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Parametrising spatially resolved H I disks

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Upcoming extragalactic wide-field H I surveys with high spatial resolution will provide the community with an unprecedented number of observations of spatially resolved (galactic) H I disks. To exploit the information contained in those data it is highly desirable to have tools at hand to efficiently parametrise H I disks based on spectroscopic data cubes. One of the challenges will be the amount of data to be processed, giving astronomers the chance to study the H I morphology and -kinematics of statistical samples, instead of concentrating on single objects. The need arises to develop sufficiently fast automated parametrisation methods based on spatially resolved spectroscopy. I will describe science cases that can be addressed using efficient parametrisation techniques, and then discuss the current state-of-the-art in kinematical- and morphological modelling of H I disks, and computational challenges in view of upcoming wide-field high-resolution H I surveys.

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1. Introduction

All-sky surveys as planned with ASKAP and Apertif will deliver resolved HI observations of $\sim 10^4 - 10^5$ galaxies of which of the order of 10^3 will be resolved sufficiently to allow for detailed morphological- and kinematical analyses. Targeted galaxy surveys with MeerKAT, the ATA, and the EVLA will complement these surveys with deep integrations of the 21cm line at high resolution, pushing up the galactocentric radii at which HI can be traced to derive its distribution and -kinematics.

This increase in observational material will lead to a quantum step in HI science and extragalactic astronomy.

The discovery and description of global features in the (HI-) kinematics of galaxies, such as the flatness of rotation curves [2], have directly influenced cosmology. Since then, the increase in computational power enabled theorists to provide testable predictions of the mass distribution on sub-galaxy scales for given cosmological models [e.g. 9], such that kinematical studies can be utilised as immediate tests for cosmology. While the long-standing debate has concentrated mainly on the spherical distribution of dark matter (DM) in relaxed systems [e.g. 15; 5], deviations from this, which are evident from lopsidedness [e.g. 11] or warping [e.g. 6; 8], came more recently into the focus of theoretical research in the cosmological context [e.g. 12; 13].

The past studies have been limited to a comparably small sample of galaxies, in many cases spending large amounts of time on the study of even single objects. Utilising the new instruments, the community will have access to a much larger data base, making extragalactic HI science on a statistical basis possible. However, a full exploit of this data set will only be feasible employing automated kinematical- and morphological analyses.

The commonly used method to quantify both the kinematics and the morphology of resolved HI disks is the so-called tilted-ring model [TRM, 10] or variants thereof. The prospect of automated applications of tilted-ring modelling are discussed in this contribution. Holwerda (this conference) presents an alternative parametrisation method, mainly aimed at the (automated) morphological quantification of HI disks.

2. The tilted-ring model

HI observations have the major advantage that via the Doppler shift one observes not only the projected total intensity of a source but also its recession velocity, giving access to the HI kinematics. However, unless observations are not directly compared to physical models, the fact that with the intensity one observes a three-dimensional projection from (6-D) phase space makes it necessary to assume an inherent symmetry to parametrise the kinematics of the observed sources.

For HI in disk galaxies, it is a good first-order approximation to assume that the gas rotates on circular orbits about a (not necessarily radially independent) centre [3; 11]. While for the bright stellar disk in many cases even cylindric symmetry may be assumed, this is not true anymore at large radii, which lead to the formulation of the TRM by Rogstad & Shostak [10] for galaxy disks. In the scope of the basic TRM a (gaseous) disk consists of a set of circular rings with increasing radius, each of which is parametrised by: i) the circular velocity; ii) the surface brightness; iii) the scale height (assuming some vertical density distribution); iv) two orientation parameters (usually position angle and inclination); v) the position angle; vi) the central position (Right ascension and Declination of the ring centre); vii) the systemic velocity; viii) the dispersion. Routines to establish a tilted-ring model for a galaxy disk may be divided into two classes. One approach consists of first reducing a data cube to a velocity field, a map ideally representing the mid-plane recession velocity of the Hɪ. Making use of the kinematical information alone, a TRM model is then established. In this case, surface-density distribution, dispersion, and scale height have to be derived in a second step. The alternative approach consists of constructing artificial Hɪ observations, based on TRM parameters, which are then directly compared to the observation to optimise the parametrisation.

3. Velocity-field based methods

The most extensively used computer routine to fit a TRM to a velocity field is ROTCUR [1]. The method has been implemented in a number of data analysis packages and a number of variants and extensions have been tested [for details see 7].

