TWO-DIMENSIONAL RESONANCE PATTERNS IN THE DISCS OF SPIRAL GALAXIES

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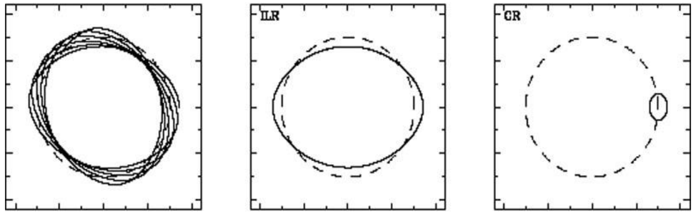
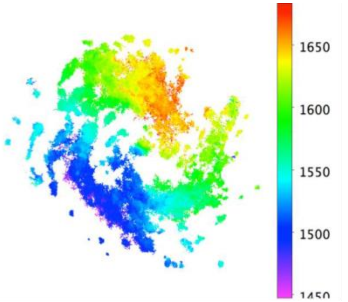
ABSTRACT.

Two major features of structure in galaxy discs: the long-term presence of spiral arms, and the continuous presence of OB stars concentrated in the arms, can be explained if a spiral density wave in the stellar population interacts with star-forming gas in the disc. With a recent method we are able to perform accurate characterization of the density wave, showing that it is not a single entity, but a system of concentric waves occupying well-defined annuli in the disc. Each wave has its pattern speed and corotation radius; the strongest wave is normally associated with a bar. Each corotation radius is marked by a change in the radial gas flow from inwards to outwards, or vice-versa. Here we go a major step further, showing that a corotation is detected just where a spiral arm crosses the corotation radius of each annulus. The arms bifurcate as they cross each boundary between the density wave annuli, and the number of the corresponding corotation detections increases accordingly, producing a two-dimensional pattern. with considerable symmetry.

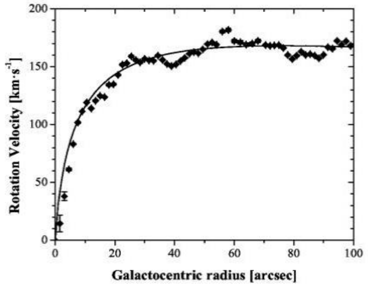
The key to the method:



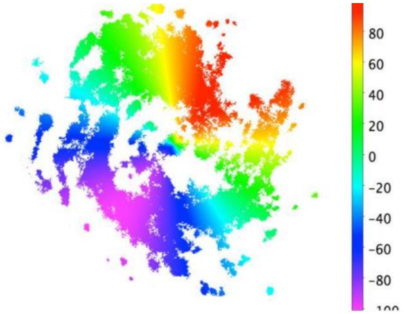
Kalnajs showed that at corotation stellar and gas orbits should be circular, while outside this radius the orbits will be prolate ellipses and inside this radius they will be oblate ellipses. Corrolary: at corotation the ***radial*** velocity of gas and stars should be zero. So we search for pixels where the radial velocity of the gas in the plane of the disc is zero. Gas is more sensitive. Also we can make high resolution velocity maps of complete galaxies with the GHαFaS Fabry-Perot spectrograph on the WHT; La Palma.



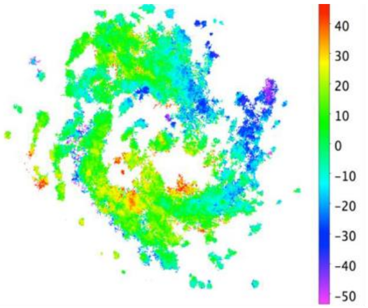
2D velocity map of disc galaxy using Hα emission from the ISM.



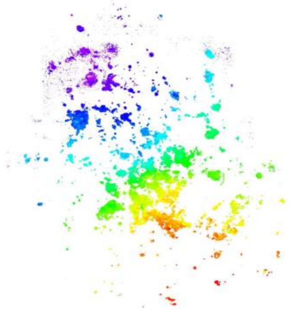
Mean rotation curve.



