RECENT RADIO STUDIES OF BRIGHT GALAXIES

J. H. OORT
Sterrewacht te Leiden, The Netherlands

Abstract. Some results are discussed of recent – still largely unpublished – high-resolution studies of bright spirals, both in the radio continuum and in the 21-cm line radiation. Special emphasis is given to observations of M51, M81 and NGC 4258.

The most important new data are (1) Estimates of the contrast in gas density between arms and interarm regions (M81 and M101); the contrast appears to be quite strong. It provides an important parameter for the density wave. (2) Evidence for a pronounced decrease of gas density along the arms when these are followed towards the centre. Considerable line radiation is observed from outer regions where the optical intensity of the arms is very low. (3) Extension of rotation curves to larger distances from the centre. (4) Data on the motions in the spiral waves. (5) Determination of the shift between synchrotron and optical arms, providing direct evidence for the formation of stars as a consequence of the passage of the interstellar gas through the spiral density wave. From the shift measured in M51 the formation time is found to be roughly ten million years. If the data for (2) are ascribed to the depletion of the gas by star formation, the average net fraction of the gas consumed in star formation is found to be between 2 % and 3 % per passage through the spiral wave (Table I). (6) Separation of nuclear and disk synchrotron radiation in spirals. (7) Evidence for a recent expulsion of about 10^6 solar masses from the nuclear region of NGC 4258.

A new era has started for the study of spiral galaxies by means of radiowaves. The completion of large synthesis radiotelescopes has for the first time opened the possibility of studying galaxies with sufficient resolution to observe individual spiral arms, and much of the following discussion is based on such observations made by Leiden and Groningen astronomers with the 1.5-km synthesis radiotelescope at Westerbork in The Netherlands.

1. Gas

1.1. General spiral distribution

For a proper study of spiral structure and its dynamics it is desirable to observe galaxies in which spiral arms can be traced throughout the entire system although, for a confrontation with spiral-wave theory, the arms should not be *very* open. Among the nearer spirals above $+30°$ declination, M81 and M51 appear to be the most suitable. M31, in which better resolution can be obtained, has too high an inclination for the arms to be traced unambiguously throughout, a difficulty which presents itself more seriously still in our own Galaxy. However, in our Galaxy the larger angular scale enables one to study much weaker features. In particular, this circumstance makes it a unique object for investigating the expanding features in the central region, and also the influx of intergalactic gas.

Hydrogen line observations at 21 cm with an angular resolution of $1'.5 \times 3'.0$ have been made of M33 in Cambridge (Wright *et al.*, 1972) and detailed optical measures of the numerous emission nebulae have enabled French observers to study the very asymmetrical motions of the irregular individual arms in this galaxy. For M31 there is a still unpublished investigation by Emerson in Cambridge, while observations

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with a 70 × 100 pc beam for a region within about $\frac{1}{2}°$ of the centre have been obtained at Westerbork. At Westerbork extensive high-resolution line observations have also been made for M51, M81, M101 and IC 342, all of which are normal spirals with well-defined spiral arms, M101 and IC 342 being more open and somewhat less regular

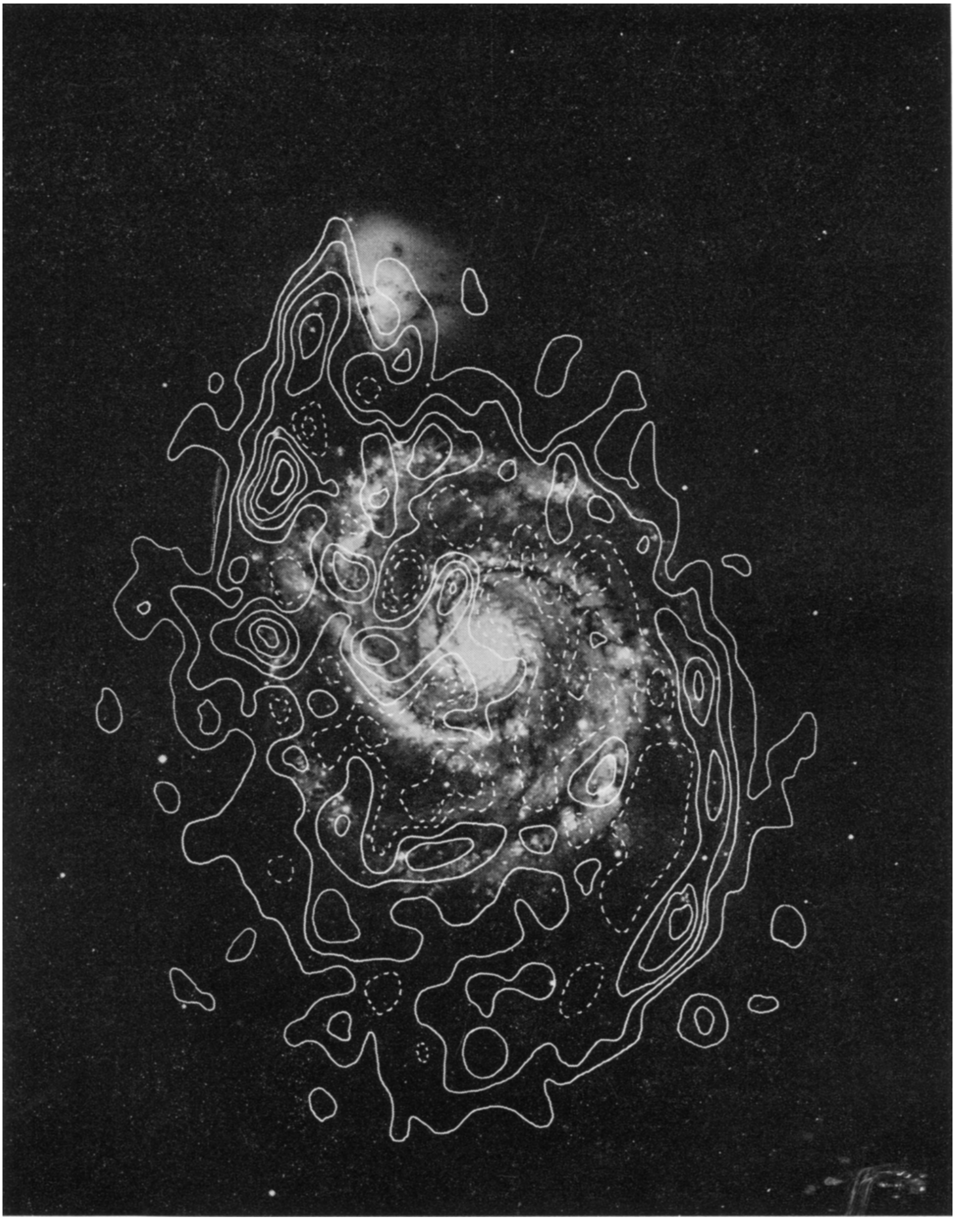

Fig. 1. **Neutral hydrogen distribution in M51 measured with the Synthesis Radio Telescope** at Westerbork. Half-power beamwidth 24″ in right-ascension and 32″ in declination. Contour interval 3.75×10^{20} atom cm^{-2} (Shane and Bajaja, preliminary results).

than M51 and M81. Equally extensive measurements were made on the explosive spiral NGC 4258 and on the barred spiral NGC 5383.

Figures 1 and 2 show the hydrogen distribution in M51 and M81, as observed in Westerbork with beams of 28″ and 50″ respectively, corresponding to 1.3 and 0.8 kpc. The two galaxies are of different types: M81, which has a strong central bulge, has been classified by Sandage as Sab, and M51 as Sc. The pitch angles of the arms are

