PUBLICATIONS OF THE NATIONAL RADIO ASTRONOMY OBSERVATORY

Volume 1 August 1963 Number 17

THE STRUCTURE OF M 82

Hugh M. Johnson

ABSTRACT

1. The origin of the A5 spectrum is discussed. 2. The image is shown to incorporate elliptical hoops of galaxy size around the rhombus of the main body.

I. INTRODUCTION

M 82 = NGC 3034 = 3C 231 has recently excited much interest because of its combination of peculiarities: (1) It is one of a small group of galaxies which Holmberg (1950, 1958) classified Ir II, i.e., it is "irregular" but not resolved into absolutely bright stars as are ordinary irregular galaxies, such as the Magellanic Clouds, or its Sb neighbor, M 81, at the same distance. (2) The integrated spectral type in the photographic region is A5 with superposed nebular emission lines (Humason, Mayall, and Sandage 1956), but the integrated international color index is +0.81 magnitude (Holmberg 1950, 1958). Indeed, the color and lack of resolution led Holmberg to believe that Ir II galaxies were composed of Population II stars, despite the early integrated spectral type. No galaxy in the list of Humason et al. is assigned an earlier type than A5. (3) The light is polarized up to 15 per cent from point to point (Elvius 1962). (4) The galaxy is a radio source with the peculiarity of a spectral index of -0.2 (Lynds 1961), -0.21 (Heeschen 1961), or -0.23 (Conway, Kellermann, and Long 1963), flatter than that of the Crab Nebula, -0.26 (Lequeux 1962a), or -0.27 (Conway et al. 1963). The half-intensity diameter of a gaussian representation of the source is only 45" at 1420 Mc/s (Lequeux 1962b). It is circular. Unfortunately, its position is not known to be centered on the optical image, because of an error of ± 3' in declination. (5) The optical radial velocity of M 82 is excessive with respect to the radial velocities of other members of the M 81 group (Holmberg 1952) and also with respect to the main component of the neutral hydrogen velocities (Volders and Högbom 1961). This is partly a question of the rather arbitrary center used for the rotational component of the velocities in M 82.

Those are a few of the peculiarities of M 82 that have been known before 1963. Some of them are discussed by Mrs. Elvius (1962) and Markaryan (1962). The most recent interpretation of M 82 is that of Lynds and Sandage (1963). The polarization of light in the galaxy, the structure of its H II regions, which happen to be filamentary, and the nearly flat radio spectrum, suggested to Lynds and Sandage an analogy between

---

The National Radio Astronomy Observatory is operated by the Associated Universities, Inc., under contract with the National Science Foundation.

M 82 and the Crab Nebula. However, in so far as the analogy depends on the filamentary structure of the two systems, it appears to be questionable for the following reasons: the filaments of the Crab Nebula show no continuum, synchrotron or other kind, are not polarized themselves, and bear no clear-cut vectorial relationship to the electric vectors of the synchrotron radiation of the amorphous structure (Johnson 1963b): the yellow continuum of the M 82 filaments observed by Lynds and Sandage may be the bound-free, two-quantum, and scattered-light continua found in ordinary H II regions that contain dust; and it is not clear that the polarized light belongs to the H II regions of M 82.

Synchrotron radiation in M 82 becomes more interesting if it is spread over the image. Figure 1 summarizes the absolute spectral information about M 82 and the Crab Nebula, connecting the radio data with the optical data. The Crab Nebula data are from O'Dell (1962) and the M 82 data from Heeschen (1961). The integrated visual and photographic magnitudes of M 82 (Holmberg 1958) and the Crab Nebula (Woltjer 1957) are respectively equal within a quarter of a magnitude, so that a radio spectral index between zero and -0.1 would extrapolate the radio data of M 82 to its observed optical flux. Monochromatic emissions add little to the integrated light of the Crab Nebula, and the same is probably true of M 82. Within the optical frequencies the slope of the spectral curve of M 82 is steeper than that of the Crab Nebula because the integrated international color index of the Crab Nebula is +0.50 magnitude. M 82 is probably affected by greater interstellar reddening, although the value of its mean surface brightness is high among the values computed from the data in Holmberg's (1958) catalogue of 300 galaxies.

