Visualizing Rotation Curves

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Fig. 2. The VIVE headset enjoyed in the Human-Computer Interaction Lab at U. Manitoba.

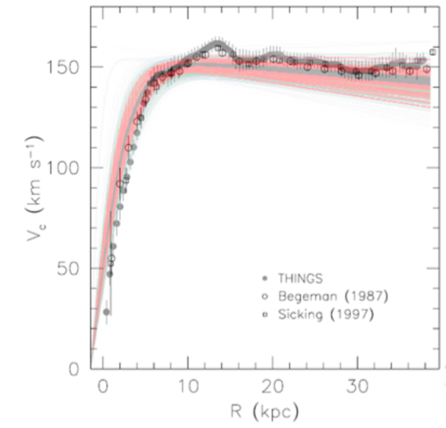

Figure 48: NGC 3198 Rotation Curve Comparison - The best-fit family of rotation curves produced by GalAPAGOS (dark gray (0 to 0.05σ level), red (0.05σ to 0.3σ level), green (0.3σ to 0.6σ level), and faint gray (0.6σ to 1σ level) solid line), see Section 5.1, is compared to that found by de Blok et al. [2008] (gray solid circles), Begeman [1987] (black open circles), and Sicking [1997] (black open squares).

Fig. 1. Comparison of GalAPAGOS RC by Blanchette 2018 with previous RC in the literature. The region in colour shows GalAPAGOS's "family" of solutions. (See Methods and Results.)

Abstract

A fundamental component for assessing Dark Matter content of a disk galaxy is the rotation curve tracing its dynamical mass. We present diverse explorations of galaxy kinematics using both rotation curve (RC) modelling and scientific visualization. Our rotation curve models are derived from full 3D atomic hydrogen (HI) and molecular gas (e.g. CO) datasets using GalAPAGOS (Galaxy Astrophysical Parameter Acquisition by Genetic Optimization Software) which also models the gas spatial distribution. GalAPAGOS uses an evolutionary algorithm for optimization of fits and produces a family of solutions per galaxy (Fig. 1) consistent with the uncertainties in the data cube. Also the position-velocity behaviour of the observational data can be explored in 3D, not by projecting onto 2D monitors, but by using 3D virtual reality (VR). We have produced a preliminary visualization tool for the VIVE headset (Fig. 2) using the Unity gaming engine. Currently we explore the effect of colour in this 3D environment.

Methods

(1) GalAPAGOS -- Modelling velocity behaviour in gas disks.

(Blanchette 2018 "Modelling the Kinematics of the Cold Gas in Galaxies Using GalAPAGOS", M.Sc. thesis; https://mspace.lib.umanitoba.ca/handle/1993/33023.)

Our semi-automated GalAPAGOS 3D data fitting software, developed in the MATLAB environment, anticipates the thousands of just resolved galaxies available in the SKA big data era and the desire for flexibility. Users insert their own parameterized modelling equations for the radial distributions of velocity (RC) and density in gas disks. Axis-symmetry is broken via the application of twist, warp (Fig. 3) and flare equations. Good initial guesses for the ~20 modelling parameters are unnecessary since the Ferret evolutionary optimizer (Jason Fiege; www.nqube.com) successfully avoids local minima in parameter space. GalAPAGOS outputs a "family" of valid solutions within 1 sigma of the intensity value (Fig. 1).

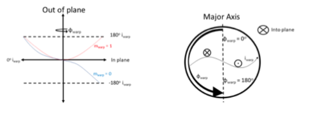

Figure 13: Warp figure. The left image represents an edge-on galaxy, with the blue line representing the $m = 0$ mode, and the red line representing the $m = 1$ mode. The right image represents a completely face-on view of a galaxy, with the $i_{warp,m}$ going into and out of the plane of the galaxy, and the $\phi_{warp,m}$ rotating the galaxy completely in the plane of the galaxy.

Fig. 3 Schematic of the warp's behaviour in GalAPAGOS from Blanchette 2018.

(2) 3D immersive Virtual Reality for displaying observational data.

(Ferrand, English &: Irani 2016 https://arxiv.org/abs/1607.08874)

The frontier of interactive and immersive 3D VR (not 3D projected to 2D) provides a powerful mode for exploring the velocity behaviour of galaxies. Our preliminary VR tool is developed in the Unity game engine environment and uses Steam VR. Our ray-tracing options mimic radiative transfer functions for gas emission. Our "game" provides standard zoom and translation functions. We currently explore how colour transfer functions that code velocity behaviour trade off with the perception of depth when the user is immersed in 3D. The experience of "walking into" the observational data cube is particularly powerful when viewed in the readily available VIVE headset.

