RESONANT STRUCTURE IN THE DISKSD OF SPIRAL GALAXIES, USING PHASE REVERSALS IN STREAMING MOTIONS FROM TWO-DIMENSIONAL Hα FABRY–PEROT SPECTROSCOPY

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Received 2011 August 1; accepted 2011 September 19; published 2011 October 12

ABSTRACT

In this Letter, we introduce a technique for finding resonance radii in a disk galaxy. We use a two-dimensional velocity field in Hα emission obtained with Fabry–Perot interferometry, derive the classical rotation curve, and subtract it off, leaving a residual velocity map. As the streaming motions should reverse sign at corotation, we detect these reversals and plot them in a histogram against galactocentric radius, excluding points where the amplitude of the reversal is smaller than the measurement uncertainty. The histograms show well-defined peaks which we assume to occur at resonance radii, identifying corotations as the most prominent peaks corresponding to the relevant morphological features of the galaxy (notably bars and spiral arm systems). We compare our results with published measurements on the same galaxies using other methods and different types of data.

Key words: galaxies: fundamental parameters – galaxies: kinematics and dynamics – galaxies: spiral – techniques: interferometric

1. INTRODUCTION

The density wave model (Lindblad 1961; Lin & Shu 1964) is the scenario of reference for understanding the prevalence of spiral structure in galaxies. A key parameter is the corotation radius, where the angular velocities of the spiral density pattern and of the matter in the disk are equal. As our knowledge of disk galaxies has grown, observers are finding that there may be more than one pattern speed, for example, one associated with a bar and another with the arm structure further out in the disk (see, e.g., Meidt et al. 2009). The importance of measuring the bar pattern speed has been enhanced by predictions that a slow bar would be consistent with the braking by a live dark halo, while a fast bar would not be (for a recent treatment see Villa-Vargas et al. 2009 and references therein).

Methods to measure pattern speeds can use morphology, kinematics, or both. Perhaps the best known, due to Tremaine & Weinberg (1984), combines stellar column density, via photometric imaging, and line of sight velocity, via long-slit spectra parallel to the disk major axis. It has been used on the stellar component of 17 galaxies (see Corsini 2011 for a review). As it assumes continuity of the emitting source, opinion is divided on whether it can also be applied using interstellar gas as shocks; phase conversions of gas and star formation may each weaken this assumption, but Zimmer et al. (2004) applied it to CO emission line maps of three galaxies and Rand & Wallin (2004) applied it to six more, while Hernandez et al. (2005) used an Hα emission line map of NGC 4321, Fathi et al. (2007) used a similar map of NGC 6946, and Fathi et al. (2009) applied this method on Fabry–Perot data for 10 galaxies. Other methods used have included predicting the Hα velocity field using measured gravitational potential distribution (Sanders & Tubbs 1980; England et al. 1990; García-Burillo et al. 1993) to derive the pattern speed, and the method of Canzian (1993) which places corotation where the azimuthal non-circular motion pattern changes from singlet to triplet. This was applied to a H1 velocity field by Canzian & Allen (1997) to NGC 4321, and we will compare their work to ours below. Sempere et al. (1995) presented a variant on the Canzian method, also related to the technique described here. Buta & Zhang (2009) used the potential-density phase shift to find corotation for 153 galaxies, which we will use for comparison with our results. In addition, Vega Beltran et al. (1998) identified resonances using rings, Athanassoula (1992) showed that dust lanes marked offset shocks in gas flows, and Puera& Dottori (1997) pinned down corotation using two-color photometry. For an overview of methods for bar pattern speeds see Rautiainen et al. (2008).

In the present Letter we present a method for finding corotation using the change in sense of the non-circular velocity components, relying on the high information density of kinematic maps in Hα and H1. The method detects such changes at more than one radius, which for the present we identify as multiple corotations, corresponding to multiple pattern speeds. We give the results for a set of galaxies chosen because their corotation radii were reported previously, allowing us to make comparisons.

