Reports

The Exploding Galaxy M82: Evidence for the Existence of a Large-Scale Magnetic Field

Abstract. *Photographs of galaxy M82 obtained in blue light show the existence of a previously unknown system of large-scale filaments extending 4000 parsec (1.2×10^{22} cm) above and below the fundamental plane of the galaxy along the minor axis. These filaments emit continuous radiation that is highly polarized, with the electric vector predominately perpendicular to the filamentary structure. A plausible interpretation is that the radiation is optical synchrotron emission caused by relativistic electrons spiraling in a large-scale magnetic field. To produce radiation in visual wavelengths, the electron energies must be in the range 10^3 to 10^4 Bev if the magnetic field is between 10^{-5} and 10^{-6} gauss.*

Optical and radio astronomical observations (*1, 2*) of the nearby radio galaxy M82 have recently been interpreted by Lynds and Sandage to show that a highly energetic explosion took place in the central regions of this galaxy about 1.5×10^6 years ago. Debris from the explosion consists of (i) electrons moving at relativistic energies which interact with a magnetic field giving rise to the nonthermal radio spectrum and (ii) a "low"-energy filamentary system of ionized hydrogen gas of total mass about 5×10^6 solar masses or 10^{40} g, which is expanding away from the explosion center with velocities up to 1000 km/sec.

One of the important problems raised by the model was the source of the energy which is required to ionize the hydrogen now recombining at the rate of 10^{40} ergs/sec in the Hα expanding filaments. Lynds and Sandage obtained partial evidence that high-frequency optical synchrotron radiation was present with sufficient intensity for frequencies greater than the Lyman limit ($\nu = 3.3 \times 10^{15}$ cy/sec) to provide the ionization energy for the glowing hydrogen. However, the evidence was not complete.

New observations of the outer regions of M82 have now been made which show an extensive new system of filaments that appear to be radiating optical energy by the synchrotron process. Our new data are shown in Fig. 1, where the bottom reproduction (*b*) is a composite of three superposed blue-sensitive (Kodak 103aO plates plus a Schott WG2 filter) negatives taken with the Palomar 200-inch reflector. The filaments are so faint compared with the sky background that composite printing of three negatives was necessary to increase the signal-to-noise ratio.

The upper reproduction of Fig. 1 (*a*) is from a 3-hour exposure taken with the 200-inch reflector with an Hα interference filter of 80 Å total half-width. This photograph was previously discussed by Lynds and Sandage (*2*, Fig. 8) as one of the primary facts establishing the nature of the explosion. The Hα reproduction has been enlarged here to the same scale as the lower photograph in Fig. 1 to show that the newly found filaments occupy a much larger volume of M82 than the Hα structures.

Parts of the new filamentary structure were discovered by Hugh Johnson (*3*) in 1963 with the 36-inch Crossley reflector at Lick Observatory. He superposed four negatives taken in blue light and found the large outer arch filament about 5 minutes of arc south of the fundamental plane of the galaxy near the minor axis. The inner filaments were lost on his reproduction because the superposition of four negatives created a total density range far in excess of the reproduction materials. The reproduction of faint detail in astronomical objects which have large-intensity variations across their surfaces always presents this obstacle unless special techniques are employed. All photographs shown in our report have been reproduced by a special process of "automasking" which effectively increases the latitude of the final print without reducing the contrast of fine structure. The technique is briefly described near the end of our report.

Two conditions must be met if the filaments radiate by the synchrotron process: (i) The energy distribution must be due to continuum radiation rather than discrete line emission. (ii) The light must be very highly polarized with the electric vector perpendicular to the magnetic field, which presumably lies along the filaments. Both these conditions exist in the blue filaments in M82. The continuous energy distribution is shown by noting that the filaments are not only visible in Fig. 1*b* but are also present on plates taken in yellow light on Kodak 103aD plates with a Schott GG11 filter, which isolates the wavelength interval from 5000 to 6200 Å where no emission lines exist in the spectrum of M82 (see Figs. 4 and 5 of reference *2*).