II. THE A5 SPECTRAL TYPE

Several per cent of galaxies (Humason et al. 1956) and globular clusters (Kron and Mayall 1960) are classified to be integrated spectral types A5-9. The mean integrated international color index of the type A globular clusters is about +0.5, at galactic latitudes $|b| \geq 37°$. Undoubtedly the 0.3-magnitude greater redness of M 82 may be a result of additional reddening by interstellar dust in M 82. However, M 82 is a peculiar radio source and is composed partly of neutral hydrogen, as globular clusters are not observed to be. These features of this galaxy make it worth mentioning a possible non-stellar source of the Balmer absorption and emission lines.

Volders and Högbom (1961) have found that about five per cent of the mass of M 82 is neutral hydrogen. It is not known how much this may be in error from the assumption of purely gravitational dynamics in the use of the radial-velocity data, or in error because these data (Mayall 1960) extend for only half of the major axis of the main body. But it is possible that the A5 spectrum of M 82 originates in its interstellar neutral hydrogen in the way that Gurzadyan (1959, 1960) has hypothesized for the origin of the Balmer absorption-line spectrum of NGC 2261, Hubble's variable nebula. This is a comet-shaped galactic nebula discovered by Herschel in 1783, when it had about the same shape and size as it has at present. Gurzadyan supposes NGC 2261 to be a peculiar source of synchrotron radiation. The incentives for Gurzadyan's hy-

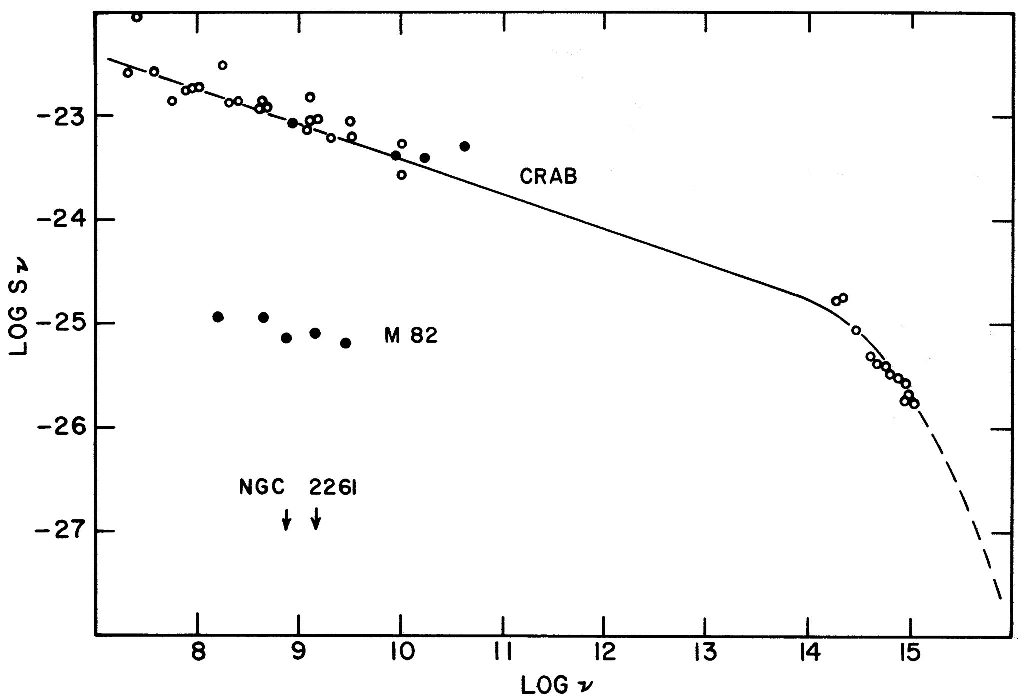

Fig. 1 -- The logarithm of the flux in units of w $m^{-2}(c/s)^{-1}$ versus frequency for the Crab Nebula, M 82, and NGC 2261. The arrows are approximate upper limits for the latter's radio-frequency flux. The optical magnitudes of M 82 practically agree with the magnitudes of the Crab Nebula, with no corrections for interstellar extinction in the data of M 82.

pothesis are the great brightness of the nebula in comparison with the star (R Monocerotis) in the nebula, the strong polarization of the nebula, and the variability of the object, which somewhat resembles that of the Crab Nebula.

