Predicting Velocities of Stars

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Summary

Mainstream mathematical descriptions of our universe are influenced by the presumed existence of dark matter which arises in part from a failure of Newton's law of gravity to predict the velocities of stars. This essay suggests a new equation for gravity derived from research undertaken by Professor Susskind and Professor Lloyd. If this equation can more accurately predict the velocities of stars, the underlying theory supports the idea that our universe originates in an Anti-de Sitter (AdS) space. In an AdS space, there may not be unresolvable Undecidability, Uncomputability, and Unpredictability issues. Our universe could have been designed to generate solutions to these issues. This essay is a first step in challenging the notion that 'there are rigorous arguments limiting what we can prove, compute and predict'. The essay describes how a new equation for gravity was derived and how it could be tested.

The new equation for the force of gravity is of the form:

$$F_g \sim \frac{(4 * m_1 * m_2 *[A_1/A_2] * [T_{12} / T_{22}])}{(G * \{d_1 * T_{12} / T_{22}\} + d_2)^2}$$

where:

~ means 'is proportional to'.
F_g = Force of gravity
G = Gravitational constant
m_1 = Mass of galaxy for star at radius d_2
m_2 = Mass of star
d_1 = Distance of star from centre of galaxy at formation
d_2 = Distance of star from centre of galaxy now
A_1 = Age of galaxy
A_2 = Age of star
T_{12} = Temperature of star at formation
T_{22} = Temperature of star now.

When A_1 is set equal to A_2, T_{12} is set equal to T_{22}, and $d_1 = d_2$, this equation reduces to Newton's Law of gravity (NL) which is:

$$F_g = (g * m_1 * m_2) / d_2^2$$

where g is a gravitational constant.

The gravitational constant, G, can be estimated by comparing the actual velocities of a sample of stars to those predicted by the new equation. Once the new gravitational constant has been estimated, this estimate can be used to predict the velocities of other stars. A comparison of the predictive accuracy of the new equation with predictions using NL (without dark matter) is a way of testing the explanatory power of the new equation.

Introduction

A new equation for gravity is derived from two mathematical propositions. The first involves extending Professor Susskind's ideas about what happens inside a wormhole in Anti-de Sitter (AdS) space. Some commentators suggest theories based on AdS space are irrelevant to our universe because our universe exists in De-Sitter space. The book, Gravity's New Clothes, explains why our universe could have been created inside a wormhole in AdS space. Tarski has shown that an AdS space allows for the existence of complete axiomatic mathematical systems where Gödel's Impossibility Theorems do not apply.

Susskind describes what happens when two black holes in AdS space are merged to create a wormhole. The AdS space created by the merger of two black holes can be described in terms of two components: AdS bulk space and the boundary of AdS bulk space. AdS bulk space consists of combinations of polyhedrons which are quantum-like objects oscillating between one of their forms and the dual of that form. These polyhedrons are holograms on the boundary of AdS space; holograms with one less dimension. The amplituhedron, discovered by Professor Arkani-Hamed, suggests AdS bulk space may include polyhedrons.

Susskind argues that the interior of a wormhole increases in quantum computational complexity over time. When Susskind's equations for computational complexity are modified to incorporate Professor Lloyd's view that our universe is a quantum computer which computes itself, Susskind's equations can be interpreted as describing phenomena on the boundary of AdS space. These equations describe (i) why the fabric of space-time in our universe is expanding at an accelerating rate; and (ii) where Newton's Law of Gravity (NL) comes from.

Susskind's discussion about what happens inside a wormhole is based on adding one unentangled qubit to a volume of qubits. This essay extends his analysis to the merger of two volumes where both volumes contain more than one qubit. An imperfect analogy is combining two similar volumes of gas which have different temperatures where one volume consists of 'matter' and the other consists of 'antimatter'. The moment of merger of the two volumes is equivalent to the Big Bang of our universe while the adjustment to thermodynamic equilibrium is equivalent to cosmological inflation where the amount of 'matter' slightly exceeds 'antimatter'.

