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The stellar kinematics of galactic disks.

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Chapter 2. Outline

1. Motivation

Looking up, at night, one can immediately notice that the universe is almost empty. On a bright night, at first glance, a few nearby bright stars are visible. It is only after ones eyes are accustomed to the dark that the milky way becomes apparent as a hazy whitish band across the sky. External galaxies are equally faint and considerable effort is needed to study such objects. Kinematical studies of galaxies are most often carried out by gathering information of emission lines of the gaseous component. Most of the emisssion is then concentrated in a few discrete and bright lines for instance Hα or the 21 cm neutral hydrogen line. The gas is a good tracer of the potential but constitutes only a minor fraction of the mass content of a galaxy. Therefore a study of the stellar component, making up the dominant mass contribution in the inner regions, is warranted. In fact, the stellar velocity dispersion is a direct indicator of the local mass density.

The first objects of which the stellar kinematics has been studied were, of course, those having the largest brightness. For instance elliptical galaxies (Illingworth 1977), bright bulges (Whitmore et al. 1985) and/or bars (Jarvis et al. 1988), or bar dominated galaxies (Kormendy 1983; 1984). These systems generally exibit a constant velocity dispersion as a function of radius, reflecting their global isothermal nature. For galactic disks the situation is different. They are much fainter and because of their local isothermal nature the velocity dispersion decreases going outwards. This makes observing the stellar motions in galactic disks more difficult.

A pilot study by van der Kruit & Freeman (1984, 1986), nevertheless, showed that it could be done. The project described in this booklet is a continuation and extension of that study. Data have been collected and analysed for more galaxies with a variety of intrinsic brightnesses. For every object an interpretation has been given of the observations in terms of a mass model. Data for the sample of galaxies gave information on the magnitude of the dispersion in external systems and this correlated with galactic parameters. General conclusions have been drawn on the mass content and stability of galactic disks.

2. Observations

As noted above, galactic disks are faint. It appeared that on average at a radius of one scalelength the intensity of the disk light became approximately equal to the combined intensity of dark skybackground plus intensity of emission from inside the instrument. Hence to obtain data over a reasonable radial extent long integrations on large telescopes were required. At the outer regions of disks the velocity dispersion is small so that an appreciable velocity resolution (1σ typically between 20 and 50 km s^{-1}) was needed. That again diluted the available light making longer observations necessary. In this booklet data are included of two observing runs of van der Kruit, one at La Palma and one at Mt. Stromlo, Australia and four observing runs of Bottema, two at La Palma and two at ESO. In the mean time data of two other observing sessions proved to be not usable and was discarded.

3. Data handling

As anybody acquainted to the field knows, data reduction of long slit absorption line spectra is comprehensive. I had the great fortune that Andrew Pickles, on his arrival to Groningen, brought the Mt. Stromlo reduction package Pandora. This could be installed at the Netherlands Foundation for Radio Astronomy's centre at Dwingeloo, where in the nightly hours most of the reduction work was performed. The Pandora package gave the possibility to do the wavelength calibration and other basic data handling precesses. Nevertheless still some new software had to be written, for instance tasks te remove cosmic rays or S-shape distortions.

Near the centre, galactic disk or the accompanying bulge are relatively bright and the velocity dispersion is, compared to the instrumental resolution, large. Towards larger radii the brightness level drops exponentially accompanied by a decreasing velocity dispersion. This results in an increased noise level superposed on more narrow absorption lines. So, in the inner parts the kinematics can be extracted relatively easy from the absorption line spectra, but matters become more and more difficult going outwards. Expressed in Fourier space: at larger radii the wavenumbers of the signal are running into the wavenumbers of the noise. The most generally used Fourier Quotient method (Sargent et al. 1977) did not work for low S/N data and in fact as demonstrated by Bender (1990) cannot work. A new method was developed to extract stellar radial velocities and dispersions, presented in Chapter 4, Sect 2. It is a highly modified version of the cross-correlation method (Tonry & Davis 1979); a fit of a grid of model cross-correlation functions is made in a least squares sense to the observed cross-correlation peak. At that time I needed a method quickly because a lot of observations awaited an interpretation. And it needed to be reliable and verifiable which has resulted in a graphical representation of observed and best fitting cross-correlation functions. In this way the determined kinematical values are certain, although the method can still be improved on sophistication.

4. Relating the observed stellar kinematic values to galaxy parameters

There are essentially two ways to determine the stellar velocity dispersions in a galaxy. At first by a direct observation of the dispersion, which is for a certain orientation a mix of dispersions in radial, tangential, and vertical direction. Secondly the amount of asymmetric drift can be determined by comparing the emission line (gas) rotation and stellar rotation, from which the radial dispersion can be calculated. When possible both methods have been applied. It is, however, not trivial relating the observed stellar kinematics to internal kinematics of a galaxy. Because the stellar disk (and bulge) has a certain thickness the line profile observed is the result of a line of sight integration process through the galaxy. For a close to face-on galaxy the vertical dispersion is the dominant contributor to the observed line profile, for an inclined galaxy ($i \sim 70^o$) the tangential dispersion dominates, and for an edge-on system it is a complicated intensity and rotation weighted addition of radial and tangential dispersion. Additionally, because of these integration effects the observed difference between gas and stellar rotation is always larger than the true asymmetric drift.