From the equivalent width of Hδ in absorption and of Hα in emission, Gurzadyan determines a ratio of ionized hydrogen to neutral hydrogen of about $n^+/n_1 = 0.1$ in NGC 2261. He relates the population of the second level of the hydrogen atom to the radiation of the hypothetical synchrotron continuum beyond the Lyman limit via its production of Lyα quanta throughout the nebula.

III. REMARKS ON NGC 2261

Of course, NGC 2261 is not a known radio source. It has not been detected at 750 Mc/s or 1400 Mc/s with the 300-foot telescope in records with an r. m. s. fluctuation of 0.1 flux unit. These r. m. s. levels are plotted as upper limits in Figure 1. Since NGC 2261 probably averages over one magnitude fainter visually than either M 82 or the Crab Nebula, its optical flux is about one-half unit in log $S\nu$ below the graph of the Crab Nebula in Figure 1. The spectral index of NGC 2261 must be positive between the radio and optical frequencies. If NGC 2261 is a source of synchrotron radiation, as Gurzadyan thinks, its magnetic field is probably bounded by a cone, the brighter nappe of which contains the source of high-energy electrons, R Monocerotis, a little north of the vertex. Few of the electrons can leak past the vertex (or field waist) into the fainter southern nappe. In this configuration all of the relativistic electrons may quickly leave the nebula, and not be trapped inside as some must be in the Crab Nebula.

IV. THE HOOP STRUCTURE OF M 82

On January 22 the writer exposed four unfiltered blue-sensitive plates on M 82 in the Crossley reflector. Each exposure was one hour long. In a way already described (Johnson 1963a), a contact positive Kodalith Ortho (high-contrast) film was made of each plate, and the four films were sandwiched in register and enlarged as a single film on Kodalith Ortho paper, from which print Figure 2 has been made. Figure 2 shows fairly well the details to be discussed here. The main body of M 82 images approximately as a rhombus, 12!8 on the major diagonal at about PA = 60°, by 5!4 on the minor diagonal, whose interior details are "burnt out" in the high-contrast process. Superposed on this image is a relatively faint system that appears to be approximately elliptical hoops. The largest of these is apparently a not quite complete ellipse 10!5 x 8!7 with a major axis at about PA = 140° and centered about 0!3 north and 1!7 east of the center of the main-body rhombus. If the perimeter of this ellipse is interpolated across the main body of the image, it passes about 1' west of the center of the rhombus. The most distinct part of the largest ellipse is in the southeast quadrant. It disappears or becomes ragged in the north. One or two smaller and less distinct apparent hoops are visible within the largest one, but they are largely masked by the main-body image. It is likely that the elliptical hoops represent extensions of

