Exploring Stellar and Ionized Gas Noncircular Motions in Barred Galaxies with MUSE

Carlos López-Cobá1 ©, Sebastián F. Sánchez2 ©, Liwai Lin1 ©, Joseph P. Anderson3 ©, Kai-Yang Lin1 ©, Irene Cruz-González2 ©, L. Galbany3,4,5 ©, and Jorge K. Barrera-Ballesteros2 ©,

1 Institute of Astronomy and Astrophysics, Academia Sinica, No. 1, Section 4, Roosevelt Road, Taipei 10617, Taiwan; calopez@asiaa.sinica.edu.tw
2 Instituto de Astronomía, Universidad Nacional Autónoma de México, Circuito Exterior, Ciudad Universitaria, Ciudad de México 04510, Mexico
3 European Southern Observatory, Alonso de Córdova 3107, Vitacura, Casilla 19001, Santiago, Chile
4 Institute of Space Sciences (ICE, CSIC), Campus UAB, Carrer de Can Magrans, s/n, E-08193 Barcelona, Spain
5 Institut d’Estudis Espacials de Catalunya (IEEC), E-08034 Barcelona, Spain

Received 2022 April 12; revised 2022 September 6; accepted 2022 September 19; published 2022 November 1

Abstract

We present Multi Unit Spectroscopic Explorer (MUSE) integral-field stellar and ionized velocity maps for a sample of 14 barred galaxies. Most of these objects exhibit “S”-shape isovelocities in the bar region indicative of the presence of streaming motions in the velocity fields. By applying circular rotation models we observe that bars leave symmetric structures in the residual maps of the stellar velocity. We built noncircular rotation models using the XookSuut tool to characterize the observed velocity fields; in particular we adopt bisymmetric models and a harmonic decomposition for a bar potential for describing the nonaxisymmetric velocities. We find that both models are able to reproduce the oval distortion observed in the velocity maps. Furthermore, the position angle of the oval distortion estimated from the bisymmetric model correlates with the photometric bar position angle ($\rho_{\text{pearson}} = 0.95$), which suggests that noncircular velocities are caused by the bar. Because of the weak detection of H$\alpha$ in our objects we are not able to compare gas to stellar noncircular motions in our sample, although we show that when galaxies are gas-rich, oval distortion is also observed but with larger amplitudes. Finally, we do not find evidence that the amplitude of the noncircular motions is dependent on the bar size, stellar mass, or global star formation rate.

Unified Astronomy Thesaurus concepts: Stellar kinematics (1608); Barred spiral galaxies (136)

Supporting material: figure sets

1. Introduction

Stellar bars are among the multiple nonaxisymmetric components observed in galaxies (de Vaucouleurs et al. 1991), and it is estimated that nearly $\frac{1}{3}$ of disk galaxies exhibit a stellar bar (e.g., Sellwood & Wilkinson 1993), with the number increasing when observing in infrared bands (e.g., Knapen et al. 2000). Commonly, bars are thought to play multiple roles in the evolution of galaxies, including the radial migration of stars (e.g., Minchev & Famaey 2010), triggering star formation (SF) and nuclear activity (e.g., Combes 2001), and for shaping the metallicity gradients in galaxies (e.g., Sánchez-Blázquez et al. 2011). All these processes are intrinsically related to the dynamics of the bar. Therefore, understanding their kinematic properties is crucial for revealing their real influence in galaxy evolution. While bars are relatively easy to recognize in continuum images (Wozniak & Pierce 1991), their kinematic counterpart is not evident until there is a detailed examination of their velocity fields. Even so, nonaxisymmetric motions induced by bars have been identified in a wide variety of objects. These bar-driven motions when projected into the line of sight manifest in the form of oval distortions, which have been observed in the velocity field of molecular (e.g., Weliachew et al. 1988), neutral (e.g., Bosma et al. 1977; Peterson et al. 1978), and ionized gas (e.g., Fathi et al. 2005; Holmes et al. 2015), as well as in stellar velocity maps (e.g., Kormendy 1983; Bettoni et al. 1988). Such distortion recognized for producing an S-shaped pattern in the velocity field is less evident when the bar axis is closely aligned parallel or perpendicular to the line of nodes; these viewing angles disfavor the detection of bar stream motions (e.g., van Albada & Roberts 1981; Pence & Blackman 1984; Athanassoula & Misiriotis 2002), making difficult to identify bar-like flows from line-of-sight velocities. Hence it is common that bar-flow studies are biased toward galaxies with bars lying at intermediate orientations from the disk major/minor axes (e.g., Pence & Blackman 1984).

With the advent of recent observational techniques such as integral-field spectroscopy (IFS) we are able to spatially resolve the ionized and stellar kinematic properties of bar-like flows (e.g., Fathi et al. 2005; Barrera-Ballesteros et al. 2014; Holmes et al. 2015; Fraser-McKelvie et al. 2020; Gadotti et al. 2020). In the optical, their kinematic counterpart have been identified mostly using H$\alpha$. This, however, tends to bias the studies toward gas-rich systems, in addition to the fact that H$\alpha$ traces in most cases the location of young stars. Conversely, stellar bars are dominated by old stellar populations (e.g., Sánchez-Blázquez et al. 2014), whose ionization is mostly dominated by old stars (e.g., Stasieńska et al. 2008; Gomes et al. 2016; Lacerda et al. 2018; Sánchez 2020).

On the other hand, studies of bars using stellar velocity maps in most IFS galaxy surveys are limited by inherent spatial resolution effects, precluding the identification of bar-driven flows (e.g., Barrera-Ballesteros et al. 2014). In the present work, we address the kinematic study of bars by taking full advantage of integral-field spectroscopic data from the Multi Unit Spectroscopic Explorer (MUSE) instrument to detect bar-like flows on the stellar and H$\alpha$ velocity
maps of 14 galaxies. We built kinematic models to describe the bar flows and try to relate the amplitude of the bar noncircular motions to some global properties of galaxies.

