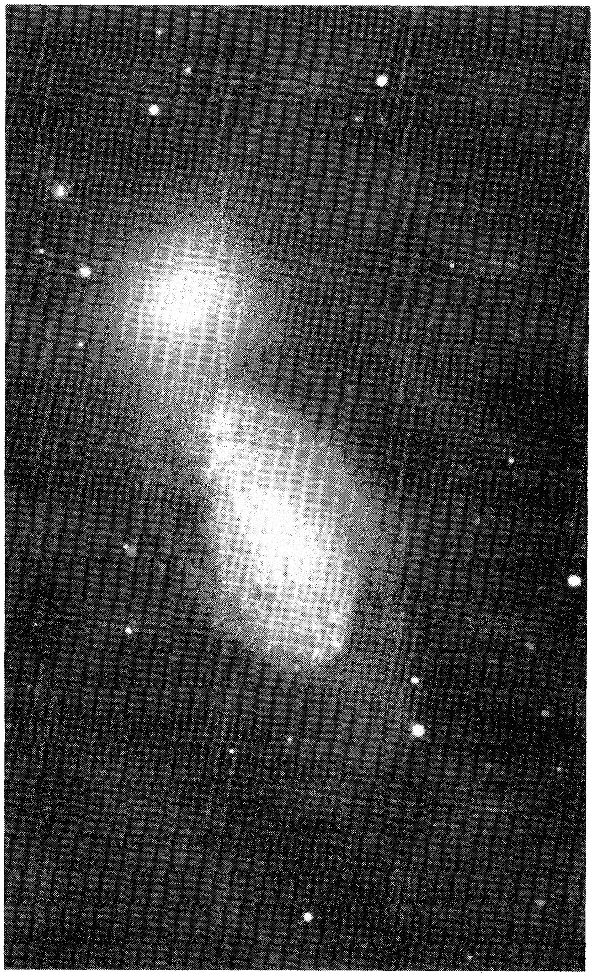

FIG. 3. NGC 3226–3227. Taken on a 103a–O plate with the 82-inch McDonald telescope. The spiral NGC 3227 has a bright nucleus and broad emission lines characteristic of the Seyfert galaxies. Very faint outer structure, like an incompleted ring, are easily seen on the original plate. Similar structures are known to exist in the other Seyfert galaxies NGC 1068, 4151, and 7489.

(2) M82

This system is the well-known irregular galaxy in the M81 group. A description has been given by Sandage (1961) and its rotation has been measured by Mayall (1960). The galaxy, which is elongated, shows a considerable amount of filamentary structure outside the main body, particularly in the region of the minor axis. A major development has been the investigation by Lynds and Sandage (1963) in which Hα filter photography shows a tremendous flux of emission in the central region with limited extensions in the direction of the major axis and long filaments of emission in the direction of the minor axis above and below the main body of the galaxy. Figures 6, 7, and 8 show that these filaments are emitting mainly in the Hα line. These filaments extend to distances of the order of 3–4 kpc above and below the main body of the galaxy. Spectra taken with the slit aligned along the minor axis show tilted Hα, and this indicates that material is either being ejected or is falling in along the minor axis. Sandage and Lynds have concluded from their study of the orientation of the galaxy that the observations are best interpreted by supposing that material is streaming out from the center in the direction of the minor axis. Making very approximate estimates to correct for projection they have concluded that the velocity at which the material is moving outward is about 1000 km/sec.

(3) NGC 5128

This galaxy consists of a large elliptical component with a broad band containing gas and dust lying across its equatorial region. Spectroscopic observations along this band (Burbidge and Burbidge 1959) show that it is rotating, and the rotation curve is roughly linear, with a total velocity difference from one edge to the other of about 600 km/sec. Only the emission features characteristic of normal ionized hydrogen regions are seen. Observations of the stellar content of the system above and below the dark lane (Burbidge and Burbidge 1962b) show that this also is rotating, but more slowly than the belt of gas and dust. The observations appear to be best interpreted by supposing that the dust and gas lie in a ring which is rotating outside the main body of the galaxy.

(4) M87

The characteristics of this giant elliptical galaxy are well known. The jet, which is due to synchrotron emission, appears to emanate from the nucleus. Figure 9 shows the jet as it appears in a rather short exposure. The energetics of this will be discussed later. That ionized gas is also present in the nucleus is clear from the presence of a strong [O II] λ3727 line (Osterbrock 1960). In contrast to many ellipticals in which this line indicates that a small amount of ionized gas is present, the line here is strong and the profile is asymmetrical and may be called double with a difference in velocity (apart from the broadening

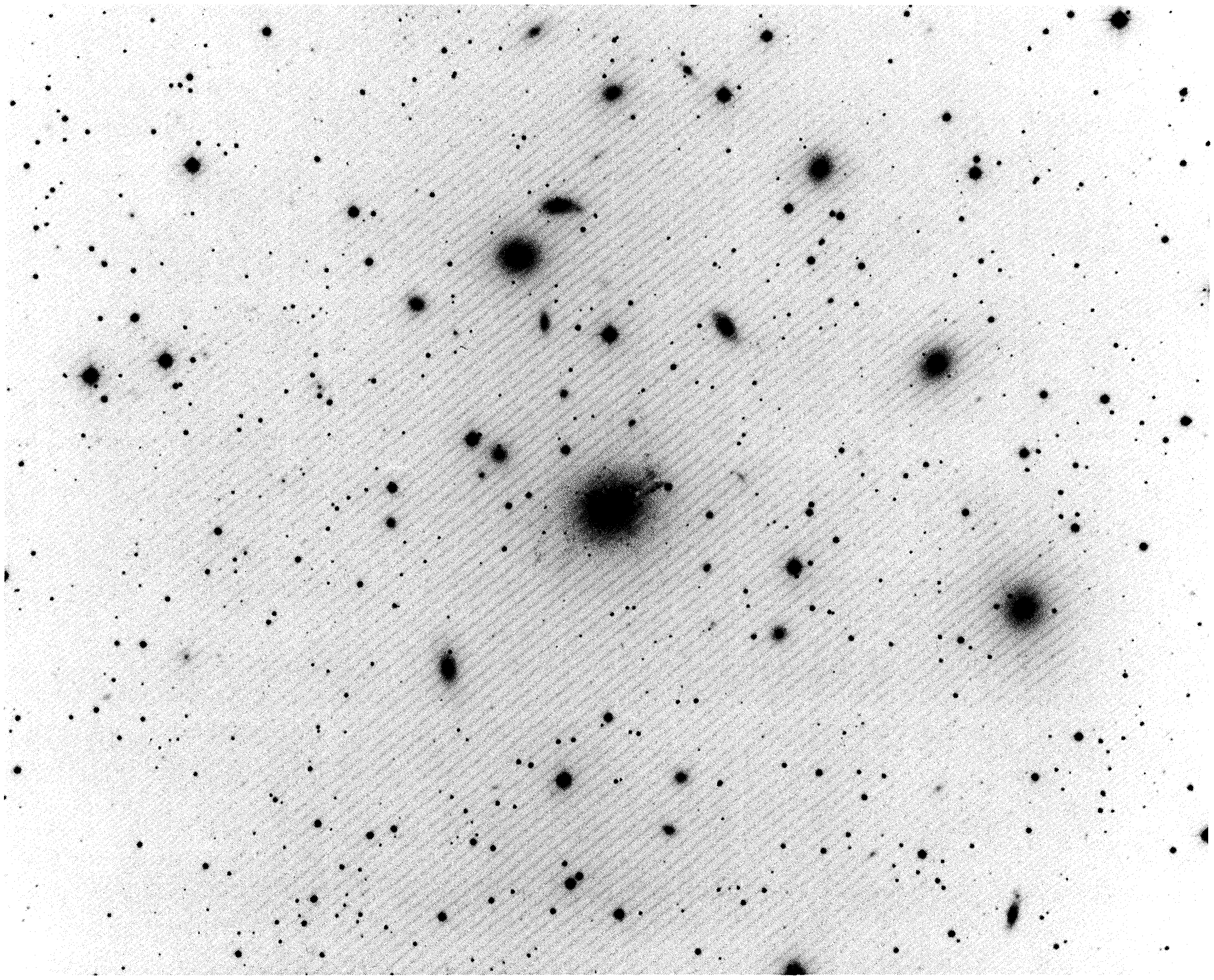

FIG. 4. NGC 1275 and surrounding galaxies in the Perseus cluster, from a 103a–O plate taken by Humason with the 200-inch telescope, showing the extensive system of filaments.

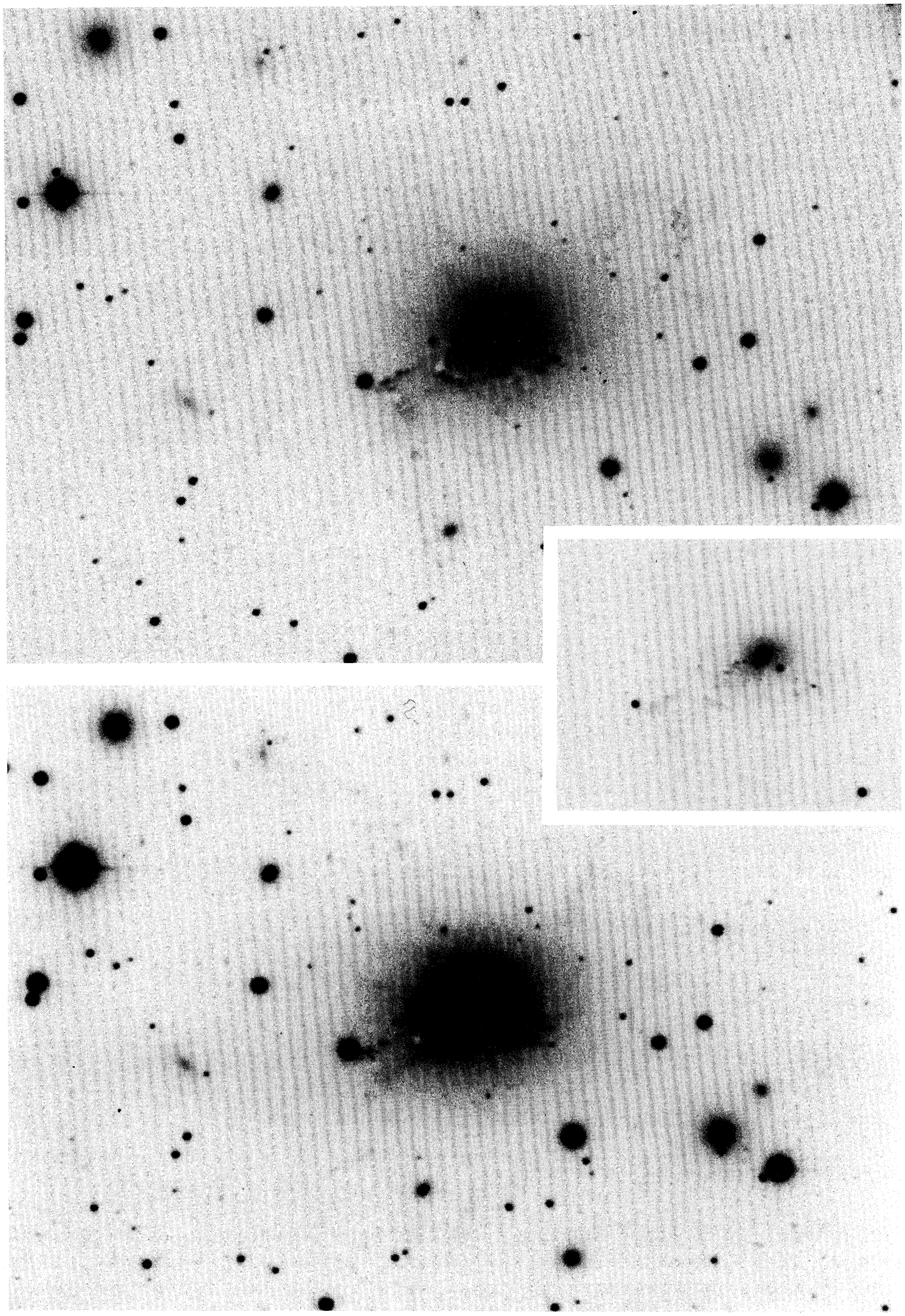

FIG. 5. NGC 1275 photographed in three different wavelengths. The upper is from Humason's 30-min 103a–O plate (λ3500–4800 Å); the bottom is from a 180-min exposure taken on a 103a–F plate behind an RG 1 filter (λ6000–6800 Å); the insert is a short exposure of the nucleus taken in the ultraviolet from a 100-inch plate by Baade (λ3300–3900 Å). The filamentary structure visible on both the blue and Hα plates extends to about 80 sec of arc on either side of the nucleus, which corresponds to about 30 kpc linear dimension (based on $H = 75$ km/sec 10^6 pc).

indicating random motions which are comparable with those of the stars) of about 900 km/sec. Osterbrock has considered that this may be associated with the radio source and optical jet centered on M87. One component gives a recession velocity corresponding to the value for the stars of the galaxy, while the other is shifted to the violet by 900 km/sec. This may indicate that gas is moving outward from the nucleus with this high velocity. However, the velocity of escape from this massive galaxy is comparable with this value. Consequently gas which is moving outward in this way may not be able to escape.

A remarkable feature of M87 is the very large number of globular clusters associated with it, greatly exceeding the number associated with any other galaxy in the Virgo cluster. We may wonder whether these are in any way connected with the fact that this is a radio galaxy; judging by the radio brightness distribution, discussed in Sec. III (4) it may indeed be a recurrent radio source. We return to this point later.

All of the systems we have described so far are galaxies with redshift velocities at maximum of about 5000 km/sec (for NGC 1275 and NGC 7469). Consequently they are sufficiently big and bright so that studies of their optical characteristics in different parts can be made without too much difficulty. Apart from the Seyfert galaxies these systems have become of especial interest because they were identified as galaxies which are associated with strong radio sources. Consequently these are not necessarily all of the bright galaxies in which such circumstantial evidence for nuclear activity exists, although it is probable that the survey of Seyfert galaxies is fairly complete out to distances corresponding to redshifts of 5000 km/sec.