AdS space

Physicists believe our universe exists in a four dimensional space. Mathematicians suggest space can be curved. Most cosmologists believe our universe exists in a de-Sitter space which has positive curvature. AdS space has negative curvature.

Second Law of Quantum Complexity

According to Susskind:

> *When a star collapses, a horizon forms and its area grows until it reaches its final value. ... There is another similar but less well-known phenomenon: the growth of the spatial volume behind the horizon of the black hole. ... The growth of the interior continues long past the time when the black hole has come to thermal equilibrium. Something else—not entropy—increases. What that something else is should have been one of the deepest mysteries of black hole physics—if anyone had ever thought to ask about it.*

Susskind believes this 'something' is quantum computational complexity. He argues that the Second Law of Quantum Complexity for a quantum system is a consequence of the second law of thermodynamics for an auxiliary classical system. The existence of a boundary in AdS space means the equations that Susskind derives for the complexity inside an AdS space (i.e. the bulk space) have a complementary interpretation for what happens on the boundary of that space.

In Susskind's view, there are two equations associated with quantum complexity inside an AdS space. The first 'measures the minimum number of gates required to prepare a given unitary operator or a given state from an unentangled product state'. This first component, computational complexity (CC), is concerned with the positional aspects of entropy. CC grows linearly with time i.e. CC(t) = K(t) for a time exponential in K where K is the number of qubits in the quantum system. The second component, Kolmogorov complexity (KC), is concerned with kinetic aspects of entropy.

According to Susskind, the entropy inside a black hole is not the same as normal entropy. The growth of a wormhole (when two black holes are merged together) loosely resembles the cosmological expansion of space in our universe. During the early period of complexity growth, the two components of complexity compete. In equilibrium, the entropy is dominated by CC. KC is a fixed overhead associated with the complexity of the algorithm. After the algorithm has run for a long time the CC vastly exceeds the fixed overhead.

Susskind's research combined with the insights of other physicists suggests the boundary of an AdS space could display a classical physics world even though the interior of the space is quantum. The CC component calculates what could happen on the boundary, KC records what does happen.

Kolmogorov complexity

Susskind analyses what happens to the complexity of the black hole when one qubit is added. When two identical thermodynamic systems are combined, the entropy is additive. Susskind demonstrates that combining two complexities multiplies the degrees of freedom i.e. when one qubit is added to another system, the complexity of the combined system is doubled. Applying this logic when both complexities have more than one qubit, the resulting complexity is the product of the complexities not the addition.

Susskind distinguishes between maximum complexity and relative complexity. He argues that the difference which he calls uncomplexity is a resource for doing work (computation). He specifically mentions Kolmogorov uncomplexity might be used as a resource for erasure (of quantum computations). One possibility is that KC is associated with work done by gravity.

Susskind derives the following expression for KC:

$$KC \sim V / (G * \ell^2_{AdS}) \quad (2.1)$$

where

V is the new space volume after inserting an unentangled qubit into a maximally complex state;
G is a gravitational constant;
ℓ_{AdS} is the AdS radius of curvature. A radius of curvature is the radius of a circle that best fits a normal section. The radius of curvature is a distance. Squaring a distance is analogous to identifying a holographic area on the boundary of AdS bulk space.

Susskind suggests that it is very difficult to calculate a value for KC. In the following discussion, the variables in the KC formula are converted into classical variables. This conversion may only approximate actual values.

Our universe is a quantum computer

Professor Seth Lloyd has proposed the idea that 'The history of our universe is, in effect, a huge and ongoing quantum computation. The universe is a quantum computer.'

Some of the ideas in Lloyd's view of our universe as a computer are:

An op is an elementary logical operation. Each collision between elementary particles acts as a simple logical operation or "op". ... the universe is nothing but ... qubits. ... since the universe registers and processes information like a quantum computer and is observationally indistinguishable from a quantum computer then it is a quantum computer.