The paper is structured as follows. In Section 2 we describe the data; in Section 3 the analysis of the velocity maps and the kinematic models adopted; in Section 4 we describe the results, and the conclusions are presented in Section 5. Throughout this kinematic models adopted; in Section4 we describe the results, the data; in Section3 the analysis of the velocity maps and the

(1) galactic compilation (Galbany et al. 2016; López-Cobá et al. 2020). AMUSING++ is a compilation of ∼600 nearby galaxies observed with the MUSE instrument (e.g., Bacon et al. 2010). With a field of view (FoV) of $1'' \times 1''$, delivering ∼90 K spectra per data cube, MUSE is the most advanced integral-field spectroscopy (IFS) instrument in the optical range covering from 4800 Å to 9300 Å. It combines both a moderate spectral resolution ($R \sim 3000$) and a high spatial resolution limited by atmospheric seeing.

The AMUSING++ cubes were analyzed using the PIPE3D package (e.g., Sánchez et al. 2016). This tool has been extensively used on a number of IFS galaxy surveys such as the Calar Alto Legacy Integral Field Area Survey (e.g., Sánchez et al. 2012), Mapping Nearby Galaxies at Apache Point Observatory (e.g., Bundy et al. 2015), and Sydney-AAO Multiobject Integral-field spectrograph (e.g., Allen et al. 2015). PIPE3D models the stellar continuum using a combination of simple stellar populations and derives the properties of the emission lines after subtracting this model from the original spectra.

On the other hand, the recovery of the stellar population properties, such as the stellar kinematics, is performed over a tessellated map of the continuum, typically around the $V$ band. This map follows the light distribution of the galaxy preserving the shape of its main structural components; the area of the resulting segments or bins depend on the target signal-to-noise ratio (S/N) of the continuum, here chosen to reach S/N > 30. For the particular case of the MUSE data, these bins hold an area that goes from $1'' \times 1''$ for high S/N regions, equivalent to 5 × 5 spatial pixels (spaxels) given the 0.2 pixel sampling of MUSE, to $2'' \times 2''$ for regions with low S/N, typically found at the outskirt of the disks. We emphasize that this is one of the major advantages of the current data compared to other IFS surveys with coarser spatial resolutions. Then the spectra within each bin are coadded, and over this spectrum a simple stellar population analysis (SSP) is performed to recover the velocity, age of the SSPs, and metallicity, among other properties; this procedure is performed over each bin of the segmented map (see Sánchez et al. 2016, for a thorough description of this analysis).

In addition to the above analysis, the ionized gas properties such as the flux, velocity, and velocity dispersion, are recovered at each individual spaxel by implementing a moment analysis on a set of ∼50 emission lines. We refer the reader to the AMUSING++ presentation paper (e.g., López-Cobá et al. 2020) for more details of this procedure. The final outputs of the PIPE3D analysis are two-dimensional maps of the main properties of ionized gas and the underlying stellar populations. For the current analysis, we selected a sample of barred galaxies from the AMUSING++ data set. Galaxies were required to exhibit clear stellar bars in the MUSE gri images. Barred galaxies in interaction were excluded as their kinematics is dominated by the interaction process and not by internal ones; in addition, we exclude those objects where the higher S/N bins have sizes larger than 3 times the seeing of the observing night (based on the ESO DIMM archive). This condition excludes galaxies observed with nonoptimal atmospheric conditions. Finally the apparent bar length must be resolved in the stellar velocity map, and it must fit in the MUSE FoV. These criteria lead to a sample of 14 galaxies. As AMUSING++ is a compilation of objects, our sample of bars is not a statistical representation of the population of barred galaxies in the local universe. Therefore, the results of this analysis are not statistically significant.

3. Analysis

3.1. Photometric Properties of Bars

Stellar bars are dominated in general by old stellar populations (e.g., Sánchez-Blázquez et al. 2014; Vera et al. 2016; Fraser-McKelvie et al. 2019; Neumann et al. 2020); therefore, it is common to study these structures in the reddest bands of the optical spectrum or in infrared bands (e.g., Díaz-García et al. 2016), where their morphological properties are enhanced. Among those properties is the bar length, albeit there is no unambiguous method for estimating it (see Athanassoula & Misiriotis 2002, for a thorough description of the methods). Parametric methods often decompose the galaxy light distribution into axisymmetric and nonaxisymmetric components to recover the disk, bulge, and bar properties (e.g., Laurikainen et al. 2018; Méndez-Abreu et al. 2019). An easier way consists of analyzing the object light distribution by tracing isophotes. Abrupt changes in the disk position angle ($\phi_d$) and the axial ratio ($e$) have been commonly used to estimate the bar length, as well as its orientation in the sky (e.g., Kormendy 1983; Pence & Blackman 1984; Bettoni & Galletta 1988; Wozniak & Pierce 1991; Pérez et al. 2009). Then, the true length of the bar along the major axis can be estimated by pure trigonometric relations as follows:

$$r_{\text{bar}} = r'_{\text{bar}} (\cos^2 \phi + \sin^2 \phi / \sin^2 i)^{1/2},$$

(1)

where $r'_{\text{bar}}$ is the apparent length of the bar in the sky, $\phi = \phi_d - \phi'_{\text{bar,phot}}$ with $\phi'_{\text{bar,phot}}$ representing the bar position angle, and $i$ is the disk inclination.