The radio sources associated with some of these galaxies are discussed in the following section. In this discussion of the optical data we wish now to

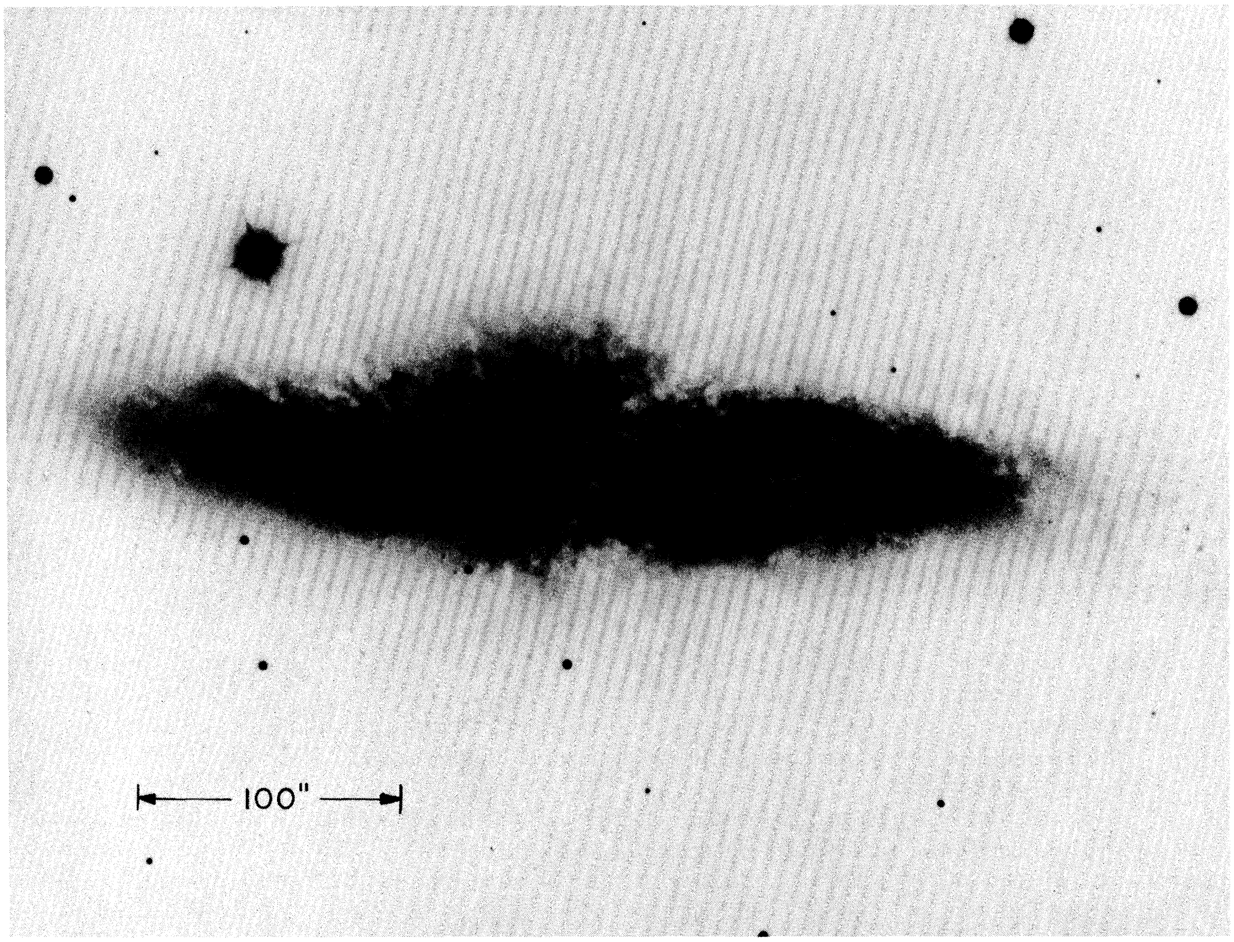

FIG. 6. M82 from a 30-min 103a–O plate behind a GG 13 filter with the 200-inch telescope (from Lynds and Sandage 1963).

turn to the optical characteristics of distant galaxies identified with strong radio sources.

(5) Cygnus A, 3C 295, and Other Faint Radio Source Galaxies

In 1953, Baade and Minkowski (1954) identified an extragalactic object associated with the very strong radio source Cygnus A. This system has a recession velocity of +16830 km/sec, and an apparent magnitude (uncorrected) m_{pg} of + 17.90 (m_{pv} = 16.22, *C.I.* = +1.68). There is undoubtedly a considerable amount of galactic absorption and reddening. Baade and Minkowski assumed $2^{m}.1$ of photographic absorption. With allowance for the diaphragm used not admitting all the light from the galaxy, their estimated corrected value was m_{pg} = 15.05. The spectrum shows strong emission lines due to Hα, [O I], [O II], [O III], [N II], [Ne III], and [Ne V]. As Baade and Minkowski pointed out, this spectrum, as far as these features are concerned, resembles the spectra of Seyfert nuclei. In this respect it satisfies criterion (ii) given in the discussion of these objects. About 50% of the total luminosity of the galaxy is emitted in the emission lines. In two other respects this system differs from the Seyfert galaxies. First, the emission lines do not have great broadening, and second, the emission comes from a much more extended region than is the case in the Seyfert nuclei. With a value for the Hubble constant of 75 km/sec/Mpc (Sandage 1958) the extent of the strong emitting region is about 6 kpc. Although the continuous spectrum may be due to stars, no absorption features have so far been identified in this spectrum [more recently, further spectra of Cygnus A have been obtained by Herbig and Schmidt (private communication)]. Consequently the character of the underlying stars in the system is unknown.

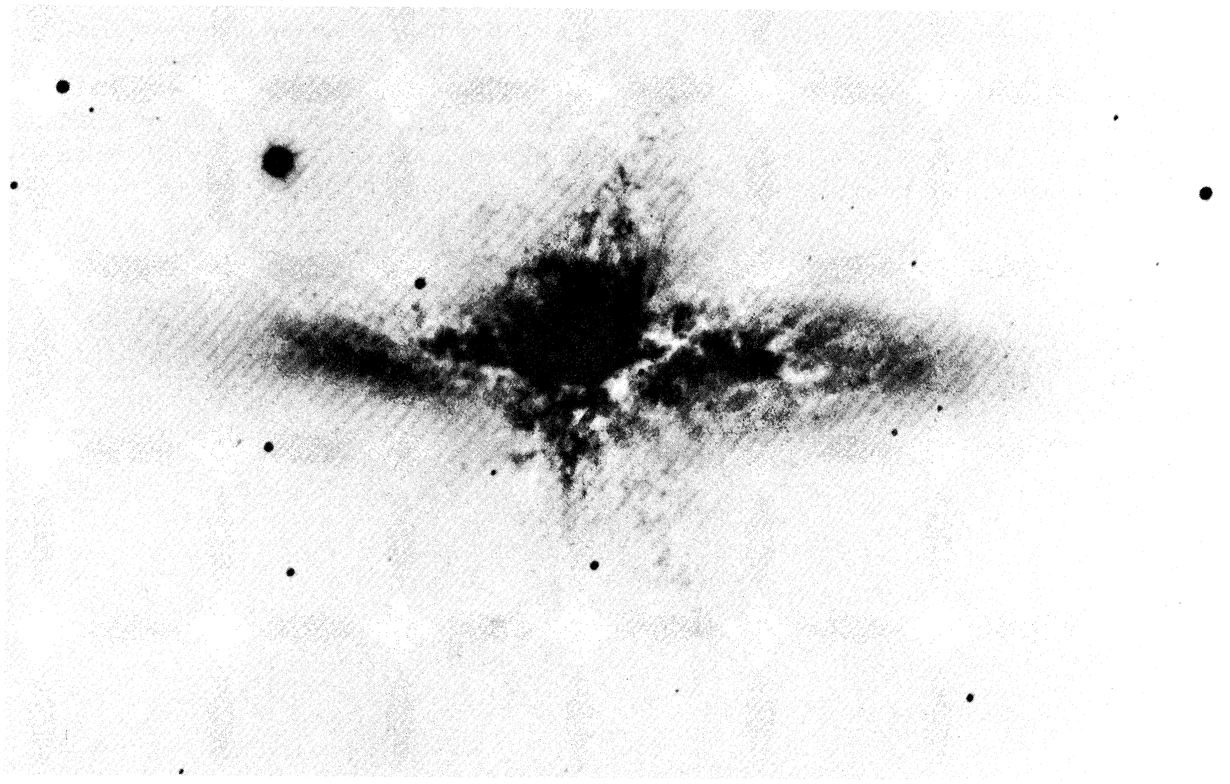

FIG. 7. M82 from a 180-min exposure taken on a 103a–E plate behind an 80 Å total half-width Hα interference filter, showing the massive Hα filamentary structure on both sides of the fundamental plane (from Lynds and Sandage 1963).

The determination of more precise radio source positions has led recently to the identification of a number of very faint galaxies associated with these sources. Minkowski (1960) identified the source 3C 295 with a system with a redshift z = 0.46 on the basis of a single emission line at λ5448 which appears to be [O II] λ3727. Recently Schmidt (1962a) has obtained spectra of a number of galaxies which have been identified as sources of radio emission. A number of these show very strong emission lines similar to those observed in the spectrum of Cygnus A and the Seyfert galaxies. Since these galaxies are very faint and small in angular size, very little is known about them other than these indications from the spectra that there is a large mass of highly excited gas present. In the case of Cygnus A, the energy output in the emission lines is of the order of 10^{44} erg/sec.

We have described so far galaxies which show either evidence for peculiar conditions in the nuclei from optical investigations alone, or peculiarities both from the optical and spectroscopic standpoints and which also are radio emitters. However, there is one final group of galaxies which have been identified as being associated with strong sources of radio emission, but which have no spectral peculiarities, and whose systemic optical peculiarities, if present, are concerned with the density distribution of the stars or with the presence of dust. We mention a few of these in the next subheading.

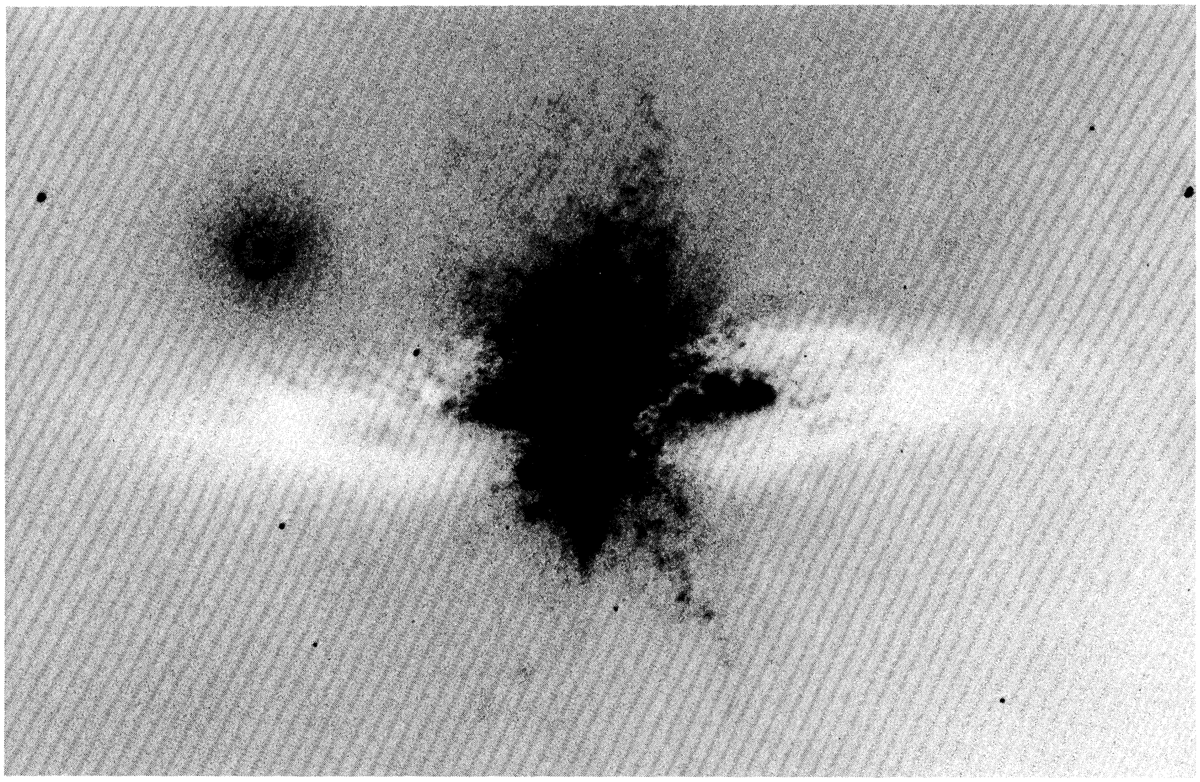

FIG. 8. Photographic "subtraction" of a yellow plate (103a–D + GG 11) of M82 from the Hα plate of Fig. 7, showing that the Hα emission region is confined predominantly to the minor axis of the galaxy.

(6) Other Single, Double, and Multiple E or S0 Systems

NGC 4782–83 (3C 278) is a pair of elliptical galaxies with a recession velocity of +4300 km/sec. Spectra were obtained by Page (1952) and Greenstein (1961). These show only the absorption features seen in normal elliptical galaxies and no emission lines. The degree of central concentration of the stars is greater in one component than in the other, and the outer isophotes of both are not symmetrical about the line joining their centers.

NGC 7236–37 (3C 442) is another pair of elliptical of S0 galaxies for which spectra have been obtained by Greenstein (1962). Apart from a weak [O II] λ3727 line seen in NGC 7237, only the absorption features of normal elliptical galaxies are seen. The recession velocity is +8100 km/sec. Again, the degree of concentration of luminosity is different in the nuclei of the two components.

NGC 545–547 is another double elliptical system and a radio source has been identified with it. No abnormal features are seen in the spectra.

NGC 6166 (3C 338) is a multiple elliptical system lying in a cluster of galaxies. No abnormal emission features are seen in the spectra of the three components. However, [O II] λ3727 is seen in the center of the brightest component (Minkowski 1961) which also has a very small, bright ultraviolet nucleus

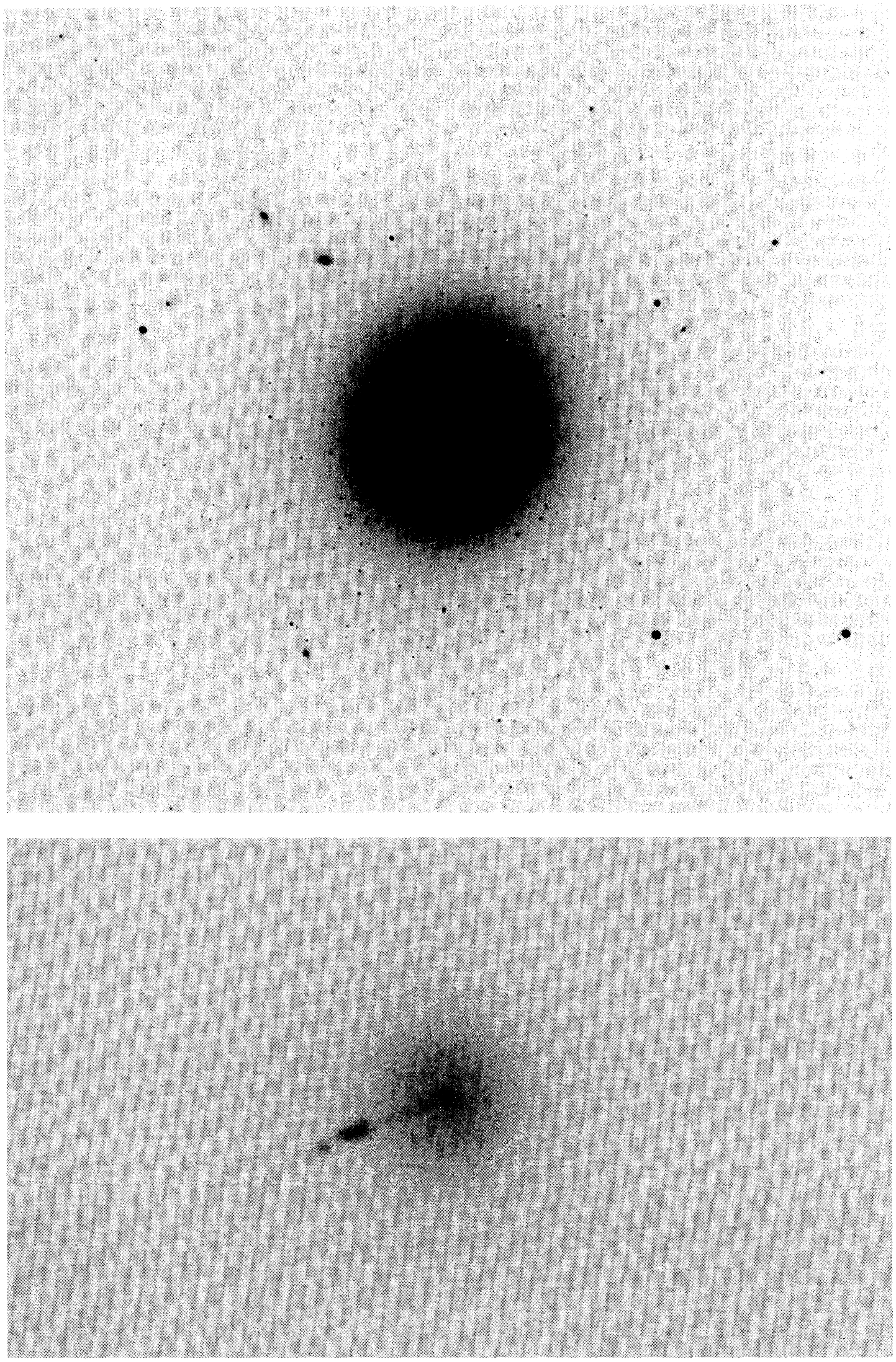

FIG. 9. Top. M87 from a 30-min 103*a*–O plate taken with the 200-inch showing the large number of globular clusters in the halo of the galaxy. Bottom. A highly enlarged short-exposure blue plate of M87 taken with the 100-inch showing the well-known jet starting from a very intense nucleus. The jet is 18 sec of arc in length, measured from the nucleus to the outer condensation. This corresponds to about 1100 pc linear dimension if $m - M = 30.6$, neglecting projection effects.