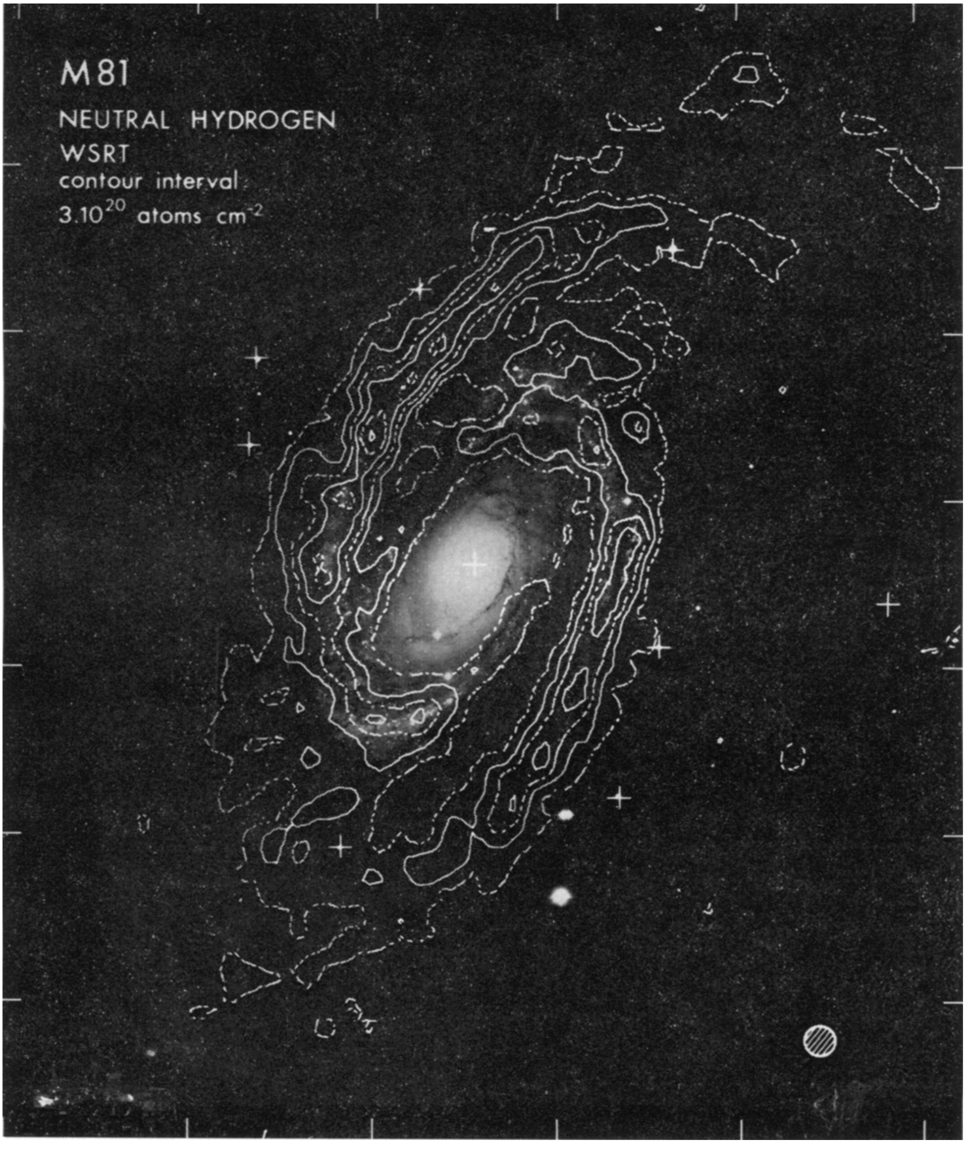

Fig. 2. Neutral hydrogen distribution in M81 measured with the Synthesis Radio Telescope at Westerbork. Half-power beamwidth is shown in the lower right-hand corner. Co-ordinate intervals are 1 min in α and 5′ in δ. (Rots and Shane, in preparation).

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not very different, being 16° out to 7–8 kpc in M51 and varying from 11° at $R=4$ kpc to about 17° at $R=9$ kpc in M81. There is a pronounced difference in the frequency of emission nebulae, which are abundant in M51 and rather scarce in M81. The fraction of the mass that is in gaseous form, as judged from the H I emission, is perhaps about 3 times larger in M51. In both galaxies the H I is strikingly concentrated in the spiral arms. It also extends to large distances from the centre, where the optical surface brightness has become small.

For the first time detailed H I observations of a barred spiral have become available, viz. of the giant SBc galaxy NGC 5383. The results, on which Dr Allen has reported (this volume, p. 425), are remarkable. Again the hydrogen extends to very large distances from the centre but, contrary to what is found in most other galaxies for which high-resolution data are available, NGC 5383 has a pronounced concentration of H I in and around the optically very bright nucleus.

It is important for the theory of the spiral waves for us to know the contrast of the gas densities in and between the arms. Unfortunately the observations are not yet quite good enough to provide a trustworthy answer. This is due to three factors: the insufficient sensitivity, the lack of knowledge about the true zero level in M81 (because the zero spacings were still missing), and finally the rapid decrease of the density with decreasing R which I shall discuss in the following. All we can say from the present data in M81 and M51 is that the ratio between the density in the central ridges of the arms and that between arms is probably at least 3. For the outer arms in NGC 4258 it seems to be much higher.

1.2. Rate of star formation at different distances from the centre

The estimates of the contrast between arms and interarm regions are difficult because of the superposition of another very striking phenomenon. Along the spiral arms the gas density decreases strongly when passing from the outer to the inner regions. In the arms of M81 the column density decreases from about 1.6×10^{21} atom cm^{-2} at $R=9$ kpc to about 0.6×10^{21} at $R=3.3$ kpc; inside this distance it becomes unmeasurable with our present equipment. (The column densities quoted are directly observed values, *not* corrected to a face-on view). This distribution contrasts with that of *light* in the arms (cf. Figure 3). The maximum H I density extends to regions where the arms are almost indistinguishable optically, then outside $R=11$ kpc there is a steep drop in the gas density. Similar changes with R are found in M51 and M101 (for the latter, cf. the report by Allen) and the phenomenon is a very general one. It was found already in 1957 when the first line observations of external galaxies were made (cf. the investigation of M31 by van de Hulst *et al.* (1957)), but Roberts (1971) was the first to draw attention to its common character. He pointed to the frequent existence of outer rings of enhanced 21-cm radiation in spiral galaxies. In M31 the central 'hole' has a radius of about 27′ ($R \sim 7.5$ kpc); the broad region of high H I density extends from there to about 18 kpc, beyond which the density falls off steeply. In M31 the region where the H I density first becomes high corresponds with that where the brightest optical arms appear. In M51, on the other hand, the arms are

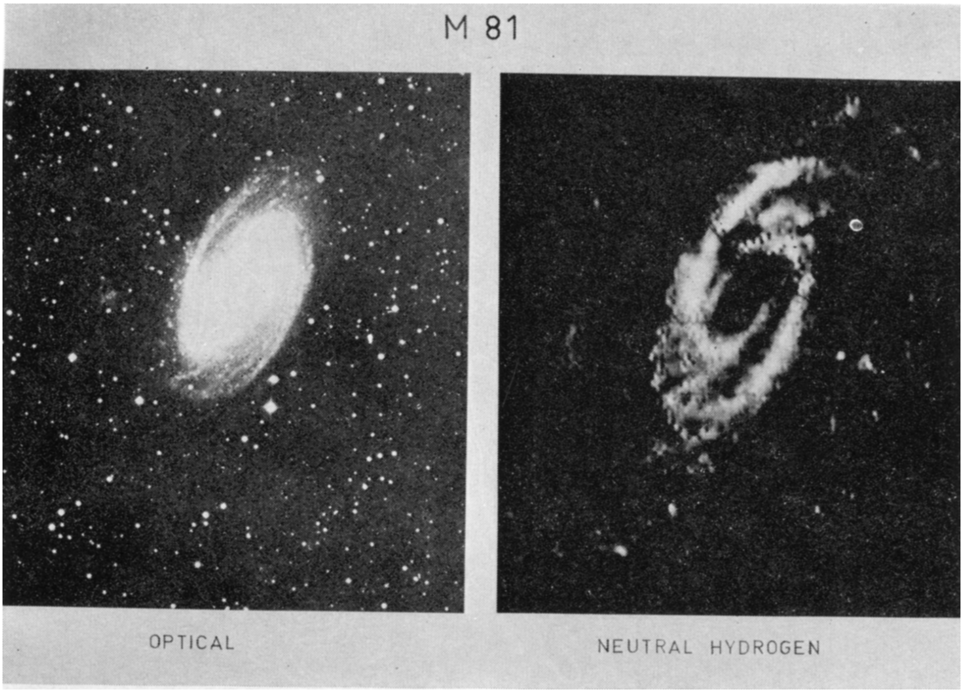

Fig. 3. Contrast between distribution of optical luminosity (at the left) and neutral hydrogen (at right) in M81 (Rots, unpublished).

optically quite bright in the inner half where the H I density is still low, but the 21-cm arms continue to very large R where the optical arms are barely, if at all, visible. A striking example is furnished by NGC 4258 (cf. Figure 4), where the H I surface density is exceptionally high in the faint outermost arms. A striking example of the contrast between the distribution of light and gas in a very late-type spiral is given by the Cambridge observers for M33 (Figure 5).

No high-resolution 21-cm observation data are available for early-type spirals. NGC 4594 has been observed at Westerbork, but the observations have not yet been reduced. In this case the *optical* data give already fairly convincing evidence that the interstellar density is very low inside the well-known dark ring, which starts at $R = 12$ kpc and extends to 24 kpc. The column density of the dust in the ring is at least an order of magnitude higher than that inside the ring's inner edge. We hope that 21-cm observations will show whether the inner region is equally devoid of *gas*.

The relatively low gas density in the inner parts of spiral galaxies is probably due to a higher rate of star formation. Observations in the radio continuum have added rather conclusive evidence that star formation in spiral galaxies is at present largely initiated by the compression occurring where the interstellar gas moves through the spiral density wave. This has been shown most clearly in M51, as I shall illustrate in the second section of my report.

