DiskFit: A CODE TO FIT SIMPLE NON-AXISYMMETRIC GALAXY MODELS EITHER TO PHOTOMETRIC IMAGES OR TO KINEMATIC MAPS

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ABSTRACT

This posting announces public availability of version 1.2 of the DiskFit software package developed by the authors, which may be used to fit simple non-axisymmetric models either to images or to velocity fields of disk galaxies. Here we give an outline of the capability of the code and provide the link to downloading executables, the source code, and a comprehensive on-line manual. We argue that in important respects the code is superior to rotcur for fitting kinematic maps and to galfit for fitting multi-component models to photometric images.

Subject headings: galaxies: kinematics and dynamics — galaxies: structure — galaxies: spiral — methods: numerical

1. INTRODUCTION

The code DiskFit may be used to fit simple non-axisymmetric models either to images or to velocity fields of disk galaxies. If the fit is successful, DiskFit provides quantitative estimates of the non-circular flow speeds and an estimate of the mean circular speed when run on velocity fields (Spekkens & Sellwood 2007; Sellwood & Zámar Sánchez 2010), while fractions of the galaxy light in a bar, disk, and bulge when run on images (Reese et al. 2007; Kuzio de Naray et al. 2012).

The kinematic branch of the code differs fundamentally from the frequently-used rotcur algorithm (Begemann 1987) since the minimization fits a global model to the complete map, rather than separate tilted rings, and it is superior to resun (Schoenmakers et al. 1997) because it does not employ the epicyclic approximation to fit departures from circular motion. The photometric branch of the code also differs fundamentally from popular algorithms such as galfit (Feng et al. 2010) in that it fits non-parametric disk and bar light profiles rather than specified functional forms. Furthermore, it is superior to all three algorithms because it is capable of providing statistically valid, but realistic, estimates of the uncertainties in the fit. (Kuzio de Naray et al. 2012) illustrate the functionality of DiskFit on high-quality kinematic and photometric data for the nearby galaxy NGC 6503.

A single code is provided to fit both photometric images and kinematic maps because, for both applications, DiskFit employs the same basic minimization algorithm originally described in the Appendix of Barnes & Sellwood (2003). The first applications were to fit axisymmetric models: the extension to non-circular flows was described by Spekkens & Sellwood (2007) and by Sellwood & Zámar Sánchez (2010), while Reese et al. (2007) extended the code to include barred models when fitting photometric images.

Note that DiskFit does not fit photometry and kinematics simultaneously: the same code simply fits either type of data depending on the users choice of inputs. Of course, if the user makes separate fits to both types of data from the same galaxy, the fitted values will likely differ.

2. CAPABILITIES OF THE CODE

DiskFit minimizes a \( \chi^2 \) estimate of the differences between a projected model and the data. The data can be either a 2D velocity map derived from Doppler shifts of spectral lines obtained using an IFU in the optical or aperture synthesis in the radio, or a photometric image. The user can supply a map of uncertainties in the data and a mask image to indicate only good pixels to be fitted.

2.1. Fitting an axisymmetric model

Aside from an optional simple warp in the outer parts, the model presented to the data is a flat disk with inclination, \( i \), and position angle, \( \phi_d \), that are assumed to be the same at all radii. Furthermore, the position of the center, \( (x_c, y_c) \) and, for kinematic fits only, the systemic velocity, \( v_{sys} \), are parameters fitted to the entire 2D data set. A simple axisymmetric model will therefore fit any or all these parameters to determine global estimates that best fit the data.

In addition, DiskFit estimates either the circular speed, for kinematic data, or the mean intensity for a photometric image, at a set of radii specified by the user. Model values at data points that lie between the specified radii are computed by linear interpolation. It is important to note that this implies the model is simply a tabulated set of values over a range of radii and has no pre-specified functional profile, such as an exponential disk, etc.
2.2. Uncertainties

Uncertainties in the parameters, and in the intensity or circular speed at each radius, are estimated by a bootstrap method. The residuals from a simple model are generally correlated at neighboring pixels, because the model ignores spirals and other sources of correlated turbulence. The bootstrap algorithms employed attempt to preserve these correlated residuals (see Spekkens & Sellwood [2007], Sellwood & Zámar Sánchez [2010] for a fuller discussion), which lead to larger and more realistic estimates of the uncertainties in the model.

2.3. Non-axisymmetric models

The most powerful aspect of DiskFit is that it can include simple non-axisymmetric features into the model and fit for their parameters. The most useful capability is to fit for a bar, which is a bi-symmetric distortion having a fixed position angle that is, in general, not aligned with, or perpendicular to, the major axis of projection. DiskFit allows for an underlying axisymmetric model on which a non-axisymmetric feature having a fixed position angle in the disk plane is superposed, and returns an estimate of the angle of its principal axis to the disk major axis. A bar that is almost aligned with the major or minor axis of projection may require that the fit is smoothed (see §2.7), but the bar cannot be separated from the disk by this algorithm when the alignment is exact; note that in such a case, an axisymmetric fit will be no worse than that obtained by other algorithms.