(E. M. Burbidge 1962). The distance of this system is about 121 Mpc. The brightest member of the NGC 6166 group shows some structure which is probably due to obscuring clouds (Burbidge 1962) and the degree of central condensation in this galaxy is very different from that in the other members of the multiple and also from that in the other cluster members, in that this galaxy is of much greater diffuseness and diameter.

NGC 1316 (Fornax A) has been classified S0 and its spectrum shows no emission features in the blue. A spectrum obtained at the McDonald Observatory shows one emission line in the red; from the known redshift of this galaxy, the line is [N II] λ6583. In this system a considerable amount of dust is clearly seen at some distance from the center. The dust arms extend inwards to the central region of the galaxy. Figure 10 shows these arms, which, after coming out radially, turn sharply and continue as spiral arms, somewhat in the way the luminous spiral arms join on to the ends of the bars in barred spirals. This dust structure somewhat resembles that visible alongside the luminous outer structure in NGC 1275 (Fig. 5). Interstellar absoption due to dust may explain why [N II] λ6583 is seen while [O II] λ3727 is absent.

NGC 4261 (3C 270) is an apparently normal single elliptical or S0 galaxy.

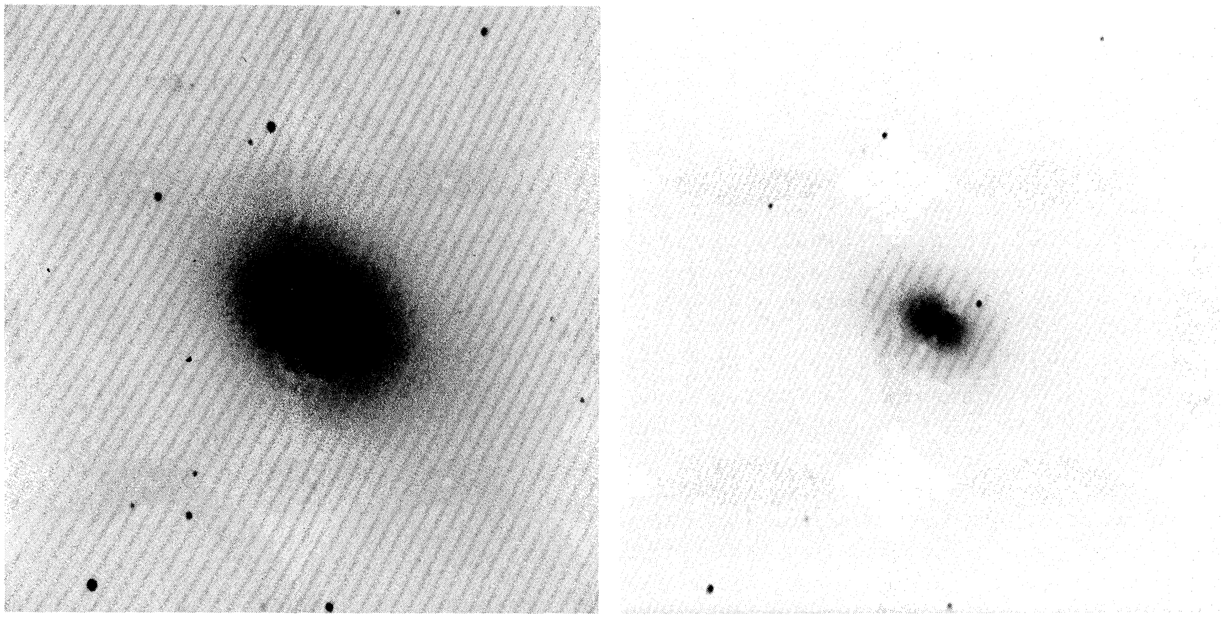

FIG. 10. Two exposures of the radio source NGC 1316 taken on 103a–O emulsion with the 82-inch telescope. A very extensive outer envelope exists, which can be seen on plates taken with the 48-inch Schmidt, but is not visible on these reproductions.

III. RADIO DATA

Apart from the Seyfert galaxies, all of the systems described in Sec. II are strong sources of radio emission, and in general it was this discovery which led to their being investigated by optical methods. It is widely accepted now that the radio radiation is emitted by relativistic electrons (and positrons) moving in weak magnetic fields, and for assumed values of the magnetic field the total energy in particles and field can be calculated if the size of the source is known. The total energy calculated when it is supposed that the magnetic energy is equal to the particle energy is the minimum energy required on the basis of this theory to explain the energy radiated. All of the sources, with the exception of NGC 1068, are much larger than the volumes occupied by the galaxies as far as the stars, gas, and dust are concerned. However, whatever the ultimate origin of the energy for these sources may be, it is most likely to have been released initially in the nuclei, since the greatest concentration of matter is there. This is borne out by the source in NGC 1068, and by other evidence, suggesting that material and high-energy particles have been shot out from the center. Consequently the energy presently contained in the radio sources gives some indication of the energy released in these nuclei. Moreover, the distribution of radio emission in the sources gives information about the ejection mechanism from the nucleus.

With these points in mind we summarize the information available on the radio emission from the galaxies described above.

(1) Seyfert Galaxies

Among this class of galaxy only NGC 1068 and NGC 1275 are known to be radio sources, and they show quite different characteristics. NGC 1068 contains a highly concentrated source with a diameter of 600 pc or less at the center of the galaxy.

This radio source is between 1 and 2 orders of magnitude stronger than normal galaxies such as our Galaxy and M31, and it is therefore considered to be a weak radio source on a scale which goes all the way from about 10^{38} erg/sec for our Galaxy to an emission rate of about 10^{45} erg/sec for Cygnus A and Hercules A. However, in view of the general idea which we are developing here that the nuclei are the ultimate sources of energy, NGC 1068 is of great importance. It would be important to study the other Seyfert galaxies beside NGC 1275, and measure the radio output from them. It is reasonable to suppose that they also contain small sources radiating at power levels comparable with that in NGC 1068, to within a factor of 10.

The radio source centered on NGC 1275 has been studied in considerable detail. The work of Leslie and Elsmore (1961) and Maltby and Moffet (1962) shows that this source has a complex structure, a central source with a diameter of about 1′ (= 20 kpc) coinciding approximately with the galaxy, and a more extended halo distribution with a size of about 90 kpc, most of which is probably associated with NGC 1275. The energetics of these sources are discussed in Sec. IV.

(2) M82

This is a comparatively weak radio galaxy with a very flat radio spectrum (spectral index = 0.2). A discussion of the radio characteristics of the system has been given by Lynds (1962) and Lequeux (1962) has shown that it is a very small source at the center of the optical galaxy (cf. Sec. VI). A very interesting feature of this galaxy is that it appears that optical synchrotron radiation is present in the filamentary structure described earlier. This has been established by the work of Elvius and Hall (1962), who found that the continuous optical emission in the halo regions shows linear polarization amounting to about 10%. The properties of this radiation and the model described by Lynds and Sandage (1962) are described in Sec. V.

(3) NGC 5128

This galaxy lies at the center of the largest radio source so far discovered, though it is not the most powerful radio emitter. The source has a complex structure with a central core and a very extended distribution with dimensions of about 0.7 Mpc by 0.25 Mpc (Bolton and Clark 1960). The extended source has two components. The central source also has two components (Twiss, Carter, and Little 1960; Maltby 1961) with dimensions of about 5.5 × 2.4 kpc separated by a distance of about 8.5 kpc. The elongation of this radio source structure is approximately in the direction of the minor axis of the galaxy as determined by the rotation curve in the dust and gas (Burbidge and Burbidge 1959). Recently, Gardner and Whiteoak (1962) have shown that this radio source has a high degree of linear polarization (38%) at a frequency of 1500 Mc. The energetics of this source are also discussed in Sec. IV.

(4) M87

The synchrotron emission from this galaxy consists of three components. These are:

(i) The jet. This is due to synchrotron emission in the optical frequency range. The measurement of a high degree of polarization of this by Baade (1956) by photographic methods and by Hiltner (1959) by photoelectric techniques confirmed the original prediction of Shklovsky (1955) that this jet consisted of synchrotron radiation. The energetics of the jet were worked out by Shklovsky (1955) and Burbidge (1956). The jet clearly comes from the center of the galaxy and provides one of the most direct pieces of evidence that violent events originate in the nuclear regions. The radio emission consists of two components, a core and halo (Biraud, Lequeux, and LeRoux 1960; Maltby and Moffet 1962).

(ii) The core source is elongated with a diameter of about 0.6′ = 3 kpc. The position angle of the major axis of this elongated source is 300°, while the position angle of the jet is 290°. This strongly suggests that the core source and the jet are genetically connected, as was earlier suggested by Baade and Minkowski (1954). The core source consists of two components according to Lequeux and Heidmann (1961) with an east–west separation of about 0.5′ = 2.5 kpc.

(iii) There is a halo distribution which has a diameter of about 6.5′ ≈ 30 kpc (Maltby and Moffet 1962).

(5) Cygnus A

This is one of the most powerful of the radio sources so far studied. It consists of two components almost equal in intensity (Jennison and das Gupta 1953). The observed separation of the components is a slowly varying function of wavelength. The separation is of the order of 1.5′, which corresponds to about 100 kpc, while the size of each component is about 40 kpc, and there is some evidence that each component is elongated in the direction of the line joining the two centers. The optical object Cygnus A is situated approximately centrally between these two components.

(6) Hercules A

This system falls into the group containing Cygnus A, 3C 295, and others because the optical object identified with the radio source (Williams, Dewhirst, and Leslie, 1961; Maltby, Matthews, and Moffet 1962) shows a strong [O II] λ3727 line (Greenstein 1962) which contributes much of the light emitted by the system. This radio source is also one of the most powerful sources so far identified. The recession velocity is +46 000 km/sec and the radio source is double with a separation of about 300 kpc between the two components each of which has a diameter of about 100 kpc.

In our discussion of the optical data we included in the category of Cygnus A, Hercules A, and 3C 295, a number of other radio sources which have been identified with optical objects and which have spectra similar to Cygnus A (Schmidt 1962). Since redshifts are now available for these sources their sizes can be obtained, and the radio power levels are found to be quite similar to many of the systems which have been discussed above.

(7) Other Single, Double, and Multiple E or S0 Systems

NGC 4782–83 is identified with a radio source that has size of about 2′ = 34 kpc and is approximately circular (Maltby and Moffet 1962). For NGC 7236–37, with a recession velocity of +8100 km/sec, the size of the radio source is about 3′ or 97 kpc. The diameter of the radio source identified with NGC 6166 is about 1′ = 36 kpc.

IV. EVIDENCE CONCERNING THE ENERGY RELEASED IN VIOLENT EVENTS

Estimates of the energy which has been released in the various systems we have described can be determined in a variety of ways. We have first the direct measurement of the optical or radio luminosities.

(1) Optical Luminosities

Most of the data are from the work of Seyfert (1943) on the galaxies discussed earlier. He estimated the magnitudes of the nuclei of NGC 1068, 1275, 3516, 4051, 4151, and 7469, and by spectrophotometric methods determined the fraction of the energy currently being emitted in the emission lines in the cases of three of these systems, NGC 1068, 3516, and 4151. We show in Table I estimates of the energy being emitted by these nuclei, which we have obtained from Seyfert's work by assuming a value of H of 75 km/sec/Mpc. In this table we give the total luminosities of the nuclei and the fractions of the energies emitted in the emission lines where they are available. We also include in Table I the estimate of the energy being emitted in the filaments in M82 in Hα light (Lynds and Sandage 1963). Also we give the luminosity of Cygnus A together with the fraction of the light emitted in the emission lines in this galaxy.

TABLE I.

	Luminosity of Nucleus (erg/sec)	Energy Emitted in Emission Lines (erg/sec)
NGC 1068[a]	20×10^{42}	2.7×10^{42}
1275	19×10^{42}	
3516	25×10^{42}	1.2×10^{42}
4051	1×10^{42}	
4151	16×10^{42}	1.2×10^{42} (hydrogen wings) 2.2×10^{42} (remainder)
7469	52×10^{42}	
M 82		2×10^{40} (Hα only)
Cygnus A	400×10^{42} (luminosity of whole optical system)	$\simeq 200 \times 10^{42}$

[a] New measure by one of us (A.R.S.)

(2) Radio Luminosities

A table of radio luminosities was given by Burbidge (1959) based on the data then available. Since that time many new identifications with optical systems have been made, and a second table has been compiled by Maltby, Matthews, and Moffet (1962). However, since the range of radio luminosities remains the same, we shall not give a tabulation here, but simply state that for the strong sources the radio output lies in the range 10^{40}–10^{45} erg/sec.

Optical synchrotron radiation is seen in M82 and M87. The energy radiated in optical synchrotron radiation in M87 was estimated by Burbidge (1959) to be about 2×10^{42} erg/sec. In M82 the continuous energy radiated in the filaments and the faint luminous halo surrounding the system can be estimated from the work of Lynds and Sandage to be about 10^{41} erg/sec, where we have assumed that the radiation is emitted over a bandwidth of 1000 Å between 5000 and 6000 Å.

Direct estimates of the energy content in these systems can be made in two ways. First we can consider the evidence of mass motions derived from spectroscopic data, and second, we can obtain evidence for the energy content in high-energy particles and magnetic fields from the observed radio luminosities and the synchrotron theory. We now consider these in turn.

(3) Kinetic Energy in Mass Motions

The Seyfert galaxies show broad emission features which indicate velocities of the order of several thousand km/sec. The structure in these emission features can be interpreted in a number of ways. At one extreme we have the possibility that we are seeing here large gas masses moving with random velocities of this order. Another possible interpretation is that we are seeing a fairly uniform gas in which shock fronts are moving with these extremely high velocities, and the gas which is radiating is that behind the shock fronts. In any case, since the motions which are seen are hypersonic with Mach numbers of the order of 10–100 it must be expected that the energy dissipation in such regions is very high. It is possible that these nuclei contain magnetic fields of considerable strength, perhaps $\sim 10^{-4}$ G, so that hydromagnetic shocks are being propagated. In this case the Alfvén velocity $(H^2/4\pi\rho)^{\frac{1}{2}}$ and not the sound velocity is the significant quantity. However, only for very low densities and high magnetic field intensities is the Alfvén velocity significantly greater than the sound velocity.

To calculate the kinetic energy present in the rapidly moving ionized gas we must estimate the density. This can be done by using the absolute intensity of hydrogen emission lines, if an estimate of the electron temperature is made. Woltjer did this for NGC 1068 and NGC 4151 by using Hβ, and we have made some calculations using Hα. The total mass of ionized gas in the nuclei of NGC 1068 and NGC 4151 calculated by this method is of the order of $10^7 M_\odot$. This is a maximum value, as was pointed out by Woltjer, since if the radiating gas is concentrated into filamentary structure or any kind of denser clouds, which may very well be the case, the radiating efficiency is increased. Woltjer has attempted to estimate a minimum mass, but the method used is very uncertain. Thus we propose to use the maximum value only. The random motions in these nuclei lie in the range 1000–5000 km/sec. Hence a reasonable estimate for the kinetic energy present in the ionized gas is $\leq 10^{56}$–10^{57} ergs. Taking into account the uncertainties and real differences between the Seyfert nuclei, in the strength of the excitation, the degree of condensation of emitting gas, and the velocity dispersion, we reach the conclusion that the kinetic energy is $10^{55\pm2}$ ergs.

