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ON THE PROBLEM OF THE ORIGIN OF SPIRAL STRUCTURE

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SVMMARIVM — In Observatorio Westerborkiano (in Hollandia), per speciale telescopium observata est ampla eruptio ex galaxiae spiralis NGC 4258 nucleo. Mutationes, quae ex hoc evenire potuerunt in vaporum formatione, accurate perpenduntur, et etiam indagatur quid hoc influat in spiralem structuram.

Galaxies can be divided into two main categories: elliptical systems and spiral systems. The former have smooth structures, in which the star density falls off quite regularly with increasing distance from the centre. The structure as seen projected on the sky is nearly always symmetrical around the major and minor axes. The axial ratios vary from one to about one half. In general the elliptical galaxies contain no dust and very little interstellar gas. The spiral galaxies are in almost all respects the opposite of the ellipticals. They always contain flat, thin disks, whose structure is extremely patchy, and often quite irregular, also on a large scale. They

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contain conspicuous amounts of gas and dust, which is arranged in large-scale spiral patterns.

There is a smaller, third family of galaxies, the so-called So systems, which may be considered as intermediate between spirals and ellipticals in so far as they share the smooth structure of the latter with the flat shape of the former.

In the present communication I shall confine myself to the *flat* galaxies. A most remarkable thing about these is the high frequency of spiral structures. The spiral arms make the impression of being quite young structures that would be wiped out in a small number of revolutions of the system. And yet we know that the systems in which they are observed are almost as old as the universe; they must have existed during times of the order of a hundred revolutions. The difficulty was enhanced by the fact that in most spirals the inner parts rotate much faster than the outer regions, and it seemed that the arms would therefore be wound up in inadmissibly short periods.

In recent years the latter difficulty has been solved by the research of C.C. LIN and others who showed that the spiral arms could be interpreted as waves revolving around the axis of the system and that the spiral could be considered as a rotating "pattern". Although this was an important advance in the understanding of spiral structure it did not yet solve the *entire* problem. For unless they are re-excited the waves will dy out after a few revolutions. Moreover, the spiral waves were a highly idealized picture of the actual structures in which the arms are usually extremely irregular, with side branches, sudden bends, and considerable variations in density along the arms. Even if the large-scale spiral waves were not damped by general energy loss they would most likely be disrupted by these numerous large irregularities.

Two possible mechanisms have been suggested for the maintenance — or the new formation — of spiral arms, viz. tidal action by an outside mass, and eruptive activity in the nucleus. The first might be responsible for the spiral arms

