Galaxy rotation curves from string theory

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ABSTRACT: This is a speculative attempt to connect string theory with cosmological observation. Inspired by an exactly solvable model in string theory, and based on the assumption that all matter is made of strings, individual stars will couple universally to this string gauge field and execute Landau orbits, much like electrons in an external magnetic field. This three-parameter phenomenological model can adequately fit the galaxy rotation curves. The extra centripetal acceleration provided by the background field can hence account for the “missing mass” needed to sustain the high rotation speed beyond the bulk of the stellar mass. The rotation speed of the stars on the outskirts of a galaxy is predicted to be linearly rising with distance.

KEYWORDS: Galaxy Rotation Curves, String Theory, String Phenomenology, Dark Matter.

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Dark Matter has been accepted by many as the leading candidate to explain the “missing mass” problem in galaxies. The problem arises because the rotational velocities of the stars about the center of the galaxy does not fall off in the Keplerian way as one exits the stellar disk. The stellar disk accommodates most of the young and bright stars which in turn are supposed to account for the lion’s share of the mass in a typical spiral galaxy. Instead, the rotational speed of the stars stays flat up to a distance ten times the size of the galactic disk. In order to explain the conundrum, Dark Matter is proposed to fill up the void in the form of a gigantic spherical halo (in the simplest case) engulfing the visible part of the galaxy in such a way that the rotational speed of the stars would be kept constant in the desired region. Usually in order to fit the data the dark matter halo alone is modelled with three parameters. Here we would like to entertain the possibility that a string background field that couples uniquely to the worldsheet of the strings, i.e. extremely natural from the point of view of string theory, can take up the bill of the missing mass and reproduce the galaxy rotation curves.

There are many contenders to the Dark Matter proposal with various degrees of success. We, instead, like to show that if one accepts the assumption that all matter is made of strings, these fields that arise naturally from string theory can put the galaxy into Landau orbits, much like an electron in the presence of a magnetic field. This produces an extra centripetal acceleration that would have been otherwise attributed to the presence of extra mass in the galaxy. Using a three parameter model we can already capture the rotational curves of galaxies of different sizes and shapes well over the extent of the galactic disk. With a suitable choice of parameters the rotational speed can be stabilized up to twenty times the radius of the stellar disk, $R_d$. We perform the fitting on twenty-two spiral galaxies with a sizeable range in luminosity, as well as size, and in different Hubble types. We obtain an average $\chi^2$-squared of 1.60 with a standard deviation of 1.68, indicating very good fitting. A
macroscopic model that describes this Landau rotation as well as gravitational lensing has been constructed from string sigma model and will be presented in forthcoming articles.

Twenty-two galaxies have been fit to the model without allowing for any Dark Matter components. This is done to test the limits of our model. In reality there are many well-motivated candidates for Dark Matter which we believe will be detected in future observations. There are a wide range of astronomical objects not giving light in the visible spectrum and therefore not included in the estimate of the mass of the galaxy from luminosity. They can be stars that are not heavy enough to ignite hydrogen, or black holes which take in all the light that shines on them. We should allow for the possibility of such ordinary matter being detected directly as a result of advances in technology. The other more likely possibility in the light of the measurements by WMAP [1] is that the Dark Matter is non-baryonic and consists of an exotic neutral particle such as the supersymmetric partners or other new candidates to be discovered in the new generation of high energy experiments. The conundrum involving Dark Energy and Dark Matter may also be resolved due to theoretical advances and we are back to the familiar universe. We may not like such an ordinary universe, without any inexplicable components. But we should keep in mind that there is such a possibility.

1. The model

In String Theory [2] it is postulated that the most fundamental constituent of matter is a string, a one-dimensional object. The observed particle spectrum corresponds to different

\[
\int B \cdot dS \quad \Rightarrow \quad H = dB
\]

\[
\int A \cdot dX \quad \Rightarrow \quad F = dA
\]

If strings are indeed fundamental objects, then \( B_{\mu \nu} \) will play a role as fundamental as \( A_{\mu} \) does.

Figure 1: Particle worldline and string worldsheets and their couplings to the corresponding gauge potentials.

quanta of excitations of the string. In particular the massless spectrum consists of a scalar, gauge bosons, graviton and their fermionic partners in a supersymmetric string theory. In one stroke it unifies Higgs-like scalars (spin zero), gauge bosons (spin one) and graviton (spin two), together with their fermionic partners of half-integral spins, in one framework.
The gauge theory of Yang-Mills fields that governed the interaction of point particles is extended to a gauge theory of a two-form gauge potential. This gauge potential couples uniquely to the worldsheet of the strings. See Fig. 1.