In M82, Lynds and Sandage have estimated that the total kinetic energy at present in the filaments which emit Hα is about 2×10^{55} ergs. They consider that this is an upper limit because they may have overestimated the mass in the filaments. However, it gives a possible lower limit to the total kinetic energy in the matter exploded from the center, since much of this may now be undetectable.

(4) Energy in Magnetic Fields and High-Energy Particles

It is well known that from the observed power output in synchrotron radiation the total energy now present in the sources in the form of magnetic field energy and high-energy particles can be calculated as a function of the magnetic field and of the energy of the particles. There are two uncertainties involved in determining these energies. First, we have no independent estimates of the magnetic field strengths in the sources, and second, it is reasonable to suppose that associated with the electrons (and positrons) there is a flux of high-energy protons which may contain the bulk of the particle energy. The arguments for this second conclusion have been described previously (cf. Burbidge 1959). The minimum total energy required to account for the observed emission is obtained when there is equipartition between the magnetic energy and the particle energy. Calculations were made on this basis for the identified radio sources by Burbidge (1956, 1959); similar calculations for the majority of the identified sources have been made more recently by Maltby, Matthews, and Moffet (1962).

If it is supposed that the energy in the proton flux is 100 times that in the electrons and positrons, then the total energy in particles and magnetic field for all of the sources described by Maltby *et al.* with the exception of NGC 1068, lies in the range 10^{57}–10^{61} ergs. The equipartition values of the magnetic field in these cases lie in the range 6×10^{-6}–3×10^{-4} G with the majority lying between 5×10^{-6} and 5×10^{-5} G.

If, on the other hand, the proton energy is only equal to the electron–positron energy, then the total energies lie in the range 10^{56}–10^{60} ergs and the equipartition magnetic field strengths are reduced by a factor of $(100)^{\frac{2}{7}} = 3.7$.

In the case of NGC 1068, the source is very small and the total energy is 4×10^{55} ergs if protons dominate and about 3×10^{53} ergs if protons are insignificant. The magnetic field strength in two cases are 2×10^{-4} and 6×10^{-5} G, respectively.

In M87 and M82, where optical synchrotron radiation is seen, the conditions in these regions are thought to be rather different from those in the radio sources in general, essentially because the presence of this radiation means that electrons of very much higher energy are present, since $\nu_c \propto E^2$, so that, e.g., if the particles are radiating in the same magnetic field, electrons which radiate in the optical region (5×10^{14} cps) must have energies of the order of 10^3 greater than those which radiate in the radio region (taken as about 5×10^8 cps).

For the jet in M87 the corresponding values for the total energy in particles and magnetic field are 2.4×10^{55} ergs with $H = 7 \times 10^{-4}$ G if protons are dominant, and 1.7×10^{54} ergs with $H = 2 \times 10^{-4}$ G if electrons contribute much of the particle energy.

For M82 the equipartition condition considering the relativistic electrons alone gives a total energy of 7×10^{54} ergs with $H = 2 \times 10^{-5}$ G, while if the protons are dominant the total energy appears to be about 10^{56} ergs in a magnetic field of 8×10^{-5} G.

This concludes the summary of the data presently available on the current rate of energy dissipation in the sources and the energy reservoirs which are seen to be present. We turn next to a consideration of the time scales associated with these events.

V. TIME SCALES ASSOCIATED WITH VIOLENT EVENTS

The different classes of object will be discussed in turn.

(1) Seyfert Nuclei

In these objects the time scales which can be derived are (a) those given by L/v, where L is the size of a nucleus and v is the velocity associated with the gas which is seen, and (b) the time scale for the energy at present in the form of kinetic energy of turbulent gas to be radiated in the emission lines. As far as (a) is concerned, for the nuclei we have $L \approx 100$ pc and $v \approx 2000$ km/sec so that $t = 2 \times 10^4$ yr. For (b), if we use the values given previously of about 10^{42} erg/sec as a rate of emission by the spectral lines and a total energy in the gas of $10^{55\pm2}$ ergs, then the time scale if all of the energy were dissipated in this way is $3 \times 10^{6\pm2}$ yr.

Since the velocities seen in the nuclei appear to be far in excess of the escape velocities, the gas will tend to escape very rapidly, except for that part which is brought to rest by inelastic collisions between gas clouds in the central region, or which is slowed down as it moves outward from the center by interaction with the gas in the disk. Thus, unless motions of the sort seen at present are being continuously generated, the time scale associated with these nuclei as they appear now must be very short, $\ll 10^6$ yr.

Another possible way of estimating a time scale is given by the optical data on NGC 1275. We have already discussed the data which show that gas is moving with respect to the nucleus of NGC 1275 with a velocity of about 3000 km/sec. As stated earlier, one interpretation is that of Minkowski, who supposes that we are seeing a collision between two previously separate galaxies. Alternatively, we may suppose that the gas which is seen at an average distance of about 20 kpc from the nucleus has been ejected from it. Then the maximum time, neglecting deceleration, which has elapsed since this event took place is L/v, where L is ≈ 20 kpc, and $v \approx 3000$ km/sec. This time is 7×10^6 yr. The fact that not a complete shell, but only a segment of a shell, is seen must then be explained as being due to different rates of cooling and recombination in different parts, so that Hα is only seen in a limited region.

(2) M82

In this galaxy the most direct method of estimating the time scale associated with the event is to determine the time taken for the filaments to have moved to their present positions above and below the main body of the system. Lynds and Sandage have made estimates of this time based on the velocities measured from their spectra along the minor axis. These spectra show in first order a linear velocity–distance relation. There are two uncertainties involved in making this estimate. One is that it has not been found possible to take account of the deceleration which must have occurred due to the interaction of the gas ejected in the violent event with the remainder of the gas present in the disk of the galaxy. Thus the time which has been derived by neglecting the deceleration is a maximum. Also there is some uncertainty in determining the tilt of the plane of rotation of the galaxy to the line of sight so that the correction which is applied to obtain true velocities of expansion is rather uncertain. Lynds and Sandage derived a time of 1.5×10^6 yr since the filaments started to move outward from the center. However, bearing in mind the uncertainties just mentioned, perhaps the time may be estimated to lie between the limits $5\text{–}20 \times 10^5$ yr.

A second time scale which can be derived is obtained from the half-lives of the electrons which are responsible for optical synchrotron radiation in M82. These half-lives depend critically on the assumed strength of the magnetic field in which the electrons radiate. If the half-life at a given frequency in a magnetic field of strength H_0 is t_0, then in a magnetic field of strength H_1 the half-life is $t_1 = t_0(H_0/H_1)^2$. For a value of $H = 2 \times 10^{-5}$ G, $t = 2.5 \times 10^4$ yr, and for a value of H of 7×10^{-5} G, $t = 2 \times 10^3$ yr.

Lynds and Sandage finally chose a value of the magnetic field of 2×10^{-6} G which gives $t = 2.5 \times 10^6$ yr. As they pointed out, this means that one generation of electrons with energies near 5×10^{12} eV will have continued to radiate for the lifetime of the source which they estimated from the rate of expansion of the filaments to be near 10^6 yr. If the magnetic field in the filaments is considerably stronger than this, perhaps having field strengths as large as the values given in the last paragraph, then many generations of electrons (of lower energies $\sim 10^{12}$ eV for $H = 7 \times 10^{-5}$ G) must have been generated in the lifetime of 10^6 yr.

Lynds and Sandage also pointed out that the structure of the filaments, the presence of optical synchrotron radiation, and the very flat radio spectrum in M82 are all reminiscent of the situation in the Crab Nebula. In that single supernova remnant with an age of about 10^3 yr, the best estimates of the magnetic field strength lie in the range $10^{-3}\text{–}10^{-4}$ G so that many generations of electrons must have been produced. Clearly the similarity between the stellar remnant and the situation in M82 cannot be taken very far because the scales and energetics of the systems are of entirely different orders of magnitude.

(3) M87

In this galaxy, as in M82, optical synchrotron radiation is seen, so that a time scale could be associated with this as was done for M82 in the discussion above. The minimum total energy required to explain this jet was given in the previous section and it suggests that the field lies between 2×10^{-4} and 7×10^{-4} G. Thus the electrons have energies in the range $2\text{–}4 \times 10^{11}$ eV, and their optical half-lives are of the order of 10^3 yr. As shown above, this time scale cannot be increased unless it is supposed that the magnetic field is much weaker, and in this case there is an imbalance between the energy of the particles and the field so that the particles cannot be contained. While we consider that this situation is probable for the extended radio sources, it does not appear likely here. Since the over-all time scale for the radio source in M87 is probably several orders of magnitude greater than 10^3 yr, then if the jet has been continuously present over the lifetime of the radio source, many generations of electrons must have been produced. These could either have come from the much larger flux of protons which may be trapped in the vicinity of the jet, or from continuous activity in the nucleus, as was recently proposed by Shklovsky (1962). There is certainly good reason to believe that many generations of optical electrons have been produced, since the core radio source is closely associated with the optical jet and it appears reasonable to suppose that it is the optical jet which has gradually increased the strength of the radio source by feeding electrons into it.

As was described in the first section, [O II] λ3727 shows a displaced component indicating a velocity of 900 km/sec in the line of sight with respect to the center of mass of the galaxy. This appears to us to be comparable in magnitude with the random motions of the stars, so that the gas will not escape. However, Shklovsky (1962) has considered that this does indicate that gas is moving outward and is escaping from the nucleus. If this is the case, then the time scale associated with its escape from the nucleus is again given by L/v, where L is the dimension of the nucleus, and this time turns out to be about 3×10^4 yr.

(4) Radio Sources in General

The majority of the radio sources show no optical features from which time scales can be obtained. Thus the conditions all derive from the properties obtained by using the synchrotron theory. As described in the earlier sections, the magnetic fields associated with the minimum total energy required to explain the radio sources all appear to lie in the range $5 \times 10^{-6}\text{–}10^{-4}$ G. The half-lives for radio electrons which emit near 100 Mc and thus have energies in the range $10^8\text{–}10^9$ eV are then $3 \times 10^8\text{–}7 \times 10^5$ yr.

Now, if a large proton flux is also present it might be thought that perhaps electrons could be produced by secondary interactions, so that the time scales given above would be less than the age of the source. However, this is probably not the case for the following reasons:

(a) The proton flux may not always be as powerful as has been suggested by the earlier arguments. This depends on the mechanism of generation of the particles.

(b) Even if the proton flux dominates as far as its energy content is concerned, the density of intergalactic gas in the large volumes occupied by the sources must be so low that nuclear collisions giving rise to secondary electrons are negligible unless the particles can be contained for times of order 10^9 yr or longer. Only in a source with a fairly high density of gas ($\sim 10^{-26}$ g/cm^3 or greater) can this secondary production process be significant. Such a high density in the large volumes of many sources implies the presence of unreasonably large concentrations of mass. Moreover, the containment of the particles also appears to be very difficult. Thus while the first generation of electrons may have arisen in a radio source in this way, many generations cannot be produced in the large halo regions unless reacceleration is an important mechanism operating there. However, in the case of M82, if such reacceleration takes place through a process in which energy is transferred from the moving filaments to the particles, the total energy in the filaments will be greater than the estimate given earlier.

Other arguments which bear on the time scales for the radio sources, and which are of more significance, are as follows. It has been pointed out elsewhere (Burbidge 1962) that these equipartition values for the magnetic field given above are very high for the large extended regions in which many of the radio sources exist. If it is considered that they are unreasonably large, as the authors believe, and if it is supposed that the average field strengths are much lower, perhaps $\sim 10^{-6}$ G, we are automatically led to the conclusion that $E_p \gg E_M$ in the sources at present. Consequently the particles must be expanding away very rapidly from their places of origin in the galaxies, and the times scales associated with the sources are then of the order of L/v, where L is the dimension of the source at present, and v is the appropriate velocity of expansion. If very large fluxes of particles are being ejected at relativistic velocities into a weak field with a much smaller energy content, then the time scale is presumably given by L/c and from the dimensions of the sources this gives times $\sim 10^6$ yr or less. If we are dealing with clouds of plasma which are expanding outward with hydromagnetic velocities, then the time scales are probably $\leq 10^8$ yr.

Radio spectra also give valuable information concerning the time scales to be associated with the radio sources. It is the electrons of highest energy which give the high-frequency part of the radio spectrum, and these have the shortest half-lives. Thus a measurement of the high-frequency cutoff can, in theory, give a measure of the time which has elapsed since the last generation of high-energy electrons was injected. The observational situation concerning high-frequency cutoffs is not clear as yet. However, we may take as an example Cygnus A. The minimum total energy required to explain the source gives a magnetic field strength near 10^{-4} G. Apparently no high-frequency cutoff is seen, even at 10 000 Mc, and the half-lives for electrons which radiate at this frequency in a field of 10^{-4} G are about 3×10^5 yr. Thus we must conclude that either electrons have been continuously injected within the last 3×10^5 yr, or else the magnetic field is weaker than 10^{-4} G. Although we are inclined to believe this latter explanation, as discussed earlier, this leads to further complications, since if the fields are weaker, the particles of highest energy will tend to escape first, thus again producing a high-frequency cutoff; this is not seen. Probably the true situation in this source is a very complex one in which particles are produced over a fairly short time scale, while some escape from the sources rapidly.

Kardashev, Kuz'min, and Syrovatsky (1962) have attempted to derive an age for Cygnus A by using the fact that the radio spectrum shows a change in slope at about 1500 Mc. On the basis that the source giving rise to the particles is short-lived (i.e., is not stationary) they have found that the age is related to the frequency at which the spectrum changes slope by the relation

$$t = 17 H^{-\frac{3}{2}} \nu^{-\frac{1}{2}} \text{ (Mc) yr} .$$

Thus if $H = 10^{-4}$ G, $\nu = 1500$ Mc, $t = 5 \times 10^5$ yr.

And if $H = 10^{-5}$ G, $\nu = 1500$ Mc, $t = 15 \times 10^6$ yr.

They pointed out that to fill the radio source in a time of the order of 10^6 yr demands velocities of the order of $\frac{1}{3}c$. However, many observers would not agree that there is a sharp change in slope at 1500 Mc.

Shklovsky (1960) attempted to determine the ages of Cygnus A and Centaurus A by supposing that the same type of event occurred in both, and that this arose by the expansion of vast plasma clouds outward at hydromagnetic velocities. The different sizes of the two sources then gave rise to ages of 10^6–10^7 yr (Cygnus A) and $\sim 10^8$ yr (Centaurus A).

We may summarize the discussion of the time scales associated with these violent events as follows:

The small-scale optical phenomena indicate very short time scales of the order of 10^3–10^4 yr. Arguments based on the radio data suggest times mostly of the order of 10^5–10^6 yr and there is some indication that a number of events with characteristic time scales of 10^3–10^4 yr are required over a time of the order of 10^6 yr.

It has been pointed out (Burbidge 1962) that if time scales as short as 10^6 yr are general for these outbursts then to account for the fraction of galaxies which are now radio sources among all of the galaxies it must be concluded that the sources are recurrent in galaxies. The frequency with which such outbursts occur will depend on whether all types of galaxy are involved or whether only certain types of galaxy have the suitable conditions which lead to an outburst.

As was pointed out by Woltjer (1959) the Seyfert galaxies are a sizable fraction of all of the Sa and Sb galaxies down to the same magnitude limit—they make up about 3% of these and if we consider them among all galaxies to the same limiting brightness they are about 1%. Thus if the time scale associated with galaxies is $\sim 10^{10}$ yr and all galaxies go through this phase then it might be expected to last on the average about 10^8 yr. However, our other arguments have suggested much shorter time scales in the Seyfert nuclei, so that it might be argued that perhaps 100 events each with a time scale of the order of 10^6 yr takes place in a galaxy over a time of order 10^{10} yr. If only certain types of galaxy are involved then an even higher frequency has to be involved in them.

For the strong radio sources Burbidge (1962) estimated that 1 in 10^3–10^4 galaxies is currently a strong source. By the same argument as that given above, if the duration of the event is about 10^6 yr each galaxy will become a source 1 to 10 times in about 10^{10} yr. If only a certain fraction of the galaxies is physically able to generate such violent events—if say only the brightest 5% of the galaxies are involved—then in them the process must have occurred some 20–200 times.