Instead of adopting narrowband images from the MUSE cubes, we use $r$, $i$, or $z$-band images from the Dark Energy Survey (DES; e.g., Abbott et al. 2018) or Panoramic Survey Telescope and Rapid Response System (Pan-STARRS; e.g., Chambers et al. 2016) whenever available. These images have a larger FoV, and they are deeper than our MUSE data. For extracting the isophotes we use the PHOTOUTILS Python package (Bradley et al. 2016), which relies on the ellipse fitting analysis introduced by Jedrzejewski (1987). After background subtraction, we adopt the last faintest isophote to derive the galaxy position angle $\phi_d$ and disk inclination. Then we trace their radial variations and measure the bar position angle and bar length based on the three consecutive isophotes that maximize the difference $\Delta P = P_{i+1} - P_i$, where $P$ is $\phi_d$ or the ellipticity ($e$). Although this analysis is just a proxy for the bar size and its orientation, it offers a first-order estimation of these properties. As a sanity check, we performed a visual comparison between our estimations of $\phi'_{\text{bar,phot}}$ and $r'_{\text{bar}}$ with

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3.2. Kinematic Signatures of Bars

A common and noticeable effect of bars on the velocity field is the change in orientation of the dynamical major and minor axes (e.g., Barrera-Ballesteros et al. 2014), a signature of bar stream flows. As mentioned before, oval distortions on the velocity field of barred galaxies are well known from the gas velocity fields (CO, H\textsc{i}, H\textsc{ii}). These kind of perturbations induce large deviations in the circular motions, which can be observed in residual maps of simple axisymmetric models of circular rotation (e.g., Bettoni et al. 1988; Bettoni & Galletta 1988). Thus, we adopt kinematic models to identify noncircular motions most likely induced by bars.

3.2.1. Kinematic Models

Multiple algorithms have been developed for describing the velocity field of galaxies. The vast majority of them are based on the tilted ring model (e.g., Begeman 1989), in which the velocity field is divided into concentric rings, each one rotating with a different velocity around a fixed kinematic center. In this work we use \texttt{XookSut} (e.g., Lopez-Coba et al. 2021), which relies on the DiskFit (e.g., Spekkens & Sellwood 2007) and RESWRI (e.g., Schoenmakers et al. 1997) algorithms. \texttt{XookSut} performs nonparametric circular and noncircular rotation models for describing the line-of-sight velocity (LoS). It adopts Markov Chain Monte Carlo (MCMC) methods for sampling the posterior distribution of the different kinematic components and creates an interpolated model based on the highest probability states.

\texttt{XookSut} adopts the following log likelihood with flat priors on the parameters:

\[
\log p(V_{\text{model}}|\hat{\alpha}) = -\frac{1}{2} \sum_{n=1}^{N_{\text{pix}}} \left( \frac{V_{\text{obs}} - \sum_{k=1}^{K} W_k V_k_{\text{model}}}{\sigma} \right)^2 \\
- \log \sigma - N/2 \log(2\pi),
\]

where \(\hat{\alpha}\) represents all the parameters describing the considered model; \(V_{\text{obs}}\) is the observed velocity map; \(\sigma\) is the error map of the measured velocities; \(W_k\) is a series of weights computed at \(k\) independent rings and will serve for creating a two-dimensional interpolated model \(V_{\text{model}}\); \(N\) is the total number of pixels included in the model. The representative values of the models together with their errors are derived by marginalizing the posterior distribution of each parameter; this is one major difference from DiskFit, which adopts a bootstrap technique for error estimation. All \texttt{XookSut} models adopt the thin-disk approximation; i.e., it assumes the disk is intrinsically flat, with a constant disk ellipticity, constant position angle, and fixed kinematic center. These conditions make it possible to represent kinematic models on two-dimensional maps (hereafter 2D model).

The circular model is the simplest model included in \texttt{XookSut}, which is described by the following equation:

\[
V_{\text{circ, model}} = V_{\text{sys}} + \sin i \ V_i \cos \theta.
\]

In this expression \(V_i\) is the circular rotation, which is a function of the radius; \(V_{\text{sys}}\) is the systemic velocity assumed to be constant for all points in the galaxy; the azimuthal angle \(\theta\) is measured on the galaxy plane and is related to the sky coordinates through the inclination angle (i), kinematic center \((x_c, y_c)\), and kinematic position angle \(\phi_{\text{disk}}\) measured from north to east from the galaxy receding side.

In order to characterize the noncircular motions in our sample, we adopt the following noncircular models included in \texttt{XookSut}. The first one is the bisymmetric model proposed by Spekkens & Sellwood (2007) and is suitable for describing noncircular motions induced by a bisymmetric distortion due to an axisymmetric potential; for instance, the one caused by a stellar bar. This model fits elliptical stream lines around a fixed angle to the LoS velocities; the equation describing this model

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Top panel: ESO476-16 DES-z image. The yellow contours represent the isophotes. Bottom panel: radial variation of the disk position angle and ellipticity of the isophotes. The vertical red line shows the approximate length and position angle of the bar, estimated to \(r_{\text{bar}} \sim 9.5 \pm 1.5\) and \(\phi = 114^\circ \pm 3^\circ\), respectively. The red shadow region represents the bar length standard deviation. The green line on top of the continuum image represents these values. The galaxy is oriented north-east with north pointing up and east to the left.

their apparent projections in the continuum images. In all cases a mutual agreement is reached.

Figure 1 shows the implementation of this procedure for one object in our sample, ESO476-16. The estimated photometric bar position angle for this object is \(\phi_{\text{bar, phot}} \sim 114^\circ\), which is consistent with the apparent orientation of the bar in the sky. We finally applied this analysis to all our galaxies in our sample.
\[ V_{\text{los model}} = V_{\text{sys}} + \sum_{m=1}^{\infty} \sin i [c_m \cos m\theta + s_m \sin m\theta]. \]

This expression represents the expected behavior of the LoS velocities induced by an elongated potential, such as a bar. Because of this, the amplitude of the harmonic coefficients has been used to prove the presence of bar-like or radial flows in the velocity field of galaxies (e.g., Wong et al. 2004; Fathi et al. 2005; Elson et al. 2011). Note that a bisymmetric perturbation also includes the \( m' = 3 \) and \( m'' = 1 \) harmonics (e.g., Spekkens & Sellwood 2007; Oman et al. 2019).