The part of the universe about which we can have information is said to be "within the horizon." .... As time passes, the horizon expands. ... As the horizon expands, more and more objects swim into view, and the amount of energy available for computation within the horizon increases. The amount of computation that can have been performed within the horizon since the beginning of the universe increases over time.

.... To get the maximum rate at which the universe can process information. ... apply the Margolus-Levitin theorem. ... the total number of ops the universe has performed in the entire time since the Big Bang is proportional to the square of that time.

... Einstein challenged John Wheeler to sum up general relativity in a simple phrase. Wheeler rose to the challenge: "Matter tells space how to curve," he said, "and space tells matter where to go." Let's rephrase Wheeler's dictum for the computational universe: "Information tells space how to curve; and space tells information where to go." In the computational universe, space is filled with "wires", paths along which information flows. The wires tell information where to go. The wires meet at quantum logic gates, where that information is transformed and processed. The quantum logic gates, in turn, tell space how much to curve at that point. The structure of space-time is derived from the structure of the underlying computation.

The "matter" in a computational universe arises out of quantum logic gates. ... any form of quantum mechanical matter that arises out of local interactions can be simulated or constructed out of quantum logic gates.

The Margolus-Levitin theorem says that the maximum rate at which a physical system can move from one state to another is proportional to the system's energy: the more energy available, the smaller the amount of time required for the electrons to go from here to there. The total number of possible ops computed by the universe is a function of the temperature of the universe.

The total number of ops that the universe could compute at any point in time increases over time due to the increase in the size of the visible universe; hence, the number of ops that the universe could have computed is proportional to the age of the universe. The total number of ops the universe could have performed since the Big Bang is proportional to the square of the age of the universe and its temperature.

Susskind suggests that KC on the boundary of AdS space could be a measure of the work being done. In terms of Lloyd's analysis, KC could be linked to the ops being performed by the universe. In particular, KC could be transformed into Lloyd's wires and quantum logic gates.

Professor Carlo Rovelli, one of the co-founders of Loop Quantum Gravity, suggests:

> *Space is a spin network whose nodes represent its elementary grains, and whose links describe their proximity relations. Space-time is generated by processes in which these spin networks transform into one another, and these processes are described by sums over spinfoams. A spinfoam represents a history of a spin network, hence a granular space-time where the nodes of the graph combine and separate.*

Rovelli's links and nodes seem to be analogous with Lloyd's wires and quantum logic gates. Rovelli also makes it clear that a spinfoam represents a history of a spin network.

Quantum and classical correspondence

The KC equation can be converted into a form consistent with Lloyd's computer ops and Rovelli's concept of spinfoam being history. KC is reformulated into an equation describing events on the boundary of AdS space. That equation incorporates information about what is happening at the time and what has happened in the past. KC transforms quantum events inside a wormhole into classical events on the boundary of the wormhole.

The volume of a wormhole grows over time. Susskind interprets this growth as quantum computational complexity which grows linearly with time i.e. the number of possible computations made inside a wormhole increases linearly over time. Using Lloyd's conclusion about the number of ops a universe could have computed over time, the growth in quantum computational complexity could be functionally related to the age and temperature of the universe. Each increase in the volume of space would be proportional to the extra information needing to be stored to accommodate increases in computational complexity.

One way to express the growth in quantum complexity in the fabric of space is: (i) identify a density that is proportional to the fabric's capacity to store computational complexity; and (ii) multiply that density by a measure of growth of space over time. The density of space is a measure of the fabric's capacity to store information while the rate of growth in the fabric of space is proportional to an increase in quantum complexity. According to Lloyd, the capacity for the universe to store information about computations depends on the temperature of space. With these insights, Susskind's equation for CC_t:is:

$$CC_t \sim [V_t / T_t] * [V_t/V_0] \qquad (2.2)$$

where:

CC_t = Quantum computational complexity at time t.
V_t = Volume of the universe at time t
V_0 = Volume of the universe at the beginning of the universe
T_t = Temperature of the universe at time t.