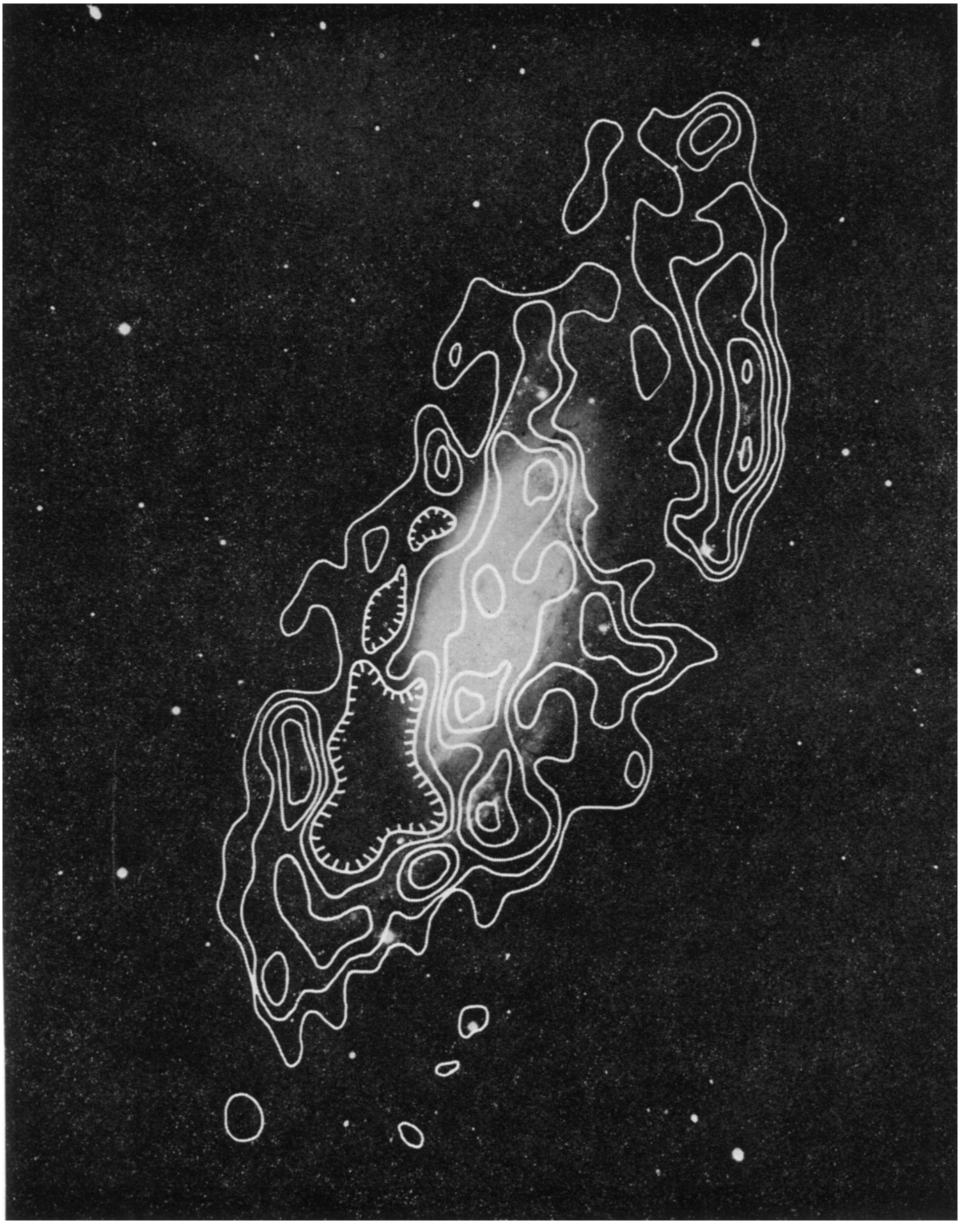

Fig. 4. Column density of hydrogen in NGC 4258 (Westerbork). Half-power beamwidth 50″ × 70″, contour interval 4×10^{20} atom cm^{-2} (Shane, preliminary results).

Actually, the observations show only the formation of OB stars and H II regions, but it is plausible that the formation of less massive stars occurs in the same regions. If, during the disk stage of spiral galaxies, the bulk of star formation takes place by this mechanism, then the rate of star formation must evidently be proportional to the

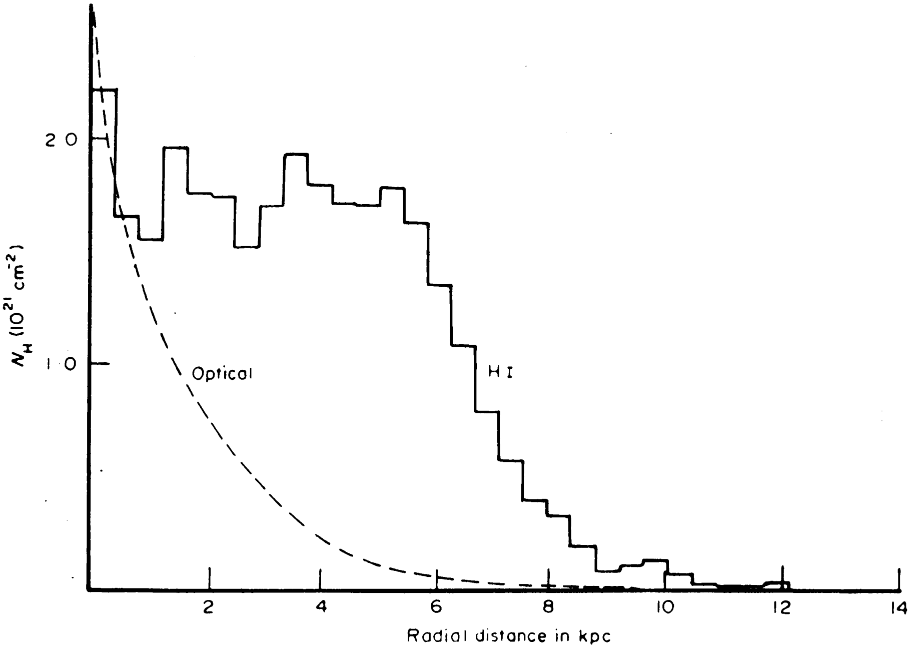

Fig. 5. Distribution of light and neutral hydrogen in M33 (Wright *et al.*, 1972).

frequency at which the interstellar gas passes through the spiral pattern; this, in turn, depends on the difference between the circular angular velocity, ω_c, and the angular velocity of the pattern, Ω. Naturally, the rate will also be proportional to the overall gas density ϱ. Other factors, such as the occurrence of a shock at the passage through the spiral wave, and the strength of this shock, as well as the thickness of the gas layer may play a role; but it is not implausible that the principal determining factors are $(\omega_c - \Omega)$ and ϱ. In the following considerations I therefore confine attention to the latter factors.

Suppose that for each passage through the spiral wave a fraction α of the gas disappears permanently into stars; then, if the initial gas density at the epoch when the stars started to be mainly formed by spiral waves is denoted by ϱ_i, the present gas density will be

$$\varrho = \varrho_i \, e^{-n\alpha},$$

where $n = 10(\omega_c - \Omega)/\pi$ is the number of times the gas has passed through the spiral wave during the 10×10^9 yr of its presumed existence (the unit of time being taken as 10^9 yr).

In practically all spirals investigated, ω_c increases considerably with decreasing distance R from the centre; n therefore *in*creases, and ϱ/ϱ_i will decrease. Qualitatively this provides a natural explanation of the decrease in gas density as we follow the arms inwards, which, as we have seen, is such a striking phenomenon in most spirals.

For a *quantitative* confrontation with the observed ratios of gas column densities we must know the way in which the initial density varied with R. If, in order to obtain an approximate estimate, we assume that this varied as R^{-2}, like the density variation of older disk populations as judged from the general light as well as the mass distribution, we find that we get a good representation of the observed relative gas density in the arms of M81 if $\alpha = 0.022$. This is shown in Table I. It should be noted that, because we consider only ratios of densities, the pattern speed drops out. The last column shows the run of the density that would follow if the fraction of the gas transformed into stars per passage through the wave is taken to be 50% higher.

TABLE I

Observed and computed column densities of the gas in M81

R kpc	ϱ 10^{20} atom cm^{-2}	$\varrho(R)/\varrho(9)$ Observed	Computed $\alpha = 0.022$	0.033
9.0	16.5			
4.8	12.0	0.73	0.54	0.22
3.3	6.0	0.36	0.35	0.07
2	3::	0.2::	0.27	0.03

Note: Values in the last line marked :: are very uncertain estimates.

The numbers in this column differ strikingly from the observed density ratios and the difference gives an indication of the margin of uncertainty of α. An additional uncertainty, however, is caused by the inaccuracy of the rotation curve. Also, the period during which fully-developed spiral structure has existed might be appreciably shorter than the assumed age of the galaxy (10^{10} yr), in which case α would be increased proportionally.

We may conclude that the observed run of density can well be explained in this way, and that the average fraction of the gas used up in star formation at each passage through the spiral wave is roughly 2%. The fraction that actually goes into stars is larger, but part of this is returned to the medium as the stars evolve. I estimate that the uncertainty in α is about ± 0.005.

It is of interest to apply the same idea to our own Galaxy. From the known density distribution of the gas we find a similar value of α. If for the vicinity of the Sun we take $\omega = 25$ km s^{-1} kpc^{-1}, and assume with Lin and others that Ω is about 15 km s^{-1} kpc^{-1}, we find $n = 32$. This gives $\varrho/\varrho_i = 0.49$. The actual ratio of the column density of the gas to that of stars plus gas in the vicinity of the Sun is considerably smaller than this, viz. about 0.10. We must therefore conclude that only about one tenth of the stars in the column have been formed by the spiral wave. The rest must either have formed in the original collapse into a disk or at later times independently of the spiral wave.

1.3. Rotation curves

The high neutral density in the outermost regions of the disks of spiral galaxies makes it possible to extend the rotation curves beyond what was accessible by optical methods. Figure 6 (from Roberts and Rots, 1973) shows typical rotation curves for some of the nearer giant galaxies. It presents two interesting features.