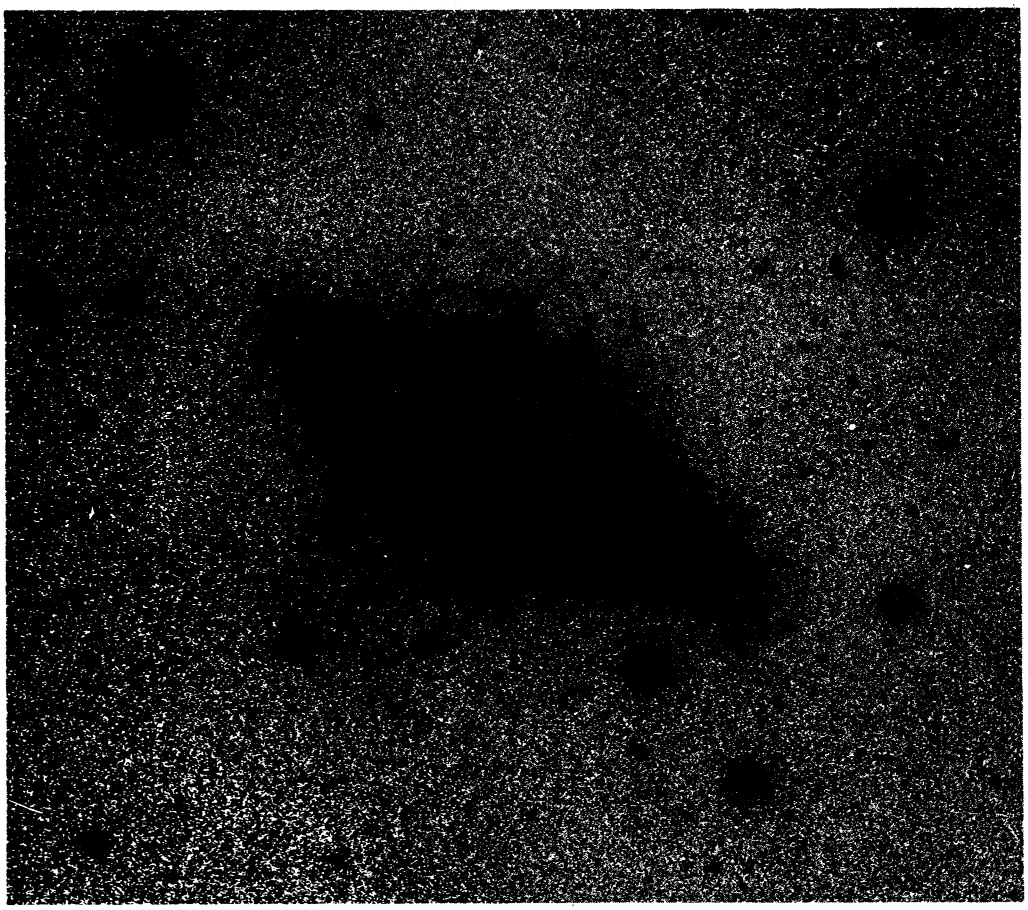

Fig. 2 -- A high-contrast print of M 82 showing a system of hoops superposed on the main rhomboidal image. It is made from a fusion of four blue-sensitive plates taken with the Crossley reflector. North is at the top, east is to the left. The scale of the reproduction is 9."6/mm.

the filamentary system discussed by Lynds and Sandage. The filaments that they discuss extend about 2' or 3' from the center, mostly in the direction of the minor axis, where they protrude somewhat from the main body of the image. Lynds and Sandage treat their new observations of the filamentary system of M 82 under the hypothesis that it is evidence for a recent explosion in the center of that galaxy. However, the next two paragraphs argue against that geometry and kinematics.

The most nearly similar galaxy known to the writer is NGC 2685 (Burbidge and Burbidge 1959, Sandage 1961). Figure 3 is a reproduction of it from The Hubble Atlas of Galaxies. Three points of similarity between M 82 and NGC 2685 are: the rhomboidal main body, the elliptical hoops extending roughly at right angles to its major axis, and, especially in NGC 2685, the appearance that the hoops encircle the main body because the dust in each hoop silhouettes where it crosses the main body. The writer suggests that the well-known rather irregular dust lanes silhouetting in M 82 are entirely analogous features. As shown in Figure 4, they tend to run parallel with the M 82 hoop where it crosses the rhombus, and not parallel with the major axis of the main body as is true of the dust in most galaxies seen edge on. The strongest dust lane of M 82 especially well parallels the transverse hoop. In fact, the eye is puzzled by the appearance of the dust in M 82 until it sees this suggestion. There is, however, the appearance of some shearing of the dust lanes as though by involvement in the rotation of M 82 on its minor axis. Such shearing is also suggested by the distortion of the Hα and [N II] emission lines that Duflot (1963) has observed near the center of the main-body image. These points are very important, since they tend to describe the hoops in three dimensions outside the nucleus of M 82. They would probably remove the filamentary system from the central seat of the explosion hypothesized by Lynds and Sandage. They also make the dust useless for determining the inclination of the equatorial plane of the main body of M 82 to the line of sight.