Lloyd argues the total number of ops that the universe could have computed is proportional to the square of the age of the universe. Thus CC_t is proportional to A_t^2 where A_t is the Age of the universe at time t.

Combining Susskind's and Lloyd's insights:

$$V_t^2 \sim \{a * t^2 * T_t\} \qquad (2.3)$$

where:

A_t is reformulated as (constant * t)

a incorporates both the constant term of the reformulated A_t and V_0. The constant 'a' has a positive value and is not a function of time.

Partially differentiating Eq. 2.3 with respect to time where temperature varies over time:

$$\text{Growth of the fabric of space} = \delta V_t/\delta t \sim \{a * t * T_t\} + \{[a * t^2 * \delta T_t/\delta t] / 2\} \quad (2.4)$$

According to physical laws, as the volume of a gas expands, its temperature falls. As each increase in computational complexity requires an increase in the volume of space, the increase in the size of the universe causes the temperature of the universe to fall; so $\delta T_t/\delta t<0$.

Partially differentiating Eq. 2.4 gives the change in the rate of change in the fabric of space:

$$\delta^2 V_t/\delta t^2 \sim [a * T_t] + [a * t * \delta T_t/\delta t] + [a * t * \delta T_t/\delta t] + [0.5 * a * t^2 * \delta^2 T_t/\delta t^2] \quad (2.5)$$

Combining terms in Eq. 2.5, the change in the rate of change in the size of the universe is:

$$\delta^2 V_t/\delta t^2 \sim a * \{T_t + [2 * t * \delta T_t/\delta t]\} + [0.5 * a * t^2 * \delta^2 T_t/\delta t^2] \quad (2.6)$$

As the temperature of the universe can never go below absolute zero, the rate at which the temperature decreases must get less over time, i.e. at some temperature $\delta^2 T_t/\delta t^2$ must be positive. The value of the expression $\{T_t + [2 * t * \delta T_t/\delta t]\}$ is uncertain but is likely to be positive until the temperature of the universe approaches zero. Thus provided the temperature of the universe is above zero, at some point in time the rate of growth of the universe will accelerate as quantum complexity increases.

The fabric of space does not require a repulsive force called dark energy to drive its expansion; the expansion is caused by the universe's need to carry out more elementary logical operations as computational complexity in the wormhole increases. Acceleration in the rate of growth is due to deceleration in the rate of decline in the temperature of the universe.

Law of gravity

KC is not linearly related to time. As described in Eq. 2.1, KC inside the AdS bulk space seems to be related to the force of gravity on the boundary of AdS space. The variables in the KC formula can be transformed using Lloyd's ideas about the number of computations that the universe makes.

Susskind suggests the work done by Kolmogorov uncomplexity may be similar to erasure of computations. Assuming that the role of the CC component is calculating all the possible permutations and combinations of quantum events that could occur in AdS bulk space, the KC component could progressively eliminate some of these possibilities as time evolves. In other words, KC describes the consequences on the boundary associated with events in AdS bulk space.

When the CC component describes what happens to the total volume of space at the boundary of AdS space, KC describes what happens to individual elements. Susskind's equation for CC describes what happens when one clean qubit is added to another thermodynamic system. Assuming the same formula is still applicable when two thermodynamic systems, each consisting of several qubits, are merged, the numerator of KC would be $V_1 * V_2$ i.e. the volumes of system 1 and system 2 are multiplied not added together.