There is only one way to achieve a proper interpretation and that is by "rebuilding" the line profile using a modelling procedure. This procedure is described in some detail in Chapter 3. It appeared that, even for an edge-on situation, observable line profiles are not very asymmetric. This is caused by the relatively large stellar velocity dispersions; relative to, for instance, dispersions of the neutral hydrogen gas. A gaussian fit to the model profile was generally sufficient to be compared to the determined radial velocity and dispersion of the observations. For a highly irregular stellar kinematics, as in Chapter 6, or for an addition of different kinematics of disk and bulge, such an approach fails, of course.

Using the modelling procedure, the internal stellar kinematics of a number of galaxies was determined. At first only for disk systems but later the influence of the bulge was included (NGC 6340 and NGC 2815). In Chapter 8 for the galaxy NGC 891 even the effect of an absorbing dustlayer was taken into account. In retrospect, galaxies with an intermediate inclination of $\sim 70^o$ are very suitable for a determination of the tangential dispersion. For such an orientation that component of the dispersion is dominant and effects of a slightly smaller z-dispersion and larger R-dispersion approximately cancel. To calculate the asymmetric drift, a proper modelling remains required. For more edge-on galaxies there is not a component of the dispersion which dominates and hence results are more model dependent.

5. Results for individual galaxies

Observations and interpretation of the individual galaxies are presented in Chapters 3 to 9. The most important result is that the stellar velocity dispersion in the radial and vertical direction is proportional to the square root of the surface brightness of a disk. This can be achieved when a constant, as a function of radius, M/L ratio is combined with a constant disk scaleheight. It appears that the determined dispersion functionality implies a nearly constant Toomre's (1964) Q value as a function of radius. Or, vice versa, a disk with constant Q value has a dispersion functionality which gives a good fit to the observed dispersions. The measurements typically comprise a radial extent between a half to two scalelengths and consequently the conclusions above are also only valid for that region. At larger radii the mass density of a dark halo will become non negligible compared to that of the disk. That will result in an additional amount of dispersion to that expected from the disk light only (see Chapter 10, Section 9).

A procedure to calculate the surface density of a disk from the observed velocity dispersion in the radial direction, is by comparing local Q values to those predicted by numerical simulations. In the first chapters of this booklet a constant Q value of 1.7 was adopted following from calculations by Sellwood & Carlberg (1984). Unfortunately these calculations employ a rather large dark halo to disk ratio and likely a smaller ratio would allow the disk to heat up till larger Q values while maintaining the spiral structure. For $Q \sim 1.7$ disk masses are calculated producing disk rotation curves in agreement with the maximum disk hypothesis (van Albada & Sancisi 1986). Increasing the value of Q results, for the same observed dispersions, in lower disk masses and the maximum disk hypothesis cannot be valid. Disk heating is a difficult problem and numerical simulations of that process are still restricted. Therefore, at present, one should keep an open mind on the exact value of Q, and realize that increasing Q results in lowering the amount of disk mass in a galaxy. In Chapter 10, Sect. 7 this matter is extensively discussed and it is concluded that in order to have a consistent picture, in agreement with the observed properties of a galactic disk, Q is preferably just above two.

The more massive systems in this study appear to have a more irregular stellar kinematics. Errors of the kinematical values are then predominantly determined by this irregularity. Smaller systems show a more regular kinematics and because the dispersions are smaller errors are dominated by the resolution of the spectrograph.

6. General results

The results for all galactic disks for which stellar kinematic observations exist are combined in Chapter 10. The sample comprises 12 galaxies covering an absolute luminosity range of $3\frac{1}{2}$ magn. (factor 25) and a maximum rotation ranging from 120 to 315 km s^{-1}. A comparison of these galaxies and their disks resulted in a number of conclusions summarized in the abstract of Chapter 10. For convenience, these conclusions will be given at this stage point by point:

- Comparison of the galaxy dispersion with absolute magnitude and maximum rotation reveals that the dispersion is larger for the more massive systems; the relation between dispersion and intrinsic brightness of the old disk population appears to be linear.
- Combination of the data for face-on and inclined systems makes the conclusion plausible that the ratio between vertical and radial dispersion in external systems equals 0.6, as for the solar neighbourhood.
- For a simple, one colour, one M/L ratio galactic disk the dispersions indicate a rather constant ratio of scalelength to scaleheight (h/z_0); possibly increasing towards the fainter systems.
- For realistic h/z_0 values, the stellar velocity dispersions only allow the disk to have a maximum rotation of on average 63% of the observed maximum rotation. The disk is then still dominant in the central parts of the galaxy but generally the maximum disk hypothesis predicting a maximum disk rotation of 85 – 90% of the observed, does not apply.
- Exploring the consequences for the Tully-Fisher relation, it is found that this relation for disks only must be positioned at lower rotational velocities than what is observed. A dark halo and bulge must supply the additional rotation.
- The relation between Toomre's Q parameter and mass-to-light ratio for a galactic disk is projected onto the observed velocity dispersions as a function of galaxy size. It is then found that the same M/L for galactic disks implies the same Q value for a disk and vice versa, which might indeed be expected when a process of self regulation is responsible for the appearance of regular spiral structure. For an $(M/L)_B$ of two which is calculated for the one colour disk model from the observed dispersions one finds Q to range between 2 and 2.5, coinciding with the general stability criterion for galaxies as derived in numerical experiments.

Let me wish you a pleasant reading !

References

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