We use XookSuut to built circular and noncircular flow models of the stellar and H\( \alpha \) velocity maps of our sample of galaxies. Unlike RESWRI (Schoenmakers et al. 1997), XookSuut does not allow the kinematic center and projection angles to change across radii. In fact, this behavior is not desired in our analysis as we expect that noncircular motions arise due to the bar potential, rather than being induced by the presence of a twisted disk. XookSuut requires guess values for the disk position angle, inclination, and kinematic center. For the first two we use the values estimated from the isophotal analysis described in Section 3.1, while the kinematic center was estimated by eye in each velocity map. As interpolated models are created over rings on the disk plane, we choose the rings to be spaced each 2\( '' \); this value is greater than the spatial resolution of our objects (FWHM\( _{\text{DIMM}} \sim 15'' \) on average).

Finally, we use the corresponding error maps for discarding spaxels with low S/N; that is, we remove spaxels with errors larger than 10 km s\(^{-1} \).

In the following we use the same galaxy ESO476-16 as a showcase to go through the different kinematic models. Figure 2 shows the circular rotation model on the stellar and H\( \alpha \) velocity maps. This figure highlights the differences in spatial resolution in both maps. Given that the recovery of the gas kinematics does not involve the binning procedure described in Section 2, the H\( \alpha \) velocity map shows a better spatial resolution than the stellar velocity.

The stellar velocity reveals a central distortion induced most probably by the presence of the bar, while the isovelocity contours appear twisted near the minor axis. The stellar circular model shows a typical rotating disk with orthogonal major–minor axes. The superimposed isovelocity contours show that the outermost regions in the galaxy are compatible with a pure rotating disk. The residual map in both cases (stars and H\( \alpha \)) show several important features in the inner parts of the disk. The highlighted region in the stellar residual map shows symmetric structures with large residual velocities of the order of \( \pm 40 \) km s\(^{-1} \). On the other side, the H\( \alpha \) velocity field shows a central ring with no data because of the low S/N of H\( \alpha \) in this region. Despite of that, XookSuut is able to predict values in these regions by linear interpolation. We notice that the previous structure with high residuals is also observed in the gas velocity field, albeit is affected by the low S/N data. Such symmetric structures with blueshifted and redshifted components have been observed in residual maps of barred galaxies with similar amplitudes (e.g., Fathi et al. 2005; Castillo-Morales et al. 2007). Thus, we may conclude from Figure 2 that a nonaxisymmetric component is present in the residual velocities from both the ionized gas and stars.

Whether the velocity field of a barred galaxy is better described by a bar-like flow or by a pure axisymmetric radial

\[ \phi_{\text{bar, kin}} = \phi_{\text{disk}} + \arctan(\tan \phi_{\text{bar}} \cos i), \]

where \( \phi_{\text{disk}} \) is the kinematic position angle major axis of the receding side, and \( i \) is the galaxy inclination.

The description of the noncircular motions in our second model is based on the epicycle theory, where the radial and tangential components of the noncircular motions are taken into account by inducing small perturbations to the circular orbits. As shown by Schoenmakers et al. (1997), the LoS velocity \( V_{\text{los}} \) can be expressed as a Fourier series as follows:

\[ V_{\text{los}} = c_0 + \sum_{m=1}^{\infty} \sin i [c_m \cos m\theta + s_m \sin m\theta]. \]

In this expression the \( V_{2,r} \) and \( V_{2,\theta} \) terms represent the bisymmetric deviations (radial and tangential, respectively) from the circular velocity represented by the \( V_i \) term. The phase \( \phi_{\text{bar}} \) represents the position angle of the oval distortion with respect to the azimuthal angle. Its sky projection is given by the following expression (e.g., Bettoni & Galletta 1997; Spekkens & Sellwood 2007):

\[ \phi'_{\text{bar, kin}} = \phi'_{\text{disk}} + \arctan(\tan \phi_{\text{bar}} \cos i), \]

This expression highlights the differences in these regions by linear interpolation. We notice that the previous structure with high residuals is also observed in the gas velocity field, albeit is affected by the low S/N data. Such symmetric structures with blueshifted and redshifted components have been observed in residual maps of barred galaxies with similar amplitudes (e.g., Fathi et al. 2005; Castillo-Morales et al. 2007). Thus, we may conclude from Figure 2 that a nonaxisymmetric component is present in the residual velocities from both the ionized gas and stars.

Whether the velocity field of a barred galaxy is better described by a bar-like flow or by a pure axisymmetric radial
flow is in general not straightforward to determine (e.g., Wong et al. 2004). In this work we will not make any a priori assumption about the kinematic model. Instead, we first adopt a bisymmetric model constraining the radial extension of the noncircular motions up to the the deprojected bar size plus an additional value ranging from 1°–2°5, which takes the spatial resolution of the data into account. In a similar way, we decompose the LoS velocity with a Fourier analysis including only the \( m' = 1 \) and \( m' = 3 \) harmonics (Equation (7)) to compare with the bisymmetric model.

The inclusion of complex models such as the bisymmetric model adds extra variables in the fitting procedure that may reduce the residuals, but at the expense of overfitting the data. In order to assess the bisymmetric model we compute the Bayesian information criterion (BIC; Kass & Raftery 1995), defined as \( \text{BIC} = N \ln(\chi^2/N) + \ln(N)N_{\text{params}} \) where \( \chi^2 \) is the quadratic sum of the residuals and \( N_{\text{params}} \) the number of parameters to estimate from the model. Unlike \( \chi^2 \), BIC is more sensitive to the number of parameters to estimate from the model, favoring less complex ones.