2. THE TECHNIQUE DEVELOPED TO EXPLORE THE RESONANCES

The method we have adopted to explore the resonant structure of a galaxy is to find the galactocentric radii at which the gas response shows a 180° change of phase. This is a more simple-minded way of probing for resonances than most of the previously used techniques, but as we will see it is powerful. It has become possible to use this because the observational
material we have at our disposal has much finer angular resolution than is customary for observations made using the interstellar gas component, for the obvious reason that we are using optical wavelengths, while until now the H I or CO maps used have had typically coarser resolution by an order of magnitude (this situation will change radically when ALMA is in regular operation). We use data cubes in Hα obtained using Fabry–Perot interferometry, which yield maps of galaxies in surface brightness, radial velocity, and velocity dispersion using the emission from their ionized interstellar gas. The technique is applied by first deriving the rotation curve of the galaxy: the circular velocity is traced by the rotation velocity of the emission from their ionized interstellar gas. The technique followed by fitting the peaks to radial plots of the streaming motions as pointed out by Kalnajs (1978). These changes should occur at resonance radii. In practice it is clear that in any non-ideal system these zeros will occur at many places where noise causes a measured transit from negative to positive velocities or vice-versa. In order to optimize the reliability of the measurement we then excluded those zeros from the map where the detected change in velocity across the zero, either positive or negative, was smaller in magnitude than the uncertainty in velocity. The following step was to plot the number of zeros in radial annuli (effectively elliptical because of the inclination of the galaxy disk) against radius. These graphs showed peaks at specific radii, often very marked and with radii easy to determine. The question of which peak corresponds to which resonance is not trivial to resolve. In this Letter, we use two methods: inspection of the morphology of the galaxy, followed by fitting the peaks to radial plots of $\Omega$, $\Omega \pm \kappa$, having selected which peak should correspond to corotation, and comparison of our results with previous results for the same galaxies obtained previously using other methods.

3. THE OBSERVATIONAL DATA

The data used here come from three separate sources: (a) the GHASP (Gassendi H Alpha Survey of Spirals; Epinat et al. 2008) survey of star-forming galaxies using a scanning Fabry–Perot interferometer on the Cassegrain focus of the 1.93 m telescope at the Observatoire de Haute Provence (data, which include observational parameters, rotation curve, and residual velocity map, are available at the Fabry–Perot database: http://fabryperot.oamp.fr/FabryPerot/index.jsp). The detector consists of a CCD camera together with an image photon counting system (IPCS) which leads to zero read out noise (Gash et al. 2002). Depending of the observation, the field-of-view of the instrument is $5.8$ arcmin$^2$ or $4.1$ arcmin$^2$, allowing us to obtain images with a pixel size of 0.68 arcsec or 0.96 arcsec, respectively. Seeing limited angular resolution is $\sim 3$ arcsec (FWHM) and spectral resolution is $\sim 30$ km s$^{-1}$. NGC 4321 does not belong to this survey although it was observed at the same telescope with the same instrument (Chemin et al. 2006). (b) The commissioning run

### Table 1

Comparison of Resonance Radii for Sample Galaxies with Hα Velocity Maps

| NGC | Type | Resonance Radii (arcsec) |
|-----|------|-------------------------|
|     |      | I            | II         | III        | IV          | V           | VI          |
| 428 | SAB(s)bc | 5.8 ± 2.2 | 17.6 ± 3.1 | 59.5 ± 3.9 | 115.6 ± 2.2 | 144.7 ± 2.2 |
| 3344| SAB(rbc) | 58.7 ± 3.8 | 74.4 ± 1.9 | 102.8 ± 2.3 | 127.3 ± 2.3 |
| 3726| SAB(rsc) | 26.2 ± 5.2b | 57.7 ± 10.4b | 102.4 ± 13.1b | 126.0 ± 15.7b | 160.1 ± 15.2b |
| 5427| SA(s)c | 25.2 ± 2.8 | 63.0 ± 2.9 | 100.1 ± 3.2 | 122.4 ± 3.2 |
| 5676| SA(rs)bc | 21.9 ± 1.0a | 65.2 ± 1.4a | 114.1a | |
| 7479| SB(s)c | 7.3 ± 0.2a | 15.7 ± 2.3 | 23.5 ± 0.8 | 47.3 ± 2.1 | 64.5 ± 0.9 |
| 7741| SB(s)cd | 18.4 ± 1.9 | 32.1 ± 1.7 | 54.4 ± 2.4 | 76.5 ± 4.6 |
|     |      | 23.2a | 38.2a | 61.2a |
|     |      | 6.3a | 37.8a | 55.8 ± 4.8 | 80.8 ± 4.9 | 98.3 ± 3.1 | 123.1 ± 3.0 |
|     |      | 35.3 ± 5.2 | 57.7±50.4±55.1±57.8 | 85 | |
|     |      | 64.5 | 17.6 | 22 | 100.1 |

Notes.

For each object, upper row: resonance radii (in arcsec) measured using the technique introduced in the present Letter. The columns are sequential from left to right, in order of increasing galactocentric radius, enumerated separately by order. Suggested corotation radii are in boldface. Lower row: measurements of the corotation radius obtained by the authors identified in the footnote, using a variety of methods.