The linearity of the graphs of Figure 5 suggest that the velocities are observed respectively in the rim of the main body and in the perimeter of the hoop as it rotates in its own plane. The period of rotation is given by the expression 9.4×10^7 yr/c, where c is the slope of the graph in km/sec per second of arc, at the distance of 9.76×10^{24} cm adopted by Lynds and Sandage. The period of the main body is then 6×10^7 yr and the period of the hoop is 4×10^7 yr, allowing for the projection of plane of the hoop on the line of sight and for the inclination of the spectrograph slit at PA = 155° to the major axis of the image of the hoop at PA = 140°.

There is an interesting dissimilarity between the hoop systems of M 82 and NGC 2685, if the M 82 hoops are generally strongest in Hα, according to the hypothesis that they are H II regions containing dust. For, on Palomar Sky Survey prints, the red image of the hoops of NGC 2685 is somewhat weaker than the blue image, contrary to the behavior of all normal H II regions, and contrary to the behavior of the nubbins of the M 82 hoops at the edges of the image on the Palomar prints. But NGC 2685 is not an observed radio source: it has not been detected with the 300-foot telescope to limits of about 0.2 flux unit at 750 Mc/s or 0.3 flux unit at 1400 Mc/s (C. M. Wade, unpublished). It is about 2.9 magnitudes fainter than M 82 (Holmberg 1958) so that its flux should be about 0.5 flux unit if it were an M 82 removed to the distance that reduces M 82's brightness by 2.9 magnitudes. Therefore, on Woltjer's (1958) and Gurzadyan's (1959, 1960) mechanism of photoionization of nebular gas by the ultraviolet