The earliest measurements of polarization were made photoelectrically in 1962 by A. Elvius (*4*) at the Lowell Observatory with the Perkins Observatory's 69-inch reflector. She observed a maximum polarization of 15 percent at the base of the filamentary structure on the south side of M82 which was interpreted as due to scattering of light from the main body of M82 by dust about 500 parsec (1.5×10^{21} cm) above the plane. Although such a result is possible for 15 percent polarization, our new results show that nearly 100 percent polarization exists in the filaments themselves. Such a high percentage is difficult to explain by dust scattering. But more important, calculation shows that the scattering hypothesis fails to account for the observed surface brightness of the outer filaments by a factor of about 100 for a dust density as high as 10^{-26} g/cm^3, which applies in the solar neighborhood of our galaxy. Even if the dust were optically thick in the halo of M82 ($\rho > 10^{-24}$ g/cm^3), the

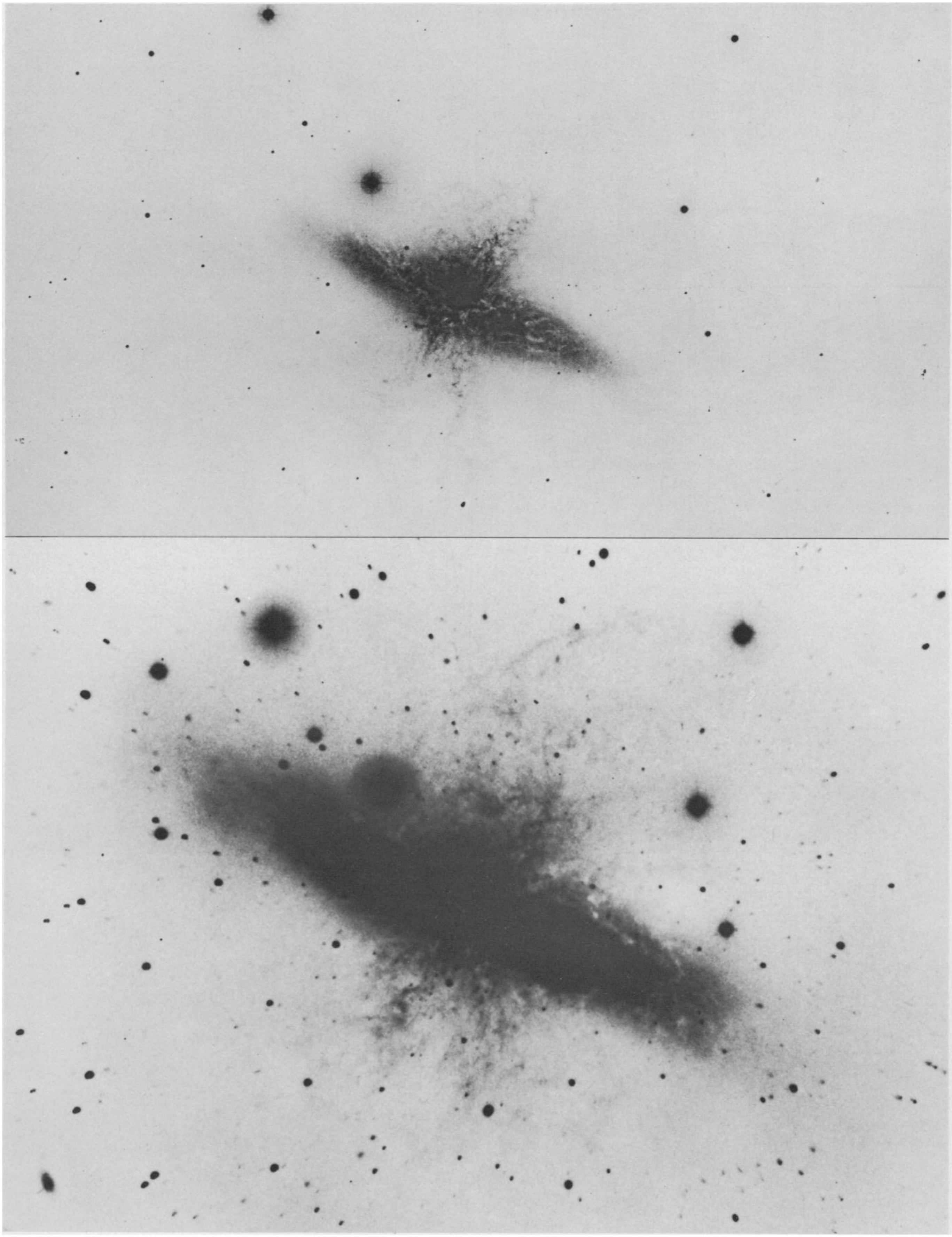

Fig. 1. (*a*) Galaxy M82 photographed with the 200-inch Hale telescope through an interference filter of 80 Å total half-width centered on the Hα emission line. This is a negative print so that the luminous areas appear dark. (*b*) Composite negative print from three superposed negatives taken in the wavelength interval 3800 to 5000 Å with the 200-inch reflector, enlarged to the same scale as *a*. The extensive filamentary structure extends about 5 minutes of arc on either side of the fundamental plane of the galaxy. North is at the bottom, east at the right.