Applications, Results and Conclusions

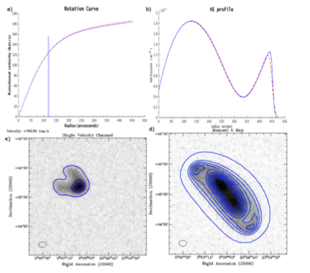

Figure 18: The input data was art3198-d (see Table 3), with noise. The best fit model (reduced $\chi^2 = 0.978$) produced after 1000 generations using the non-optically thin version of the code is shown. There were 6 SDMs searched for. Shown in a) is the input RC (red), and Model RC (blue). Note that the maximum difference in velocity is only 0.3 km/s. b) Input HI profile (red), Model HI profile, using 6 SDMs (blue). c) Single Velocity Channel Input is the greyscale data; the model is shown as the blue contour at the 3σ level. The maximum discrepancy found in the cube between the input artificial galaxy and the output model was 0.2x the beam size at the 3σ level. d) The zeroth moment map of the input and output models with the same contours as in c).

Fig 4. An example from the tests on parametric artifical galaxies by Blanchette 2018. Our fitness function is the chi-squared statistic. An SDM is a Surface Density Modulation term that is applied to the fundamental sigmoid function used to fit the radial density distribution.

(1a) Quality of the solutions: Fig. 4 demonstrates that GalAPAGOS recovers the known parameters of artificial galaxies that have been generated using GalAPAGOS modelling equations. Fig. 1. demonstrates that the non-optically thin modelling of HI produces a family of RC solutions comparable to RC derived other methods. We intentionally do not model every wiggle in the curve.

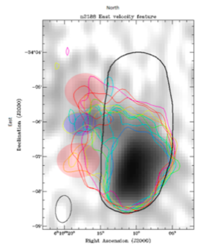

Figure 49: NGC 2188 Renzogram Figure - The greyscale background is the unbinned NGC 2188 data (Section 3.2.2), and the coloured renzogram (described in Section 5.2) contours are at the 4σ level of the data. Here we only plot channels 10-21. The black ring represents the extent of the model, which is taken to be the extent of the HI disk of the galaxy. The feature to the east of this disk is highlighted via the blue and red ellipses along with the renzogram contours. It can be observed in the renzogram contours that there is a lower velocity (red) feature to the north and south of the higher velocity (blue) feature.

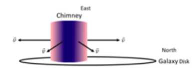

Figure 50: A schematic representation of the chimney found in NGC 2188. This is representative of a nearly edge on view of NGC 2188, with the chimney protruding to the east, from the southern face of the galaxy. The blue indicates that the velocity from the expanding bubble is aligned with the observer's line-of-sight, with the light red at the edges indicating that the velocity from the expanding bubble is perpendicular to the observer's line of sight. The blue in the center of the chimney roughly corresponds to the blue highlighted region in Fig. 49, as well as the red on the edges of the chimney roughly corresponding to the red highlighted regions in Fig. 49.

Fig 5. Example of an application of GalAPAGOS models from Blanchette 2018. Observational data is from the LVHIS survey. Renzograms plot one specific intensity contour in a different colour for each velocity channel. The blue and red regions in the upper figure can be associated with the blue and red regions in the lower figure, which is rotated in orientation by 90 degrees.

(1b) Using the model disk as a mask: Non-optically thin HI modelling of NGC 2188 demonstrates that GalAPAGOS produces reasonable solutions for highly inclined galaxies. This galaxy also displays extensions away from the plane in HI (Kirby et al. 2012, MNRAS, 420, 2924) and H_alpha (Domgoergen et al. 1996, A&A, 313, 96). Our best fit solution was applied as a mask to the disk ensuring that we only studied extraplanar HI emission; Fig. 5. Some of this structure may be associated with blow out from a giant HI region.

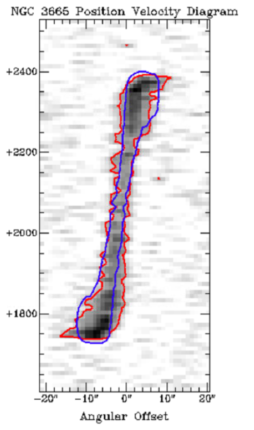

Figure 46: NGC 3665 Position-Velocity Diagram - The observational CO data is presented as the greyscale, with the red contour being a contour of the data at the 3σ level. The blue contour overlaid is the best fit model contour, at the same level as the data contour.

Fig. 6. The PV diagram of the best fit GalAPAGOS model of the carbon monoxide disk in NGC 3665 compared to the observed data.

(1c) Modelling CO cubes: Motivated by the increase in highly resolved CO data from the Atacama Large Millimetre/Sub-millimetre Array (ALMA), we tested our optically thin approximation CARMA data with 4 arcsecond resolution (Alatalo et al. 2013, MNRAS, 432, 1796). Our best solution for the central CO disk (r=~2 kpc) of the early type galaxy NGC 3665 has a chi-square of 0.997 and we compare the model position-velocity diagram with the observed plot in Fig. 6. More highly resolved CARMA data (Onishi et al. 2017, MNRAS, 468,4663) is less contiguous and the current version of GalAPAGOS is unable to converge on solutions.