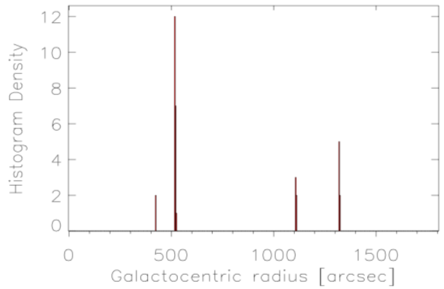
2D model made by 360º rotation of rotation curve.



2D map of radial velocity In the disc. We select the zeros.



2D velocity map of M33.



Histogram: 1D radial map of the zeros. There are 4 corotations!

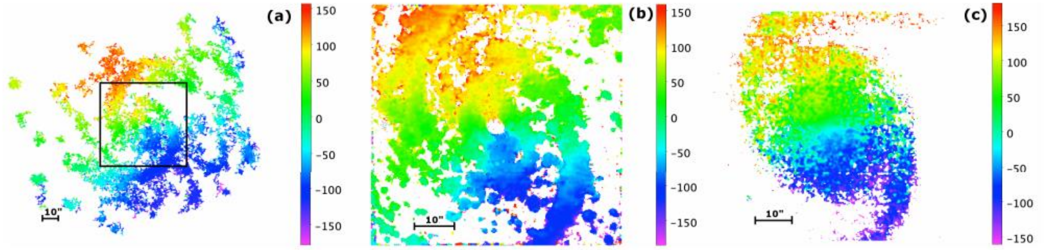
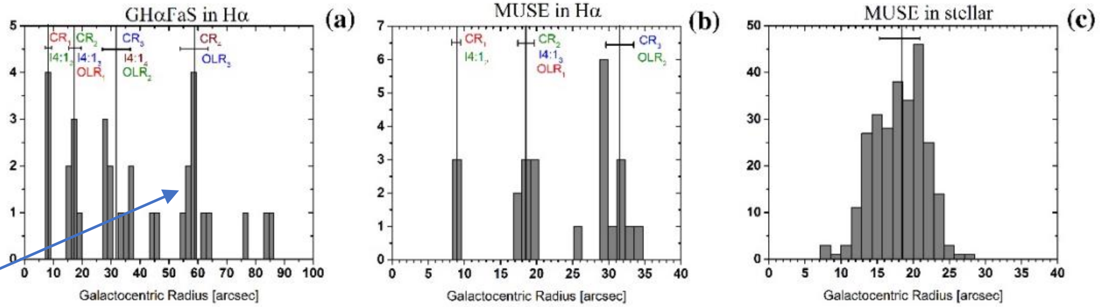
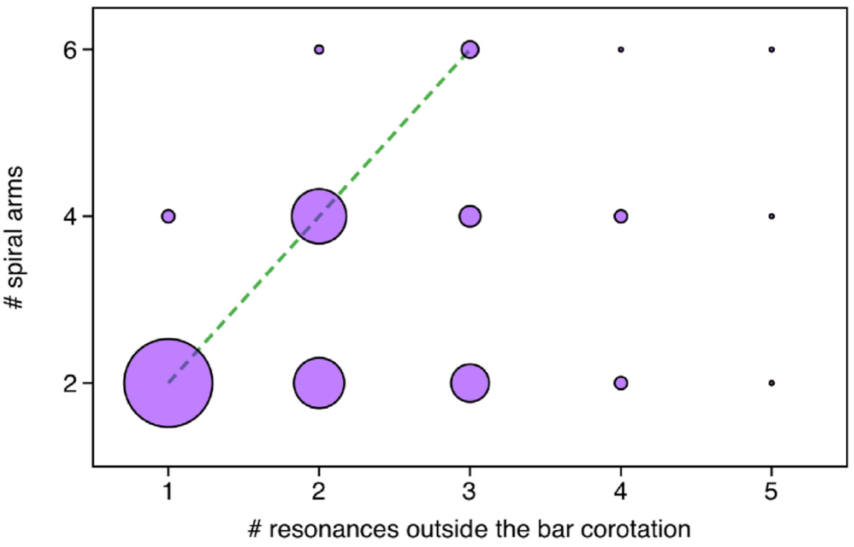


Figure 2. Panel a: velocity map of NGC 3433 using 1st moment map of Hα emission in the FP data cube from GHαFaS. The box in black shows the size of the MUSE data. Panel b: velocity map of Hα emission from the central armin^2 from the MUSE data cube. Panel c: velocity map of the stellar component from the MUSE data.

