THE SPIRAL STRUCTURE OF M 31

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RELEVANT OBSERVATIONAL MATERIAL

- The H I, H II, and OB-association densities, as a function of radius, have the same structure, reminding one of a ring with a maximum at $r \simeq 50'$.

- There is an H I excess on the NE side of the galaxy.

- From H I measurements along the major axis there is an evident asymmetry between the N and S sides. The positions of the maxima on one side correspond to the minima on the other, and vice versa.

- The rotation curve has a steep rise near the centre, then remains quite flat.

- There are systematic differences between the rotation curves of the two semi-major axes: for radii smaller than $r = r_1$, SP rotates faster than NF. At $r = r_1$ the two rotation curves cross, and for $r > r_1$ the values for the NF side are larger than the corresponding ones for SP. The values of r_1, as given by various authors, vary between 40′ and 60′. Similarly, an asymmetrical behaviour is found for other opposite semi-diameters of the galaxy.

- Kalnajs (1975) Fourier-analysed i) the H II regions given by Baade and Arp (1964); ii) the 106 brightest of the above regions; iii) the OB-associations given by van den Bergh (1964); iv) the H I surface brightness distribution observed by Emerson (1974). In all cases he found a one-armed leading spiral. The corresponding Fourier transform $A_1(a)$ of the function $r^2\sigma$ has a maximum at $a = -11$ (pitch angle $\simeq 5^\circ$). In the case of the H I he also found a dominant peak at $a = 0$, expressing the H I excess on the NE side of the galaxy.

E. M. Berkhuijsen and R. Wielebinski (eds.), Structure and Properties of Nearby Galaxies, 163-167.

THEORETICAL APPROACH

We will try to reproduce the observational data by assuming that M 31 is forced by an orbiting retrograde companion galaxy. Our model has been described previously (Athanassoula 1977, hereafter paper I). M 31 is supposed to be a disk of zero thickness, and no z-motions are considered. The companion's orbit is assumed to be on the plane of the disk and its parameters are taken such as to mimic M 32. Our model is linear, self-consistent, non-local, and non-asymptotic (the spiral can be open). Both stars and gas are taken into account.

The orbit of M 32 gives rise to an inner Lindblad resonance. The existence of such a resonance is important since the mass of M 32 is only a few percent of that of M 31 and yet the amplitude of the gaseous spiral reaches $\gtrsim$ 30% of the axisymmetric gaseous background. This can be achieved only with the help of a resonance. For a retrograde orbit of the companion, no m = 2 resonance is possible.

We want to stress here that our model cannot describe the full complexity of the causes of the spiral structure in M 31. Non-circularity of the companion's orbit, the effect of other companions, e.g. NGC 205, and especially motions in the z-direction can modify the picture.

The spirals in the gas and in the stars are found as the solutions of two coupled integral equations. The method and the parameters and symbols used can be found in paper I. To simulate the effect of the observed variation of the gaseous axisymmetric density with the radius, we have multiplied the gaseous density by the radial distribution of H I, taken from Emerson's data. This weighting affects the spiral only slightly, attenuating low-level extensions in the inner parts and accentuating low-level noise in the outer parts.

The force field from the stellar spiral is a significant fraction of the total tidal field felt by the gas. It is thus possible to achieve a good approximation of the form and orientation of the observed spiral (e.g. Fig. 1), which is impossible if the stars and self-consistency of the gas are neglected (Kalnajs 1965). The pattern speed is $\Omega_p = -10.5$ km sec^{-1} kpc^{-1}.

The perturbation in the stars forms a much more open spiral (a = −3) with its maximum well within resonance. The perturbation contrast in the stars is roughly 0.1 of that seen in the gas. This can explain why the spiral structure is not evident in the isophotes.

There is angular momentum exchange between the spiral wave and M 32. The wave loses positive angular momentum while M 32 gains it, and since it is in a retrograde orbit it spirals inwards. Its eccentricity grows in time.