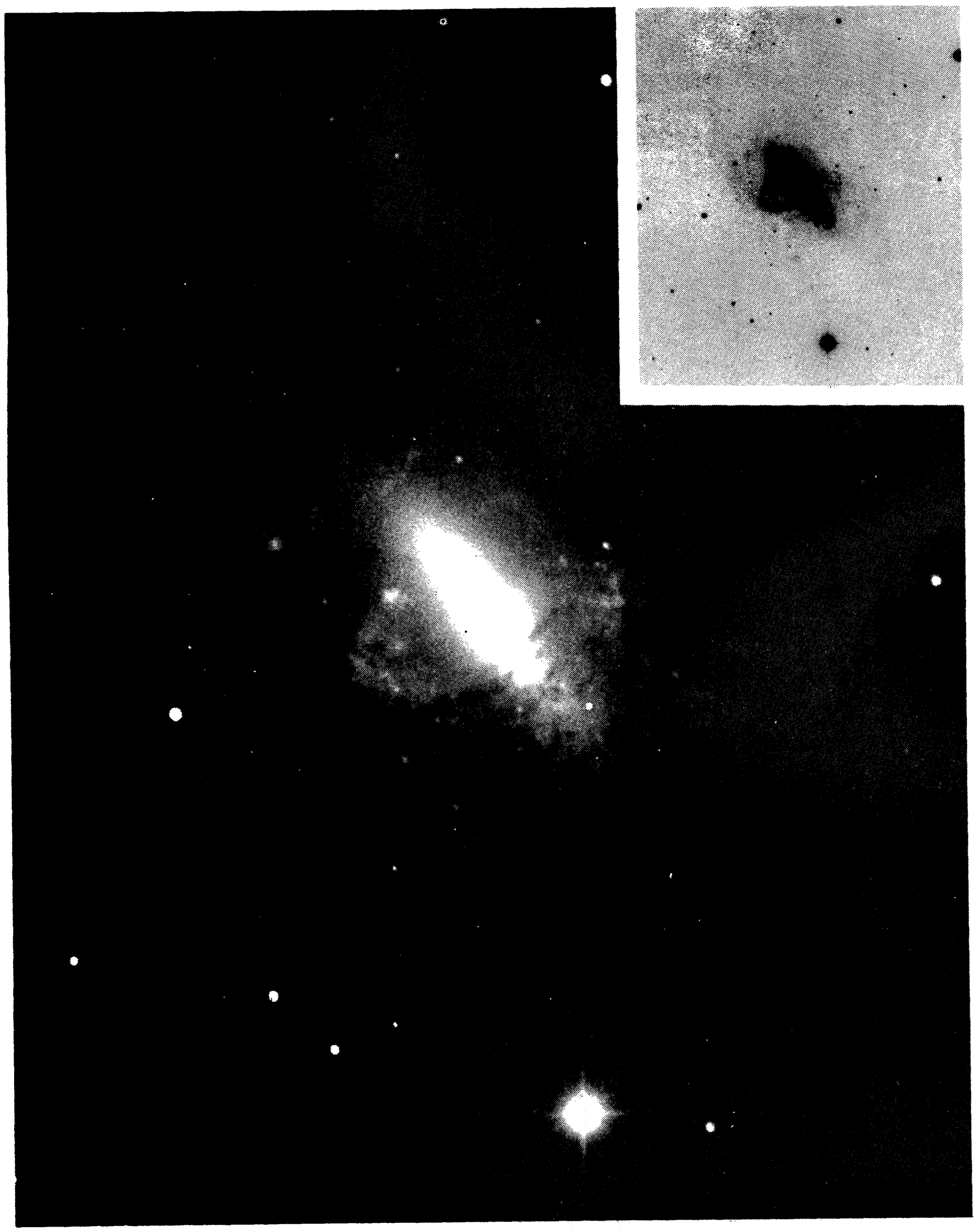

Fig. 3 -- NGC 2685, reproduced from page 7 of The Hubble Atlas of Galaxies, for comparison with M 82. By courtesy of the Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology.