Figure A. This is a radial 1D histogram



Complete analysis of NGC 3433 using stars and gas, with data from GHαFaS and also from MUSE (gas plus stars) but only in the centre (smaller field). Result: 4 corotations found using gas, only 1 with stars, as they have 3D orbits which make this method much harder to use.



We have measured these radial resonance distributions in over 100 galaxies. In the barred galaxies there is always a corotation just beyond the end of the bar, but in all the galaxies there are further corotation annuli further out.

This figure is a plot of the number of corotations outside the bar corotation in a given galaxy v. the number of spiral arms.

Note: The number of arms grows with distance from the centre because of bifurcations., and the numher of arms plotted here includes all the bifurcations in a given galaxy.

The circles represent the number of galaxies in each two-parameter bin.

The dotted line joins the bins with the maximum number of galaxies for any value of the arm number.

You can see that it maximizes along the line of two arms per resonance.

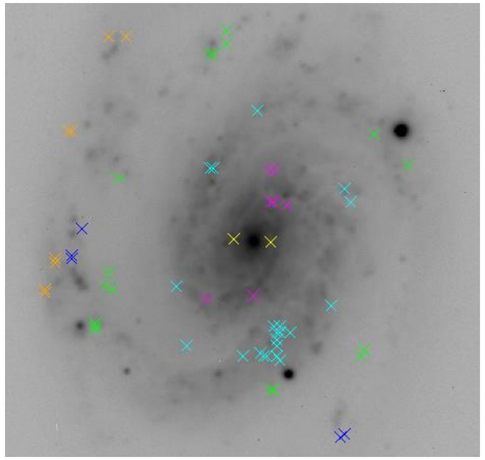
When an arm crosses from one resonance ring to the next, it tends to bifurcate.

New work presented here:

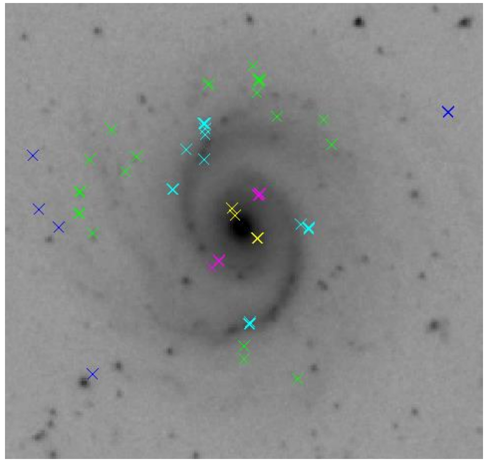
Two-dimensional plots of the positions of the zeros for a first sample of three galaxies.

Figure B.

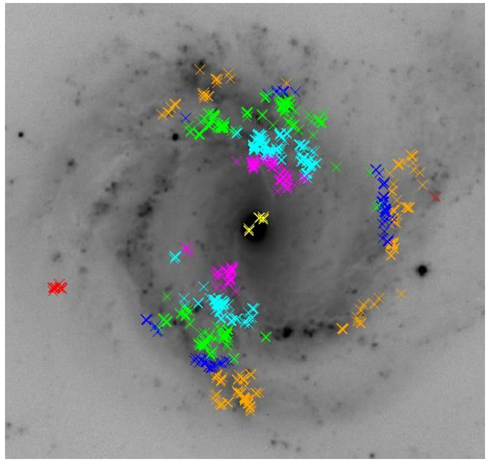
Images of three galaxies with the positions with zero radial velocity plotted. Colours code the different corotations.