Firstly, there is clear evidence for a considerable range in the shapes of these curves: while the Sab and Sb systems M81 and M31 show a pronounced maximum at a

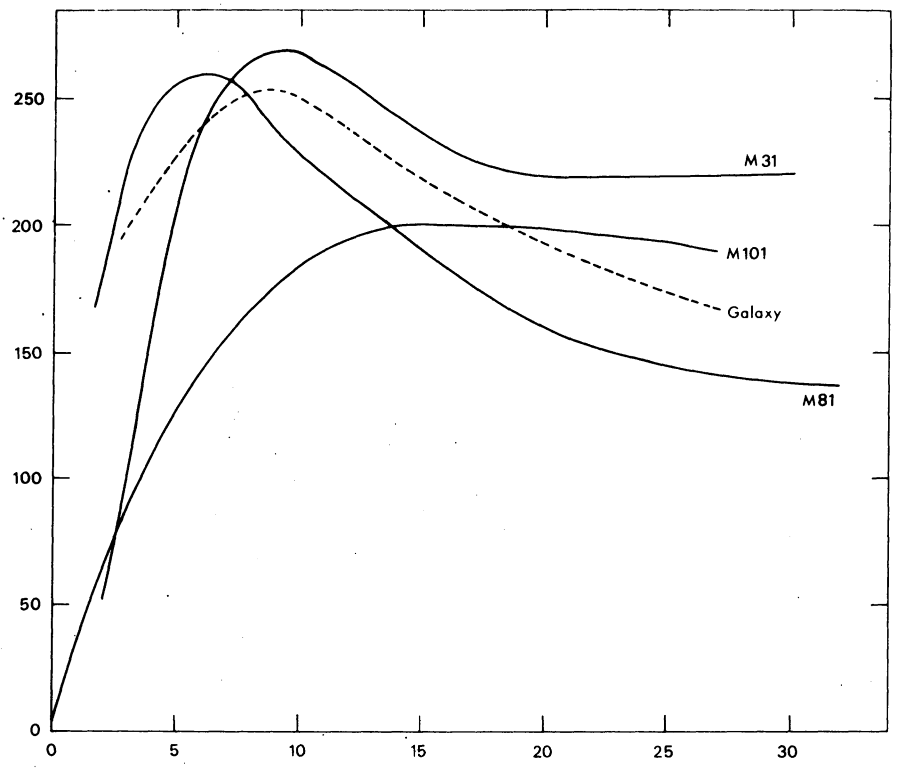

Fig. 6. Some typical rotation curves (Roberts and Rots, 1973). Ordinates km s^{-1}, abscissae kpc.

distance well within the optically bright parts, the Scd galaxy M101 has a rotation curve which reaches a maximum only in the outermost region of the visible galaxy, beyond which it remains almost constant.

Secondly, the rotation velocity in the outer parts of giant spirals has a tendency to remain practically constant. Judging from present data, this seems to be a general property of giant spirals. Recent Westerbork observations show that the rotation velocity of NGC 4258 remains virtually constant at a value of 220 km s^{-1}, from $R = 3$ kpc to the farthest distance from the centre at which it can be measured ($R \sim 20$ kpc). For the giant SB galaxy NGC 5383 it was found constant and high from $R \sim 4$ kpc to the outermost observed points around $R = 35$ kpc (Sancisi; cf.

report by Allen, p. 425). A similar behaviour was found in M51 by W. W. Shane and Elly Dekker (unpublished). If the rotation velocity remains constant over a large range in R this indicates that the mass inside R increases approximately proportionally with R. These rotation curves therefore indicate that the masses of giant galaxies may be considerably higher than has previously been assumed.

In NGC 4258 the rotation curve on the northern side shows a sharp maximum within about 800 pc from the centre. This is shown both by the 21-cm observations and by the optical emission lines (Chincarini and Walker, 1967). The rotation in this central part closely resembles that of the nuclear disk in our Galaxy.

1.4. Large-scale deviations from circular motions

Because of its three-times-smaller distance, M81 is better than M51 for a study of the systematic streaming motions that should accompany the spiral density waves. The 21-cm observations clearly show the presence of waves, but observations and reductions are not yet sufficiently refined to permit a trustworthy derivation of their amplitudes. The observations will be discussed in the report by Lindblad (this Volume p. 399). For M51, 21-cm observations as well as very extensive Fabry-Pérot Hα observations (Tully, R. B.: 1974, *Astrophys. J. Suppl.* **27**, 415) are available. The former indicate again fairly convincingly that wave motions of the expected nature are present.

The velocity fields shown by the high-resolution observations of the later-type spirals IC 348 and M101 have not yet been analysed sufficiently to permit a full report. In both galaxies there is a large asymmetry in the distribution of the neutral hydrogen. In M101 Rogstad (1971) finds that the north-east half contains 1.5 times as much H I as the south-west half (see also the report by Allen). A general investigation of such asymmetries has been made by the French observers. From a careful discussion of 21-cm observations of the Scd spiral M33 the Cambridge astronomers concluded that the velocities showed no evidence of a regular spiral wave. If there is such a wave its amplitude must be smaller than 3 km s^{-1} (Wright *et al.*, 1972).

For the frequency of large asymmetries see Bottinelli, 1971.

2. Synchrotron Radiation from Spiral Arms, Disks and Nuclei

At 1400 MHz, the frequency at which practically all continuum observations of high resolution have been made, the radiation of all spirals, except possibly a few very-late-type systems, is largely synchrotron in origin. The surface brightness is generally low and observation with unfilled-aperture telescopes is difficult. Only in a small number of galaxies has it so far been possible to study the distribution in sufficient detail to determine its general relationship to the optical arms.

The most illuminating cases are M51 (cf. Figure 7, Mathewson *et al.*, 1972), and M31 (Pooley, 1969; van der Kruit, 1972). In both galaxies the radiation is strongly concentrated near the brightest optical arms. The contrast of the intensity in the arms to that in the interarm regions is considerable.

Fig. 7. Isophotes of 1415 MHz radiation in M51 and NGC 5195 superimposed on a 200-in. plate taken by Humason. The contour unit is 0.8 K brightness temperature. The half-intensity beam is 24″ × 32″ (Mathewson *et al.*, 1972).

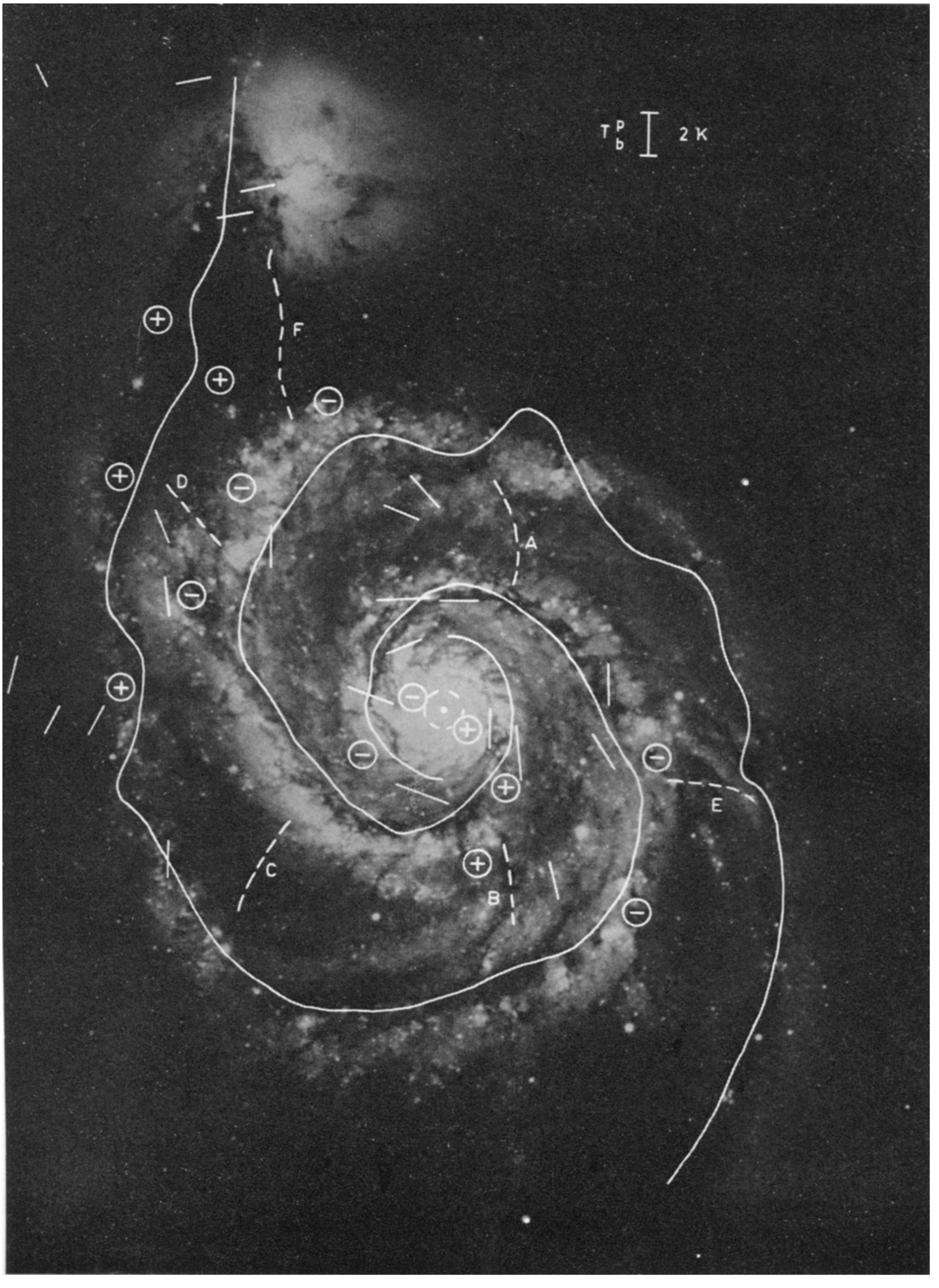

Fig. 8. The peak lines of the synchrotron emission in M51 (Mathewson *et al.*, 1972).