To convert V_i into Lloyd's number of ops, assume that information is instantiated into both the fabric of space and matter. As indicated earlier, Lloyd explains '*The "matter" in a computational universe arises out of quantum logic gates*' and '*Information tells space how to curve; and space tells information where to go.*' The definition of matter includes its age which relates to the quantity of stored information and temperature which relates to the speed of communication. This suggests that a volume in AdS bulk space, V_i, could be represented on the boundary as:

$$V_i \sim m_i * A_i * T_i \quad (2.7)$$

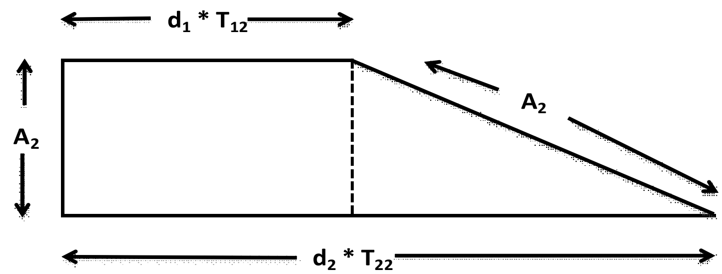
where:

V_i is the volume of system i in AdS bulk space with i being 1 or 2. V_1 is the volume of system 1 before interaction with V_2. V_2 is the volume of system 2 before interaction with V_1;
m_i is the mass at the boundary associated with the V_i in AdS bulk space;
A_i is the age of m_i;
T_i is the temperature of m_i (a positive number).

In the denominator of the formula for KC (Eq. 2.1), the term ℓ^2_{AdS} which measures the curvature of AdS space, is transformed using Lloyd's model for calculating the computational ability of the universe. As implied earlier, ℓ^2_{AdS} could be instantiated as a holographic area in a two dimensional space. Adopting Rovelli's idea that Loop Quantum Gravity's (LQG) description of space includes history, transforming ℓ^2_{AdS} into a holographic area could include instantiating information about the history of interactions into the distances between the two masses.

Figure 1 is a two dimensional geometric representation of the history of interaction between the two masses. As suggested by Rovelli, distance between masses (links in LQG, wires in Lloyd's terminology) incorporates information about the number of ops and the speed of computation. Using Figure 1 as an example, a mathematical expression describing the history of interactions could consist of the sum of the area of a square i.e. height (A_2) times its base ($d_1 * T_{12}$) and the area of the triangle i.e. half the height (A_2) times its base ($[d_2 * T_{22}] – [d_1 * T_{12}]$) where T_{12} is the temperature of a star when it was formed and T_{22} is the current temperature of the star.

Figure 1: History of interaction between two masses



The areas in Figure 1 represent the history of the interaction between m_1 and m_2 encoded in the fabric of space for the life of the younger mass. During this lifetime, the masses may have moved together, moved apart or the distance between them could have fluctuated. The more likely history for a star in galaxy is that the two masses moved apart because of the expansion of the fabric of space. When the temperatures associated with m_1 and m_2, are ignored, the history of interactions between the two masses (H_{12}) could replace ℓ^2_{AdS} in the denominator of Eq. 2.1. The formula for this history is:

$$H_{j2} \sim A_2 d_1 + [0.5 * A_2 * (d_2 – d_1)] \quad (2.8)$$

where:

H_{j2} is the history of interaction between the two masses over time j (the age of the star);
A_2 is the age of the star;
d_1 is the distance between the star and the centre of mass of the galaxy when the star was formed;
d_2 is the current distance between the star and centre of the galaxy.

Eq. 2.8 can be rearranged into:

$$H_{j2} \sim [A_2 * (d_1 + d_2)]/2 \quad (2.9)$$

Changes in temperature can be incorporated in Eq. 2.9 by recognizing that the temperature is equivalent to modifying the distance because the temperature affects the maximum number of possible computations. Assuming the temperature of the galaxy is always greater than the temperature of a star, only the temperature of the star is relevant for the calculation of the history because the rate of communication is limited by the temperature of the star. After incorporating temperature, Eq. 2.9 becomes:

$$H_{j2} \sim \{A_2 * [(d_1 * T_{12}) + (d_2 * T_{22})]\}/2 \quad (2.10)$$

where:

T_{12} is the temperature of the star at birth;
T_{22} is the temperature of the star now.

The denominator for KC also includes a gravitational constant, G. Thus, the complete denominator for KC is G times a history that takes into account both the age of the star and changes in temperature of the star. Eq. 2.10 is an approximation because the distance of a star from the centre of the galaxy may not increase linearly over time.