In one type of string background, corresponding to plane-polarized gravitational fields, string theory can be solved exactly [3]. Furthermore in one particular model, the Nappi-Witten model [4], the space where the strings propagate is as close to four-dimensional Minkowski space as one can get with the presence of the string background field\(^1\). This model enjoys an infinite dimensional symmetry at the quantum level [4] which in turn enables us to obtain a complete and covariant solution [5] of the first quantized string theory in this background\(^2\). This model is valid at all energy scales as long as the string coupling is small. The symmetry of the model is exactly the same at high energy as at low energy. This in turn lends hope that the certain phenomenon which originates at higher energy scale from string theory will persist at an energy much lower and a scale much bigger than those natural for the fundamental strings. The corresponding string sigma model action is

\[
L \sim \int_\Sigma G_{\mu\nu} \partial X^\mu \cdot \partial X^\nu + B_{\mu\nu} dX^\mu \wedge dX^\nu \quad (1.1)
\]

where \(X(\sigma)\) is a mapping from the two-dimensional worldsheet, denoted by \(\Sigma\), to the spacetime, parametrized by \(X\)'s with a metric \(G_{\mu\nu}\), in which strings can propagate and interact. It is this two-dimensional conformal theory with quantum fields, \(X\)'s (and possibly \(\Psi\)'s in the supersymmetric version) capable of capturing the interaction of the strings and hence offers a UV finite completion of Einstein’s theory of general relativity.

The geometry of the plane-polarized gravitational wave background is encoded in the metric \(G_{\mu\nu}\):

\[
G_{mn} = \begin{pmatrix}
0 & 1 & a_2H & -a_1H \\
1 & 0 & 0 & 0 \\
a_2H & 0 & 1 & 0 \\
-a_1H & 0 & 0 & 1
\end{pmatrix} \quad (1.2)
\]

The gauge potential, \(B_{\mu\nu}\), coupled to the worldsheet of strings, is linear, \(B = H \cdot X\), giving rise to a constant field strength, \(H\):

\[
B_{mn} = \begin{pmatrix}
0 & 1 & a_2H & -a_1H \\
1 & 0 & 0 & 0 \\
-a_2H & 0 & 1 & 0 \\
a_1H & 0 & 0 & 1
\end{pmatrix} \quad (1.3)
\]

In the presence of this field, the center of mass of the closed strings undergoes circular motion in the \((a_1, a_2)\) plane transverse to the light cone, \((X^+, X^-)\), much like the motion

\(^1\)As soon as the background gauge field is turned on, the spacetime back reacts and settles into another spacetime with a different geometry. In other words one cannot treat the resultant spacetime as the Minkowski space with a small perturbation due to the field.

\(^2\)The construction of the string vertex operators that are responsible for the creation of the string states, and the computation of the correlation functions of an arbitrary number of scattering particles have been reported in [5].
of electrons in the presence of a constant magnetic field perpendicular to the plane of rotation. The centre of mass of these strings follows the Landau orbits as depicted in Fig. 2.

If all matter is indeed made of strings each star inside the galaxy can then be thought of a coherent state of its constituent strings. The whole galaxy will be charged under this gravimagnetic field and each star will likewise follow the same trajectory as the individual string constituents\(^3\). Therefore the equation of motion of an arbitrary star in the galaxy will be modified by presence of this additional Lorentz-like force:

\[
\frac{v^2}{r} = \frac{Q}{m} H v + F_N(\vec{r})
\]  

(1.4)

where \(F_N(\vec{r})\) is the Newtonian attraction due to a stellar mass distribution \(M(r)\) within a radius of \(r\). \(H\) is the magnitude of the gravimagnetic field perpendicular to the galactic plane while \(Q\) is the charge of the stellar matter under this field. Note \(Q\) gives rise to the gravitational attraction. So it should be proportional to \(m\) as we shall see. To model the distribution of the stars in the stellar disk we take a continuum limit and use the parametric distribution with exponential falloff due to van der Kruit and Searle:

\[
\rho_{KS}(r, z) = \rho_0 \exp \left(-\frac{r}{R_d}\right) \text{sech}^2 \left(\frac{6z}{Z_d}\right)
\]  

(1.5)

with \(\rho_0\) being the central matter density. \(R_d\) is the characteristic radius of a galaxy, and \(Z_d\) the characteristic thickness. Let us stress that \(\rho_{KS}\) is the mass due to the visible stars only. There is no allowance for contribution from the Dark Matter halo. We have also ignored the contribution from gas and dust.