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In the few galaxies which are usable for such a detailed comparison there is a distinct separation between the synchrotron ridges and the ridges of the H II regions. This can best be observed in M51. Around $R=2'$, or 5 kpc, the latter precede the former by about 18° in the direction of the rotation (Figure 8). Furthermore, it is interesting to note that the synchrotron arms coincide closely with the dust concentrations. These phenomena show convincingly that star formation is initiated through the compression of the interstellar medium by the spiral wave, and more particularly in the shock caused by the wave. From the separation between the synchrotron arms and the H II arms, the time between the passage of the shock and

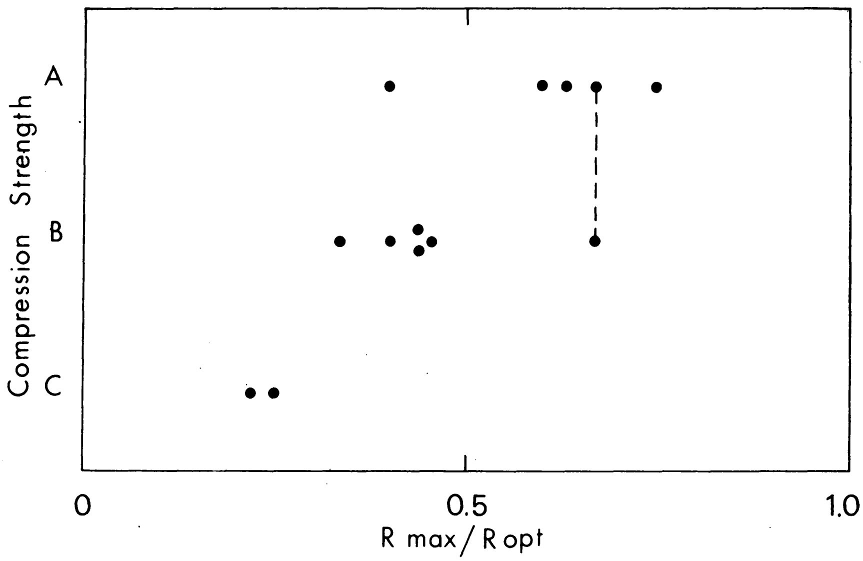

Fig. 9. 'Compression strength' and differential rotation. Abscissae are ratios between the radius where the rotation velocity has a maximum and the optical outer radius of the galaxy; these ratios are used as measures of the amount of differential rotation (van der Kruit, 1973).

the birth of OB stars is found to be about 10 million years. The synchrotron emission provides a particularly sensitive means for measuring the compression, as the emissivity can go up with nearly the third power of the compression.

From a dozen spirals for which the ratio of the intensity in the arms to that in the base disk could be determined with the Westerbork array, van der Kruit (1973) found that this ratio, which he called the 'compression strength', is higher for galaxies with strong differential rotation (cf. Figure 9). It is also correlated with the van den Bergh type and with the value of M/L, possibly because the rate of star formation increases with the compression.

In M51 the synchrotron intensity increases as we follow the arms inward, in contrast with the H I radiation which *de*creases considerably. In many other galaxies, however, such as M31 and probably also M81, there is an extensive hole in the synchrotron radiation, much like that in the hydrogen distribution. However, right in the centre we often see strongly enhanced radiation due to activity in the nucleus. In M31 the hole extends to about 5 kpc. The nucleus will be discussed in the report by Ekers (p. 257).

An interesting feature in M51 is the link with the satellite NGC 5195. There is a bridge of synchrotron emission between the two galaxies; also the radio brightness of the northern disk is about twice as high as that on the southern side opposite the companion.

Aperture synthesis has made it possible to separate the radiation from the nuclear region and the disk component in a considerable number of galaxies. Radio luminosities of the nuclear regions have now been measured in 44 spirals, although for 16 of these only upper limits have been found. There is a very large range in this

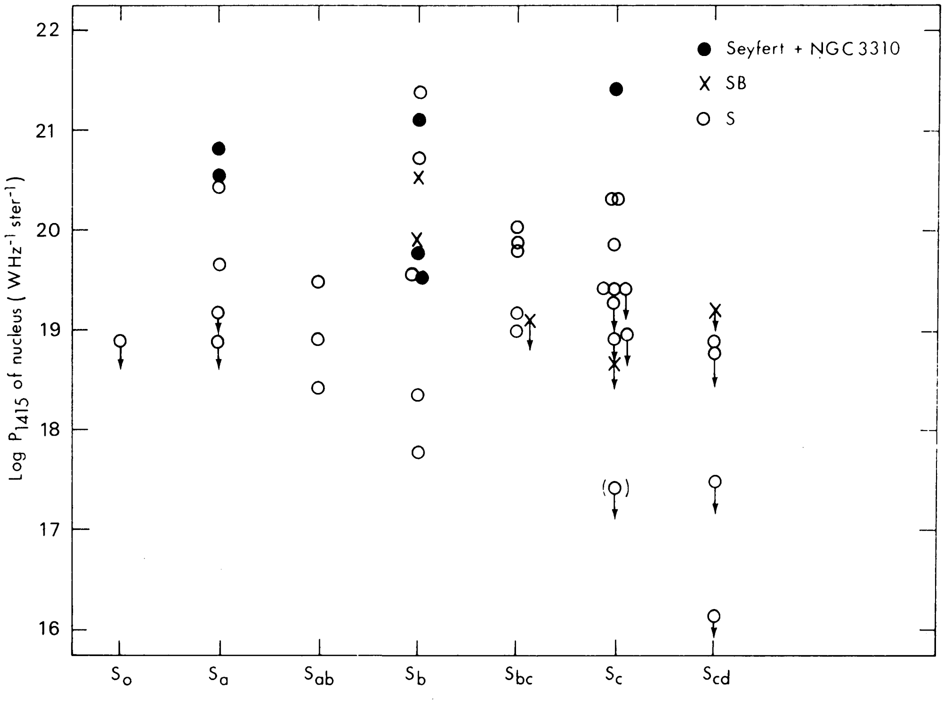

Fig. 10. Luminosity of the nucleus at 1415 MHz against Hubble type (van der Kruit, 1973).

luminosity, as shown in Figure 10. The brightness of the nucleus is not clearly correlated with the Hubble type, except that the Scd galaxies have all very faint nuclei, mostly unobservable in fact. Within each of the other types the nuclear power varies over a range of about 1000:1. The average brightness of the nuclei of Seyfert galaxies is a factor of about 100 higher than that of normal galaxies. In general the activity of the nucleus appears to have no intimate relation with the general structure of a galaxy. It might be that such activity develops intermittently in all galaxies, on which view Seyfert galaxies may be spirals in which the activity is in an initial, violent stage.

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The disk brightness shows a similarly large range, without a very clear correlation with other properties of the spirals, although on average the types earlier than Sbc seem to have lower radio surface brightness than Sbc and Sc galaxies. The spread in the disk brightness is probably connected with a spread in the production of relativistic particles, and may be related either with the frequency of supernovae or with the activity of the nucleus.

There is some evidence for a correlation between disk and nuclear brightness. Of the ten systems in which the brightness temperature of the 'base disk' could be measured by van der Kruit, the three with $T_b \geqslant 2°$ have an average of 19.4 for the logarithm of the power of the nucleus, while in the four with $T_b \leqslant 0.°3$ the average $\log P$ is less than 18.

In the case of the ellipticals the occurrence of strong radio emission is highly correlated with the optical luminosity and the mass, and it seems that only the most massive elliptical galaxies can become strong radio sources. There is an indication that the more flattened systems are generally weaker radio emitters. Ellipticals have a very large range in radio brightness and for about 60 or 70% of the bright E's the emission lies below the limit to which observations have been made. All E galaxies with measurable radio emission have a bright radio nucleus, and about half of these have also a radio halo. In a number of cases the nucleus has a small linear size and a flat spectrum.

3. Explosive Events

Because synchrotron radiation is strongly enhanced by compression of the medium, observations of this emission are particularly suited for studying the effects of explosive events. The most interesting case observed is that of the large spiral NGC 4258 in which, superimposed on the ordinary spiral arm radiation, a much stronger pattern of totally different structure was found from observations with the Westerbork telescope. It shows two opposite curved radio ridges running across the optical spiral arms (Figure 11). These ridges have a remarkably smooth structure and extend to the outermost limits of the optical and the H I arms. In their inner parts they coincide precisely with a set of filamentary Hα arms which had been discovered already a dozen years earlier by French observers (Courtès and Cruvellier, 1961), and which were likewise found to be of a novel nature (Figure 12). They are similar in having an unusually smooth texture, without any evident localized emission patches. And they contain no blue stars, being, in fact, invisible on ordinary exposures in blue light. The radio ridges have steep edges on the sides which precede in the direction of the rotation, and are followed by wide plateaus of enhanced radiation. It seems that the Hα filaments are similarly followed by regions of somewhat enhanced Hα radiation. There are indications that both the anomalous Hα arms and the anomalous radio arms lie in the same plane as the ordinary spiral arms. In a face-on picture the outer parts of the radio ridges are straight and roughly perpendicular to the outer optical arms, the various fragments of which have nearly circular shapes (cf. Figure 13).