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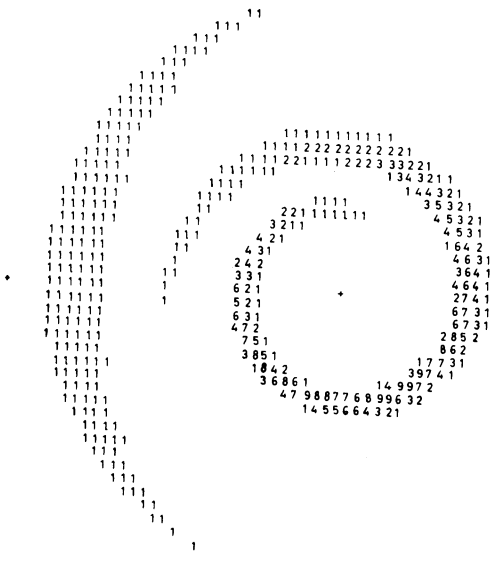

Figure 1. The gaseous spiral corresponding to the parameters: $r_R = 50'$, $u_R = -0.5$, $\Gamma = \sqrt{2}$, $\varepsilon = 0.1$, $d_0 = 0.3$, $b_s = 0.1$, $b_g = 0.005$, $C_1 = 0.01$. (see paper I for the definition of symbols).

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DISCUSSION FOLLOWING PAPER III.3 GIVEN BY E. ATHANASSOULA

OORT: Baade found about six arms crossing each side of the major axis. This is a rather different picture than that of the one-arm spiral you derived.

VAN WOERDEN: Baade found six arms crossing with each half of the major axis, not "six arms". With a small pitch angle, one can obtain many axis crossings with one arm.

COURTÈS: It is obvious that a small pitch angle gives a fundamental ambiguity but it is strange to see that the one arm leading model fits better with the HII region distribution (Courtès, Mancherat, Monnet, Pellet and Simien, presented to A.A.).

ATHANASSOULA: The two-armed trailing pattern with a 7^o pitch angle of Baade and Arp gives a reasonable fit only near the major axis. The corresponding fit obtained with a 5^o one-armed spiral is much better.

VAN DEN BERGH: Inspection of the optical spiral arm tracers shows that they form a number of rather short arcs. Some imagination is required to fit these arcs into an "Andromeda-wide" one or two arm spiral pattern. Interpretation of the data is complicated even more by the fact that the fundamental plane of M31 is warped.

ATHANASSOULA: The optical picture is quite complicated due, mainly, to the superposition of many components. It becomes, however, much clearer after a Fourier series decomposition.

MARK: It seems that such Fourier analysis of observations is difficult to do properly and especially so for M31 because of its inclination to us. Take the hypothetical situation of a strictly two-armed spiral which is not sinusoidal in its azimuthal profile but say narrower near the peaks due to young stars forming there. Fourier analysis of this two-armed structure will give contributions to the Fourier spectrum at multiarms and with a rather flat spectrum. Extra care should be taken especially when the galaxy is so inclined. Perhaps the procedure should first be applied to a more face-on galaxy whose major spiral structure is more directly observable.

ATHANASSOULA: A Fourier decomposition of your "strictly two-armed" example (or of a "strictly one-armed" similar example) would give contributions at multiarms, but this would not affect the $m = 1$ component we are studying here. As regards the application of the Fourier decomposition procedure, it has already been applied to M51.

VAN WOERDEN: Does not the diagram for HI peaks at a pitch angle zero suggest that the gas is predominantly arranged in circular rings?

ATHANASSOULA: No. There is a peak, at $a = 0$, of the $m = 1$ Fourier component ($A_1(a)$) obtained from the HI distribution (small values of a

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correspond to open spirals and large values to tightly wound ones). This peak at a = 0 comes from the HI excess on the NE part of the galaxy, which can be considered as a "one-armed bar".

COURTÈS: The interpretation in multiarms corresponds to the first HII region survey of Baade and Arp. The situation is a little clearer now after the study of associations of OB stars of van den Bergh (1964, Ap.J. Suppl. 9, 65) and our deeper HII region survey (in press) which show some evidence of continuity. I agree that anyway the structure of M31 remains very ambiguous.

ATHANASSOULA: The logarithmic spiral obtained from a fit of the deeper Hα survey you mentioned agrees completely with that presented here.