We use the outputs of the circular rotation model (namely, \( x_c, y_c, i, \phi_{\text{disk}}, V_{\text{sys}} \)), as input for the harmonic and bisymmetric models. We note that there is no significant differences in the results if we fix these parameters or we let them vary during fitting. In any case, we let \texttt{XookSuut} to derive the best set of parameters. The results adopting the bisymmetric model on the stellar velocity map of the showcase object are shown in Figure 3. This figure is a corner plot for the parameters describing the disk geometry and the bar orientation. The bisymmetric model finds an oval distortion oriented at \( \phi_{\text{bar}} = 43^\circ \), with its corresponding sky projection (Equation (5)) oriented at \( \phi_{\text{bar,km}} = 289^\circ \pm 1^\circ \). Notice that the position angle of the oval distortion is in agreement with our previous estimation for the photometric bar position angle \( (114^\circ \pm 3^\circ) \).

The 2D representation of the bisymmetric and harmonic models together with the radial profile of the different velocity components are shown in the top and bottom panels from Figure 4, respectively. The bisymmetric model reproduces successfully the “S”-shaped distortion observed in the inner regions; furthermore the residual map no longer exhibits the symmetrical patterns observed in Figure 2. On the other hand, the noncircular velocities, \( V_{\phi} \) and \( V_{\psi} \), show maximum amplitudes of the same order as the residuals in the circular rotation model, i.e., \( \sim 40 \text{ km s}^{-1} \), with smooth profiles as those observed in gas velocity fields (e.g., Sellwood & Sánchez 2010; Holmes et al. 2015).

The bottom panels of Figure 4 show the results of the harmonic decomposition. Again the 2D model seems to be a good representation of the LoS velocities, and no residual structures are observed in the central regions. The radial behavior of the \( c_1 \) harmonic and \( V_r \) from the bisymmetric model suggests that the disk circular rotation is similar in both models; hence, the difference in the models must reside only in the amplitudes of their noncircular components. The inclusion of the \( m' = 3 \) terms reproduce much better the features observed in the velocity field; however the residual map is, at first sight, indistinguishable from the bisymmetric model indicating that the harmonic decomposition produces results as good as the bisymmetric one. In order to assess these differences we computed the dispersion of the residuals but only within the bar region; we find that both models show the same dispersion of \( 11 \text{ km s}^{-1} \), which means that for this object there are no quantitative differences between these models. Nevertheless, the interpretation of the harmonic coefficients is not straightforward. Based on the epicyclic theory, Fransx et al. (1994) and Wong et al. (2004) attempted to derive the behavior of the \( m' = 1 \) and \( m' = 3 \) harmonics for an elliptical potential (i.e., an \( m = 2 \) perturbation). They found that for their proposed models the slope between the \( s_3 \) and \( s_1 \) coefficients (hereafter \( ds_3/ds_1 \)), is found to be negative, i.e., \( ds_3/ds_1 < 0 \); meanwhile for an axisymmetric radial flow, \( |ds_3/ds_1| < 0.1 \), which means that \( s_3 \ll s_1 \). However, they also find that this simple diagnostic does not always allow a clear distinction between radial and bar-like flows. For this reason, in this work we only compare our harmonic analysis with the method of Wong et al. (2004). The bottom rightmost panel of Figure 4 shows the \( s_1/c_1 \) versus \( s_3/c_1 \) ratio together with the best-fit line to the points. For the considered galaxy, the slope of the noncircular velocities is found to be \( -0.11 \), which is consistent with a bar-driven flow according to the harmonics diagnostic of Wong et al. (2004).

4. Results

So far we have described our methodology for a single object. In the following we describe our results when applied to our sample of galaxies. Prior to the kinematic modeling we removed spaxels with errors larger than \( 10 \text{ km s}^{-1} \) to exclude low \( S/N \) data that could affect the final models. For all objects we first create circular models with initial values taken from the

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6 Position angles are measured from north to east. The photometric P.A. goes from 0° to 180°, while the kinematic P.A. goes from 0° to 360° and is measured from the receding side of the galaxy. Therefore there could be differences of 180° between both angles.
isophotal analysis. The 2D models for each individual object are shown in Appendix A. Then we use the best-fit values of the geometric parameters (namely, $\phi'$, $i$, $x_c$, $y_c$ and also $V_{sys}$) as inputs for the bisymmetric and harmonic decomposition models.

It is expected that bar-like flows are not present across the entire disk, but only in the region influenced by the bar as observed from the residuals of Figure 3. Therefore, we fit noncircular motions up to the size of the photometric bar, plus a constant value that goes from $1''$ to $2.5''$ to compensate for the binned spaxels observed in the stellar velocity maps. The two-dimensional noncircular models for the stellar and gas velocity maps are shown in Figures 10 and 11 from Appendix B.

Table 1 shows the XookSuuT results for the constant parameters, namely, $\phi_{disk}$, $i$, and $V_{sys}$. The photometric estimations of the bar position angle and true bar length (i.e., Equation (1)) are shown in the third and fourth columns, respectively. In general, we do not find large differences in the constant parameters, when adopting a bisymmetric or a harmonic decomposition model. This means that the flat-disk assumption is adequate for our objects, besides that both fits are numerically stable despite their different underlying assumptions. An exception to this might be IC 0004, where a constant ellipticity by XookSuuT does not seem to reproduce the kinematic orientation of the disk. Table 1 also shows the BIC value of the bisymmetric model but normalized to the BIC circular model. With this definition, models with BIC $>1$ would not favor the bisymmetric model. We note that only in one object (PGC 055442) BIC definitely favors the circular model over the bisymmetric one; however, the bar orientation in this object is closely aligned with the kinematic major axis, which hampers the detection of the expected bar-like flows.

