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GALACTIC ROTATION CURVES

Rotation curves for spiral galaxies remain prime evidence for dark matter (and is sometimes used to argue for even more exotic physics). This is a review for physicists of the actual evidence, in particular what one can infer from optical data collected by Mathewson et al.

Rubin and Ford [1] found in 1970 that the rotation velocity of spiral galaxies did not decrease at large radial distance, and concluded that galaxies might contain large amounts of non-luminous — dark — matter. This conclusion was reinforced by Ostriker and Peebles [2], who argued that galactic disks have to be dynamically stabilised by a spherical halo of matter, and by cosmological models which predict much more matter than we see. By now, it is sometimes forgotten that the presence of dark matter is only a hypothesis. One of us [3] recently studied optical data on 967 galaxies with a view to investigate whether there is anything to the opposite point of view, that there is something wrong with Newtonian gravity [4]. We naively imagined that with 967 galaxies the statistics would be enough to settle this question, but in the course of the work we learned that astronomy is much more difficult than that. We tell the story here with an emphasis on possible pitfalls, because it might be instructive to non-experts to hear about them. Many similar studies exist in the literature.

The rotation velocity of a galaxy is measured through the redshift of the light emitted, usually the H_α line in the optical part of the spectrum or the 21 cm line in the radio part — that is to say that what is actually being measured is the velocity of hydrogen clouds along the line of sight. This must be deprojected to yield the rotation velocity as a function of radial distance. The optical data rely on the existence of ionised hydrogen, which is in fact not present in sufficient amount in the outskirts of galaxies. Neutral hydrogen emitting 21 cm radiation is often present very far out, but it is only in some cases that it forms an extended smooth disk. Galaxies with warped and disturbed hydrogen disks are usually disregarded in this context, so that there are only some tens of galaxies with radio data suitable for our purposes. This implies a considerable risk for selection effects!

About the photometry: The outskirts of galaxies are much dimmer than the night sky, so that subtraction of the sky background is a delicate issue. The usual way to estimate the background is to use pixels along the border of the CCD plate. There is a possibility [5] that one could mistake a weakly luminous halo for the background, and hence subtract it! The size of CCDs is increasing rapidly though, and astronomers we have talked to are confident that this problem can be dismissed, since they do not see a pattern of falling background with increasing CCD size. A luminosity profile is obtained by approximating the isophotes with ellipses, of varying ellipticity and position angles. We need to correct for the redshift of the galaxy. Next, the light we receive will depend on the galaxy's inclination. What we measure is the projection of the light — to compare different galaxies we need a face-on value. So we need to know their inclination. By comparing the major and minor axes of the fitted ellipses (boldly assuming the galaxy to be circular!) one can compute the inclination and correct the luminosity. The third correction adopted is due to the extinction of the light when it passes through dust in our own galaxy, which depends on the direction in which we view the galaxy. But presumably there is extinction in other galaxies too! There are actually two effects here, both of which are functions of the inclination of the galaxies: Galaxies may be optically thick, and there is an inclination dependent reddening. This is a subject of controversy among astronomers [6]. We followed Tully and Fouqué [7] on this matter, but there is a potential source of errors here.

The next step is to convert the measured light to a mass density. The conversion factor is the ratio M/L for the galaxy. We choose units so that this ratio equals one for the sun, and we expect that M/L for a spiral galaxy should be similar to but somewhat higher than that of the sun. Theoretical predictions apply to star populations rather than to individual galaxies, for which the deviations can be quite large. So we keep the M/L ratio as a free parameter, and use it to fit the calculated curve to the measured one.

When we have a mass density, the velocity of bodies is calculated from the law of gravity. In practice, a simplified model is needed. Most spiral galaxies can be modelled [8] as a large thin disc with exponential light density $I(r) = I_0 e^{-r/r_0}$ and a smaller spherical 'bulge' in the centre. These are purely empirical observations, and it may come as a surprise that there is so little structure. Some azimuthal averaging is involved in the determination of the luminosity profile. For our purposes this not so misleading, since the spiral arms contain many young luminous stars with low M/L ratio; the mass distribution is more nearly axisymmetric than appearances suggest. For an exponential disk we have a natural length scale available. Astronomers also use r_{83}, which is the radius containing 83% of the light. For an exponential disk r_{83} corresponds to 3.2 scale lengths r_0.