The mass in Eq. 2.1 could be considered to be the consequence of that mass interacting with a single qubit. When there are two masses both involving more than one qubit, each individual mass needs to be divided by a denominator like that in Eq. 2.10. The denominator for each of the interacting masses will be the same assuming each mass records one way communications with the other mass. Thus the KC equation for the interaction between two masses includes the square of Eq. 2.10.

The full equation for KC in terms of events on the boundary is:

$$KC \sim m_1 * m_2 * A_1 * A_2 * T_{12} * T_{22} / (G^2 * H_{j2}^2) \text{ or}$$

$$KC \sim \{4 * m_1 * m_2 * (A_1 / A_2) * (T_{12} / T_{22})\} / (G^2 * \{[d_1 * (T_{12} / T_{22})] + d_2\}^2) \qquad (2.11)$$

When $A_1 = A_2$, $T_{12} = T_{22}$, and $d_1 = d_2$, Eq. 2.11 reduces to NL (although the gravitational constant may not be the same). NL is:

$$F_g = (g * m_1 * m_2) / d_2^2 \qquad (2.12)$$

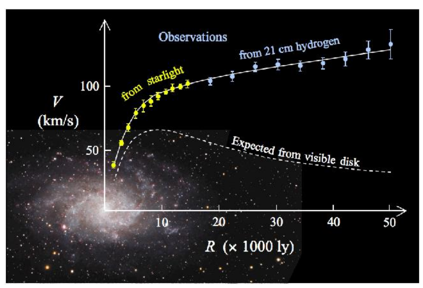
where:

m_1 is the mass of the galaxy at radius d_2;
F_g is the force of gravity;
g is the gravitational constant.

Rotation curve of stars in galaxy

One of the occasions when NL appears to break down is when the velocities of stars in a galaxy are measured. Figure 2 shows the actual and expected velocities for the Messier 33 galaxy. According to cosmologists, the difference between the expected and observed velocities can be explained by the existence of a hypothetical substance called dark matter. However, cosmologists have not yet been able to find dark matter.

Figure 2: Messier 33 galaxy



Rotation curve of spiral galaxy Messier 33 (yellow and blue points with error bars), and a predicted one from distribution of the visible matter (dotted gray line).

The masses of the galaxies and stars are derived by applying NL. A change in the formula for the law of gravity could change the masses of the galaxies and stars. Tests of Eq. 2.11 may require stellar and galactic masses to be recalculated. If so, only when the masses are recalculated will it be possible to compare actual and estimated velocities for the stars using Eq. 2.11. However, the required modifications to most stellar masses may be relatively small. An indication of whether Eq. 2.11 is an appropriate modification to NL may be obtained by using existing estimates of the masses of stars and calculating new rotation curves using Eq. 2.11.

Predicting velocities of stars

Eq. 2.11 describes the force of gravity. Additional mathematical transformations are required to predict the velocities of stars. For a mass orbiting another mass, the gravitational force is known as centripetal acceleration. The relevant equation is:

$$\text{Centripetal acceleration (i.e. Force)} = \text{mass} * v^2 / \text{radius} \qquad (2.13)$$

where:

mass = mass of star
v = velocity of star;
radius = the radius of a star orbiting the centre of a galaxy.

On rearranging terms: $v^2 = \text{Force} * \text{radius} / \text{mass}$ (2.14)

From Eq. 2.14, it can be seen that the velocity of a star is proportional to the gravitational force. This means it should be possible to analyse what Eq. 2.11 could predict about the shape of the rotation curve of a galaxy without knowing the value of the gravitational constant. The following calculations assume that the radius in Eq. 2.14 is d_2 and not a combination of the ages of the masses, d_1 and d_2.