4.1. Circular Rotation Models

Figure 9 shows the 2D circular models of the stellar and Hα velocity maps, as well as the residual maps of the models. We notice that in the vast majority of cases Hα is not detected in the inner disks; however, a careful analysis of the residual velocities in both stellar and Hα, large-scale residuals are observed around the bar region in most cases, for instance, in NGC 692. Furthermore when Hα is detected, symmetric structures are observed in the inner regions of the residual maps, with antisymmetric velocities about the center; for instance, IC 2160, IC 0004, PGC 055442, and ESO 18-18. Other objects show a high residual toward the center but appear to be affected by other sources of noncircular motions, such as spiral arms, as in NGC 289 and NGC 3464.

On the other hand, the residuals of the stellar velocity maps show many examples of galaxies with “S”-shaped isovelocities together with symmetric residual structures around the bar. Such residuals are not compatible with an axisymmetric rotating disk and are most probably induced by the presence of the stellar bar. The fact that we are clearly detecting oval distortions in most of our stellar velocity maps is likely a consequence of the high spatial resolution of our data, as similar IFS studies with coarser resolution do not observe such structures (e.g., Barrera-Ballesteros et al. 2014).

4.2. Stellar Noncircular Motions

Figure 10 shows the bisymmetric and harmonic decomposition models for the stellar velocity maps. Bisymmetric models tend to reproduce much better the observed velocity map than circular rotation models do. For most objects, $V_{2,r}$ and $V_{2,t}$ show smooth behaviors, with velocities decaying at large radius, a possible signal of the kinematic ending of the bar. NGC 289 is the only object where the bisymmetric model, for both gas and stars, does not seem to be a reasonable
physical model given the erratic behavior of the circular and noncircular velocities. As observed in Figure 10 and Table 1, the bar in NGC 289 is closely aligned with the major axis, being separated by less than $10\degree$, and it is well known that bar stream lines in the velocity field become less evident when the bar lies close the galaxy major axis (e.g., van Albada & Roberts 1981). Moreover, when $\phi_{\text{bar}} = 90\degree$ or $0\degree$, $V_{2r}$ and $V_{2t}$ from Equation (4) become degenerate with the disk circular rotation, making it impossible to separate the noncircular velocities from the circular rotation. As a result, $V_{r}$, $V_{2r}$, and $V_{2t}$ can lead to unphysical absurd values as is probably the case in NGC 289; for instance, note that for $r < 40''$ the three velocities show the same uncommon radial profiles. On the other hand, the harmonic model does not depend on the bar phase; thus, the
disk circular rotation related through $c_1$ seems to offer a better representation of the rotation curve in this case.

When comparing the BIC ratio from the bisymmetric to circular models we note that, in the case of the stellar maps, these values are mostly close to 1, with the aforementioned exception. We expect BIC ratios lower than 1 would favor the bisymmetric model. While this is mostly observed in our sample, in some cases the differences with the circular model are only marginal, and therefore BIC is not conclusive about which model describes better the observed velocity field. It should be noted that because of the binning procedure during the SSP analysis, spaxels are correlated in the stellar maps, which could affect the estimation of the BIC value. In addition to that, BIC seems to be sensitive to the orientation of the bar with respect to the line of nodes, as noted in PGC 055442 and NGC 289, preferring simpler models when the bar is close to the kinematic major axis, and therefore mislead the interpretation of the circular model.

The bar position angle is the main parameter in the bisymmetric model as it defines the orientation of the oval distortion. To visualize better this parameter, Figure 5 shows the photometric bar position angle versus the sky-projected kinematic bar position angle for the objects in the sample. It can be seen that there is a good agreement between both angles; indeed, the Pearson correlation coefficient for this relation is extremely high, being $p_{\text{pearson}} = 0.95$; this result suggests that the coincidence between the kinematic and photometric bar position angle is a possible indicator of the presence of bar-driven flows in barred galaxies.

On the other side, the harmonic decomposition models show good representations of the LoS velocities. Table 1 shows that at least in one velocity map (stellar or ionized), the slope in the harmonic coefficients $ds_3/ds_1$ is negative, which according to the harmonic ratios diagnostic should be compatible with the bar-like flow scenario. We also notice there are objects where $|ds_3/ds_1| < 0.1$; however, this simple diagnostic does not permit to clearly identify radial flows in barred galaxies, as noted by other studies (e.g., Wong et al. 2004; Haan et al. 2009). We will discuss this scenario in the coming sections.

4.3. Ionized Gas Noncircular Motions

As bar-like flows are expected along the bar, the lack of gas in the inner regions affects directly the estimation of $\phi_{\text{bar}}$, and hence the amplitude of the noncircular motions. Because of the weak emission of Hα in the inner disks in our objects, the bar region provides little or null information of the behavior of the noncircular motions. Only in six objects we observe plenty of gas in the inner disk that can perform reliable noncircular flow models. These objects are shown in Figure 11; however, the bars in NGC 289 and NGC 3464 are closely aligned parallel to the disk position angle, preventing the bar streams from being separated from the disk circular rotation, as mentioned before. Even so, the residuals observed in these objects (Figure 9) show a large presence of noncircular motions across the disk, although in NGC 289 a considerable fraction of them could be attributed to the prominent spiral arms (e.g., Pence & Blackman 1984).

We notice however that oval distortions appear in the Hα velocity maps when galaxies are gas-rich; and such distortions are pronounced when the bar is elongated at an intermediate position angle from $\phi_{\text{disk}}$. A remarkable example is observed in IC 2160 where the bar is oriented $\sim 40^\circ$ away the kinematic position angle. As a consequence, a strong twist is observed along the kinematic minor axis.

4.4. Stellar and Ionized Gas Bar-like Flows

As to whether the ionized gas and stars have similar amplitudes of the noncircular motions, the lack of ionized gas in the bar regions precludes a direct comparison between them. Figure 6 shows bisymmetric models for IC 2160, where oval distortions are observed simultaneously in the Hα and stellar velocity maps. We notice similar behaviors between the circular and noncircular motions of gas and stars, albeit ionized gas have much larger amplitudes. Such differences in amplitudes could be related to the dynamical origin of the
tracers. As stars are dynamically hot, they are more affected by the asymmetric drift (AD) than the gas. Although the AD is more important in pressure support systems, like dwarf galaxies (e.g., Oh et al. 2011), in spiral galaxies the bulge and stellar bars, composed largely by old stellar populations, dominate the AD contribution (e.g., Shetty et al. 2020). Thus, the lower amplitudes observed in the stellar noncircular motions could be explained by the AD.