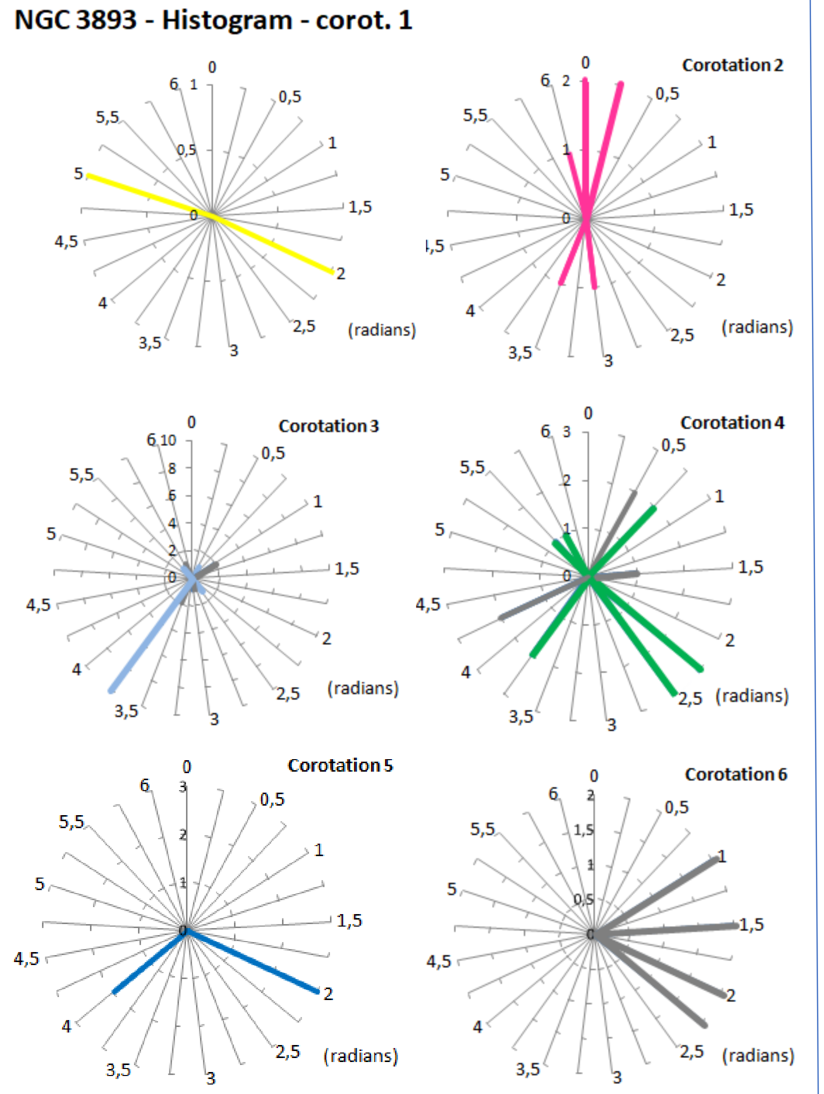
NGC 3893

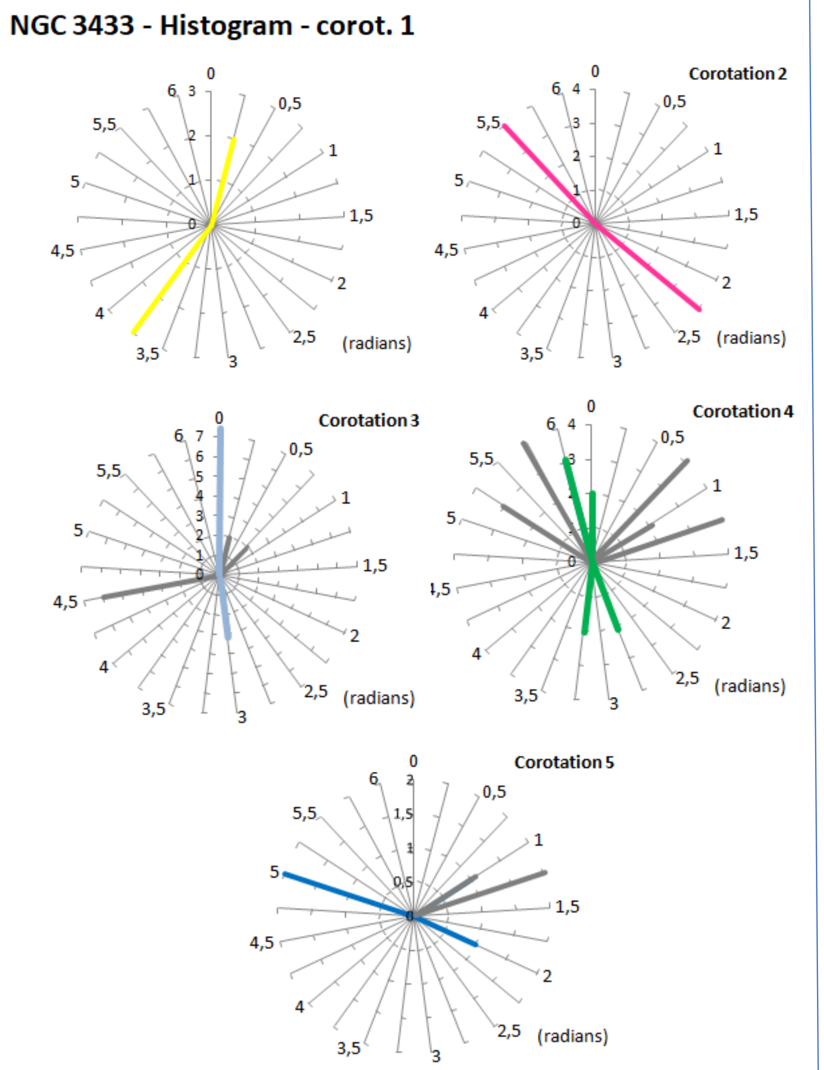


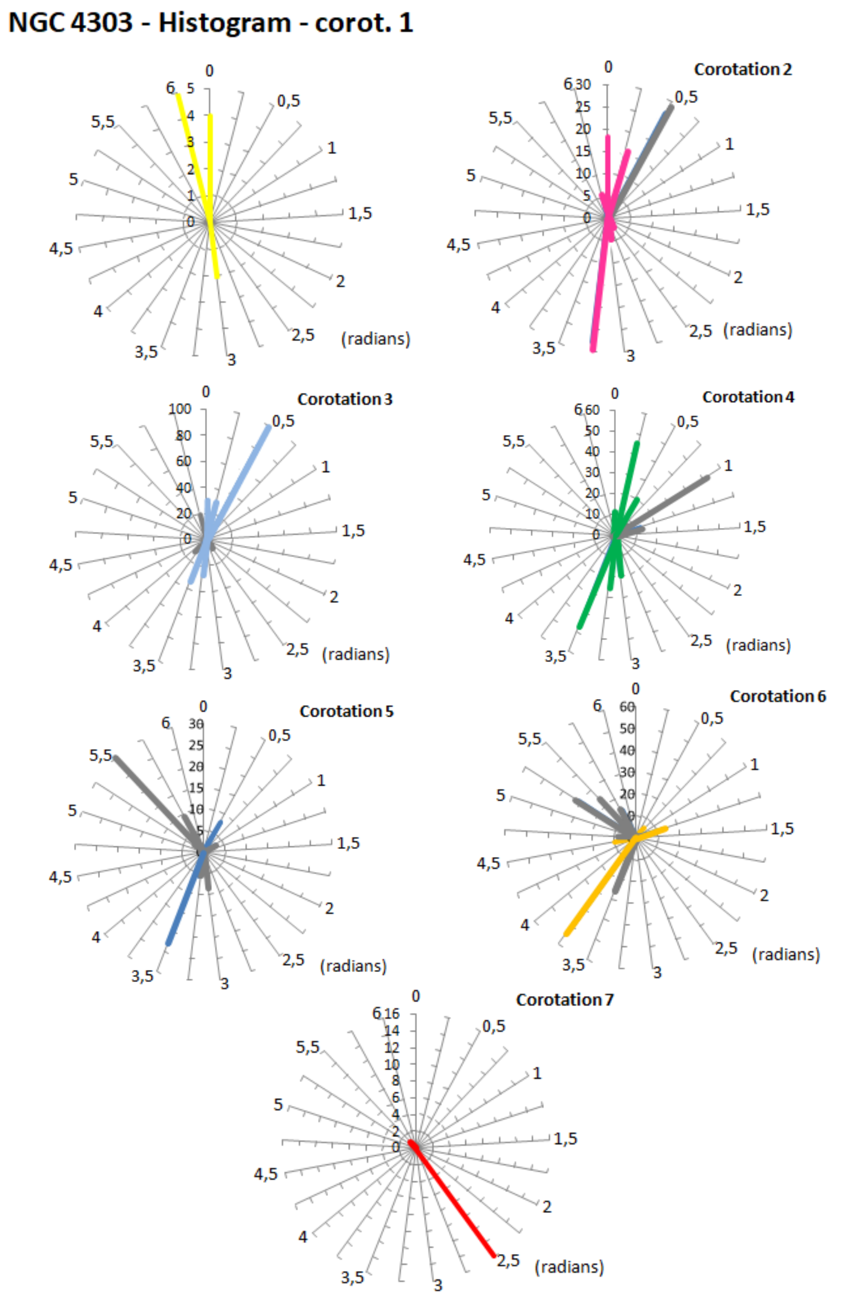
NCG 3433



M61 (NGC 4303)







Colour coding for the corotations is the same as in the images of Figure A.

Each histogram shows the directions of the zero velocity pixels; the length of each bar is proportional to the number of those pixels.

Figure C

Explanation of the images and the histograms.

I. Each corotation is defined by a peak in the radial distribution of the zeros. These peaks are found by plotting the histogram (1D) of the pixels with zeros in annuli from the centre (e.g. Figure A)

II. A zero is found at a point where the radial velocity of the gas changes sign from inflow to outflow or viceversa. But noise and projection effects are minimized by eliminating those zero pixels where the radial velocity change is less than 2σ, (where σ is the uncertainty in any velocity measurement)