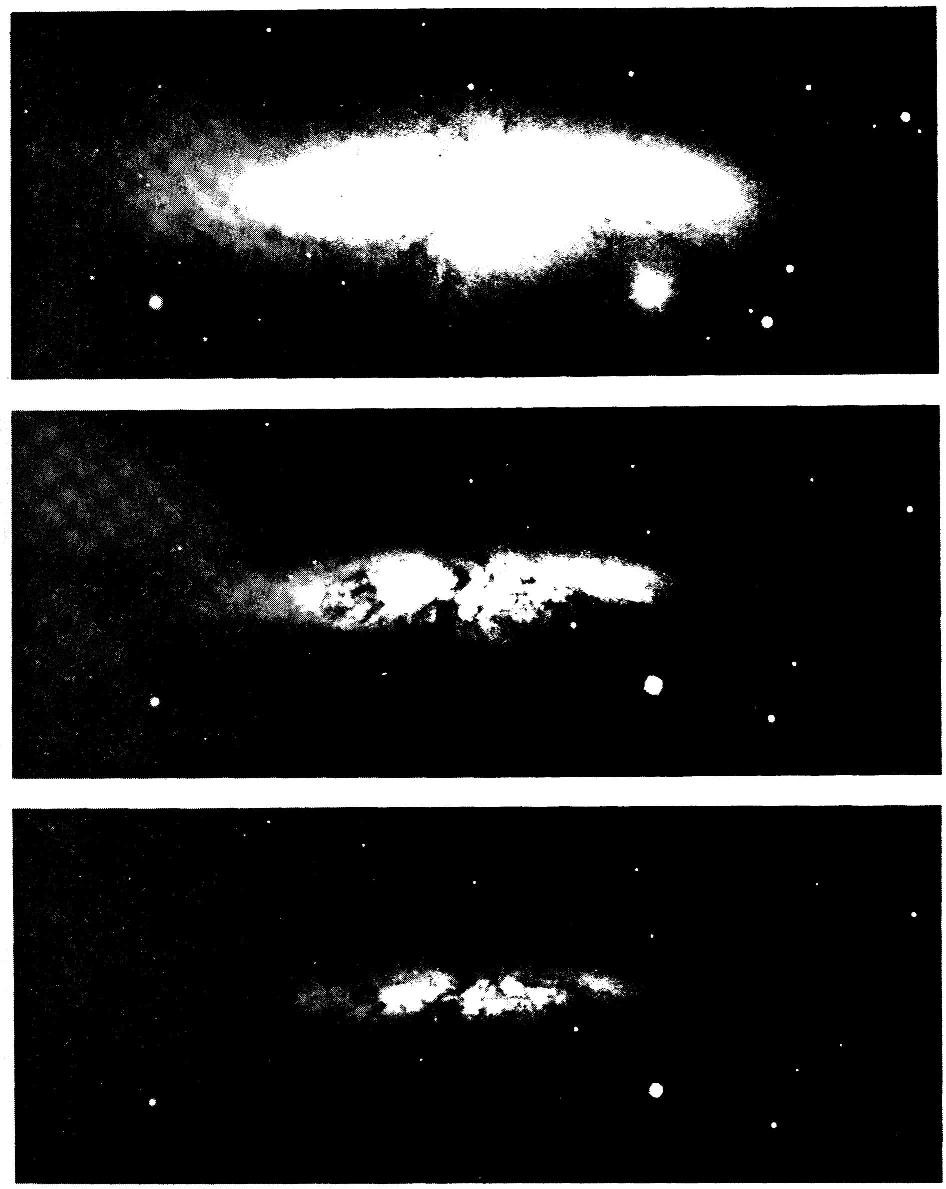

Fig. 4 -- M82, reproduced from page 41 of The Hubble Atlas of Galaxies, showing the inner details, especially the dust lanes. North is toward the upper left, west is toward the upper right (see the diffraction spikes on the brightest star). The scale of the reproduction is 5ʺ.6/mm, so that it would have to be multiplied by a factor of 0.58 to be on the same scale as that of Figure 2. By courtesy of the Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology.

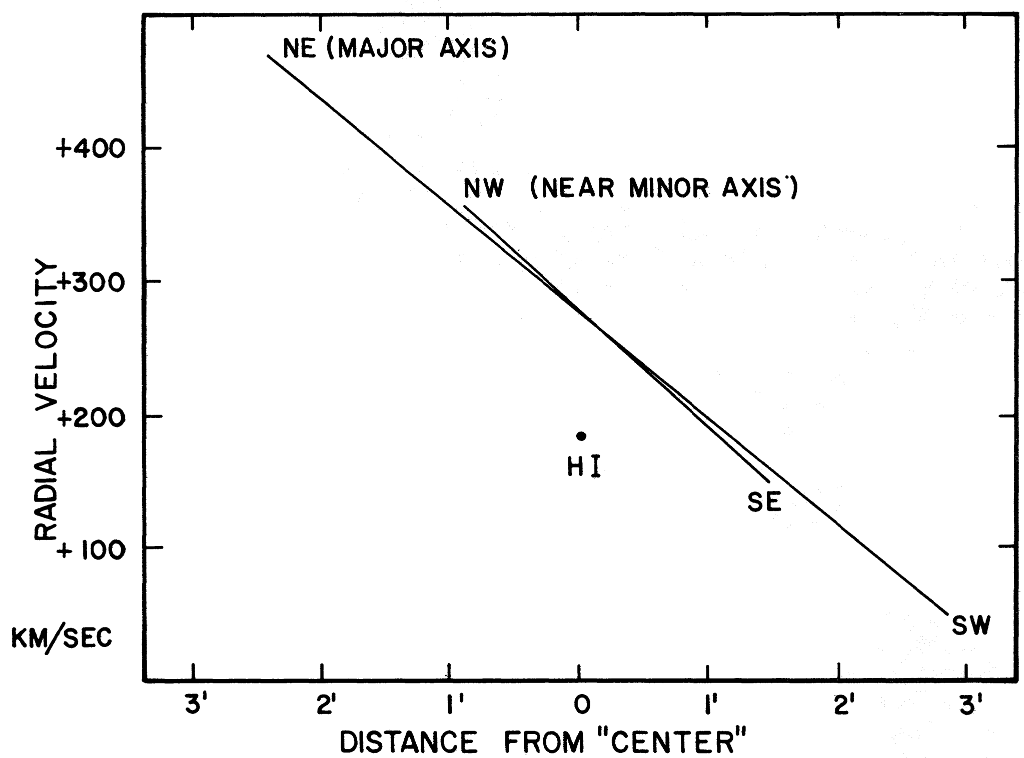

Fig. 5 -- Radial velocities (reduced to the sun) in M 82: Mayall's (1960) graph of velocities on the major axis of the main body, and Lynds and Sandage's (1963) graph of velocities on a slit in PA = 155° near the minor axis. The point labelled H I shows the radial velocity of the main component of the neutral hydrogen (Volders and Högbom 1961). The "central" axis is fairly arbitrary.

synchrotron radiation of a radio source, the hoop structures of M 82 and NGC 2685 may be quite analogous except that the gas in the latter is deprived of an ultraviolet source of ionization.