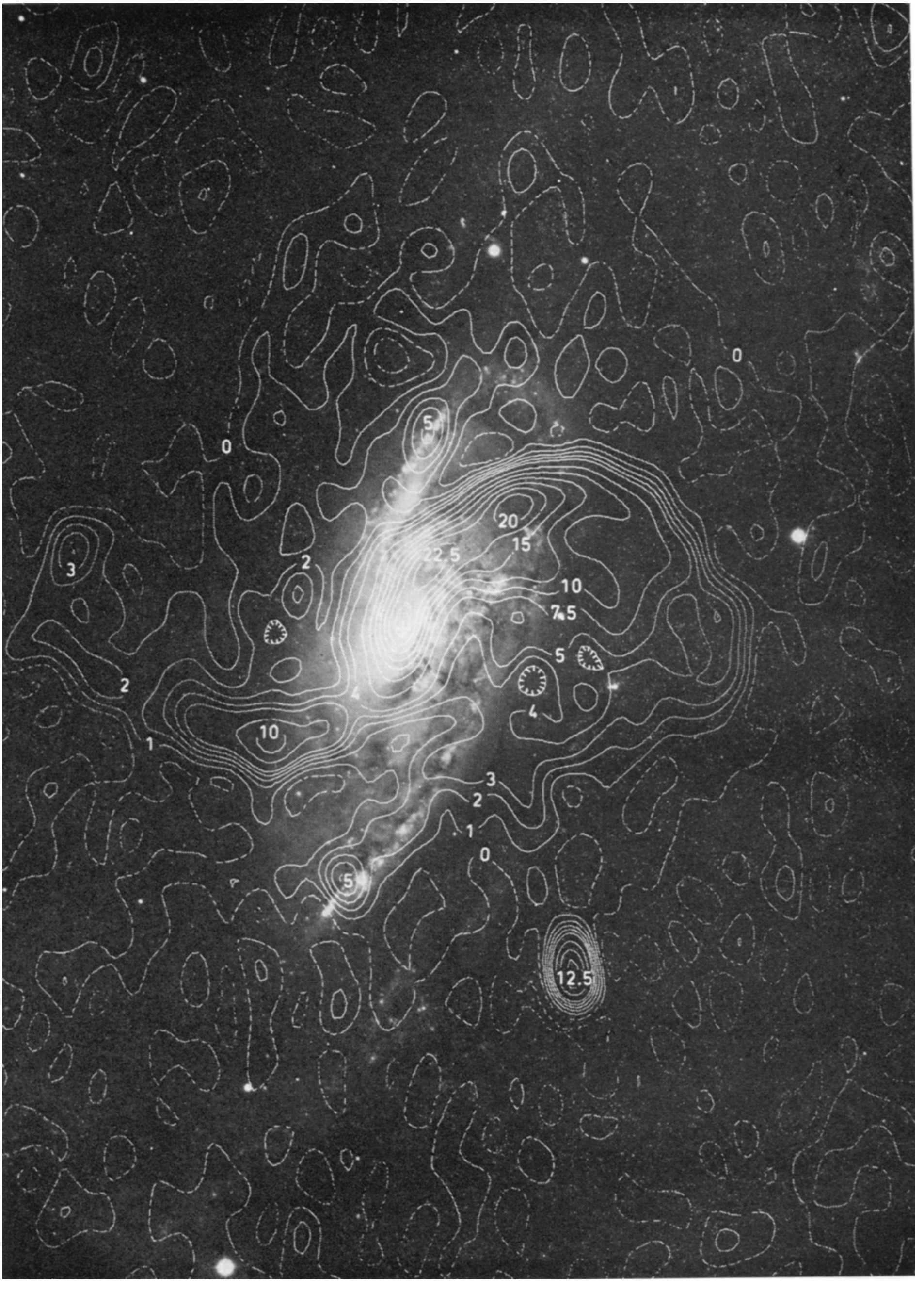

Fig. 11. NGC 4258. Radio contour map at 1415 MHz superimposed on optical 200-in. photograph by Sandage. The position of the optical nucleus is indicated by a cross (van der Kruit *et al.*, 1972).

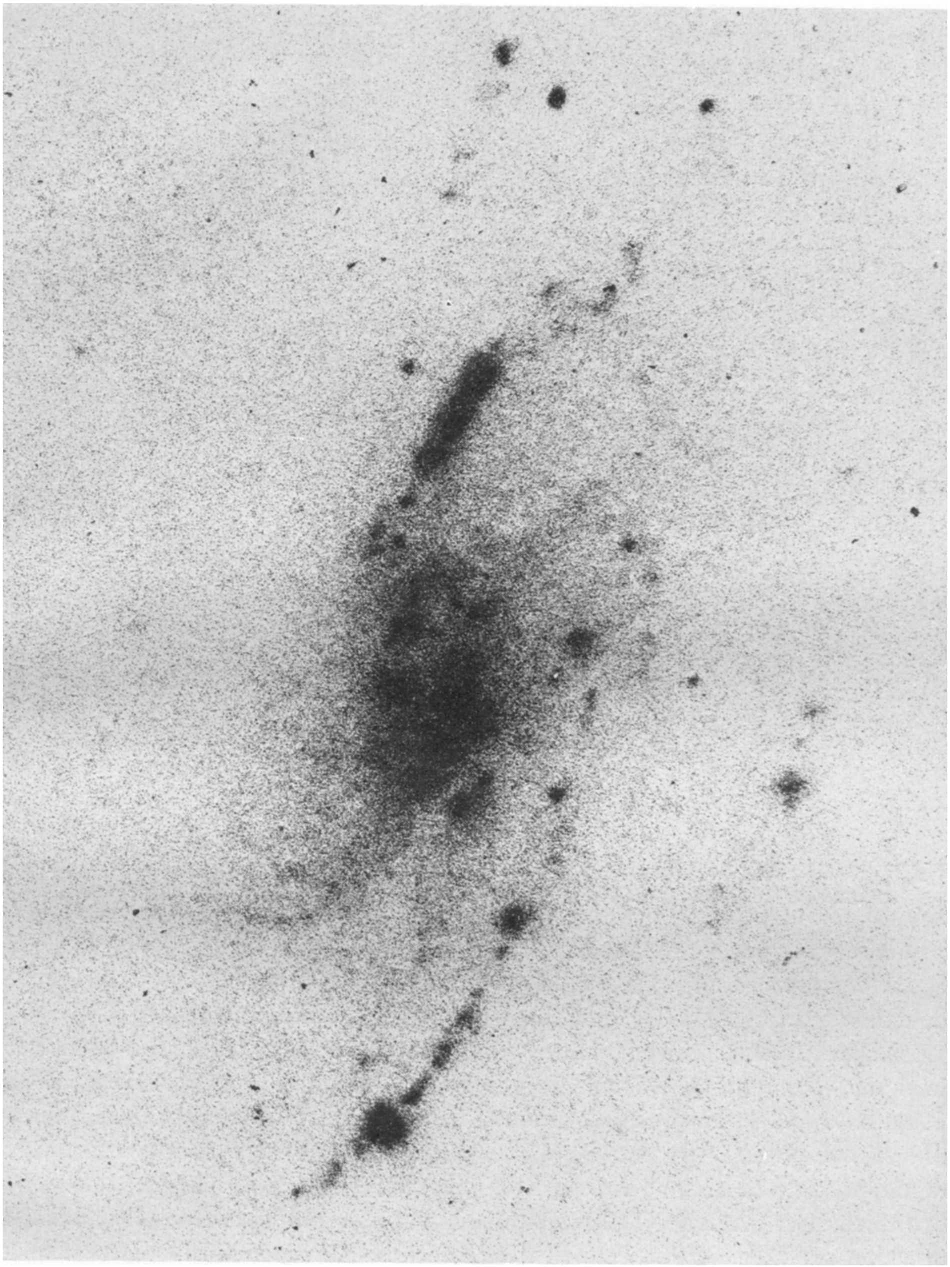

Fig. 12. NGC 4258, Hα photograph through interference filter of 10 Å half-width (Deharveng and Pellet, 1970).