For kinematic fits, the non-circular flows have two $m$-fold symmetric components ($m = 2$ for a bar): a radial part that is the mean flow away from and towards the model center, and an azimuthal part that is the departure above and below the mean streaming speed. Each component varies in azimuth in the disk plane as a cos($m\theta$) or a sin($m\theta$) function, respectively, with zero phase on the bar major axis. These additional velocities are fitted at the same radii as those used to tabulate the circular speed, although the user can specify that the distortion has a smaller radial extent than the entire disk. DiskFit does not impose any relation between the radial and azimuthal velocity distortions, which can be arbitrarily large compared with the mean circular speed – i.e. it is not restricted to a small amplitude distortion. If the distortions turn out to be small, Sellwood & Zámar Sánchez [2010] give formulae that can relate the fitted velocity distortions to the ellipticity of the potential.

For photometric fits, the bar represents a light component that increases the fitted intensity above the axisymmetric mean along the bar major-axis, with a corresponding reduction along the bar minor axis. The bar light profile is again tabulated at the same radii as the mean axisymmetric light profile.

In principle, DiskFit can fit for distortions having other rotational symmetries, such as $m = 1$ (lopsided) or $m = 3$ (trefoil) distortions, although they could not be spiral in form as the algorithm restricts the non-axisymmetric component to having a fixed position angle in the disk plane at all radii.

Less usefully, DiskFit can also fit for axisymmetric radial flows. However, radial flow velocities would need to be unrealistically large – at least a few percent of the circular speed – to be detectable. Axisymmetric flow speeds of this magnitude would indicate the galaxy is in a transitional state and that extensive rearrangement of the mass distribution is taking place on a dynamical time-scale.

2.4. Spiral distortions

The largest residuals in fitted models generally arise from spiral arms, which are non-circular flows in kinematic maps and coherent features in photometric images. DiskFit does not attempt to fit these distortions, and merely treats them as sources of error that are allowed for in the bootstraps.

The reason is that these features are hard to model. Unlike bars, which are strong, clearly bisymmetric, and long-lived, mild spiral distortions are transient and probably result from multiple, superposed modes having different pattern speeds, and rotational symmetries.

2.5. Warp fitting

DiskFit allows the model to be warped in a simple, parametric manner. The code assumes that the line of nodes of the warp is at a fixed position angle, the warp begins at a certain radius, and increases in amplitude as a quadratic function of radius to some maximum amplitude at the last measured point. Since the kinematic signature of a warp closely resembles that of an in-plane bar, DiskFit will not allow the user to select both options in the same fit.

2.6. Bulge fitting

Photometric images can be fitted with a disk, bar and bulge model if desired. DiskFit makes the (highly questionable) assumptions that the bulge is both axisymmetric and symmetric about the disk mid-plane, and has a flattening that is constant with radius. It also assumes the parametric form of a Sérsic profile for the bulge, and will fit, if desired for the Sérsic index, $n$, effective radius, $R_e$, central intensity, $I_0$, and flattening $\epsilon$. A very high spatial resolution image is generally required to fit for all these parameters, and it is usually safer to hold at least $n$ fixed at some reasonable value.

The user of this capability should bear in mind that the fitted values provided by the code are meaningful only if the above listed assumptions about the bulge light profile are valid for his/her data.

2.7. Seeing corrections

If the user requests, DiskFit will blur the model, by convolving it with a point spread function, before comparing it with the data, which can be done for either photometric or kinematic fits. The blurring function is a Gaussian of specified width; note that the FWHM cannot be greater than 3 pixels. The code to compute these seeing corrections had a bug in version 1.1, which has been fixed in the present release.

2.8. Smoothing penalties

In general, DiskFit places no restrictions on the tabulated values of radial variation of the light profile, rotation curve, bar distortion amplitudes, etc. We note that DiskFit has an option to apply a smoothing penalty
to the radial variation of these tabulated functions, if desired. Since the smoothing penalty will affect the fitted values, it should never be large, and no smoothing is recommended in most cases. However, Sellwood & Zánmar Sánchez (2010) found that when fitting for the flow velocities of a bar that was inclined by just a small angle to the projected major axis, the velocity distortions became absurdly large and variable, and some smoothing was necessary to obtain meaningful fits.

3. OBTAINING DiskFit

The code is available from http://www.physics.rutgers.edu/~spekkens/diskfit. This website includes links to a comprehensive manual, giving full details of the procedure to use the code, data requirements, and illustrative examples, software update history, as well as executables and the source code. Versions 1.0 and 1.1 were released previously, in September 2012 and May 2013 respectively, and this posting is to announce version 1.2. The improvements at this version are that arrays are dimensioned dynamically, so that there are no software limits to the size of the dataset that can be fitted, and several bugs have been fixed.

The authors encourage feedback from users, and will make every effort to correct bugs and inconsistencies. Requests for additional capabilities will be considered and may be provided in future releases, but the authors cannot undertake to meet every possible request.

4. COPYRIGHT AND LICENSE ISSUES

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