The hoops of NGC 2685 may shine simply as reflection nebulae, the light source being the galaxy. It is also a possibility for explaining the light of the faint northeast-southwest extensions of NGC 5128 (Johnson 1963a). The electric vectors of the polarized light of M 82 in the fringes of the main body, at all position angles around the center, are arranged very nearly as normals to radii from the center. This is consistent with scattering of central light by dust (Elvius 1962); it might also be consistent with polarized synchrotron radiation in a special arrangement of the magnetic field.

V. SUMMARY

This paper has dealt with two aspects of M 82: the problem of the spectrum, and the problem of the hoop structure.

It is suggested, following Gurzadyan's treatment of cometary nebulae, that the second level of the interstellar hydrogen atoms in M 82 may be populated so as to produce the A5 spectrum. The continuum may be a mixture of the direct light of absolutely faint stars, direct optical synchrotron radiation, and light scattered by dust. It remains to be seen whether synchrotron radiation contributes enough light to reduce mass/luminosity ratios below "normal" in M 82 or other galaxies.

An analogy with the hoops of NGC 2685 is suggested. The M 82 hoop is very faint, so that spectrographic velocity observations completely around it would be costly. Obviously, a rotating hoop can give the same change of sign of the radial velocities, depending on position in the hoop, that a central explosion confined to a tilted axis can give.

VI. ACKNOWLEDGEMENTS

The writer thanks Dr. G. H. Herbig for granting him time to use the Crossley reflector in January, 1963, and again in April, when, unfortunately, it was cloudy. He also thanks Mr. J. B. Breckinridge for an attentive induction into the use of the Crossley reflector, Drs. Lynds and Sandage for the opportunity to read their paper in February before publication, and Dr. Wade for his unpublished data on NGC 2685.

REFERENCES

Burbidge, E. M., and Burbidge, G. R. 1959, Ap. J., 130, 20.

Conway, R. G., Kellermann, K. I., and Long, R. J. 1963, M.N., 125, 261.

Duflot, R. 1963, C. R., 256, 3965.

Elvius, A. 1962, Lowell Obs. Bull., 5, 281.

Gurzadyan, G. A. 1959, Comm. Burakan Obs., No. 27, p. 73.

______. 1960, Dokl. Akad. Nauk U.S.S.R., 130, 47 = Soviet Phys.-Dokl., 5, 7.

Heeschen, D. S. 1961, Pub. N.R.A.O., 1, 129.

Holmberg, E. 1950, Medd. Lunds Astr. Obs., Ser II, No. 128.
__________. 1952, ibid., Ser. I, No. 180.
__________. 1958, ibid., Ser. II, No. 136.
Humason, M. L., Mayall, N. U., and Sandage, A. R. 1956, A. J., 61, 97.
Johnson, H. M. 1963a, Pub. N.R.A.O., 1, 251.
__________. 1963b, Pub. N.R.A.O., 1, 261.
Kron, G. E., and Mayall, N. U. 1960, A. J., 65, 581.
Lequeux, J. 1962a, Ann. d'Ap., 25, 221.
__________. 1962b, C. R., 255, 1865.
Lynds, C. R. 1961, Ap. J., 134, 659.
Lynds, C. R., and Sandage, A. R. 1963, Ap. J., 137, 1005.
Markaryan, B. E. 1962, A.J.U.S.S.R., 39, 1041 = Soviet Astr. - AJ, 6, 808.
Mayall, N. U. 1960, Ann. d'Ap., 23, 344.
O'Dell, C. R. 1962, Ap. J., 136, 809.
Sandage, A. 1961, The Hubble Atlas of Galaxies (Washington: Carnegie Institution of Washington).
Volders, L., and Högbom, J. A. 1961, B.A.N., 15, 307.
Woltjer, L. 1957, B.A.N., 13, 301.
__________. 1958, ibid., 14, 39.