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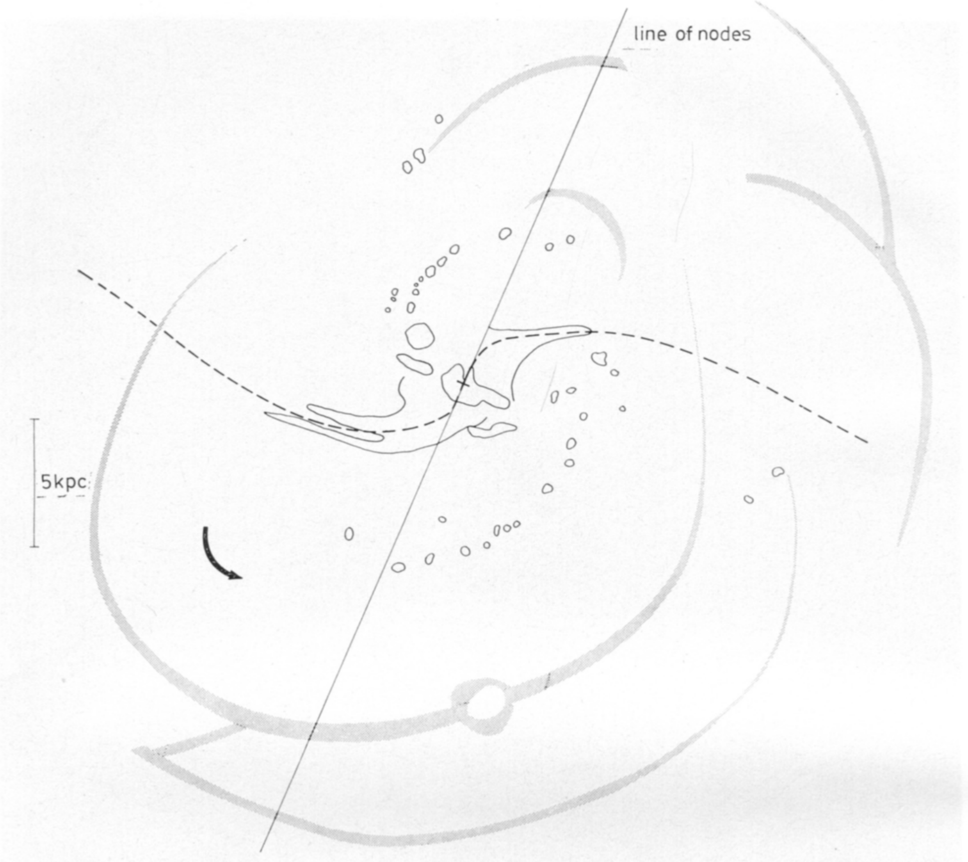

Fig. 13. NGC 4258. Schematic face-on sketch of anomalous radio ridges (dashed lines) and Hα filamentary arms (contours), as well as ordinary spiral arms (patches and shaded arms).

It seems possible to explain the anomalous arms and their accompanying 'plateaus' as the consequence of a vast expulsion of gas from the nucleus into two opposite directions making relatively small angles with the spiral disk (van der Kruit *et al.*, 1972). The expelled gas would have swept up the gas initially present in the disk and in doing so would have acquired angular momentum. The radio ridges and Hα filaments would be the present location of the expelled clouds, the Hα emission being due to the ionization of the medium by the collision. The enhanced synchrotron radiation might have come directly from the nuclear explosion. The plateaus may be due to the fact that the ejection continued over a certain period during which the direction of the expulsion rotated over an angle corresponding with the angular extent of the plateaus. In this model the expulsion would have taken place about 18 million years ago, with initial velocities ranging from about 800 to 1600 km s^{-1}.

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Fig. 14a. Contour diagram of column density of neutral hydrogen in NGC 4258 having velocities between +70 and +130 km s^{-1} relative to the centre.

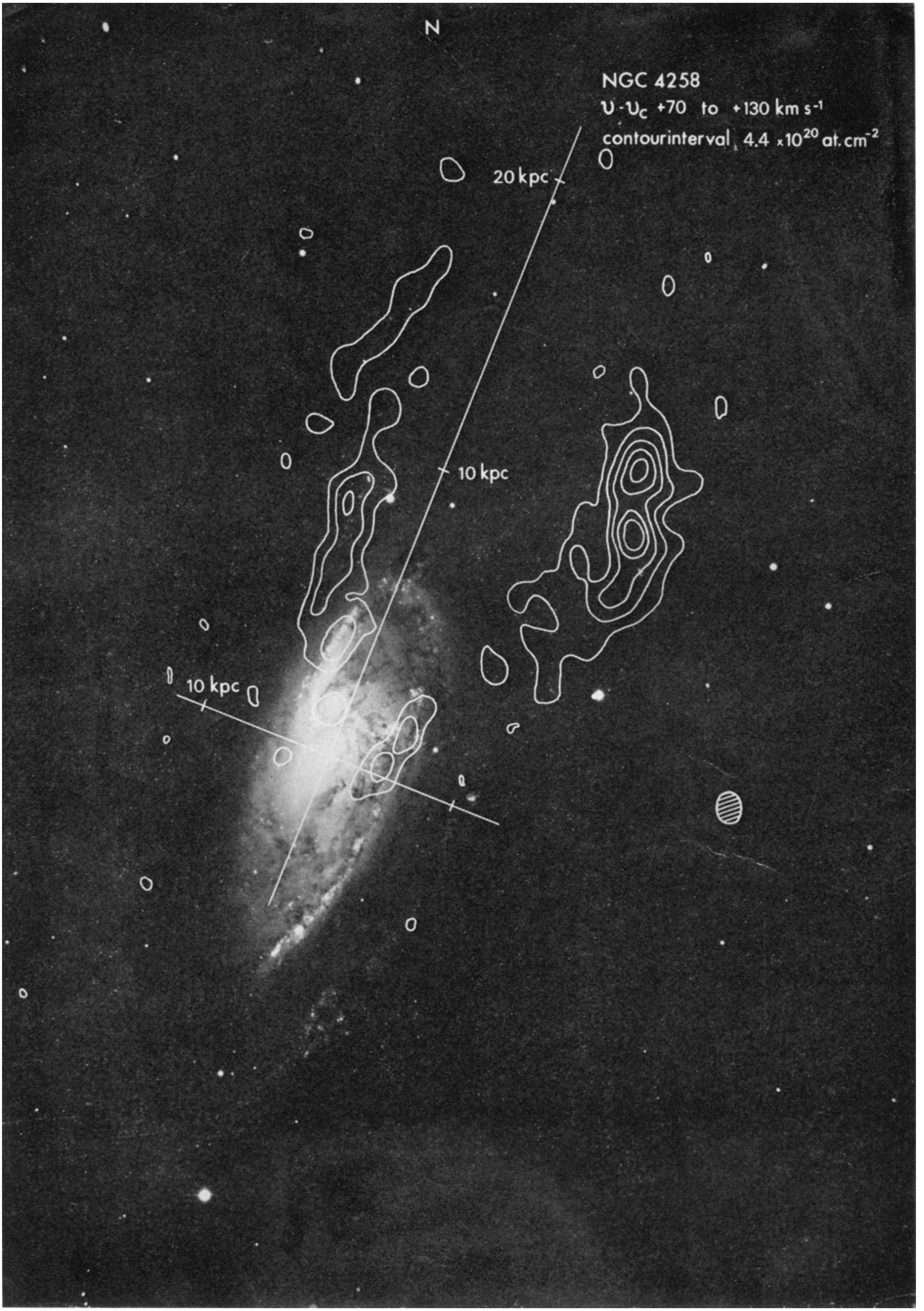

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Fig. 14a.