Having described these properties based on the observational evidence associated with galaxies, we turn to a brief discussion of the starlike objects. After this we consider the general circumstances of the outbursts.

VI. STARLIKE OBJECTS ASSOCIATED WITH RADIO SOURCES

A very recent development which bears on our understanding of violent events is concerned with the properties of the so-called radio stars. The identification of the radio sources 3C 48, 196, and 286 with what appeared to be stars in our own Galaxy has been described by Matthews and Sandage (1963). They measured the colors and magnitudes of these objects and obtained spectra of 3C 48. The spectral features are broad and weak in most cases and consequently there has been great difficulty in making any identifications with well-known lines (cf. Schmidt 1962b). However, the recent spectroscopic investigation of the starlike object associated with 3C 273 by Schmidt (1963) shows that this has a number of broad emission features which can be identified as Hβ, Hγ, Hδ, Hϵ, Mg II λ2798, and [O III] λ5007 which show a redshift $\Delta\lambda/\lambda_0 = 0.158$. Following this work, Greenstein and Matthews (1963) have now identified features in 3C 48 as Mg II λ2798, [Ne V] λ4685, [O II] λ3727, [Ne V] λ3346, [Ne III] λ3868, and [Ne V] λ2975 which show a redshift $\Delta\lambda/\lambda_0 = 0.368$. The observations of the energy distribution of 3C 273 over a wide wavelength region by Oke (1963) show a feature which is due to Hα with a redshift in agreement with Schmidt; they also show that the object is exceedingly blue and cannot be represented by a blackbody, so that part at least of the optical continuum radiation may be synchrotron radiation.

The spectrum lines are broadened by amounts which correspond to random motions of the order of 1000 km/sec, i.e., they are comparable with but less than the random velocities seen in the Seyfert nuclei.

If the redshifts are due to recession of the objects then it is clear that we are seeing the early stages of outbursts in the nuclei of very distant galaxies. For a value of the Hubble constant of 75 km/sec/Mpc the absolute magnitudes of 3C 48 and 3C 273 are $M_v = -24.9$ and -26.2, respectively [here the $(1+z)^2$ corrections for number and energy effects having been taken into account using the equations discussed by Sandage (1961b)].

The radio source associated with 3C 48 is then comparable in strength to the strongest sources known, but the radio and optical dimensions are $\lesssim 5.5$ kpc. In the case of 3C 273, a small optical wisp or jet is associated with the object and one component of the radio source extends to a distance ~ 50 kpc from the starlike object which has a dimension $\lesssim 1$ kpc.

It may be argued, therefore, that such objects represent the first stages of evolution in a violent event in the nucleus of a galaxy, and at later stages the optical luminosity decreases and the radio source expands. The ages of such objects must be significantly less than the ages of the majority of extended radio sources and we may suppose from the scales involved that they lie in the range 10^3–10^5 yr.

However, 3C 48 has been shown by Matthews and Sandage (1963) to show variations in light of about 0.4 mag. over a period of about a year. This means that a small region within the volume of the optical source with a dimension $\lesssim 0.1$ pc has varied in light enough to have made the whole object change in brightness. Thus we must suppose that violent activity is still occurring in the source.

It is clear that if these objects are indeed distant galaxies no very short period light variations can be present. An observational program to see if this condition is fulfilled is therefore of great importance.

The alternative explanation of these redshifts is that they are gravitational in origin. It has already been proposed that small redshifts $\Delta\lambda/\lambda_0 = 0.005 - 0.05$, if they were found might indicate that the radio stars were highly evolved objects with neutron cores and masses of about 3 $M_\odot$ (Burbidge 1963). However, in the cases of 3C 273 and 3C 48 the magnitudes of the redshifts and their constancy from line to line indicate a very small gravitational potential gradient and hence an unreasonably small volume in which forbidden lines are produced has led to this possibility being discounted. On the other hand, an intermediate situation in which it is argued that the gravitational redshifts arise at the surfaces of massive objects ($\sim 10^5$ $M_\odot$) with radii $\sim 10^{11}$ cm and distances ~ 1 Mpc (similar in mass and distribution in space to intergalactic globular clusters) may be considered. There appears to be an upper limit for gravitational redshifts near $\Delta\lambda/\lambda_0 = 0.1$ for objects in which the gravitational field is static. If it can be shown that gravitational redshifts greater than this can never be observed then we shall have a firm theoretical basis for supposing that these objects are distant galaxies with nuclei which have exploded comparatively recently.

VII. OUTBURSTS IN GALAXIES

The material that has been summarized in the previous section shows, in general, that:

(1) Violent events can originate in elliptical, spiral, or irregular galaxies. The data on irregulars come from M82 alone.

(2) The outbursts vary considerably in the amounts of energy released. All the energetic considerations show that the range is from 10^{55}–10^{61} ergs.

(3) These events produce effects which manifest themselves in a number of ways and these are seen to persist for periods of up to 10^6 yr after the first event occurred. However, activity over as short a time scale as 10^3 yr is indicated in some cases.

(4) Mass motions of many thousands of km/sec are generated.

(5) Very large fluxes of relativistic particles may be generated in the outbursts.

The mechanism which may lead to these events is discussed in the following section. However, it is necessary here to come to closer grips with the types of event which are possible. The most important point to stress first is that very large mass motions are involved. As far as we are aware, such velocities can be generated only in two ways—either in an explosion, which by necessity must involve the condensed material already present, or by an electromagnetic acceleration process, such as that seen in a discharge or in the acceleration of a plasma. Quite high random motions are present in the stars in the nuclei of galaxies, but they are an order of magnitude less than the velocities seen in the violent events described here. The mechanism of acceleration of gas clouds by the so-called rocket effect described by Oort and Spitzer (1955) and Biermann and Schlüter (1955) cannot be invoked since no mechanism of this type can generate velocities significantly higher than the velocity of sound. In our own Galaxy velocities $\geq 10^3$ km/sec have been observed only in supernova remnants, where they are attributed to the supernova outbursts, or in the sun, where they are associated with some forms of solar activity due to electromagnetic processes. It is thus natural that all of the proposed explanations for the occurrence of violent events in galaxies have suggested that the large velocities and the high-energy particles have been generated either by explosive processes or by electromagnetic acceleration processes.

The generation of very large mass motions in different types of galaxy will have different effects depending on the amounts of gas which are already present in the system. In a spiral galaxy there is a considerable concentration of gas in the disk, and the degree of concentration towards the center depends on the type of galaxy. In the irregular galaxy M82 there is obviously a tremendous amount of uncondensed gas and dust. In most elliptical systems there is apparently only a very small amount of ionized gas present, and the concentration of neutral gas is not shown. There are many systems showing the symmetry associated with ellipticals in which all that can be seen are stars and dust. These systems are not classified as ellipticals because of the presence of dust, but are usually put into the category of S0. The presence of such systems indicates that much uncondensed interstellar matter may be present in systems which differ markedly in their form and, to a lesser degree, in stellar content, from the spiral and irregular galaxies. In explosions that occur in nuclear regions of spiral and irregular galaxies, the role of the gas already present will be of importance. In some elliptical systems enough gas may be present to influence the development of the explosion, but in many cases there may be only a negligible amount of gas available.

The generation of very large fluxes of high-energy particles will also have different effects depending on the density of interstellar matter and the magnetic fields into which the particles are injected. The high-energy particles will give rise to a number of effects. If the flux consists of protons and electrons with relativistic energies we can consider the following situations.

(a) The gas and magnetic field have an appreciable density and energy content. In this case,

(i) Relativistic electrons will radiate in the magnetic field thus providing a synchrotron source in the central region of the galaxy. As has been pointed out by Lequeux (1962), the very small radio sources which lie well within the confines of the optical galaxy and hence in the gas near the centers all tend to have rather flat spectra. These must arise because of the moderating effect of the comparatively dense gas.

(ii) As the electrons lose energy by synchrotron emission they will radiate successively at lower frequencies, but, depending on the density of the gas and the strength of the magnetic field, an energy level will be reached at which the energy losses are predominately due to atomic processes. When this level is reached the synchrotron emission will grow significantly weaker and the heating effect in the gas will be increased. In practice, since an electron spectrum of the form $N(E) = kE^{-n}$ is expected to be generated in the outburst, the synchrotron source and the heating will be coexistent in time and space.

(iii) The relativistic protons will lose energy only by nuclear collisions in which electrons, positrons, gamma rays, and neutrinos will be the stable end products. The electrons and positrons will thus provide a source of synchrotron radiation, and ultimately of heating. Any low-energy nucleons will also provide a source of heating.

(b) In the case in which the particles are injected into a medium of very low or negligible density and very weak magnetic field the effects will be very different. In this case if $E_p \gg E_m$ the particles will be shot out of the galaxy and will rapidly escape. Synchrotron emission in the radio-frequency range will be seen only if the electrons pass through a region of suitable magnetic field strength. Moreover, when very little gas was present originally, secondary production of electrons and positrons by nuclear collisions cannot be an important effect.

This, then, summarizes some of the effects which the particles will have when they are injected at the center of a galaxy. However, in addition to this, in the first case, in which the ejected particles immediately become coupled to the magnetic field in the ambient gas already present, they will do work in expanding this gas. A much more important effect which gives rise to the outward motion in the gas in the central region if it is present, will be due, however, to the mass motions which are generated in the outburst.

As shown in a previous section, the data on the Seyfert galaxies suggests that the energy available in the form of ionized gas with velocities of several thousand km/sec lies in the range $10^{55\pm2}$ ergs. Although more energy may have originally been made available in these forms in some of the strong radio sources, we take only what is indicated in the Seyfert galaxies here, since in those systems we are presumably seeing an event in its early stages. The energy corresponds to about 10^6–10^7 $M_\odot$ moving with velocities of 1000–3000 km/sec.

The escape velocity from the center of a normal spiral galaxy is only of the order of 500 km/sec, while for a massive elliptical system it may be as large as about 1500 km/sec. Therefore when a large amount of momentum is suddenly generated in the nuclear region of a galaxy it will push out material ahead of it and whether or not it will escape depends on the amount of gas present and its distribution. The directions in which it will escape will therefore depend critically on the original distribution of gas. In spiral galaxies this distribution is obviously strongly concentrated to the plane of rotation. In elliptical galaxies too, the uncondensed gas which is concentrated to the center will show an equilibrium distribution which is flattened if the system has an appreciable angular momentum. In this connection it must be remembered that even a spherical elliptical system may have a considerable net angular momentum. All that is required is that the stars form in the proto-galaxy before the gas reaches an equilibrium configuration characteristic of its angular momentum. In the subsequent evolution gas ejected from stars will collect in such an equilibrium configuration.

It is clear, therefore, what the sequence of events following the explosion will be. That part of the exploding gas with high linear momentum which is moving towards the comparatively thin sheet of gas in the plane will compress and push the original gas outward. Thus it will generate outward radial motions in the plane. Simple arguments based on the momentum balance show that, for example, if half of the momentum of $10^6\ M_\odot$ traveling at 1000 km/sec is transmitted to the disk, where we assume that we have a characteristic thickness of 500 pc and a mean density of gas and dust of 10^{-24} g/cm^3, then at a distance of about 1 kpc from the center the outward velocities will be about 50 km/sec. If the initial explosion generates $10^7\ M_\odot$ at 3000 km/sec, then at a distance of about 4 kpc the outflow velocity will be about 50 km/sec.

In the direction of the minor axis the situation will be quite different. The total mass of gas in a sphere of radius 250 pc surrounding the center will be only about $10^6\ M_\odot$ so that the sudden impulse involves a mass of comparable order to that which it encounters. Consequently the deceleration will be very limited, and the whole of the cloud will be blasted out in two cones whose axes are the axis of rotation of the galaxy.

It is thus clear that by this process the axis of symmetry of the results of the explosion will be always perpendicular to the equatorial plane. This will also apply to the high-energy particles, which, as described earlier, will cause only a local synchrotron source and heating in the plane, in the direction in which the gas is concentrated, but will be blasted out in the direction of the axis of rotation.

This then gives an obvious qualitative explanation of the well-known feature of many strong radio sources in which two strong components are seen lying along an axis in the system. In the case of NGC 5128, for example, there is both a large source lying approximately perpendicular to the plane of gas and dust, and a small double source which may be the result of a more recent event also lying along a line perpendicular to the plane of gas and dust. Spherical symmetry is also seen in some cases, and clearly these different distributions show that the form of the source depends on the total amount of gas which was originally present, and whether or not there was a preferred plane of symmetry due to the angular momentum originally present. If practically no quiescent gas was present then we might see the exploding gas in a spherical shell expanding with velocities of thousands of kilometers a second far from the center. This would be the gas generated in the explosion itself. It is this effect we may be seeing in NGC 1275. Since many double radio sources are centered on elliptical galaxies this necessarily implies that in these galaxies before the outburst took place enough gas was originally present to prevent the explosion being spherically symmetrical.

It is also required, to explain the extended radio sources, that the particles are shot out freely in these preferred directions, in order to avoid the well-known difficulties associated with the adiabatic expansion. This suggests that the magnetic field is weak and that the field configuration already has a radial form in the direction of the axis of rotation when the particles are shot into it. If there are successive outbursts, then it can be supposed that this configuration of the field has been produced by the first outburst involving the large-scale mass motions. In the first outburst the particles will move ahead of the shell so that this flux will encounter the original configuration. Provided that the energy density in the magnetic field and in the ambient gas is small enough the particles may be expected to be blasted straight through this material.

VIII. MECHANISM OF OUTBURSTS

A very considerable number of proposals have been made to try to explain the source of the energy and the mechanisms by which outbursts of this type occur in galaxies. This problem at present is one of the most important of the unsolved problems of modern astronomy. The reasons for this, in the opinion of the authors, are as follows:

(1) The apparently short-lived character of the outbursts and the observed frequencies of the outbursts as seen in the Seyfert galaxies and in the radio sources, among the total population of galaxies, shows that the outburst may recur in galaxies. Since 10^{55}–10^{62} ergs are released in an outburst this energy dissipation may play an important role in the rate of evolution of the galaxy.

(2) The dissipation of this energy, much of which goes into the intergalactic medium, may continuously increase the energy density in the medium, particularly the cosmic-ray energy density. This energy increase is made at the expense of the condensed material in the galaxies.

It can be seen that these arguments are not without their cosmological implications, since they both bear on the evolution of galaxies and provide a reason for supposing that there is constant and energetic interaction between the condensed and uncondensed material in the universe. In fact, different assumptions about the structure of the universe in which we live, i.e., the cosmological model employed, will lead to different conclusions about the role that the outbursts play. For example, in the majority of the discussion concerning the outbursts which give rise to nonthermal radio sources, beginning with supernova remnants, it has been argued that in the explosions, plasma containing magnetic field is ejected, and high-energy particles are generated as well. If we take the conventional view, then it has been shown (Burbidge 1962) that, provided that the strong radio sources are short-lived, they build up a "local" intergalactic cosmic-ray density of the order of $10^{-13\pm1}$ erg/cm^3, in a time of the order of H^{-1}, i.e., in the lifetime of the universe in an evolutionary cosmology. On the other hand, the proponents of the hot universe version of the steady-state model (Gold and Hoyle 1959) have argued that the cosmic-ray density throughout space is of the order of 10^{-12} erg/cm^3. Consequently, in that picture, a strong radio source will arise if the magnetic field is increased sufficiently by the outburst and no particles need necessarily be produced by the outburst itself. [See a more recent discussion of this by Hoyle and Burbidge (1963).] However, this is not adequate to provide an optical source of synchrotron emission as appears to be present in M87 and M82, since for reasonable values of the magnetic field the particle energies must be far in excess of those created in the hot universe. Thus if this picture is accepted, it is still necessary to suppose that some acceleration of electrons has taken place in the source. It is necessary to add here that if electrons and positrons are produced by any other process, as for example in the annihilation of nucleons and antinucleons (cf. Burbidge and Hoyle 1956) local increases in the magnetic field will also give rise to a radio source.