The shortcomings and the major advantages of the velocity-field analysis to derive TRMs have their roots in the reduction step from a data cube to a single velocity map. One loses a large amount of information (e.g. the surface-brightness), while the method is computationally very efficient and fast.

There are drawbacks. For an inclination of a galaxy of $\gtrsim 70^\circ$, the method becomes unreliable [1], basically, because the information about the recession velocity perpendicular to the projected major axis of a galaxy starts to become unconstrained. For warped disks and edge-on disks, where the line-of-sight may cross the disk twice, an unambiguous velocity field does not exist, making the construction of a TRM impossible. While well-resolved galaxies with a moderate inclination can be analysed successfully [5], resolution effects mainly play a role for less resolved galaxies (the bulk of galaxies from blind galaxy surveys are marginally resolved, see above), where the “beam-smearing” effect plays a major role [see also 7]: the recession velocity is derived from spectra which are averages over a large portion of the disk, hence leading to biased estimates. Many authors put large efforts in the calculation of reliable velocity-fields to overcome the effects of beam smearing. However, the problem is inherent to the method. Certain a-priori assumptions have to be made about both, the unknown surface-brightness distribution, as well as the disk thickness, which systematically enter estimates of the recession velocity.

4. Direct fitting

The limitations of fits to the velocity field led some authors to the conclusion that for certain applications (observations at low resolution, warps) a reliable velocity field cannot be derived. They thus started to fit disk models by hand, comparing a galaxy observation with a modeled data cube by eye [e.g. 14]. Early attempts to automatically fit a kinematical model similar to the TRM directly to a data cube were either restricted to a flat disk geometry, or failed due to limited computing power. The first automated fitting of a TRM was performed by Corbelli & Schneider [4] analysing single-dish observations of the spiral galaxy M33.

Recently, two realisations of generally applicable automated fitting routines have been documented. TiRiFiC [7] is a straightforward application of the TRM, which has successfully been

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tested in analyses of HI observations [6; 8]. GalAPAGOS [17] uses more restricted, empirical galaxy models.

Both applications use the χ^2 as a measure for the quality of a galaxy model, which is then minimised to reach a best-fit solution. It could be shown that this approach overcomes the problems that arise due to the construction of a velocity field on the expense of a large computational effort [7; 6; 8].

TiRiFiC will remain under development for a while and has a number of shortcomings to be addressed:

- the use of a very inefficient, local minimising algroithm makes human intervention necessary to find a global, physically meaningful best fit.
- for the same reason, statistical errors are not well established (the same accounts for velocity-field methods, since the information about the reliability of data points in a velocity field is hard to estimate).
- the computation of synthetic data cubes is computationally expensive, which makes the computation of a best-fit model slow.

GalAPAGOS is addressing two of the issues, making use of a modern global, genetic minimisation algorithm. For an empirical kinematical model with 23 parameters (compared to e.g. 54 parameters for a simple TRM with nodes at 10 radii), a stable solution can be reached including statistical errors without human intervention (Fiege 2009, priv. comm.). The major task in the further development of GalAPAGOS consists of finding suitable, physically meaningful parametrisation models, while it can be shown that a global parametrisation of a galaxy disk is possible using a direct-fit approach. It is to be expected that this can be expanded to the TRM approach as used in TiRiFiC, despite the increase in parameters (Fiege 2009, priv. comm.).

A major concern is the slowness of both methods. A rough estimate shall be given here for TiRiFiC to estimate the computational power needed in the analysis of HI surveys as outlined above: currently, the establishment of a best-fit model for a 20MB data cube is possible in the course of a day, including human intervention, while a single fit run takes 3 hours on a single core. The computing time scales approximately with the size of the data cubes. For 200 galaxies per day (as may be expected as the outcome of a large galaxy survey) with an average size of 10 MB (e.g. $256\times256\times40$ pixels), a fully automated code may require 200/(24/3) = 25 cores or 8-9 average workstations with 4 cores each for parametrisations without error estimates. For the calculation of statistical errors no time estimate yet exists. A considerable improvement in terms of computing speed might be achieved by employing GPU (Graphics Processing Unit) technology.

5. General considerations

Many disk galaxies *can* be parametrised using the TRM, which explains the wide use of this simple parametrisation method. Moreover, the simplicity of the model and the very few basic physical assumptions motivating the assumed symmetry (conservation of angular momentum) allow a very wide applicability.