III. The zeros are assigned to a given corotation if they lie within the half-width of the peak in the 1d radial histogram.

IV. Once the zeros have been assigned to a given corotation, we can plot the images with their zeros colour-coded for that corotation, (Figure B) and we can derive the circular histograms for their azimuthal distribution (Figure C)

Key point to note: For the inner 4 corotations in all three galaxies the zeros are found generally in pair groups, at opposite ends of their radius vectors, separated by close to 180º in angle.
Exceptions in grey.

But this simple relation tends to break down in the corotations further out.

Interpretation:

I. In the inner part of a barred disc galaxy the corotation is directly related to the bar and corotation is detected near opposite ends of the bar, i.e. detection points separated by 180º.

II. This should hold for the main bar, and also the nuclear bar in a double barred galaxy.

III. In a classical two-armed galaxy corotation will be detected where the spiral arms cross the corotation radius. The detection points will be separated by 180º by symmetry.

IV. In the annular dynamical stucture we have found, the arms bifurcate when crossing from one annulus to the next. The number of azimuthal crossing points for the corotation should Increase by a factor 2. The detections should still be in pairs separated by 180º.

V. But galaxies are not perfectly organized systems. They get ”messier” towards the edge. The outer arms are diffuse, star formation fades out, and the detection of corotation gets patchy. Also in very tightly wound arms, corotation can be detected in a more distributed way along the arm.

We are at the beginning of this work, and will extend it to tens of galaxies, to draw the most general conclusions possible.

REFERENCES:

1. Font, J. et al. ApJ Letters, 741, L14, 2011
2. Font, J. et al. ApJ Supp. Ser. 210, 2. 2014
3. Beckman J.E. et al. ApJ. 854, 182, 2018
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