The possible energy sources can be considered in three groups. They are:

(a) Energy which is released by the interaction of a galaxy with material that was previously unconnected with it.

(b) Internal energy in a galaxy in the form of rotational energy, turbulent energy, or magnetic field energy which is released by some catastrophic process.

(c) Energy which is released in the evolution of stars. Included here is the gravitational energy released when stars are formed, the nuclear energy released in thermonuclear explosions, and gravitational energy which is released if the star goes to a highly collapsed phase.

We now give a critical discussion of all of the proposals which have been made, each of which appears in one or other of the above categories.

In category (a) the first proposal which was made was that the energy was released in collisions between galaxies (Baade and Minkowski 1954). It is clear now that this argument cannot be sustained either on theoretical grounds or on the basis of the identifications of radio sources (cf. Burbidge 1961). In addition to the arguments given in the latter reference, the observational evidence now available shows that a very large number of the sources of violent activity are centered on single galaxies, and, as discussed earlier, the violence appears to start at their centers. NGC 1275 still presents an ambiguous situation in that it may be two systems in collision, but an alternative explanation has been discussed earlier in this paper.

A second proposal which falls into category (a) is that the energy is produced by the interaction of material in the galaxy with antiparticles or antimatter and the subsequent annihilation. This was proposed by Burbidge (1956) and Burbidge and Hoyle (1956). The general difficulty with any hypothesis of this type is that the presence of antimatter in the universe appears, from the point of view of fundamental physics, highly improbable, although all possibilities have not been explored.

The most recent proposal in this category is that made by Shklovsky (1962), in which it is supposed that a galaxy interacts with material which has come from outside. He specifically considered the case of M87, and argued that the material which is accreted by such a massive system falls into the center. Energy is released and material in the central region is accelerated outward in the form of plasma jets. While the rate at which material falls in is estimated by Shklovsky to be about 10 $M_\odot$/yr, and this is compatible with the normal accretion rate for a galaxy of mass of the order of $10^{12}\,M_\odot$ in a medium of density $\sim10^{-29}$ g/cm^3, the details of this process are not at all clear. In particular, it is not obvious how the acceleration occurs. However, if such a mechanism is supposed to be operative for violent events which occur in the nuclei of galaxies of all types, as is required from the observational arguments summarized above, then it is difficult to see how a process of infall of material could always give rise to a violent event which appears to emanate from the center. The infalling gas would first interact with gaseous material far from the center wherever it is present. Thus we see that all of the proposals which have been made which fall naturally into category (a) have very severe difficulties associated with them.

We next turn to the processes involved in category (b). In its process of formation a proto-galaxy must dissipate energy both by radiation and by the generation of large-scale motions in the fragmentation which is required if stars are to form (cf. Hoyle 1953). This fragmentation will eventually give rise to star clusters and associations. It might well be asked whether the violent release of energy in some systems is associated with this stage of evolution. The obvious objection to this is that the vast majority of systems in which violent events are taking place are well organized and often highly evolved galaxies, i.e., the elliptical galaxies. M82 may be in a fairly early stage of evolution as deduced from the integrated spectral type of A5 and the large amount of uncondensed material, but it does not appear to be at the very early stage of which the dissipation of energy in this way is important. None of the many peculiar systems catalogued by Vorontsov-Velyaminov (1960) and studied by us, and others, and which are thought in some cases to be systems of a very early stage of evolution, are associated with radio sources or other violent events. The only possible exception to this is NGC 4038–39, which is one of the weaker of the identified radio sources.

The question therefore arises as to whether any of the internal energy in a well-developed galaxy could be released suddenly to give rise to a violent event. The only proposal of this type which has been made is that by Hoyle (1961), who argued that in galaxies with considerable amounts of gas containing magnetic flux and large angular momenta galactic flares could arise through discharges following the winding up of the magnetic fields in the centers. This mechanism is similar to that proposed by Gold and Hoyle (1960) for the generation of solar flares. While the model proposed by Hoyle is not unattractive, it suffers from the disadvantage that the discharge conditions cannot be reached unless there is a very large amount of gas already present in the galaxy, and also a very large amount of angular momentum per unit mass. This means that very massive systems with high rotations and containing large amounts of uncondensed material are the obvious candidates to produce violent events. However, most of the galaxies in which violent events are seen do not fulfill all of these conditions. The elliptical galaxies which are massive, often contain little gas, and probably have little angular momentum. The Seyfert galaxies which do contain considerable amounts of gas and are fast rotating do not appear to have sufficiently large masses nor large mass concentrations.

Finally, therefore, we come to the processes which are contained in category (c). Ginsburg (1961) has attempted to show that high-energy particles can be produced in the early stages of formation of a galaxy when gravitational energy is released. However, as we have described earlier, it appears that none of the galaxies from which radio sources have emanated are systems which are recently formed.

As will be seen in what follows, energy release following star formation and evolution appears to give the best hope of explaining the phenomena. As described earlier, the observations of the Crab nebula and other supernova remnants in our Galaxy show that in, or following, such a stellar explosion the necessary conditions for a synchrotron source to appear are produced. Also, only in stellar explosions (novae and supernovae) are velocities generated of the magnitude seen in the Seyfert nuclei. Thus it is natural to suppose that the violent outbursts in galaxies are the result of multiple supernova outbursts or their equivalent in energy output. It is normally estimated that some 10^{50} ergs are emitted in a supernova outburst (this number is uncertain and in large part it is based on the observational side from studies of the Crab nebula and the supernova in IC 4182). However, the total amount of nuclear energy available in the conversion of one solar mass of hydrogen to helium is about 10^{52} ergs. It must be stressed, however, that this amount of energy cannot be released catastrophically. On the other hand, the upper limit to the gravitational energy which can be released if a configuration collapses to the Schwarzschild limit is about 10^{53} ergs. If we take the more conservative estimate of 10^{50} ergs then it is clear that the energy required to explain the various types of violent events described above demand explosions involving 10^5–10^{11} $M_\odot$. This upper limit (corresponding to the energies in the most powerful radio sources) is so large that it alone may already indicate that the release of gravitational energy must be important. This possibility was first mentioned by Burbidge (1962b). However, we describe next the various proposals which have been made involving the stars.

Shklovsky (1960) has argued simply that the supernova rate must have been very considerably enhanced so that some 10^6 or more supernovae have gone off at a rate of about 1 per year in an object like M87. However, he gave no argument as to why this should occur. Since supernovae only occur at the end of a star's evolution it is not reasonable to take this view unless it is supposed that the outbursts (a) are causally connected, or, (b) unless stars of very great mass are continuously being formed and evolve very rapidly. It was proposed by Burbidge (1961) that a chain reaction of supernovae could be caused in the nucleus of a galaxy if one supernova went off naturally and the stellar density was sufficiently high so that other stars could be exploded.

It was estimated that the star density required if such a mechanism were to work must be of the order of 10^6–10^7 stars/pc^3 and it was pointed out that there was no observational argument against this, particularly for the elliptical galaxies. Even higher star densities may be acceptable. The difficulty lies in understanding how a detonation wave can propagate even if sufficient light nuclei are present. This problem has not been solved, partly because the geometry involved is exceedingly difficult to handle. Also, modern ideas concerning supernova outbursts suggest that an integral part of the normal supernova process is a catastrophic collapse due to a phase change in the material or neutrino emission at very high temperatures in an evolved core. The chain reaction mechanism would not lead to this. Finally, if the magnitude of the energy which is released suggests that gravitational energy release is involved, this cannot be expected by such a mechanism. These difficulties and unsolved questions have led some authors to consider a somewhat different approach. There is obviously only one other possibility left. This is to suppose that stars are formed and rapidly evolve in the nucleus of a galaxy to give rise to such events. This is essentially what was implied by Shklovsky in his 1960 attempt at understanding what is taking place in M87.

The first and quite fundamental question is to consider the formation of new stars in the nuclear region of a galaxy. This was considered briefly by Cameron (1962), who wrote down the condition for gravitational instability in a gas cloud containing a magnetic field with conditions which he considered were reasonable for a gas cloud in the central parts of an elliptical galaxy. Unfortunately, in deriving the critical condition, he omitted the contribution to the internal energy from the random motions in the gas. All indications from observations of the quiescent centers of galaxies suggest that either the gas has turbulent motions of comparable order to the motions of the stars (several hundred km/sec) or else ordered rotational motion of the same magnitude. In this case this contribution to the internal energy dominates (Burbidge 1962) and the critical mass becomes unreasonably large. Although the conditions can be improved by supposing that the initial density of the gas in the center is very much higher than assumed by Cameron (perhaps 10^{-22} g/cm^3 instead of 10^{-26} g/cm^3) there obviously is considerable difficulty in understanding how stars can be formed under such conditions. Two factors which do not have to be considered in star formation in spiral arms, but which must be taken into account here, and which have not been properly evaluated so far are:

(i) Star formation is taking place in a deep potential well at the center;

(ii) the star density is rather high,—at least $\sim$1000 stars/pc^3 and the proto-stars have got to condense in this medium.

The first of these conditions may help star formation. However, the effect of the second is more difficult to understand. It seems possible that these stars will have a general disrupting effect on a condensation because they will continuously stir the material and also tidally disrupt condensations.

However, it is possible that the observations of the state of the gas in the centers of galaxies may be misleading for this problem. The observations come from the ionized gas, and it is not impossible that the presence of such ionized gas indicates an abnormal state of activity. Our discussion of the relative strength of the Hα and [N II] λ6583 emission lines in a wide range of spiral and elliptical galaxies (Burbidge and Burbidge 1962c, 1963) indicates that the electron energies determined from the strength of the lines and their relative intensities, are incompatible with excitation of the gas from the comparatively low luminosity stars which are present. This might suggest that what we are seeing in the majority of cases in which ionized gas appears strongly in the central region, is a remnant of the violent activity arising from an earlier outburst which has not yet died out completely. Obviously we have no observational information on the presence of neutral gas in the nuclear regions of galaxies apart from that in our own, but the ideal situation for star formation will be reached if gas, perhaps originally ejected from stars in an ionized state, slowly cools and condenses in the center.

If the time scale of the outburst is 10^6 yr or less, then if star formation and evolution are occurring, stars with masses $\sim 100\ M_\odot$ or greater must be formed. The upper limit to the total mass involved is about $10^8\ M_\odot$ if we suppose that it is gravitational energy and not nuclear energy which is mainly responsible. In many cases, however, the total energy in the outburst indicates that a lesser mass is involved. Thus we may need to consider a wide range of masses if star formation and evolution is responsible. If stars can be formed in the nucleus of a galaxy the masses depend on the degree of fragmentation which can occur. From the theoretical standpoint we have little indication at present of what is possible, though it is an obvious requirement that much larger masses must appear than is normally the case when stars are formed in spiral arms. Moreover the suggestion that continuous activity may occur with time scales of the order of 10^3–10^4 yr over a total period of about 10^6 yr may indicate that not just one sudden event corresponding to the evolution of single massive object occurs, but that a number of smaller masses may sometimes be involved. Thus the evolution of stars in the range 10^2–10^8 $M_\odot$ must be investigated. The fragmentation is presumably controlled by the magnetic field conditions in the original medium, but no real understanding of this point is available as yet.

The first discussions of the evolution of stars with masses in the range 10^5–10^8 $M_\odot$ have been made by Hoyle and Fowler (1963 a,b). However, they have not discussed the formation process, but have begun by considering the main-sequence configurations of such objects. Their investigations suggest that the subsequent evolution will rapidly lead, following neutrino emission, to a collapse to a radius near to the Schwarzschild limit at which point relativity effects become of importance.

At this early stage in the investigation of these fascinating phenomena it must be stressed that the idea that gravitational energy release may explain these events is very attractive. However at the present time it must be emphasized that we have little idea of how such objects can first be formed in the nuclei of galaxies.

CONCLUSION

In this paper we have attempted to describe the many arguments which now suggest strongly that violent events occur in the nuclei of galaxies, that they are fairly frequent, and may have many effects on the structure and evolution of galaxies. Ambartsumian (1958 and other references given there) for many years has stressed the importance of events which occur in the nuclei of galaxies. Although he has described these in terms of the "splitting of the nuclei" of galaxies and has related this to his ideas concerning intrastellar matter, it is clear that our general conclusions follow rather closely his original thinking on these topics. It now seems difficult to underestimate the importance of these new concepts. We have described in some detail the observational evidence which leads to the conclusion that such events are of importance. However, there are many other effects which must be considered, few of which have been investigated as yet. Some of these are as follows:

(1) It seems probable that the type of weak galactic radio halo which is seen in M31 and other comparable nearby galaxies is produced by events such as those described. If this is so, an important feature of such a halo is that it will be a transient phenomenon with a lifetime in the range 5×10^7–10^9 yr. Other properties of such a halo have been described by Burbidge and Hoyle (1963).

(2) Some theories concerning the origin of cosmic rays must be revised if these ideas are correct. If particles are produced in the outbursts they may make a significant contribution to the intergalactic cosmic ray flux (Burbidge 1962a). In any case, if the halo in our own Galaxy is a transient phenomenon it can no longer be supposed that galactic cosmic rays alone are present in the Galaxy. If we take the view that the cosmic ray density everywhere is $\sim 10^{-12}$ erg/cm^3 (Gold and Hoyle 1959) then the radio sources appear because of the magnetic field and acceleration effects which take place in the outbursts.

(3) Noncircular motions in the disk of a galaxy will be produced by these outbursts. Thus the outward moving gas seen in our own Galaxy and departures from rotational motions seen in other spirals are easily explained by such effects.

(4) It is entirely possible that the outward radial motions generated in such explosive events in the disks of a spiral galaxy may be an important factor in explaining the appearance and maintenance of spiral structure. This question demands close study.

(5) It has frequently been argued (cf. proceedings of the Princeton Conference on Interstellar Matter in Galaxies 1963) that it is very difficult to account for the energy input into the interstellar gas in the disk of our Galaxy by means of processes involving normal O and B stars alone. It is clear that repeated outbursts in the nuclear regions of a galaxy of the type we have described here may contribute significantly to the energy input.

(6) It is well known that in the nuclei of some spiral galaxies a number of large ionized regions (hot spots) can be observed (cf. Morgan 1958). It is obvious that such features are probably associated with the occurrence of nuclear outbursts. Whether they indicate regions in which outbursts have taken place in the past, or whether they have something

to do with the conditions which are building up prior to new outbursts demands investigation.

(7) If massive objects evolve rapidly or if the supernova frequency is vastly increased in the nuclear region of a galaxy element synthesis may be expected to go on at an enhanced rate there. Which of the many processes will be especially involved will not be clear until we have a definitive model of the mechanism of the outbursts. However, it has already been proposed (cf. Hoyle and Fowler 1963) that much of *r*-process material might be produced in this way.

(8) If violent events recur frequently in some types of galaxy, and a large amount of material is ejected from the nuclear regions it is possible that some of this material may not escape from the galaxy but condense into stars in the halo regions. It is perhaps suggestive that M87 which shows all of the signs of violent activity in its nucleus has more globular clusters than any other elliptical galaxy known. A survey of the elliptical galaxies in the Virgo cluster shows that M87 has more than ten times more globular clusters than any other elliptical there.