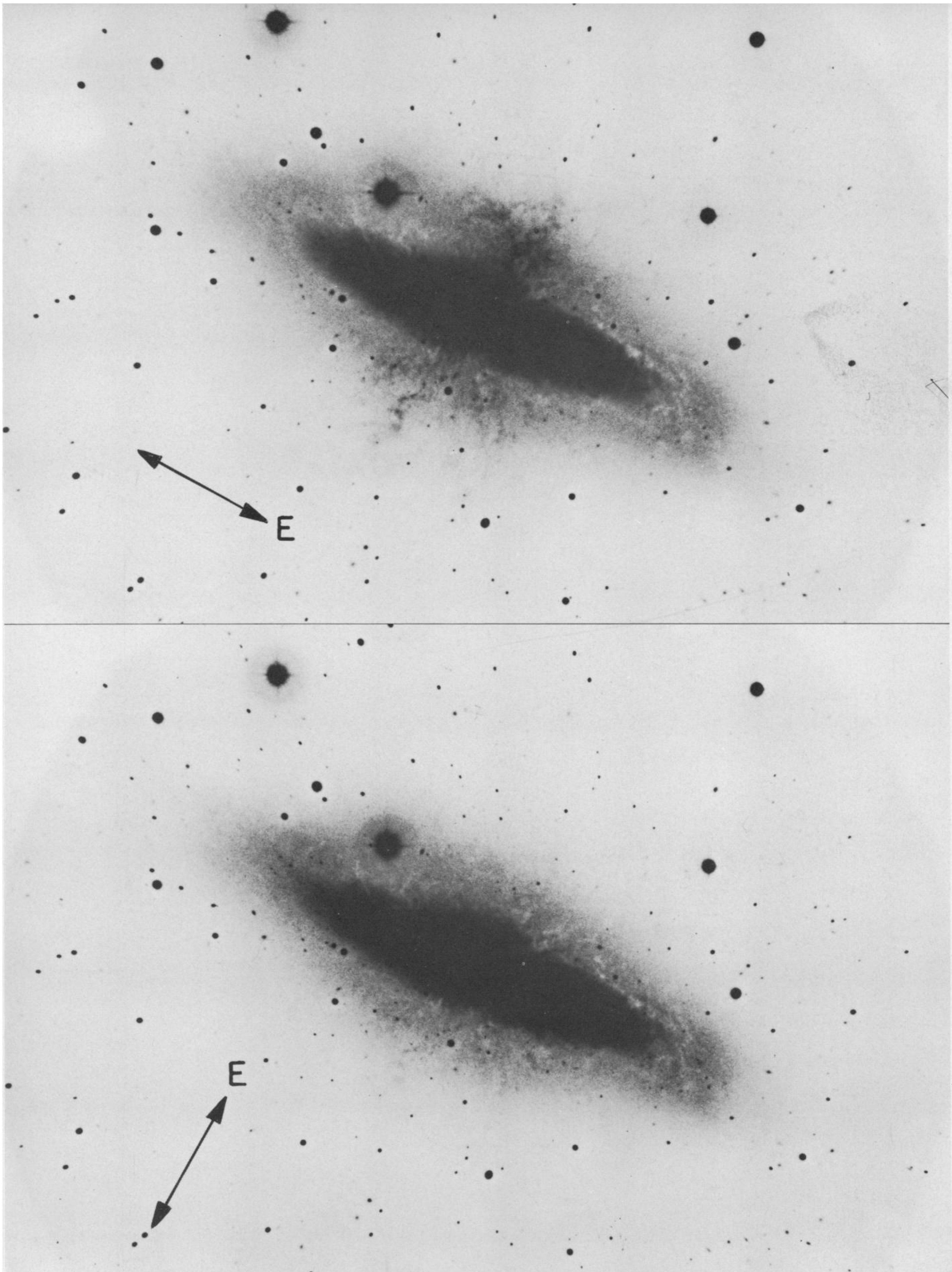

Fig. 2. (*a*) Composite of two superposed yellow-sensitive plates exposed through a Schott GG11 filter and HN38 Polaroid sheet, recording the wavelength interval 5000 to 6200 Å, made with the 200-inch reflector. The electric vector of the Polaroid sheet is at position angle 61.5° (north through east) which is predominately along the major axis. The filaments radiate strongly in this position of the electric vector. (*b*) Same as *a*, but with the electric vector of the Polaroid sheet at 151.5°, which is predominately along the minor axis. The filaments nearly disappear in this position of the electric vector.

observed surface brightness of the brightest filaments is 10 times higher than can be accounted for by dust scattering alone.

Our new interpretation in terms of synchrotron radiation rests on the evidence of Fig. 2, which shows the results of photographic polarization plates taken in yellow light with the 200-inch Palomar reflector in February 1964. The plate and filter combination of Kodak IIa-D plates plus 2 mm of Schott GG11 glass plus a sheet of HN38 Polaroid material records in a region of the spectrum free of emission lines from 5000 to 6200 Å. The upper reproduction of Fig. 2 (*a*) is made from two superposed negatives, one of 120-minute and the other of 68-minute exposure, with the electric vector of the Polaroid sheet at a position angle (measured north through east) of 61.5°—that is, nearly along the major axis of the galaxy. The lower reproduction (*b*) is made