5. Discussion

5.1. Bar-like or Radial Flows?

Wong et al. (2004) categorized different sources of noncircular motions based on the slope of the $s_1$ and $s_3$ coefficients. For radial-flow-dominated systems, they found that $|ds_3/ds_1| < 0.1$. Table 1 shows objects that fall into this category; however, for describing barred galaxies the bisymmetric model is usually preferred over radial flows. In this model the perturbation is driven along a fixed axis $(\phi_{bar})$, and the noncircular velocities correspond to those of elliptical orbits. In the epicyclic theory, radial stellar motions are not expected to contribute significantly to the noncircular motions (e.g., Sellwood & Binney 2002). In addition, the large speeds on the observed noncircular velocities could not persist for a very long time without rearranging the mass distribution of the disk (e.g., Wong et al. 2004; Spekkens & Sellwood 2007); therefore, invoking pure axisymmetric radial flows (inflows/ outflows) brings considerable consequences in the stability of stellar disks.

In addition, numerical simulations also show that inflows in bars are expected to be $<5$ km s$^{-1}$ (e.g., Athanassoula 1992), but not of tens of kilometers per second as observed in most objects. Recent studies however observe radial motions in spirals of the order of 10–30 km s$^{-1}$ (e.g., Di Teodoro & Peek 2021). Such large speeds of gas inflow/outflow would invoke necessary efficient mechanisms of gas depletion through star formation processes or galactic scale wind to remove gas out of the galaxy. In the former scenario, although it has been widely observed (e.g., López-Cobá et al. 2019, 2020), the link of axisymmetric radial flows with out-of-plane outflows is a subject that has not yet been addressed. For all the above reasons pure axisymmetric radial flows are infrequently considered for describing the noncircular flows in barred galaxies.

5.2. Deficit of Ionized Gas in Bars

The absence of ionized gas in the central regions observed in half of our sample suggests that it could be related to the presence of the bar itself. In fact, in most barred galaxies there is an observed lack of gas in the inner disk (e.g., Erroz-Ferrer et al. 2015; Fraser-McKelvie et al. 2020). However there is no clear explanation in the literature for why bars tend to not exhibit ionized gas. Two scenarios are related to the absence of molecular gas. If there is absence of molecular gas along the bars, no new stars are formed. Closely related might be the presence of, indeed, radial flows that could have transported cold gas toward the center. In such a case one should expect a higher SFR toward the center, which is not yet observed (e.g., Erroz-Ferrer et al. 2015). It is therefore important to trace the cold gas abundance in bars to help distinguish between both scenarios.

5.3. Connection between Noncircular Motions and Galaxy Properties

As noted in Figures 10 and 11, the amplitudes of the noncircular velocities $V_{2,2}$ and $V_{2,1}$ vary widely from galaxy to galaxy. Thus, we ask whether the amplitude of the noncircular motions depend on some galaxy properties or they are local processes. For instance recent studies show a two-slope relation between the stellar mass and the bar length (Erwin 2019). As bars are composed largely of old stellar populations, the bar must contribute to a large fraction of the total stellar mass, as observed in some barred galaxies (e.g., Sánchez-Blázquez et al. 2011). Thus the relation between $r_{bar}$ and the host galaxy stellar mass should be expected as well with the bar mass.

Figure 7 shows the deprojected stellar bar length (Equation (1)) versus the stellar mass obtained from the SSP analysis. We notice that our objects fall around the steeper slope of this relation where galaxies with larger bars are located. Indeed most of our objects have deprojected bar sizes larger than 2.5 kpc.

We investigate if the stellar mass, size of the bar, and SFR are coupled with the amplitude of the noncircular motions. Instead of adopting the average value of the circular rotation residuals, we characterize the noncircular motions with the amplitude of the bisymmetric components $V_{2,2}$ and $V_{2,1}$. As these terms are a function of the radius we define their amplitude, $A_{bis}$, as the quadratic sum of both components:

$$A_{bis}(r) = \sqrt{V_{2,2}^2(r) + V_{2,1}^2(r)}$$

and the fraction of noncircular over circular motions as:

$$f_{nc}(r) = A_{bis}(r)/V_t(r) \text{ for } r \leq r_{bar},$$

where $V_t$ is the tangential velocity component of the bisymmetric model, which gives a better description of the circular rotation than if we consider the pure circular model. Note again that these two parameters depend on the galactocentric distance. Thus in the second expression we are comparing at each distance the noncircular motions with the local circular velocity.
Figure 8 shows $A_{\text{bis}}$ and $f_{\text{nc}}$ computed for the stellar velocity maps against the stellar mass and the bar lengths of our objects. In this figure we also include the integrated SFR derived with H$\alpha$, with the dust attenuation correction using the Cardelli et al. (1989) extinction law and case B of recombination (e.g., Osterbrock & Miller 1989), and use the distances reported in the AMUSING++ paper (e.g., López-Cobá et al. 2020). The first thing to notice is the strength of noncircular motions ranges between 10%–50% of the local circular rotation on average, which is similar to what other studies have found (e.g., Bettoni & Galletta 1997).