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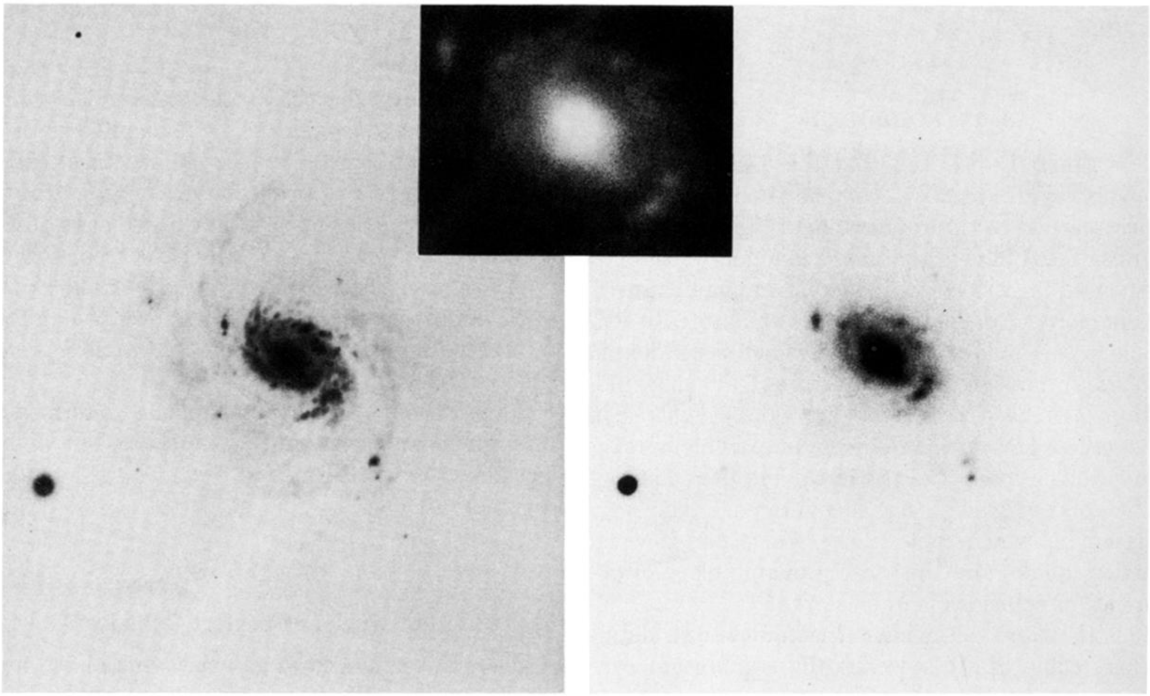

FIG. 1. NGC 1068. The inner parts of this Seyfert galaxy have an abnormally high surface brightness. The nucleus itself, burned out in these photographs, is exceedingly small and bright. The left photograph, taken with the 200-in. telescope, is a 1-min exposure on a 103*a*–O plate behind a GG 13 filter. The right photograph is a 30-min exposure on a 103*a*–E plate behind an Hα interference filter of 80 Å total half-width. The insert is an enlarged portion of the Hα plate. There is some suggestion of an Hα filament coming from the central region.

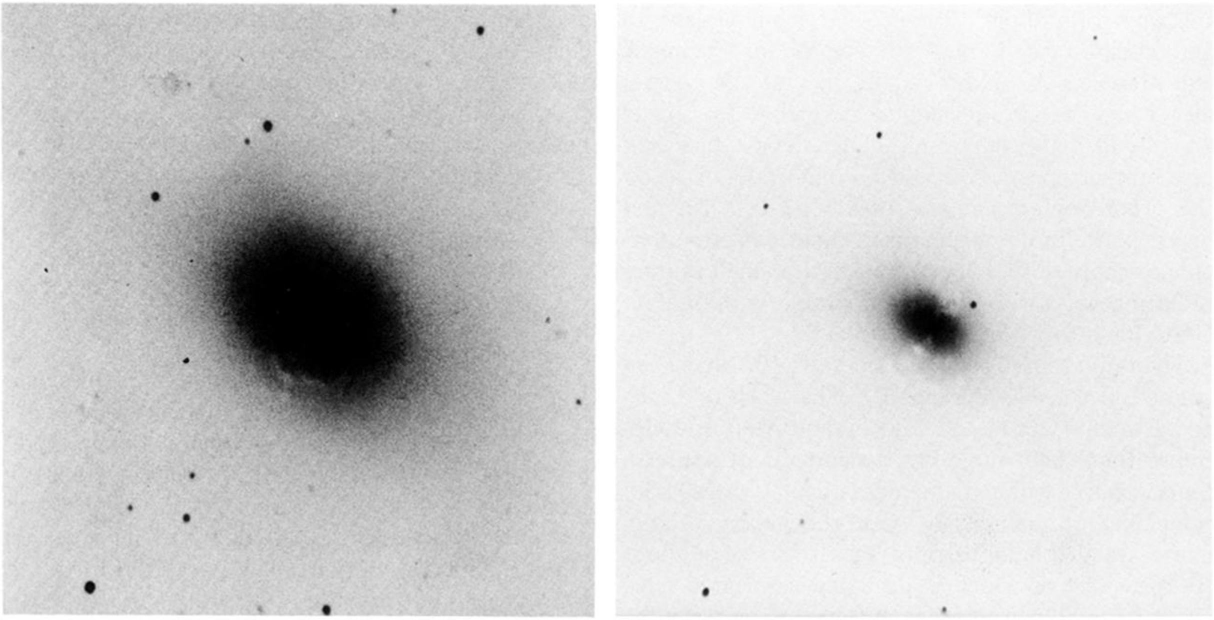

FIG. 10. Two exposures of the radio source NGC 1316 taken on 103*a*–O emulsion with the 82-inch telescope. A very extensive outer envelope exists, which can be seen on plates taken with the 48-inch Schmidt, but is not visible on these reproductions.

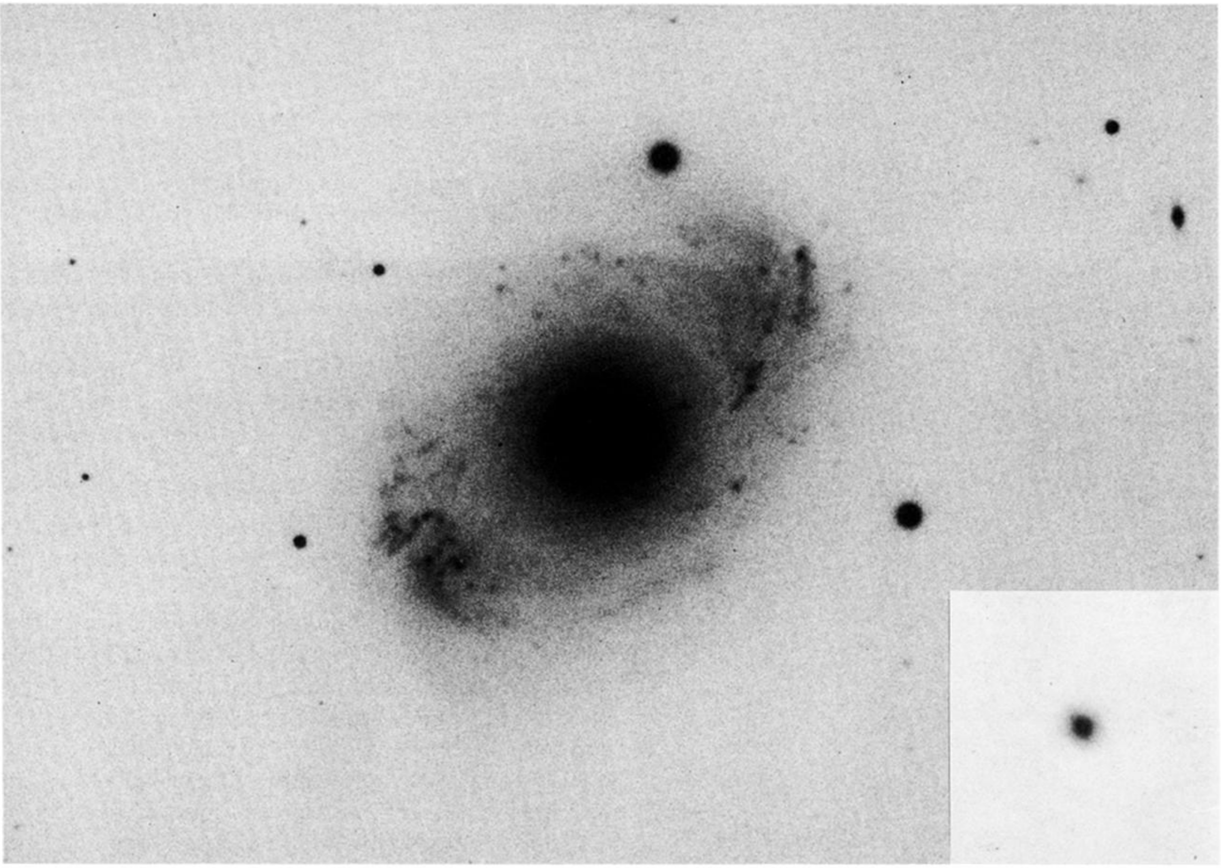

FIG. 2. The Seyfert galaxy NGC 4151 from a 30-min 200-inch photograph taken on 103*a*–O emulsion behind a GG 13 filter. Very faint outer arms exist. They are not visible on this reproduction, but can be seen on the Palomar Sky Survey prints. The nucleus appears stellar on visual inspection in the telescope. Short-exposure photographs show diffraction spikes on the nuclear image, which shows that the nucleus is of very small angular size. The insert is greatly enlarged from a short-exposure blue plate taken with the 100-inch, where the diffraction spikes are easily seen on the original.

FIG. 3. NGC 3226–3227. Taken on a 103*a*–O plate with the 82-inch McDonald telescope. The spiral NGC 3227 has a bright nucleus and broad emission lines characteristic of the Seyfert galaxies. Very faint outer structure, like an incompleted ring, are easily seen on the original plate. Similar structures are known to exist in the other Seyfert galaxies NGC 1068, 4151, and 7489.

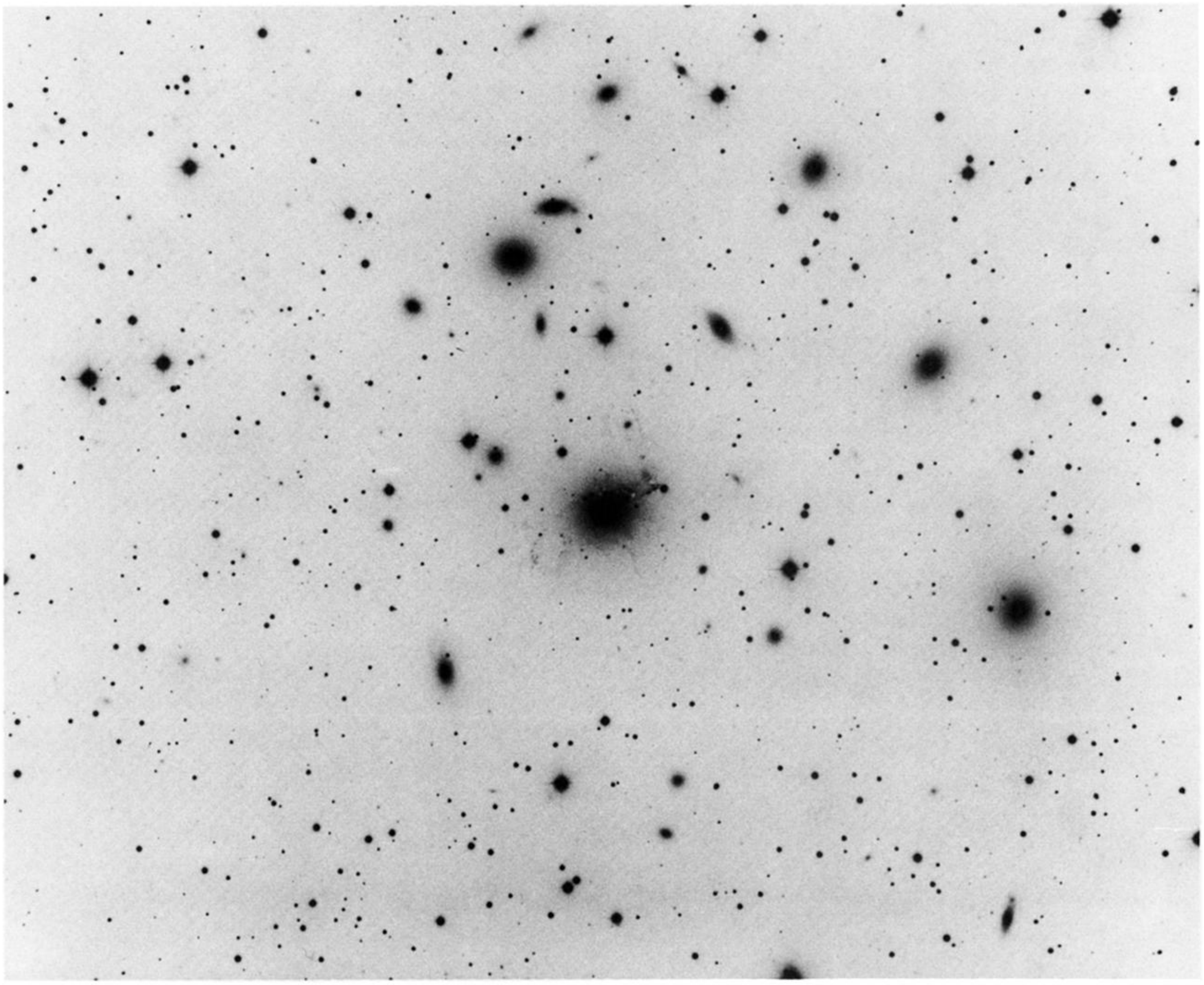

FIG. 4. NGC 1275 and surrounding galaxies in the Perseus cluster, from a 103*a*–O plate taken by Humason with the 200-inch telescope, showing the extensive system of filaments.

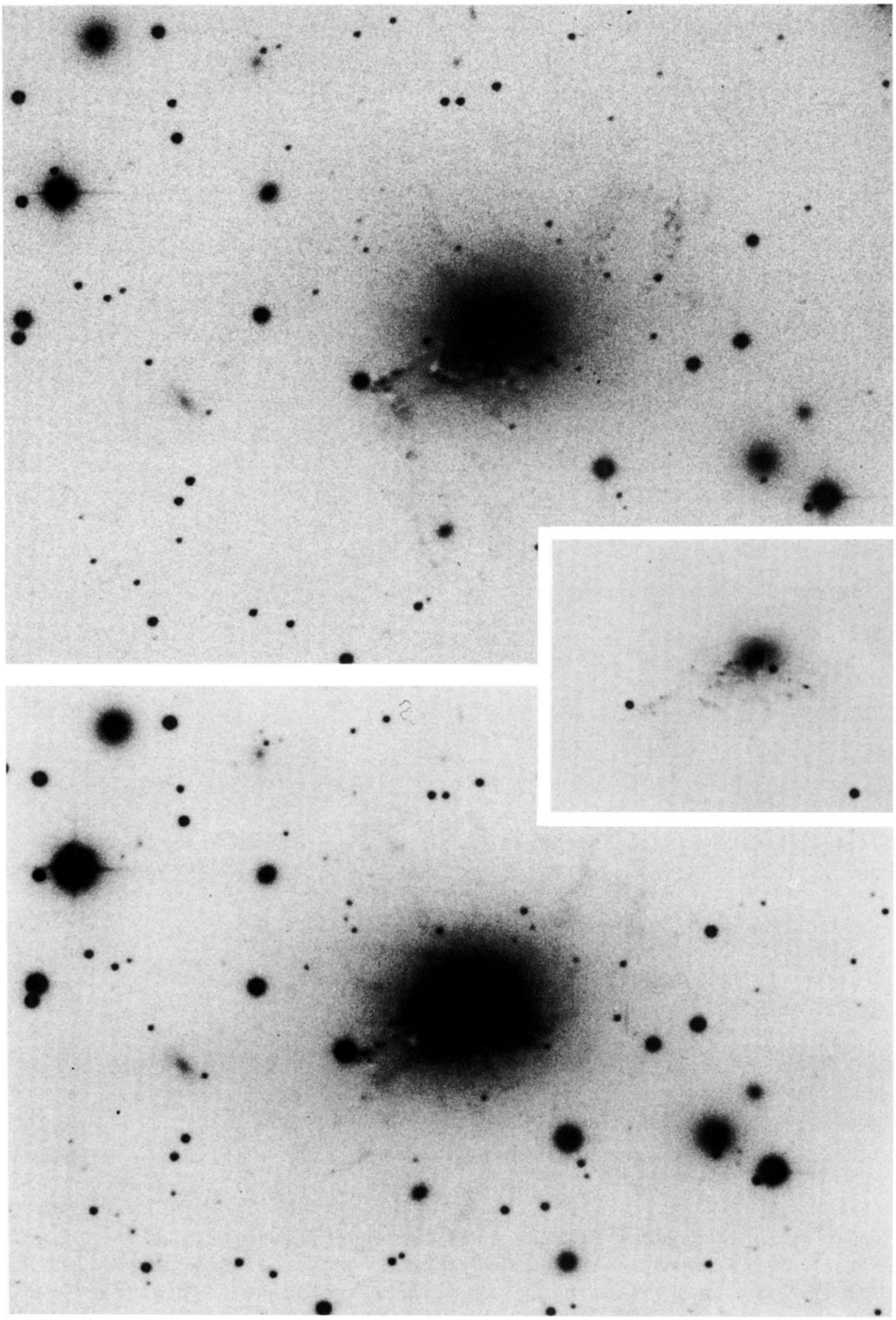

FIG. 5. NGC 1275 photographed in three different wavelengths. The upper is from Humason's 30-min 103*a*–O plate (λ3500–4800 Å); the bottom is from a 180-min exposure taken on a 103*a*–F plate behind an RG 1 filter (λ6000–6800 Å); the insert is a short exposure of the nucleus taken in the ultraviolet from a 100-inch plate by Baade (λ3300–3900 Å). The filamentary structure visible on both the blue and Hα plates extends to about 80 sec of arc on either side of the nucleus, which corresponds to about 30 kpc linear dimension (based on $H = 75$ km/sec 10^6 pc).