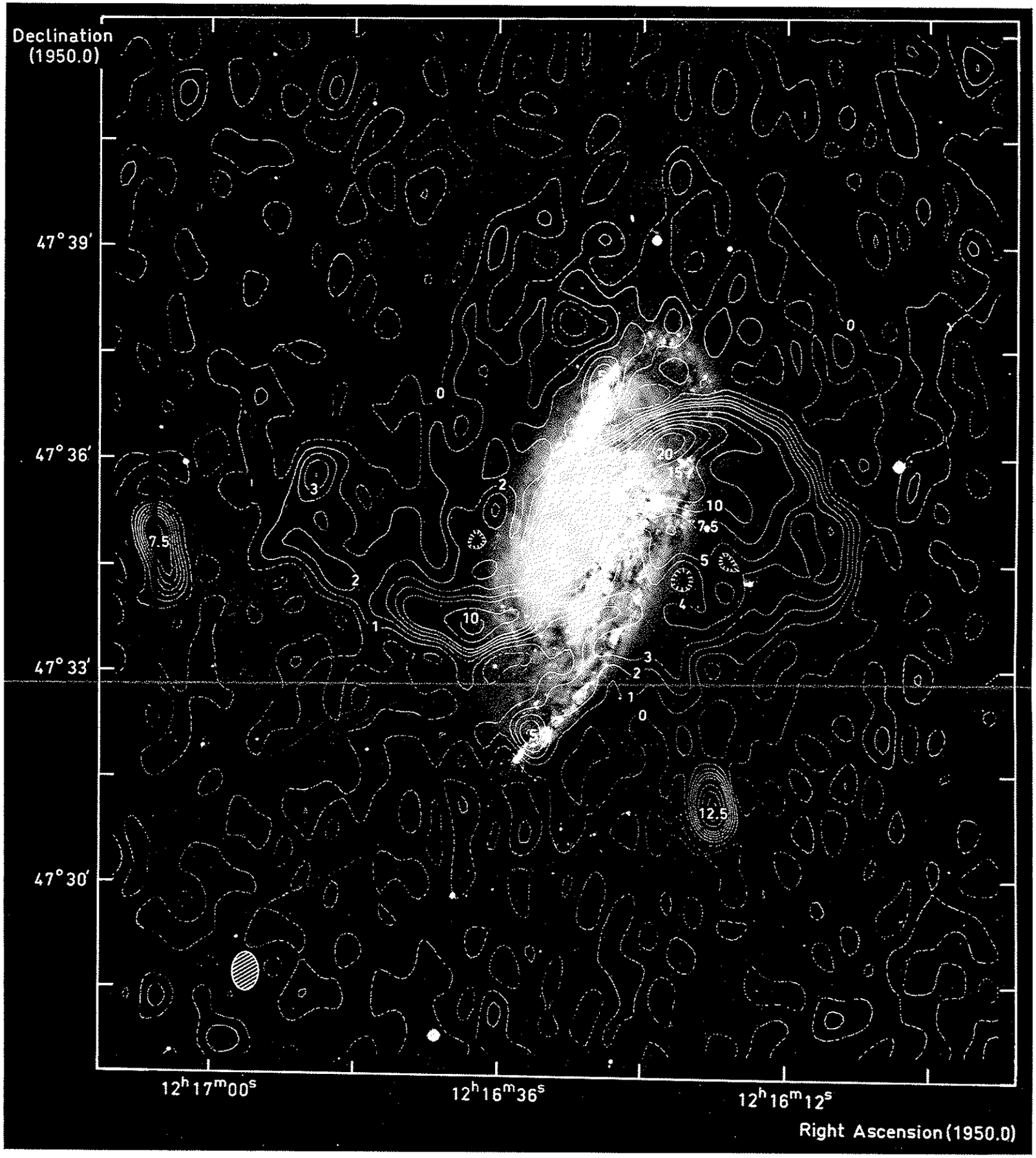

FIG. 1 — Observed radio contour map of NGC 4258 superimposed on the optical photograph. The contour units are 1 m.f.u. per synthesized beam, or 0.9 K brightness temperature. The optical photograph is a reproduction of a 200-inch IaO plate taken by A. R. SANDAGE, kindly made available to us by him and through the help of Mr. WILLIAM C. MILLER. The position of the optical nucleus is indicated by a white cross.

in systems having a near-by companion of sufficient mass, such as M 51 with its companion NGC 5195. But as there are many spirals without distinct companions it is difficult to believe that this mechanism could be responsible for spiral structure in general.

As regards the second possibility it should in the first place be noted that strong nuclear activity is a rather common property of galaxies. Evidence of strong recent activity is observed in about half of the brightest galaxies (including our own Galaxy). Thus far, however, it was unknown in what manner this activity could maintain or bring about spiral structure encompassing an entire system.

In the course of a programme with the synthesis radio telescope at Westerbork for determining the radiostructure of bright northern galaxies a remarkable pattern was found in the spiral galaxy NGC 4258 which may show the birth of spiral arms by expulsion of gas from the nuclear region. The radio telescope used consists of ten 25-metre aperture dishes evenly spaced at distances of 144 metres along an east-west line, and two similar dishes mounted on rails running similarly east-west. The dishes are mounted equatorially, and form twenty interferometers covering baselines from 36 to 1458 metres at intervals of 18 metres. Working at a frequency of 1415 MHz the instrument has a beamwidth of 24 arc seconds in α and 24 cosec δ arc seconds in δ. At the distance of NGC 4258 the synthesized beam measures 0.8 × 1.0 kpc.

The brightest parts of the optical arms show up clearly in the radio emission, but there is also another, and much more intense radio structure which is radically different from the optical structure (fig. 1). This shows two principal "ridges" which run straight accross the normal optical arms, and are remarkably smooth wer their entire length. Inside about 5 kpc from the centre these radioarms coincide with two remarkable filamentary "arms" which had been discovered in 1961 by COURTÈS and collaborators on interference filter expo-