In the disk (if it is optically thin!) the measured light is the total light density. For the bulge we must take into account that the measured light is the integrated quantity along the line of sight. To decompose each galaxy into a bulge and a disk part we use an iterative method presented by Kent[9]. Sometimes the bulge is ignored and the whole galaxy fitted to an exponential disk, but this has the effect that when fitting a disk to the light distribution one will put too much of the disk in the inner part, thereby predicting a smaller galaxy, with lower velocity far out! So our mass model for a galaxy consists of a disk and a bulge with a mass distribution derived from the data, with M/L as a free parameter. One could assign different M/L ratios for the disk and the bulge, but we did not.

The Newtonian force is calculated numerically from the mass model, and then the predicted rotation curves can be computed. In Newtonian gravity the mass enters linearly, so M/L does not affect the shape of the curve. The most common way to fix it is used in "maximum disk" models, where the parameter is chosen to give the best fit inside (say) $\frac{2}{3}r_{83}$, taking care not to predict velocities higher than observed further out. In other words we take the highest M/L value that we can get away with. Too low predicted velocities in the outskirts is then evidence for dark matter further out.

We now come to a brief sketch of our results — the reader is referred to the original paper [3] for all details. We used optical data collected by Mathewson et al [10], which includes both photometry and H_α measurements. Deprojection of the rotation curves was performed by Persic and Salucci [11]. We used two selection criteria: That both velocity and luminosity curves are smooth and reach at least 1.4 r_{83}, and that the acceleration in the outskirts of the galaxy should fall below the a_0 acceleration in Milgrom's proposed modification of Newton's laws. Most of the 967 galaxies fail to fulfil the first condition, so our sample was disappointingly small: Only some 50 galaxies. The decomposition of galaxies into bulge and disk components worked well. Inspection of the measured rotation curves shows that they are not 'flat and featureless', as they are sometimes described. In a few cases there is a clear discrepancy which can be interpreted as evidence for dark matter, but for most of the galaxies the Newtonian curves without any dark halo actually give quite reasonable fits to the measured curves — the optical data do not reach sufficiently far out into the outskirts of the galaxies to reveal the presence of any dark matter. We here disagree somewhat with Persic and Salucci [11], who found evidence for dark matter well inside the optical radius for the same sample. A possible explanation for this might be the modelling; Persic and Salucci used an exponential disk to model the galaxies and then compared the derivative of the measured and calculated curves, thereby avoiding the 'maximum disk' fitting. Such a model might yield lower velocities in the outskirts, compared to our integration, while the maximum disk model that we used might underestimate the amount of dark matter. The M/L ratios that we found lie in the range 0.6 - 2.0 in solar units, which we believe to be reasonable for the I-band where the photometry was performed.

Let us add a few words on non-Newtonian gravity. Simple modifications like adding a λ/r-term to the Newtonian force did not work at all, since a dependence on galactic size should have been seen in our sample. Milgrom's theory [4], in which the breakdown of Newtonian gravity happens for accelarations less than a_0 fared better. However, examples like 59-g24 where the measured curve declines pose a serious problem for Milgrom's idea, since it can not explain this unless we assume a huge M/L ratio in the bulge. When we made fits with variable a_0 the parameter varied with a factor of 3, which is a little too large for comfort. Finally, since mass enters non-linearly in Milgrom's theory the M/L ratio affects not only the scale but also the shape of the calculated curves, so that the fact that the fits are good is less striking than it appears at first sight.

In conclusion, we did not find the evidence for or against dark matter from optical rotation curves to be as conclusive as we thought it was. And we certainly did not find strong evidence for non-Newtonian gravity.

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