We first compute the force at radius \(r\) due to the mass distribution:

\[
F_N(r) = -G_N \nabla_{\vec{r}} \int \frac{\rho_{KS}(\vec{r}')}{|\vec{r} - \vec{r}'|} r' \, dr' \, dz \, d\phi
= \rho_0 G_N R_d \tilde{F}(\vec{r}) .
\]  

(1.6)

\(^3\)In a forthcoming article we formulate an effective field theory description for this process.
where the integration is taken over all spatial volume. In the last line we have integrated over $z$ and $\phi$ and defined a dimensionless radius parameter $\tilde{r} \equiv \frac{r}{R_d}$. Hence $\tilde{F}(\tilde{r})$, a dimensionless quantity, can be thought of as the universal Newtonian force function due to a vdK-S mass distribution and can be computed numerically. Two additional parameters, $\Omega \equiv \frac{QH}{2m}$, and $\rho$, are introduced into our model as follows:

$$v^2 - 2\Omega rv - \rho r \tilde{F}(\tilde{r}) = 0$$

(1.7)

whereas $\rho$ is related to the original $\rho_0$ by:

$$\rho = \rho_0 G N R_d.$$  

(1.8)

Of the parameters in the model $\rho$ and $R_d$ can be crosschecked or fit with the photometric data using the vdK-S formula, whereas $m$, $Q$ and therefore $\Omega$ are not available through other observations as yet.

2. A falsifiable prediction

Let us now examine the physical consequences due to the addition of a term linear in $v$ into the force law (eq. 1.6). At radius smaller than $R_d$, the rotational velocity rises linearly as it is in the case of pure Keplerian way, except with a steeper slope due to the introduction of the background rotation. So it will attain the maximum rotation speed faster at a smaller radius, given a mass distribution. This means that less mass is needed to reach a given rotation speed. Therefore we expect that the total mass of a galaxy determined from this model will be smaller than the one from a purely Newtonian model. Furthermore those galaxies which enjoy the background rotation have much more reasonable mass to light ratios, in the vicinity of unity (as tabulated in the last column of Table 3 and shown in Figure 3 in Section 3 below) than the ones would have gotten from the Dark Matter model.

As we exit the galactic disk where the majority of the stars reside, at a distance exceeding $2 R_d$, a drop in the Newtonian attraction due to the decrease in stellar mass is compensated by the linear rise in $v \sim \Omega r$ such that a plateau in rotation speed is obtained. By tuning $\Omega$ in the model one can generically obtain a plateau extending from $2 R_d$ to about $20 R_d$. Way beyond the extent of the stellar disk the background rotation dominates and the rotation curve rises linearly again. This prediction is compatible with the rising rotation velocity of the individual stars on the outskirts of a galaxy. This can happen at a distance as far as $20 R_d$ which has yet reached by observations. Measurement is difficult there because of the lack of bright stars so far away from the centre of the galaxies.

This linear rise in rotation speed far away from the centre of the galaxy is a signature prediction of our model which can be tested in the following ways:

- by a larger sample of data with measurements extending to the outer part of the galaxies;
- by observations measuring the rotation speed of small satellite galaxies;
- by improved precision on current measurements.
If all of these prefer a flat, or even falling rotation curve in the range beyond $2.2R_d$, then our model is disfavoured. The model in the simplest form involves a constant string background field can be easily refuted by a direct measurement of the falling rotation speed of satellite galaxies. In the future as the precision of velocity measurement around $10R_d$ increases one can readily distinguish the three types of models, namely the dark matter model, MOND and our model as they predicts a falling rotation curve, a flat rotation curve and a rising rotation curve respectively.

3. Data processing and fitting:

We obtained our data of the twenty-three galaxies in the SING group from FaNTOmM [6]. The fitted galaxy rotation curves are presented in Appendix A. The stars with error bars indicate the data points while the dots indicate theoretical predictions. The values of the best fit parameter for $R_d$, $\rho$, and $\Omega$, along with the $\chi^2$-values (per degree of freedom) of