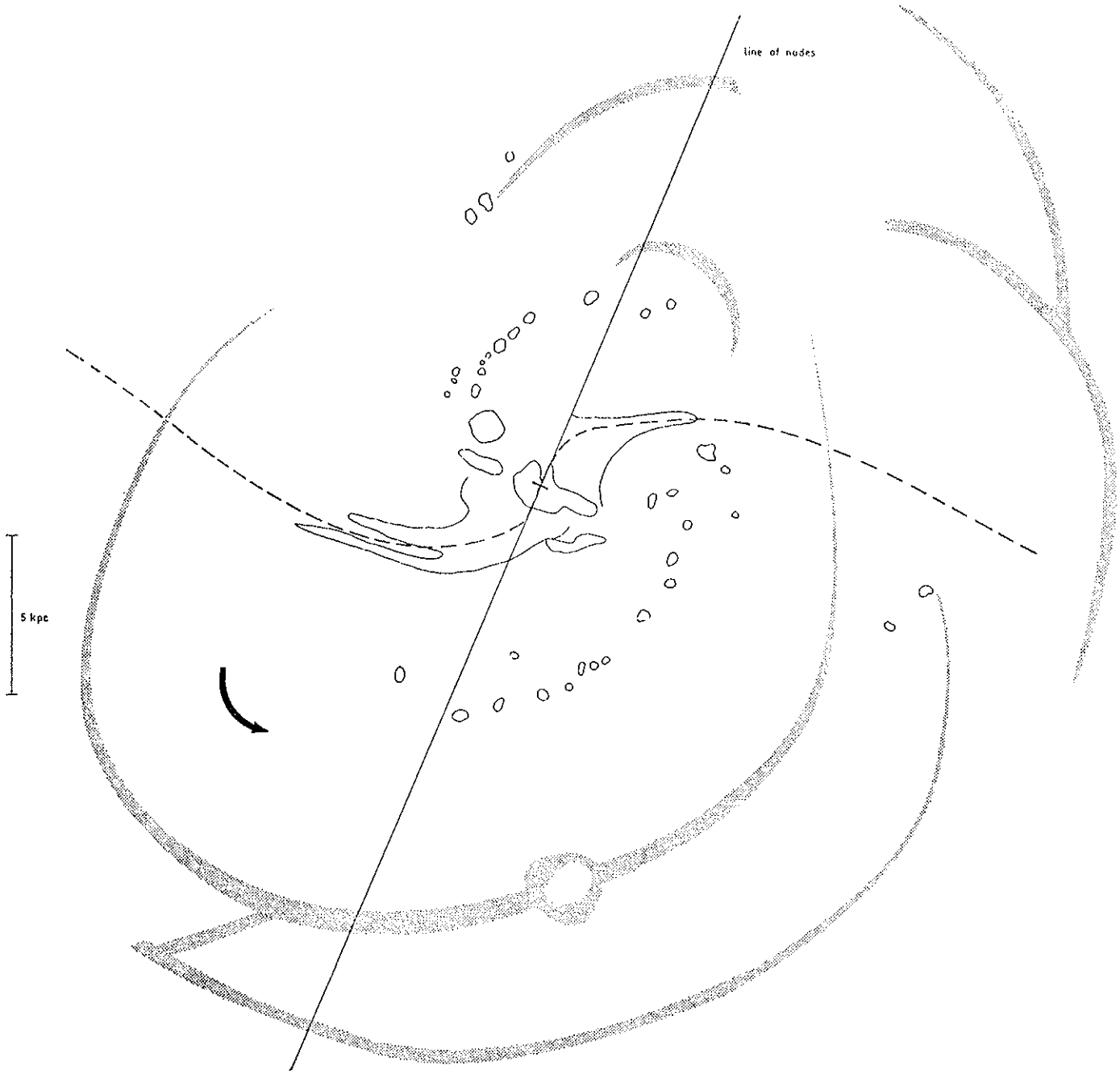

FIG. 2 — Radio arms, anomalous H_{α}-arms and ordinary spiral arms drawn in the galaxy's equatorial plane on the supposition that all arms lie in this plane.

sures transmitting the H_α line. The French authors had already stressed the abnormal nature of these arms which have an unusually smooth texture, can only be observed through narrow interference filters and are invisible in the blue light where normal spiral arms are brightest. They contain no bright OB clusters and their radiation is likely to be excited by a mechanism different from that of ionization by hot supergiants.

The radio ridges have steep edges on the sides which precede in the direction of the rotation. On the other side they merge into "plateaus" of lower intensity and considerable extent. Except perhaps for some condensations in the normal arms the radio emission is non-thermal so-called "synchrotron" radiation.

On various grounds we believe that the strong radio arms and the filamentary H_α arms lie in the same plane as the main optical spiral. In this plane the radio ridges are practically straight between 5 and 15 kpc from the centre (cf. fig. 2).

The radio ridges and the accompanying H_α-arms are interpreted as the present location of "clouds" expelled from the nucleus in two opposite directions in the equatorial plane about 18 million years ago, at velocities ranging from about 800 to 1600 km/s. The clouds are braked by the interstellar medium, and have thereby acquired angular momentum. In the outer parts of their orbits the shocked interstellar gas has been able to cool and form a region of compressed gas; the corresponding compression of the magnetic field causes the enhanced synchrotron emission. The H_α-emission is ascribed to ionization in the shock front. The normal arms show evidence of having been affected by the expelled material; on the west side at least they appear to have much decreased in brightness in those parts where this material would have moved through.

The total ejected mass must lie between 10^7 and 10^8 solar masses; in due time most of this should be concentrated near the "ridges". By the differential rotation the latter will after

some 100 million years develop into a normal spiral pattern extending over the whole system. The suggestion is made that processes like that which we suppose to be resonsible for the radio arms of NGC 4258 may be the mechanism by which spiral structures are re-born at such intervals that they can replace structures that have become worn out.

The investigation was made in collaboration with Drs. P. C. VAN DER KRUIT and D. S. MATHEWSON in Leiden. The Westerbork Synthesis Radio Telescope is operated by the Netherlands Foundation for Radio Astronomy with financial support from the Netherlands Foundation for Pure Research.