Table 1 presents a spreadsheet simulation showing the difference between the shape of the rotation curve predicted by Eq. 2.11 and the shape predicted by NL for stars at various distances from the centre of the galaxy. This spreadsheet uses simplifying assumptions and does not reflect the actual distribution of stars in any galaxy. Each line in Table 1 represents a different star. The purpose of the spreadsheet is to give an idea how Eq. 2.11 might describe the rotation curve for a galaxy. The simulation does not include stars closer than 5 light units to the centre of the galaxy. The assumptions used in the calculations are:

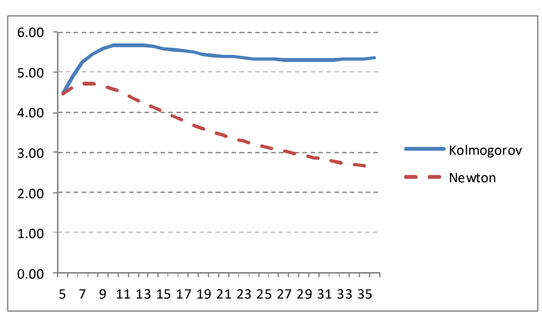
1. **Column m_1** is the mass of the galaxy for various radii (r). The first row is for a radius of 5 light units. Each row represents one light unit increase in the radius. Galaxy mass increases by $\{1 + [0.6 * (0.7)^{(r-4)}]\}$ for each increase in r above 5.
2. **Column A_1** is the current age of the galaxy (light years).
3. **Column A_2** shows the current age of a star in light years.
4. **Column d_2** is the current distance of a star from the centre of the galaxy in light units.
5. **Column d_1** indicates where the star was formed in light units.
6. Temperatures of stars do not change and they are less than the temperature of the galaxy.

The columns headed Kolmogorov and Newton show index values for the velocity rotation curves at different distances from the centre of the galaxy. All values for the Kolmogorov equation have been divided by √2 so that the Kolmogorov and Newton curves have the same index value for the first row.

The results in Table 1 and Figure 3 show that the rotation curve could be relatively flat when the outer rings of a galaxy are places where stars are formed. Not all stars in the outer rings, however, need to be newly formed as stars are assumed to move away from the centre of the galaxy. Furthermore, when a star cools, an increase in the force of gravity would allow a star's velocity to be greater than that predicted by NL without causing it to leave the galaxy. If Eq. 2.11 is shown to be a significantly better predictor than NL, the observed galaxy rotation curve might be explained without the need for dark matter.

Table 1: Hypothetical rotation curve for stars in galaxy using Eq. 2.11 and NL; and Figure 3: Comparison of Kolmogorov and Newton velocity rotation curves

m_1	A_1	A_2	A_1/A_2	d_2	d_1	Kolmogorov	Newton	Ratio
100	10	5.00	2.00	5	5.0	4.47	4.47	1.00
129	10	4.80	2.08	6	5.5	4.92	4.64	1.06
156	10	4.61	2.17	7	6.0	5.24	4.72	1.11
179	10	4.42	2.26	8	6.5	5.46	4.72	1.16
197	10	4.25	2.35	9	7.0	5.59	4.67	1.20
210	10	4.08	2.45	10	7.5	5.66	4.59	1.23
221	10	3.91	2.56	11	8.0	5.69	4.48	1.27
228	10	3.76	2.66	12	8.5	5.68	4.36	1.30
234	10	3.61	2.77	13	9.0	5.66	4.24	1.34
238	10	3.46	2.89	14	9.5	5.63	4.12	1.37
241	10	3.32	3.01	15	10.0	5.60	4.01	1.40
243	10	3.19	3.13	16	10.5	5.56	3.89	1.43
244	10	3.06	3.26	17	11.0	5.53	3.79	1.46
245	10	2.94	3.40	18	11.5	5.49	3.69	1.49
246	10	2.82	3.54	19	12.0	5.46	3.60	1.52
246	10	2.71	3.69	20	12.5	5.43	3.51	1.55
247	10	2.60	3.84	21	13.0	5.40	3.43	1.58
247	10	2.50	4.00	22	13.5	5.38	3.35	1.61
247	10	2.40	4.17	23	14.0	5.36	3.28	1.64
247	10	2.30	4.34	24	14.5	5.35	3.21	1.67
247	10	2.21	4.52	25	15.0	5.33	3.15	1.70
247	10	2.12	4.71	26	15.5	5.32	3.08	1.73
247	10	2.04	4.91	27	16.0	5.32	3.03	1.76
247	10	1.96	5.11	28	16.5	5.31	2.97	1.79
247	10	1.88	5.33	29	17.0	5.31	2.92	1.82
247	10	1.80	5.55	30	17.5	5.31	2.87	1.85
247	10	1.73	5.78	31	18.0	5.31	2.83	1.88
247	10	1.66	6.02	32	18.5	5.32	2.78	1.91
247	10	1.59	6.27	33	19.0	5.33	2.74	1.94
247	10	1.53	6.53	34	19.5	5.33	2.70	1.98
247	10	1.47	6.81	35	20.0	5.35	2.66	2.01
247	10	1.41	7.09	36	20.5	5.36	2.62	2.04