from two negatives of the same type and exposure times, taken on the same night and developed with the first pair, but with the electric vector of the Polaroid sheet in a position angle 151.5° (nearly parallel to the minor axis of the galaxy). The brighter parts of the filaments are nearly 100 percent polarized with the electric vector perpendicular to the predominant direction of the filaments. The southern outer arch filament near the top of Fig. 1*b*, originally discovered by Johnson, appears faintly on both Fig. 2*a* and 2*b*, but this is to be expected even if it is highly polarized because its position angle is nearly midway between the positions of the instrumental electric vectors of Fig. 2*a* and 2*b*. No photographs have yet been obtained at the proper position angles to check the polarization of this feature.

Figure 3*a* shows a highly enlarged part of the minor axis of M82 on the south side to show the details of the filamentary structure. The topmost picture is enlarged from the composite blue photograph of Fig. 1*a*. Here several rope-like structures are seen rising out of the main body of the galaxy. The same features appear in nearly every detail in Fig. 3*b*, which is enlarged from the yellow polarization photograph of Fig. 2*a* where the electric vector is along the major axis. The filaments are, however, fainter in yellow wavelengths than in blue, which is characteristic of optical synchrotron radiation as observed with broad-band filters of the U,B,V system (see the calculations by Sandage in the appen-