| galaxy    | likelihood | $\Omega$ | $\rho$ | $R_d$ (kpc) | total mass(Msun) | B magnitude | $\Upsilon$ |
|-----------|------------|----------|--------|-------------|----------------|-------------|------------|
| ngc0628   | 4.35       | 8.872    | 11738  | 1.803       | 3.35E+10        | -20.60      | 1.24       |
| ngc0925   | 2.45       | 5.077    | 500    | 2.473       | 3.68E+09        | -20.05      | 0.23       |
| ngc2403   | 4.25       | 13.418   | 16497  | 0.518       | 1.12E+09        | -19.56      | 0.11       |
| ngc2976   | 0.40       | 0.100    | 2135   | 1.867       | 6.76E+09        | -18.12      | 2.45       |
| ngc3031   | 5.70       | 2.000    | 3187   | 4.389       | 1.31E+11        | -21.54      | 2.04       |
| ngc3184   | 0.57       | 0.655    | 1552   | 4.685       | 7.77E+10        | -19.88      | 5.58       |
| ngc3198   | 0.27       | 1.968    | 1971   | 3.522       | 4.19E+10        | -20.44      | 1.80       |
| ngc3521   | 0.59       | 6.046    | 26678  | 1.479       | 4.20E+10        | -21.08      | 1.00       |
| ngc3621   | 0.37       | 10.338   | 7413   | 1.084       | 4.60E+09        | -20.51      | 0.18       |
| ngc3938   | 1.03       | 9.722    | 16199  | 1.240       | 1.50E+10        | -20.01      | 0.96       |
| ngc4236   | 0.33       | 0.12     | 110    | 4.83        | 4.42E+09        | -18.10      | 1.60       |
| ngc4321   | 2.07       | 5.208    | 3752   | 3.148       | 5.70E+10        | -22.06      | 0.55       |
| ngc4536   | 0.74       | 1.465    | 734    | 5.867       | 7.22E+10        | -21.79      | 0.89       |
| ngc4569   | 0.66       | 16.370   | 12262  | 1.042       | 6.75E+09        | -21.10      | 0.16       |
| ngc4579   | 0.69       | 7.385    | 5164   | 3.000       | 6.79E+10        | -21.68      | 0.93       |
| ngc4625   | 0.55       | 0.100    | 1140   | 1.446       | 1.68E+09        | -17.63      | 0.96       |
| ngc4725   | 0.27       | 1.378    | 1523   | 6.726       | 2.26E+11        | -21.76      | 2.87       |
| ngc5055   | 3.52       | 4.064    | 24581  | 1.544       | 4.40E+10        | -21.20      | 0.94       |
| ngc5194   | 0.81       | 3.186    | 10718  | 1.102       | 6.98E+09        | -20.51      | 0.28       |
| ngc6946   | 6.03       | 7.440    | 4980   | 1.805       | 1.43E+10        | -20.89      | 0.40       |
| ngc7331   | 0.52       | 8.465    | 18613  | 1.680       | 4.30E+10        | -21.58      | 0.64       |
| m81dwb    | 0.13       | 1.119    | 15919  | 0.147       | 2.46E+07        | -12.5       | 1.58       |
| $<\chi^2>$ | 1.65      |          |        |             |                 |             |            |

Table 1: The best fit values for the parameters $R_d$, $\rho$, and $\Omega$. Mass for the galaxie as well as the mass to light ratio, $\Upsilon$ as computed from the best fit parameters.
the fitting, are tabulated in Table 1. Out of the twenty-three galaxies one, NGC 5713, turns out to be two merging galaxies. We will henceforth drop this galaxy from the rest of the analysis.

The radii in the data set are quoted in arcsec. We need to convert the data into distance in kilo-parsec. This is done as follows. Let us denote the angular extent of the galaxy on the detector screen by angle \( \alpha \). We hence have the relation:

\[
\frac{r}{d} = \frac{\alpha}{360 \cdot 60 \cdot 60 \cdot 2\pi}
\]

where \( d \) is the distance, in kilo-parsec, between the galaxy and us. Kinematic distance modulus is encoded by the parameter “mucin” in the FaNTOMM database. It is the difference between the apparent magnitude, \( m \), and the absolute magnitude, \( M \), of a star or a galaxy, given by the following formula:

\[
mucin = m - M = 5\log(d) + 10
\]

The in-falling velocity of the Local Group onto the Virgo cluster has been corrected for in mucin. In the case that mucin is not available in the database, we use “mup,” without such correction, instead, in the distance determination, at the expense of a small error. In one extreme case in our sample this introduces a 10% error. Otherwise the errors are less than 5%, negligible compared to the errors in velocity measurements. In this way we convert the radius of the galaxy from arcsec to kilo-parsec.

Next we turn to determining the luminous mass of the galaxies from the density parameter \( \rho \):

\[
m_\star = \int \rho \rho_\star(r, z) r \, dr \, dz \, d\phi
\]

\[
= 2.0944 \rho_0 R_d^3
\]

where we have integrated over \( 0 < \tilde{r} < \infty \), and \( -\infty < \tilde{z} < \infty \). The mass of a galaxy is finally computed using the best fit value of \( \rho \) for the galaxy according to the following formula:

\[
m_\star = \frac{2.0944}{G_N} \rho \cdot R_d^2
\]

making use of the relation (eq. 1.8) between \( \rho \) and \( \rho_0 \). Newton’s constant takes the value

\[
G_N = 4.32 \times 10^{-6} \text{ km}^2 \text{ s}^{-2}/\text{kpc}/M_\odot
\]

in the units convenient for our calculation.