In Figure 8 we tried to find possible correlations between kinematic properties and global properties, while Table 2 shows the Pearson and Spearman coefficients for those relations. We find however only weak correlations between these parameters. Even more, the large $p$-values show that such correlations are not statistically significant. These results are in line with recent studies (e.g., Erroz-Ferrer et al. 2015), where

| $f_{\text{nc}}$      | $\rho_{\text{pearson}}$ | $\rho_{\text{spearman}}$ |
|----------------------|--------------------------|-------------------------|
| log $M_*/M_\odot$    | -0.42 (0.13)             | -0.31 (0.28)            |
| max $A_{\text{bis}}$ | 0.37 (0.19)              | 0.45 (0.11)             |
| $\langle A_{\text{bis}} \rangle$ | 0.37 (0.19)         | -0.38 (0.2)              |

| $f_{\text{nc}}$      | $\rho_{\text{pearson}}$ | $\rho_{\text{spearman}}$ |
|----------------------|--------------------------|-------------------------|
| log $M_*/M_\odot$    | -0.58 (0.03)             | -0.31 (0.28)            |
| max $A_{\text{bis}}$ | 0.39 (0.17)              | 0.45 (0.11)             |
| $\langle A_{\text{bis}} \rangle$ | 0.40 (0.16)         | -0.38 (0.2)              |
no obvious relation is observed with the residuals of circular rotation and morphological properties of bars. However, we are aware of the low statistics provided by this sample.

6. Conclusions

In this study we analyzed the incidence of noncircular flows in the stellar and Hα velocity field of a sample of noninteracting barred galaxies observed with the MUSE spectrograph. The exquisite resolution of the data allowed us to detect oval distortions in the stellar velocity maps most probably associated to the presence of the bar. Such perturbations are recognized in the residual maps of pure circular rotation models as symmetric structures around the center, with antisymmetric velocities about the kinematic center, clearly evidencing the presence of a nonaxisymmetric potential affecting the expected circular rotation of the disk. Despite not observing ionized gas in the inner disk in most of the objects, the bar leaves imprints in the circular residual velocities in regions close to it. When
ionized gas is observed along the bar, the oval distortion is also revealed in the H$_\alpha$ velocity field. This evidence that both stars and gas is affected by the bar potential.

We characterize the kinematics of these galaxies with models that include noncircular motions, in particular, the bisymmetric model and a harmonic decomposition for a $m = 2$ potential perturbation. We use the slope of the harmonic coefficients, the $ds_3/ds_1$ ratio, to compare our results with the harmonic ratio predicted by idealized models of radial and elliptical flows. Based on this parameter we find that at least in one velocity map, either stellar or ionized, the harmonic decomposition is compatible with the bar-like scenario. However, in some objects this same diagnostic concludes that radial flows are unlikely. These results only show evidence of the complex structure of bar-like flows in real galaxies.

We find that the bisymmetric model produces successful fits of the velocity maps within the bar region. We also find that the position angle of the oval distortion correlates with the photometric position angle of the bar. This supports the scenario of a stellar bar potential inducing deviations of the circular rotation in the observed velocity fields. We find that the lack of ionized gas along the bars restricts the robustness of a modeling of the noncircular motions, in which case the stellar velocity could be considered for studying bar-like flows when no gas is detected. However we notice that not only the stellar circular rotation is affected by the asymmetric drift, but also the noncircular motions as gas appears to rotate faster.

In terms of the residuals, we find that bisymmetric model and the harmonic decomposition for an elongated potential lead in general to similar results with the amplitude of the noncircular motions being the only difference between both models.

We find that the average amplitude of the noncircular motions in our sample is $\sim 30$ km s$^{-1}$ for stars and ionized gas, while the strength of the noncircular motions reaches values of up to 50% of the local circular velocity, although this fraction varies among galaxies.

When trying to relate the noncircular motions to galaxy properties we do not find any clear correlation with the stellar mass, the bar size, or the global SFR. These results point that bar flows are rather local process; however, we stress that larger statistical samples of barred galaxies with high spatial resolutions are required to reveal possible correlations between kinematic properties of bars and global properties of galaxies.

We would like to thank the anonymous referee for their comments and suggestions that contributed to the improvement of the quality of this paper.

L.L. and C.L.C. acknowledge support by the Academia Sinica under Career Development Award CDA-107-M03 and the Ministry of Science & Technology of Taiwan under grant MOST 108-2628-M-001-001-MY3. I.C.G. acknowledges support from DGAPA-UNAM grant IN113320. L.G. acknowledges financial support from the Spanish Ministry of Science, Innovation and Universities (MICIU) under the 2019 Ramón y Cajal program RYC2019-027683 and from the Spanish MICIU project HOSTFLOWS PID2020-115253GA-I00.

Appendix A
Circular Rotation Models

Below we show the maps of the circular and noncircular kinematic models for the sample of galaxies shown in Table 1. In each figure, only one object is shown as an example; the remaining figures are available in the online journal. Figure 9 shows the circular rotation models derived by XookSuut for the ionized gas and stellar velocity maps of each object. The three figures on the left (right) correspond to the observed velocity map, the best kinematic model, and the residual map for the ionized (stellar) velocity maps.

Appendix B
Noncircular Rotation Models

Figure 10 shows the results from the isophotal analysis together with the kinematic modeling of XookSuut adopting bisymmetric and harmonic decomposition models. In this set of figures, only one object is shown as an example; the remaining figures are available in the online journal. This figure shows results only for the stellar velocity maps.

Similarly, Figure 11 shows results for the H$_\alpha$ velocity maps, but only for those objects with H$_\alpha$ emission detected along the bars. The complete figure set is available in the online journal.

ORCID iDs
Carlos López-Cobá https://orcid.org/0000-0003-1045-0702
Sebastián F. Sánchez https://orcid.org/0000-0001-6444-9307
Lihwai Lin https://orcid.org/0000-0001-7218-7407
Joseph P. Anderson https://orcid.org/0000-0003-0227-3451
Kai-Yang Lin https://orcid.org/0000-0002-8698-7277
Irene Cruz-González https://orcid.org/0000-0002-2653-1120
L. Galbany https://orcid.org/0000-0002-1296-6887
Jorge K. Barrera-Ballesteros https://orcid.org/0000-0003-2405-7258

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