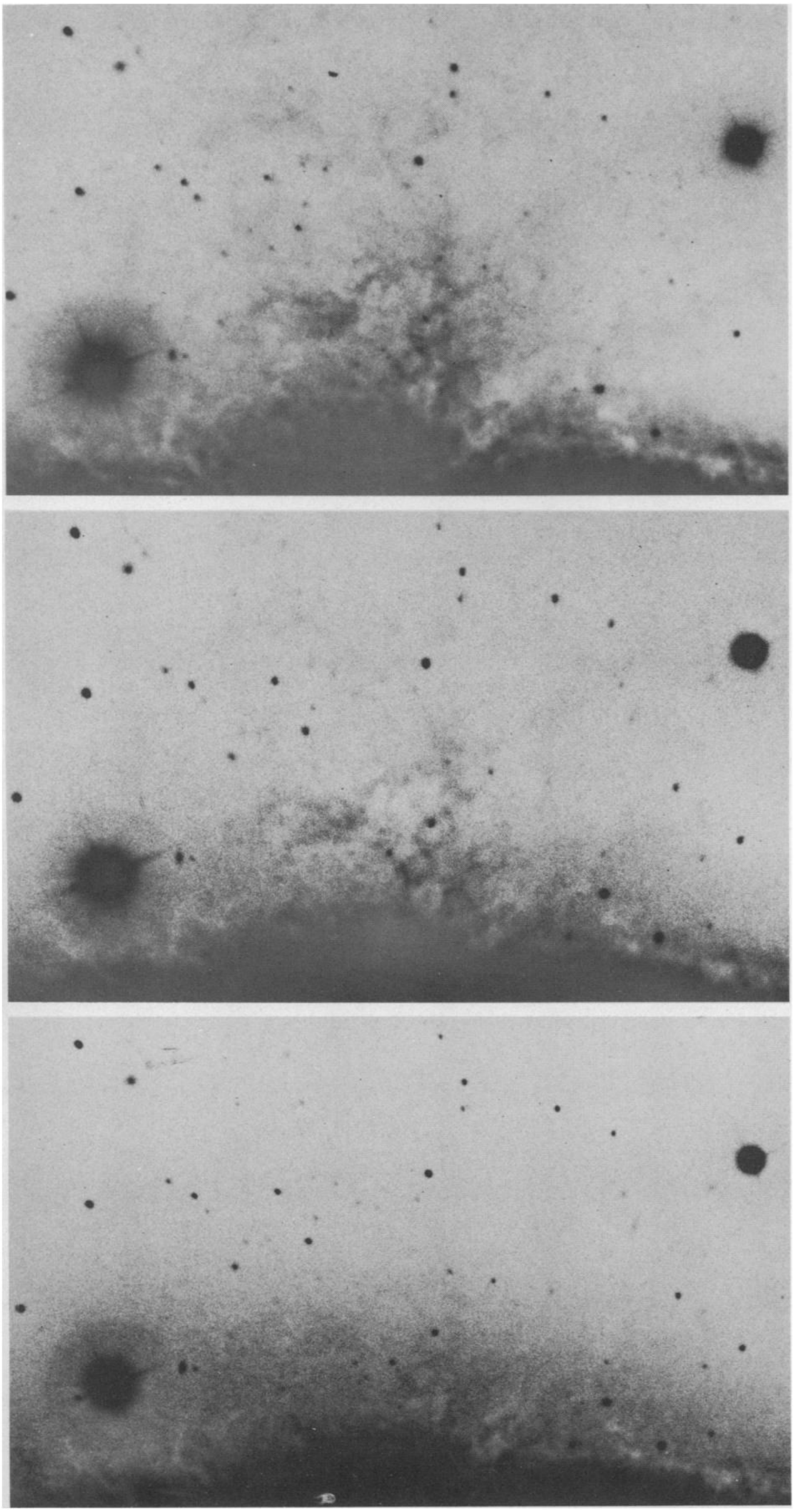

Fig. 3. (*a*) Enlarged section of Fig. 1*b* taken in blue light, showing details of part of the southeast section of the minor axis near the fundamental plane. The rope-like structure of one of the filaments is a prominent feature. (*b*) Enlarged section of the polarization composite in Fig. 2*a* taken in yellow light, showing that most of the details of Fig. 3*a* are visible when the electric vector is along the major axis. (*c*) Enlarged section of Fig. 2*b* taken in yellow light with the electric vector of the Polaroid sheet nearly along the minor axis, showing that most of the filamentary detail disappears.

dix of reference 5). Most of the structures disappear in Fig. 3*c*, which is enlarged from Fig. 2*b* where the electric vector is along the minor axis.

The most likely interpretation of these results is that a magnetic field is present and is aligned predominately along the minor axis of M82. This field extends into the halo above and below the major axis to angular distances of 4.8 minutes of arc on the south side and 3.9 minutes of arc on the north side, which is the extent of the filamentary system shown in Fig. 1*b*. The distance of M82 is estimated to be $d = 9.8 \times 10^{24}$ cm (*2*), which gives the extent of the magnetic field as 4.4×10^3 parsec (1.3×10^{22} cm) from the plane of the galaxy on the south side and 3.9×10^3 parsec (1.2×10^{22} cm) from the plane on the north side.

It would seem that M82 may be the first galaxy in which large-scale magnetic field structure has actually been observed. Detailed mapping of the field is planned when more extensive polarization plates, taken in blue light at a variety of position angles, are available. The origin of the field can only be guessed, but it may have originally been present in the main body of the galaxy and have been drawn out by the plasma thrown poleward in the initial explosion along the minor axis.