Empirical validation of Eq. 2.11 could be difficult for a number of reasons:

1. The distance between a star and the centre of its galaxy may not vary linearly over time.
2. The equation assumes the temperature of a galaxy is greater than that of a star. But such an assumption may be invalid when gases inside a galaxy are included in the temperature of a galaxy.
3. Determining a star's age, temperature and location when it was formed.
4. Are current estimates of the masses, velocities, ages and distances of stars and galaxies valid for use in Eq. 2.11? E.g. do galactic masses estimated from gravitational lensing methodologies need to be revised?

Estimating the new equation

Two steps will be involved in testing Eq. 2.11. First, the constants in Eq. 2.11 need to be estimated. One method could be to convert Eq. 2.11 into an equation that predicts the velocity of stars. Actual data for a selection of stars could then be used in a regression equation to estimate the size of the constants.

The second step involves using different data sets (of stars and galaxies) to that used in step one. Predictions for the velocities of these data sets are made using the gravitational constant estimated in step one. These predictions can then be compared to similar predictions using NL without including dark matter.

Conclusion

Eq. 2.11 which was derived on the basis of a theory is an approximation to a more complex equation. As such, the ideas set out in the previous section may not be conclusive in terms of which equation is the better predictor of the velocities of stars. Nevertheless, the principles from which Eq. 2.11 was derived also provide an explanation for the acceleration in the rate of growth of the universe. This discovery alone justifies further investigation of the ideas in this essay.

The primary objective of this essay is to encourage physicists to look at gravity in different ways. In particular, these ideas may lead to physicists developing a theoretical justification for NL that does not require hypotheses about dark matter in order to predict the velocities of stars.

To fund the research that is needed to test the performance of Eq. 2.11, it is proposed to set up a crowd-funded project. For more details, visit the website www.glaid.com.

References

Arkani-Hamed, Nima and Trnka, Jaroslav; The Amplituhedron, 2013, https://arxiv.org/pdf/1312.2007.pdf

Brown, Adam and Susskind, Leonard. The Second Law of Quantum Complexity, 2018, https://arxiv.org/pdf/1810.11563.pdf

Dalton, Michael; Gravity's New Clothes: The origin of gravity, 2020, available from www.amazon.com

Lloyd, Seth; Programming the universe, Vintage Books, London, 2007

Rovelli, Carlo; Reality is not what it seems, Penguin Random House, 2016

Susskind, Leonard; Entanglement is not Enough, 2014, https://arxiv.org/pdf/1411.0690.pdf

Tarski, Alfred and Givant, Steven; Tarski's System of Geometry, Bulletin of Symbolic Logic, Volume 5, Number 2, June 1999, https://www.cambridge.org/core/journals/bulletin-of-symbolic-logic/article/tarskis-system-of-geometry/C09B82FD277EB5D05BF303C43DD11156

Source of Figure 2:
https://commons.wikimedia.org/wiki/File:Rotation_curve_of_spiral_galaxy_Messier_33_(Triangulum).png