- a From potential-density phase-shift method (Buta & Zhang 2009).
- b Calculated from the pattern speed of Meidt et al. (2009) applying our rotation curve.
- c From the Tremaine–Weinberg method on Hα data (Fathi et al. 2009). (These authors could not obtain an upper uncertainty limit for the corotation of NGC 7741 with the data available to them).
- d From simulations (Laine & Gottesman 1998).
- e From band crossing method (del Rio & Cepa 1998).
- f From morphological method (Puerari & Dottori 1997).
- g From simulations (Sempere et al. 1995).
- h From morphological inspection (Elmegreen & Elmegreen 1995).
Figure 1. Normalized histograms of the number of zero crossings in the residual velocity fields of the galaxies measured, as functions of galactocentric radii (i.e., radii in the galactic plane). In all cases the graphs show well-defined maxima, which we associate with the effects of resonances corresponding to density wave structure, generally denoting corotation radii. (Vertical dotted lines locate the resonance radii and horizontal segments on top of the histogram show the uncertainty bar associated with each radius.)

of GH$\alpha$FaS (Galaxy H$\alpha$ Fabry–Perot System; Hernandez et al. 2008) in July of 2007, a new generation scanning Fabry–Perot interferometer-spectrometer on the 4.2 m William Herschel Telescope, Observatorio del Roque de los Muchachos, La Palma, Canary Islands. The instrument is used at the Nasmyth focus of the telescope, for practical ease of operation, leaving a field of view no larger than 3.5 arcmin$^2$ which, with the CCD camera used, gives a pixel size of 0.398 arcsec. The $\sim$1.5 arcsec of seeing (FWHM) achieved in that run limits the angular resolution, and the spectral resolution in velocity was fixed to $\sim$16 km s$^{-1}$. (c) The VIVA (VLA Imaging of Virgo in Atomic Gas survey, where VLA is the Very Large Array; Chung et al. 2009) consisting of H$\text{I}$ data of 53 late type galaxies with a typical spatial resolution of 15 arcsec (FWHM) and velocity resolution of $\sim$10 km s$^{-1}$; data are available at the VIVA Web site: http://www.astro.yale.edu/viva/.

4. RESULTS

The results presented here are for a sample of eight galaxies (for one of which, NGC 4321, there are both H$\alpha$ and H$\text{I}$ velocity maps, while for the other seven only H$\alpha$), chosen because their resonance radii had been published previously; the references are specified in the footnote to Table 1. In Figure 1 we have plotted the number of zero velocity crossings in annuli of equal width as a function of galactocentric radius, normalized
to unity at the highest peak in each distribution. In all cases there are well-defined peaks, at radii we can take as indicating corotation. The peaks are narrow enough for us to make clean measurements of these radii, as shown in the figure, and we present the resulting sets of radii in Table 1. These are presented sequentially in order of increasing radius in the left hand section of the table with their errors, which take into account the standard deviation of Gaussian fit to each peak and angular resolution. In the right hand section we include, for comparison, measurements described by their authors as corotation radii. The principal corotation radii measured using our method are noted in boldface. The published values used for our comparisons were obtained by several of the methods described in the introduction. We will discuss them galaxy by galaxy.

4.1. Corotation using Hα velocity fields

NGC 428. We find five resonance radii for this object (Figure 1(a)). The resonance at 59 arcsec by far gives the strongest signal, and we assign this as corotation; it is located at a 1.2 times the radius of the weakly defined bar. The only literature value, from Buta & Zang (2009), is 54.8 arcsec, which may be compatible within the error bars.

NGC 3344. Of our four resonance peaks (Figure 1(b)), that at 102.8 arcsec is by far the strongest, so we assign corotation to this radius. It is clearly not associated with the central weak bar, so we assume that it is a feature of the spiral arm system. Meidt et al. (2009), using CO velocities, derived a pattern speed via the Tremaine–Weinberg method, which we have used to determine the radii of corotation, and of the two Lindblad and the two 4:1 resonances. The agreement for corotation (102.4 arcsec) is excellent, and the radii of the 4:1 resonances, 57.7 arcsec and 126.0 arcsec, agree very well with two of our peaks (58.7 and 127.3 arcsec).

NGC 3726. In Figure 1(c) we show five resonance peaks, of which the peak at 100.1 arcsec is clearly the strongest, so we assign corotation to this value. Inspection shows that this is around 1.25 times the length of the main bar. The innermost peak appears to be associated with an inner boxy mass concentration of the bar, while the two outermost peaks are disk features. Only one of Buta & Zang’s three corotations at 65.2 arcsec is compatible with our results.