As a check we compute the mass to light ratios for the twenty-two galaxies. We expect the mass-to-light ratios of these spiral galaxies to be smaller than the mass-to-light ratio of the sun which is set to unity \(^4\). The reason being that these galaxies have many young stars which are very bright. Compare to the sun they emit more light for the same mass. We would therefore like to see that the mass-to-light ratios of our galaxies to lie

\(^4\)We thank Frank van den Bosch for useful discussion regarding this point.
between $1 < \Upsilon_{\text{galaxy}} < 0$. The results are tabulated in the last column of Table 3 and shown in Figure 3. We compare only the B-band magnitude of these galaxies to the B-band magnitude of the sun, $M_B = 5.48$. Ideally one would like to compare the absolute magnitude in the K-band, which is believed to be a better indicator of the stellar mass. Unfortunately in this data set the K-band data is not available.

Let us remark that for those galaxies enjoying the benefit of the background rotation the range of mass to light ratios obtained from our model lies in a much narrower range than that obtained from Dark Matter models (See, for example, [7]). In a companion paper [8] we compare our model with the dark matter model by fitting the same group of twenty-two galaxies with Navarro-Frenk-White [9] profile. Indeed the values of the mass-to-light ratio span less than two orders of magnitude while those from the NFW profile for these twenty-two galaxies scatter five orders of magnitude. The total mass of the galaxies computed from our theory as well as their mass-to-light ratios are tabulated in Table 3. We also notice an intriguing trade off between values of the mass-to-light ratio with the strength of the gauge field, shown in Figure 4. This relationship deserves further investigation. Some of the galaxies have strictly flat rotation curves beyond the stellar disks. MOND [10, 11] can
perhaps do a good job fitting them. However those with linearly rising speed, for example NGC 2403, are difficult for MOND to capture.

4. Discussion

In this note we entertain the idea that a string background field contributes a Lorentz-like force to sustain the galactic rotation in spiral galaxies. This force gives rise to an extra centripetal acceleration in addition to the gravitational attraction due to the visible stellar mass. If not accounted for properly it would appear to be mass mysteriously missing in the galaxies. This missing mass is currently accounted for by postulating the existence of “Dark Matter.” Together with “Dark Energy,” they present two important conundrums for physics in the twenty first century. Until these two roadblocks are removed we cannot arrive at a comprehensive physical theory of Nature. Until hard proof is presented for the nature of Dark Energy and Dark Matter, one should explore all venues for their explanation.

At this point it is worth mentioning that a critical reanalysis of available data on velocity dispersion of F-dwarfs and K-giants in the solar neighbourhood by Kuijken and Gilmore concluded that the data provided no robust evidence for the existence of any missing mass associated with the galactic disc in the neighbourhood of the Sun [12]. Instead a local volume density of \( \rho_0 = 0.10 \text{M}_{\odot}\text{pc}^{-3} \) is favoured, which agrees with the value obtained by star counting. Dark matter—if existed—would have to exist outside the galactic disk in the form of a gigantic halo. Their pioneer work was later corroborated by [13] using other sets of A-star, F-star and G-giant data. Note that this observation can be nicely explained by our model as the field only affects the centripetal motion on the galactic plane but does not affect the motion perpendicular to the plane.

With a three parameter phenomenological model we are able to explain the shape of the rotation curves of the spiral galaxies way beyond the stellar disks where the majority of the visible matter resides. Abstractly speaking to capture a “Universal Rotation Curve” [14] one really needs three parameters to specify the initial slope, where it turns and the final slope. In this sense our model utilizes just right number of free parameters. Working from first principles we are formulating a string sigma model description giving rise to this Lorentz force at a macroscopic scale. We are also able to explain gravitational lensing phenomenon which is often cited as another strong evidence for the existence of Dark Matter. However we are not able to explain the velocity dispersion of galaxies inside a cluster with this simple model. Some other mechanism will have to be invoked to account for it. We are investigating if some other aspects of string theory can naturally give rise to such a mechanism, but to no avail at the moment of writing. If succeeded we hope that other researchers will be encouraged to look harder for experimental and observational connections with string theory, however unlikely they may seem at first sight.

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Appendix A. The Galaxy Rotation Curves

The galaxy rotation curves are fit by the three-parameter model. The stars with error bars indicate the data points while the dots indicate theoretical prediction.

NGC0628

NGC0925

NGC2403

NGC3031

NGC3184

NGC3198