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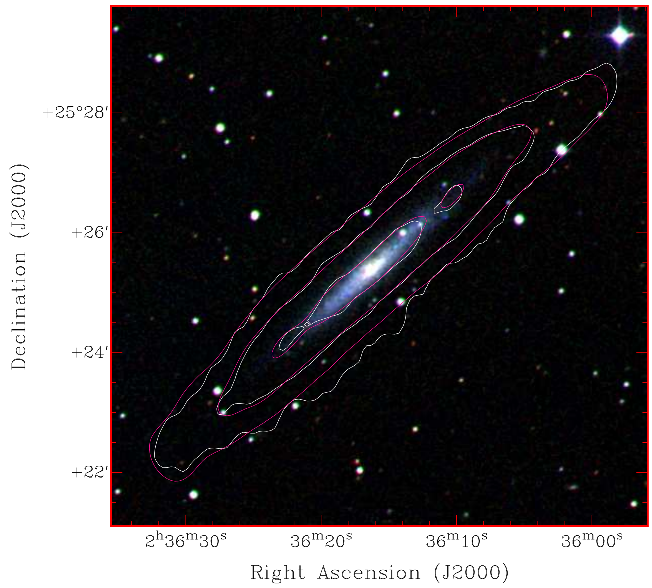

Figure 1: UGC 2082, total intensity map overlaid on DSS image. White contours: total intensity map derived from a 10×12 hour integration with the WSRT. The galaxy was observed as part of the HALOGAS (Hydrogen Accretion in LOcal GAlaxieS, PI: G. Heald) sample. Pink contours: total intensity map derived from a TiRiFiC tilted-ring model. The good match was achieved by introducing higher-order warp modes. Contours: $2, 8, 32, 128 \cdot 10^{19}\,\mathrm{atoms\,cm^{-2}}$.

However, in detailed studies it has become clear that second-order effects like local distortions of the disk or large-scale asymmetries, present in basically all disk galaxies, may affect both the stability of a fit, as well as the interpretation of the data. In rotation curve analyses, one of the basic steps is the attempt to show that asymmetries are small enough to allow for a straightforward interpretation of the rotation curve. Local distortions like spiral arms or local kinematical departures of cloud complexes often impose their imprint on the TRM parametrisation which ideally should rather represent a global trend.

As a consequence, firstly, some smoothness of the parameters in dependence of the radius has to be enforced [e.g. 5], and, secondly, global asymmetries have to be quantified. The latter is usually done by introducing harmonic expansion (of velocities) along the TRM rings [e.g. 16]. This is still insufficient, as illustrated Fig. 1. The Hɪ disk of UGC 2082, a galaxy in the HALOGAS sample[1], shows an asymmetric warp in its Hɪ component, which can only be parametrised (in this example using TiRiFiC) by including higher-order vertical distortions of the disk as an extension to the TRM.

This highlights a generic problem of the TRM. To parametrise galaxies in terms of the TRM, one has either to accept a course model, or one has to introduce a large number of new parameters quantifying deviations from the TRM symmetry. In the first case, a detailed study of introduced biases is necessary to scientifically interprete the models, in the second case, the scientific interpretation and ambiguities of newly introduced parameters have to be studied.

[1] In the scope of the ongoing Hydrogen Accretion in LOcal GAlaxieS (HALOGAS) Survey, 22 galaxies will finally be observed with the WSRT, each integrated for 10×12h. PI: George Heald

6. Summary and discussion

The TRM is the traditional method to parametrise the morphology and the kinematics of (galactic) HI disks. The success of this method in the past motivates to invest in the full automatisation of TRM software to be used in the analysis and in cataloguing galaxy characteristics in upcoming HI surveys with SKA precursor telescopes. While applications based on an analysis of velocity fields are advanced, they are bound to fail or to introduce biases for observations of highly inclined, warped, and poorly resolved galaxies. Applications that perform direct fits to data cubes are not (yet) well developed, although they promise to overcome the problems of fitting to velocity fields. The major concern in using the TRM as a general-purpose parametrisation method for galactic HI disks is probably not the computational power needed to cope with the large amount of data, but the general applicability of the TRM or its extensions.

Both, programming- and scientific efforts are still needed to establish an automated way to fully exploit the high-resolution properties of the upcoming HI surveys.

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