Calculation of the energetics of the entire system (*2*) has shown that the average magnetic field strength probably lies between 10^{-5} and 10^{-6} gauss. The energies of the electrons causing the optical radiation are then exceedingly high, as shown by the following calculation.

A single relativistic electron of energy E moving in a field of strength $H_\perp$ perpendicular to the motion of the electron will radiate energy near frequency ν given by

$$\nu = 1.6 \times 10^{13} H_\perp E^2$$

where ν is in cycles per second, H is in gauss, and E is in Bev (10^9 ev). It is likely that ν for the optical synchrotron component of M82 is at least 10^{15} cy/sec as required by Figs. 1*b*, 2*a*, and 2*b*, and by the condition that the photoionization energy of the Hα recombination filaments comes from the synchrotron emission. This gives $E = 2.5 \times 10^3$ Bev if $H = 10^{-5}$ gauss and $E = 8 \times 10^3$ Bev if $H = 10^{-6}$ gauss—energies which are in the cosmic ray range. On the previously proposed M82 model (*2*) the average energy density of the electrons alone is in the range of 10^3 ev/cm^3, which is about 1000 times the energy density of the proton component of cosmic rays in the solar neighborhood of our own galaxy. Thus, on energy density arguments alone one might speculate that cosmic rays in our own galaxy may have originated in an event similar but less energetic than the explosion now occurring in M82.

A final word is necessary concerning the methods used in preparing the illustrations for this report. First, all reproductions are in negative form, that is, black stars against a light background. This technique is widely used in the preparation of astronomical prints intended to show threshold images because the eye detects a small increment of density much more readily against a light background than against a dark one.

Second, all reproductions except Fig. 1*a* are composite prints made from two or more superposed original negatives. Such prints gain over a single negative print in the detection of faint images for two reasons. (i) The signal-to-noise ratio increases by $N^{1/2}$ where N is the number of plates stacked together to make the composite. (ii) The contrast of the final print for threshold images is increased by N. The main disadvantage of superposition photography is that the increase in contrast, so essential to bring out the faint details, exceeds the latitude of the printing material to such an extent that detail is quickly lost in the bright parts of the image.

The problem can be overcome by the use of "masks" to control the gross density gradient over the area of an image. It is a refinement of the method of manual "dodging" during the printing operation to prevent over-exposure of bright areas and is more satisfactory because the images do their own dodging by "negative feedback" control.

An unsharp print of the printing positive is made on a suitable film or plate, with exposure and development time controlled to produce a density range which is the reverse of and slightly less than that of the printing positive. When registered with the positive and printed on high-contrast paper or film, the faint structural details of the image are retained without exceeding the latitude of the printing material.

In the case of Figs. 1*b*, 2, and 3, the density range of the combined images so far exceeds the latitude of the positive material that no amount of masking will retrieve detail in the brightest regions near the center. Hence no detail is visible in the nucleus of the galaxy. However, the masks have so greatly reduced the density gradient along the edges of the galaxy that detail has been held in areas that would otherwise have been completely black.

Since the masking technique has a progressive effect upon the image as one nears the bright portions of the galaxy, it is important to remember that no conclusions can be drawn from the illustrations in this report concerning the relative brightness of filaments at different distances from the galaxy.

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Fission Damage in Calcite and the Dating of Carbonates

Abstract. *Fission damage induced in calcite is shown by etch pits developed with weak acid at the damage sites. The damage can be differentiated from dislocations by annealing. By this method we have observed fossil fission damage in natural samples. Thus, some etch pits previously attributed to dislocations actually result from such damage. Annealing studies indicate that the damage should persist for about 4×10^7 years at 50°C, and direct evidence suggests that the fission damage has persisted for at least 10^6 years in one specimen.*

The discovery of fossil fission tracks in micas and glasses, and their use for dating these minerals correctly in many cases is a very significant development (*1, 2*), particularly since it is now known that etchable damage may be produced by fission fragments in other minerals, notably gypsum, quartz, and othoclase (*2*). Etch pits may be produced in such minerals as lithium fluoride by preferential chemical attack at the sites of damage produced by fission fragments penetrating the crystal (*3*). The dating of any mineral by a similar technique appears possible if (i) the