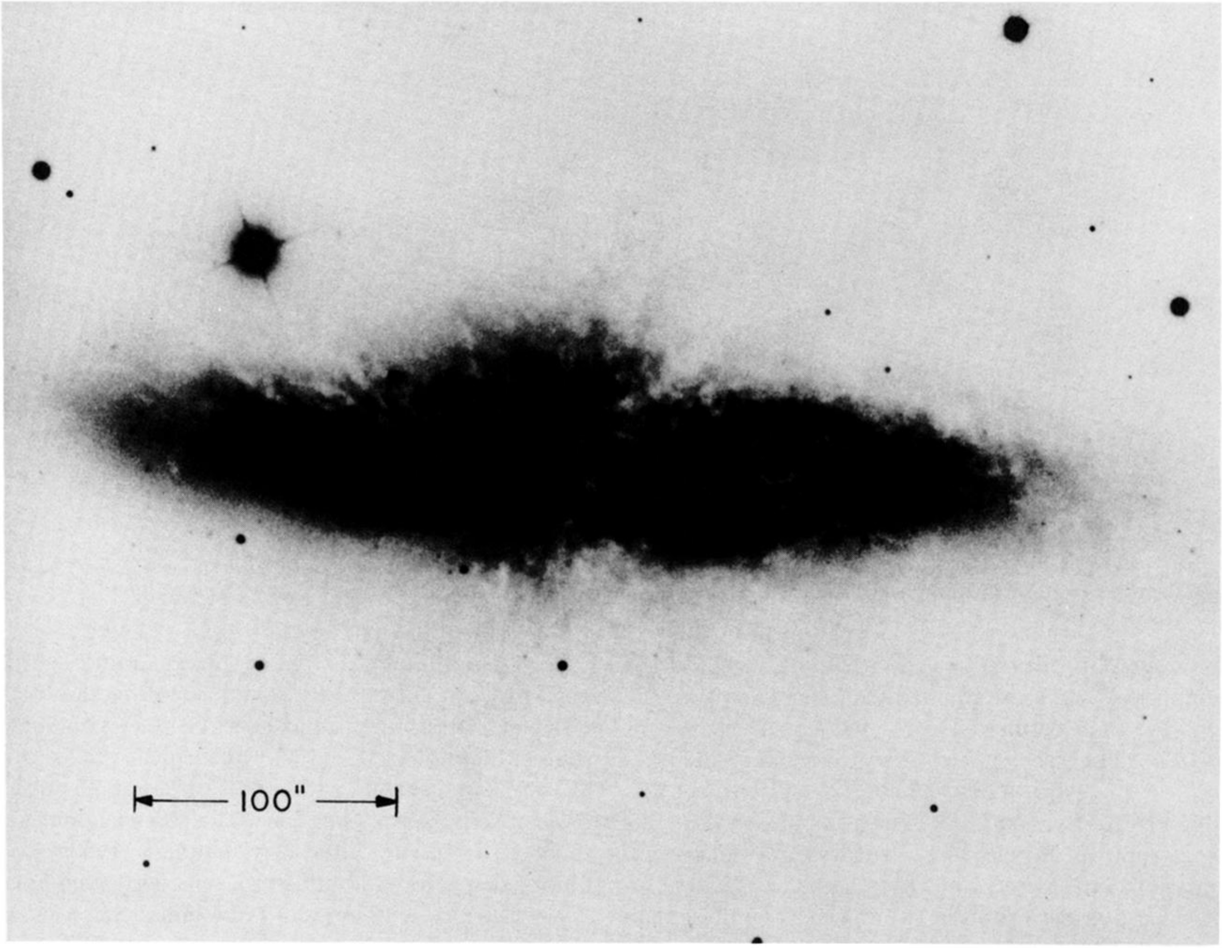

FIG. 6. M82 from a 30-min 103a–O plate behind a GG 13 filter with the 200-inch telescope (from Lynds and Sandage 1963).

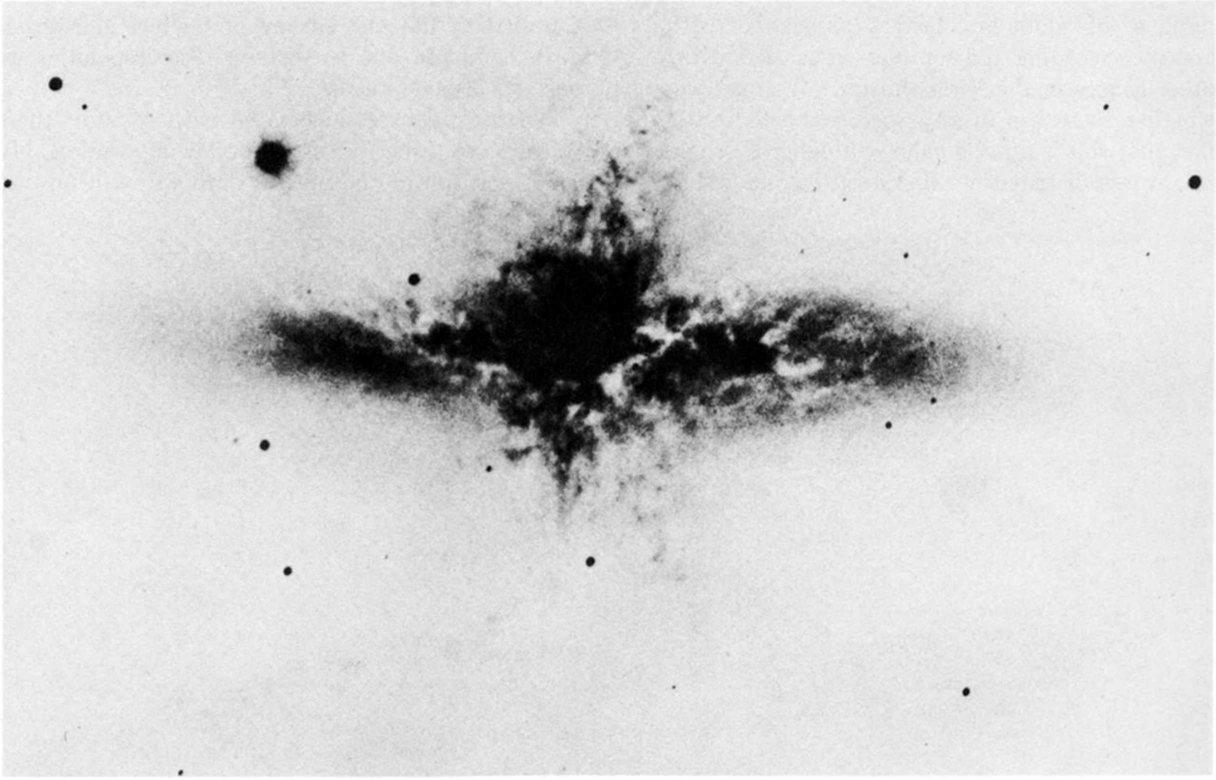

FIG. 7. M82 from a 180-min exposure taken on a 103a–E plate behind an 80 Å total half-width Hα interference filter, showing the massive Hα filamentary structure on both sides of the fundamental plane (from Lynds and Sandage 1963).

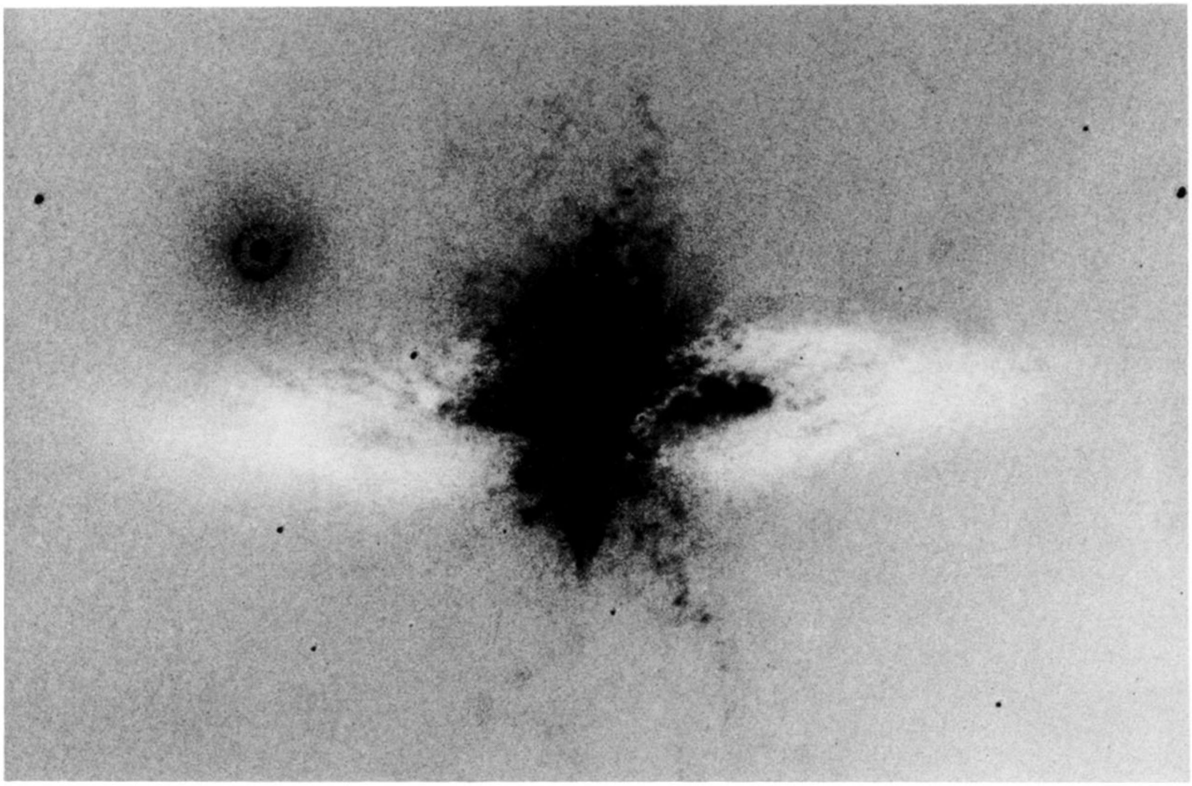

FIG. 8. Photographic "subtraction" of a yellow plate (103a–D + GG 11) of M82 from the Hα plate of Fig. 7, showing that the Hα emission region is confined predominantly to the minor axis of the galaxy.

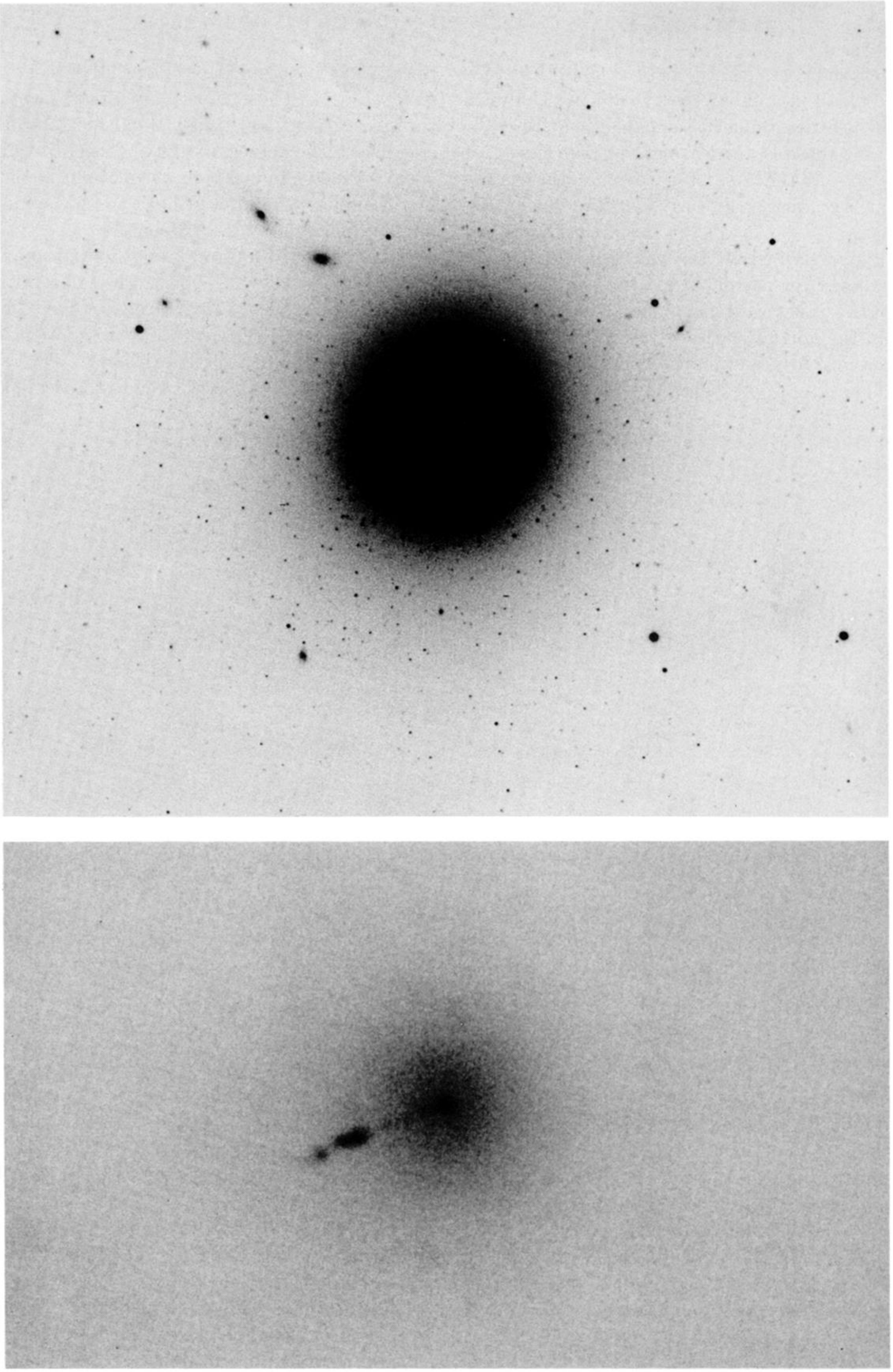

Fig. 9. Top. M87 from a 30-min 103*a*–O plate taken with the 200-inch showing the large number of globular clusters in the halo of the galaxy. Bottom. A highly enlarged short-exposure blue plate of M87 taken with the 100-inch showing the well-known jet starting from a very intense nucleus. The jet is 18 sec of arc in length, measured from the nucleus to the outer condensation. This corresponds to about 1100 pc linear dimension if $m - M = 30.6$, neglecting projection effects.