NGC 5427. As seen in Figure 1(d) the two outermost peaks are strong, and we have selected the stronger, 47.3 arcsec for corotation, with no clear help from the morphology. The peak at 23.5 arcsec appears associated with the inner bar. Of Buta & Zang’s three corotation values, the third at 63.3 arcsec coincides with our fourth peak.

NGC 5676. In Figure 1(e) we see four resonance peaks and have assigned corotation to the outermost, most intense, peak at 76.5 arcsec. The inclination makes it hard to find correspondence with a specific feature. The peak at 18.4 arcsec appears to be associated with the small bar. None of Buta & Zang’s corotation radii coincide with ours.

NGC 7479. As seen in Figure 1(f) we show six peaks for this very strongly barred starburst galaxy (Laine & Gottesman 1998). Using criteria of peak intensity, and in agreement with other
authors (see Table 1), we selected 55.8 arcsec and 98.3 arcsec as two corotation radii, one associated with the bar and the other with the disk. The innermost peak, at 13.2 arcsec, belongs to the central mass concentration.

NGC 7741. Figure 1(g) shows four peaks, of which three are comparably strong, and we assign to each of these a corotation. The peak at 36.8 arcsec is linked with the central mass concentration of the bar that at 66.3 arcsec is associated with the bar (at ~1.3 the bar radius), while that at 95.3 arcsec is due to the disk system. Buta & Zang’s value of 51.9 arcsec is due to the disk system. Buta & Zang’s value of 51.9 arcsec would be reproduced by a smoothed averaged contribution of our inner two peaks, while Fathi et al. (2009) find corotation consistent, within the error bars, with our outermost peak.

4.2. Corotation in NGC 4321 using Hα and Hα: Comparison with Canzian’s method

In Figure 2(a) we show the five peaks tabulated in Table 2. Of these, the innermost peak at 31.8 arcsec is associated with the central mass concentration (a small bar), while the second peak at 97.0 arcsec is linked to the weak long bar. We have termed both of these corotations. Both are also detected directly in Hα (Figure 2(b)) and in Hα by Canzian & Allen’s (1997) range of 88–108 arcsec the 97.0 peak is included. In Figures 2(c) and (d) we show, respectively, the residual velocity maps in Hα and Hα (used to prepare Figures 2(a) and (b)), which both show the transition from a single azimuthal cycle of velocity transitions in the central zone to a triple cycle in the outer zone.

The radius of the peak close to 100 arcsec in the histograms of Figures 2(a) and (b), marked on the maps (Figures 2(c) and (d)), is that of the singlet–triplet transition. Our technique thus picks out this transition, but more sharply, using the Hα field.

It is notable, however, that Hernandez et al. (2005), using the Tremaine–Weinberg method on the same Hα velocity map, and with 12%, which we obtain using our method but with lower angular resolution Hα data from VIVA (Chung et al. 2009). We believe that the method presented here is a significant step forward in quantifying the resonant structure of disk galaxies, but understand that there are issues to resolve for this method and for the others, related to the nature of the resonances, their structure, and their lifetimes.

This work was supported by projects AYA2007-67625-C02-01 of the Spanish Ministry of Science and Innovation, and project 3E 310386 of the Instituto de Astrofísica de Canarias. We thank Sharon Meidt, Scott Tremaine, and Phil James for very useful discussions, and the anonymous referee for valuable comments.

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Table 2

Comparison of Resonance Radii of NGC 4321

|   | I     | II    | III   | IV    | V     | VI    | VII   | Reference |
|---|-------|-------|-------|-------|-------|-------|-------|-----------|
|   | ± 10.6 | 67.5 ± 6.8 | 108.8 ± 10.3 | 123.5 ± 2.1 | 147.9 ± 10.7 | 166.3 ± 6.0 | 188.2 ± 9.5 | Hαb       |
| 31.8 ± 3.4 | 97.0 ± 2.2 | 110 | 71.8 | 123.1 | 97 | 150 | 42 | 1         |

Notes.

a. Resonance radii (in arcsec) measured using the technique introduced in the present work using velocity map in Hα by Chung et al. (2009) and in Hα by Chemin et al. (2006). b. Calculated from results of Hernandez et al. (2005) who used the Tremaine–Weinberg method on Hα observations. The three radii correspond to three corotations: nuclear, bar, and spiral, respectively.

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