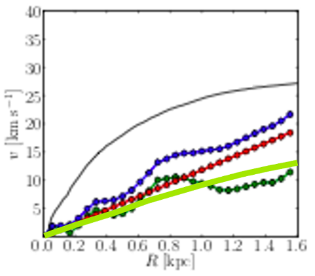

Fig. 7. RC of a hydrodynamically simulated galaxy. The original plot from Verbeke et al. 2017, A&A, 607, A13 shows the dark matter halo RC in black, the mock HI RC in dark green,. The latter curve is combined with a pressure support term (red) and an asymmetric drift correction to produce the blue curve. The GalAPAGOS HI RC is bright green.

(1d) Modelling numerically simulated galaxies: Isolated galaxies can be numerically simulated using dark matter halos and merger trees from cosmological simulations as input to hydrodynamical codes, which evolved galaxies to the current redshift. Mock HI data cubes can be generated and analyzed as if they were observational data. Fig. 7 shows that our preliminary GalAPAGOS solutions are consistent with RC from ROTCUR in Gipsy. Both indicate that the dynamical mass estimated using HI for the MoRIA dwarf galaxies is less than the halo mass (Verbeke et al. 2017, A&A, 607, A13).

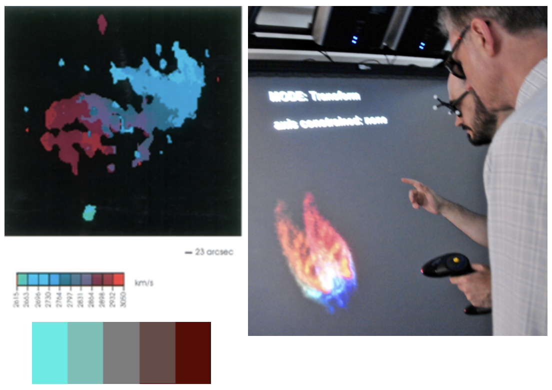

Fig. 8. Examples of the colour schemes that are explored in our 3D VR tool. The colour codes velocity. Perceptually dark red (red-shift) recedes and the bright blue (blue-shift) approaches the viewer. The tool can be used in the CAVE environment, on the zspace monitor, and the VIVE headset.

(2) Kinematics in fully immersive 3D VR: Scientific visualization works well when it follows the principles of human perception and incorporates an understanding of physics. Fig. 8 shows the effect of perception in the form of a divergent colour scheme. First, it employs compensating tones generated by mixing complementary colours across from each other on a standard colour wheel. Second, this colour scale diverges from grey in the centre, perceptually approaching towards the light blue end and appearing to recede at the dark red end. In 2D this supports measurements of blue- and red-shifted velocities, which in galaxies provide the signature of rotation. However the orientation of the viewer immersed within data can decrease this depth illusion. Thus immersive 3D environments require research to discover principles of colour in 3D combined with other tool capabilities such as interactivity (Ferrand, English and Irani; https://arxiv.org/abs/1607.08874). Future tools aim to provide experiences of 3D relationships, including visual trends analogous to RC.

Motivation and Summary

The velocity behaviour throughout a spiral galaxy has long been studied using velocity vs. radius plots, rotation curves (RC). These are critical for estimating the mass contribution of dark matter and illuminating galaxy evolution. For example their central portion probes the region of influence of a galaxy's central supermassive black hole. Inflow from the cosmic web may be discovered by discerning gas fragments that differ from the rotation curve's behaviour. The shapes of rotation curves may be used to construct classes of velocity behaviour (Wiegert & English 2014, New Astronomy, Vol. 26, P. 40). Templates of each class may subsequently be compared to more poorly-resolved high redshift galaxies in order to estimate a galaxy's type and characteristics.

Our projects modernize rotation curve studies using two methods. Firstly, we construct RC, using the full 3D cube in a semi-automated fashion using an innovative evolutionary optimizer called Ferret. HI and molecular gas data cubes or galaxies from hydrodynamical simulations can be input into GalAPAGOS, the software that harnesses Ferret. GalAPAGOS simultaneously models the RC and the radial density distribution of a disky gas distribution. This poster shows examples of how the resultant RCs can be applied to the explorations previously listed. Secondly, we are developing 3D immersive Virtual Reality tools to enhance the discovery science in both observed 3D data cubes and their GalAPAGOS 3D models. Rather than assessing velocity behaviour via position-velocity diagrams, a researcher will be able to walk into their data and visually discern anomalous features and discover trends.