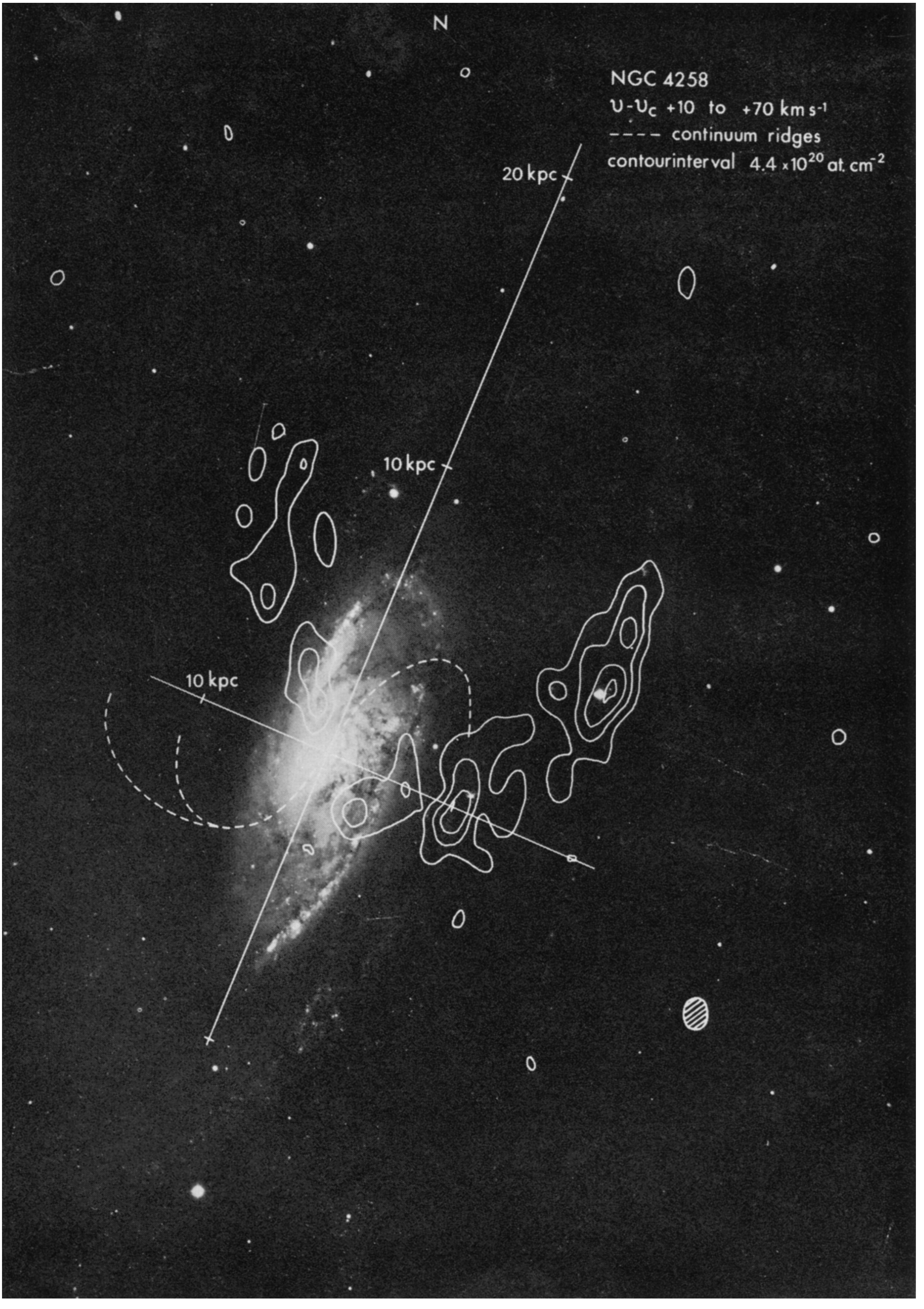

Fig. 14b.

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The total ejected mass would have been between 10^7 and 10^8 $M_\odot$. Support for this interpretation is found in the fact that the optical arms show signs of having been swept away in the regions through which the ejected clouds would have moved. An event like this would result in a re-arrangement of a large fraction of the interstellar medium into a very regular spiral pattern.

As NGC 4258 is at present the only case in which a phenomenon of this sort and this magnitude has been observed, it is not possible to say anything about the frequency with which such vast ejections occur in spiral galaxies, nor about their significance for the general problem of spiral structure.

Direct support for the hypothesis of a large-scale expulsion from the nucleus of NGC 4258 has now been found from the 21-cm line observations. These show that there are large masses of gas around the minor axis moving with radial velocities between +30 and +130 km s^{-1} relative to the centre (cf. Figure 14). On the opposite side of the minor axis there is a considerable amount of hydrogen with high *negative* velocity relative to the centre. If this gas lies in the equatorial plane of the galaxy it would be moving towards the centre. In the model proposed by van der Kruit *et al.* the gas within about 5 kpc from the centre should indeed be falling back and have velocities in the inward direction similar to those observed.

Closer to the nucleus Chincarini and Walker (1967) had likewise found considerable motions in radial directions. These observations have recently been confirmed and extended by van der Kruit on spectra taken with the 200-in. Hale reflector. This gas close to the nucleus may well lie in the plane of the disk and be moving *in*ward.

The total mass of the neutral hydrogen with radial velocities between 60 and 130 km s^{-1} is roughly 6×10^7 $M_\odot$, while that with +50 km s^{-1} velocity is 9×10^7 $M_\odot$. Though these data do not suffice to determine the epoch of the hypothetical expulsion it might well have been the same event as that which produced the anomalous synchrotron arms. The amounts of high-velocity hydrogen observed on the minor axis are of the same order as those which had been proposed to explain the anomalous features in the plane of the spiral. The 21-cm observations appear to confirm that an enormous expulsion of gas has occurred in this galaxy. On the other hand we find no very clear signs of a heaping-up of neutral gas near the radio ridges. If our model is correct we must therefore conclude that the interstellar medium that was swept up is still largely ionized.

Except for our own Galaxy this is the first case in which the mass involved in the explosion from a galactic nucleus has been directly measured. The total mass must be higher than the 1.5×10^8 $M_\odot$ given above, because not all of the exploded hydrogen will have a large velocity component in the radial direction, and because the gas with highest velocity may have escaped.

The high density of H I in the inner region of NGC 4258 (cf. Figure 4), which contrasts with the central 'holes' observed in other spiral galaxies, may well be connected

←

Fig. 14b. Same for velocities between +10 and +70 km s^{-1} (D. van Albada, Oort and Shane, preliminary results).

with the explosion. The *total* amount of H I within 5 kpc is about twice that observed to have high velocities. It may well be, therefore, that practically all the gas found within this distance has been ejected from the nucleus. The kinetic energy involved in the expulsion may be roughly estimated at $\sim 10^{57}$ erg.

The Seyfert galaxies provide interesting information on what may be the initial stages of eruptive periods. So far, however, no neutral hydrogen observations for Seyfert spirals are available which could give an indication of the total mass of gas involved. The only cases of eruption which have been observed in the nearest galaxies, and which are *somewhat* similar, are the expanding arms in the central region of our own Galaxy and the well-known filamentary features around M82. In the former, 21-cm observations have shown the presence outside the galactic disk of clouds with a total mass of about $10^6\ M_\odot$, moving away from the centre at velocities of the order of 100 km s^{-1}, having probably been expelled about 6 million years ago. If the motions of the 3 kpc arm and the expanding arm at +135 km s^{-1} are supposed to have been caused by similar expulsions, there should have been another 'eruption' about 12 million years ago in which a mass of the order of $10^7\ M_\odot$ was involved.

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DISCUSSION

van Woerden: In M81 you find that a fraction $\alpha = 0.022$ of the gas condenses into stars, per passage through the spiral shock. This must be a *net* fraction; the fraction condensed originally must be higher, but part of the matter condensed returns into the gas by mass loss from stars and by supernova explosions. Can you estimate the fraction originally condensed?

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Oort: The fraction 0.022 represents indeed the *net* amount of gas going into stars and remaining in them. I cannot say off-hand how large a fraction goes into stars temporarily and is returned to the interstellar medium.

van Woerden: In M101 the arm/interarm contrast can be estimated more easily than in M81, since almost any radius vector crosses three spiral arms (or segments). Allen, Goss and I estimate preliminarily that the surface density in the arms is about three times the *average* surface density. Since the arms may cover about one-third or one-quarter of the area of the galaxy, the *interarm* density may be quite low – but we have no direct measures of that yet.

G. Burbidge: How did you measure this rotation of the anomalous radio arms in NGC 4258?

Oort: We did not. What I referred to was the rotation measured in the anomalous Hα arms.

Baldwin: Is the major axis of NGC 4258 well defined dynamically from the H I measurements?

Oort: Yes, and it agrees fairly, though not completely, with the axis of the optical picture.

van der Kruit: At Palomar I have measured optically the velocity field in NGC 4258. These measures show three important features:

(a) The velocities in the normal arms indicate the non-circular motions indicated earlier by the Burbidges and Prendergast (*Astrophys. J.* **138**, 375, 1963). However, if we assume that the line of nodes and the inclination are those of the weak, outer structure (p.a. about 145° instead of 157° and $i \simeq 72°$ instead of 64°) we find that these non-circular motions disappear.

(b) The Hα arms are rotating then more slowly than the rotation curve from the normal arms would indicate. In the model this is explained by the fact that the swept-up gas must have a lower rotation velocity than the circular rotation, because the expelled matter from the nucleus has little or no angular momentum.

(c) Along the minor axis and the region of the 'radio plateau' I find motions which, if in the plane, would indicate that these are contractions. If the plateaus are remnants of earlier phases in the explosion this is expected to be the case because, due to the longer time-scale and possibly lower expulsion velocities, this gas will have been stopped and, due to the lower angular momentum, is now falling back to the nucleus.

Finally, the line-strengths in the Hα arms favour collisional ionization over photo-ionization. This question is being studied at present by Miller and Osterbrock.

Oort: The total kinetic energy involved in the explosion is $\sim 10^{57}$ erg.

Arp: How do you envisage the expulsion of the gas? In particular, how narrowly is it directed, does it spread out as it goes, and what initially directs the expulsion?

Oort: The observations indicate that the expulsion has taken place in a rather wide cone. For the radio ridges one requires gas to be ejected at relatively small angles with the equatorial plane.

I have no suggestion as to what initially directs the expulsion, but would refer you to the report on this subject by Saslaw (p. 305).

Pishmish: You showed us that in some galaxies, for example in M81, there is a lack of neutral hydrogen in the nucleus. Would this also imply that hydrogen gas would not exist in any other form, say in its ionized state? I have in mind in particular the giant H II regions, presumably in an early stage of development, when they are surrounded by a 'cocoon' dust cloud making them optically unobservable. Such regions could, however, be detected by radio recombination line studies.

Oort: In M81 there are relatively few large emission nebulae. Nor do radio observations of the continuum give evidence of the presence of a great number of large H II regions. On the basis of this evidence it seems unlikely that the decrease in neutral hydrogen towards the centre could be compensated by ionized hydrogen.

Allen: Since radio recombination lines always seem to be accompanied by radio continuum emission, the presence of optically-obscured giant H II complexes in the central regions of galaxies would not go undetected in the high-sensitivity radio continuum maps now being produced by aperture synthesis radio telescopes. In the case of M101, for example, Westerbork radio continuum maps at 21-cm wavelength currently being prepared for publication by Goss, Israel and myself do not show a relative excess of such giant H II regions in the central areas.