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*Commentary*

# Institute of Space Sciences and Astronomy - Modified Gravity Research

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## 1 The Gravity Research Group

Gravity forms an integral part of our everyday lives, but we rarely reflect on its inner workings. Its attractive pull is an essential part of understanding how many of the phenomena around us take place. Isaac Newton was the first physicist to put together a global approach to understanding the effects of gravity. However, it wasn't until Einstein that we got a holistic snapshot of how gravity works on larger scales.

In his model of gravity, Einstein gives us a picture of gravitational fields shaping the intrinsic structure of spacetime, such that particles no longer move in straight lines, but along the so-called "straightest possible line". This is the source of John Archibald's famous quote "Spacetime grips mass, telling it how to move... Mass grips spacetime, telling it how to curve" (Wheeler, 1999). This reshaping mechanism revolutionized the foundations of gravitational physics. The model passed all solar-system scale tests and reduced numerically to Newtonian Physics for weaker fields, such as in galaxy systems and clusters thereof. It wasn't long until problems started to arise. Firstly, galactic dynamics suffered from large deficiencies in that not enough gravitational pull was being produced to create the observed star dynamics. Moreover, going to the cosmological scale, that is, the observable universe as a whole, a repulsive effect was measured. While gravity appears to only attract for us, the cosmos appears to be expanding and at an accelerating rate. To account for this, two new concepts were put together, one being dark matter, which would account for the galactic dynamics. In proportion of about one (observed matter) is to six (dark matter), this would account for the stronger gravitational field effects.

On the cosmological setting, so-called dark energy would express a negative pressure on the universe, forcing it to expand. This would not translate to much for local phenomena, but on the cosmological scale it would force space itself to expand. In this way, observations would show stars and celestial objects to be moving apart.

Dark matter and dark energy may exist, however it may also be the case that gravity needs some tweaking in its description. This is where modified and alternative theories of gravity come in. The idea here is to take Einstein's working model of gravity and to extend it, either by adding parts that take hold at different scales (such as the galactic and cosmological scales or the quantum scale), or by completely reformulating the approach with the aim of recovering the Einstein model in the solar system.

Our approach is the latter of the last two, we work on teleparallel gravity. In this model gravity is equivalently reformulated as being expressed through torsion rather than curvature. The advantage in this case is that the resultant theory has a straightforward generalization, in the sense that its governing equations remain tractable. Moreover, the model incorporates an important idea in gravitational physics, called the equivalence principle. The equivalence principle concept is associated with how local dynamics are shielded from gravitational effects. In particular, an experiment being conducted in a laboratory will not be effected by the global gravitational field in the sense that the same outcome out be observed in a rocket being accelerated at the same rate.

Teleparallel gravity is built on elementary fields that relate these local systems with global coordinate systems. In this way, the model takes on an organic relation to how gravity works. Our group is working on studying the cosmological history of the universe within this model. We also work on studying how star and galaxy dynamics are effects by this change in model.

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## 2 Cosmology and Gravity: The dark side of the universe

Einstein's theory of General Relativity (GR) has been very successful in predicting various phenomena, most recently that of gravitational waves (Abbott, 2016). The gravitational field, described as a curvature of space-time, has been used to try to explain how the universe came to be. From the earliest of time till now, the universe has been expanding, something which was observed by various astronomers in the 20$^{\text{th}}$ century. However, an important independent discovery by the Supernova Cosmology Project and the High-Z Supernova Search Team in 1988 found that the universe was not only expanding, but expanding an accelerating rate (Riess, 1998).

This discovery led to various questions about the current best known theory of gravitation, since all observational components of the universe could not explain such acceleration. A possible alternative was proposed, a fluid with the property of exhibiting negative pressure, strong enough to counteract the force of gravity and force the universe to expand at an accelerating rate. This fluid, called dark energy, was and still is hypothetical leaving the theory of gravitation in a questionable state. If such a fluid did not exist, this leaves us with no possible explanation of this phenomenon. However, GR does not have to be a perfect theory, but rather a step forward closer to reality. This is the reason why alternative and modified theories of gravity exist, as an another and possibly a better way to describe the force of gravity.

Recently, the theory of teleparallelism and torsion has been revived, a concept which was originally proposed by Moller and later by Einstein in the 1920s, but left to wither as Einstein failed to unify electromagnetism to gravitation. Work in the 1960s and 1970s by various researchers (Cho, Pellegrini and Plebaski to name a few) revived this theory and showed that there was a link between describing torsion and gravitation. In fact, it was possible to equally describe gravitation as a manifestation of curvature in GR, through torsion in what was originally called New Gravity (now known as Teleparallel gravity) (De Andrade, Guillen & Pereira, 2000; Cai, Capozziello, De Laurentis & Saridakis, 2016).

Although being equivalent, the foundations are different, allowing links between local and global systems (those which are or are not affected by gravitation) and describing gravity back as a force. However, equivalence between the theories implied the same problems. Hence, some modifications to the theory were considered.

Teleparallel gravity describes gravitation through a Lagrangian, composed of a quantity which quantifies by how much the space-time has been twisted due to gravity called the torsion scalar, $T$. However, it might be the case that gravity does not simply function under this single scalar. Instead, this might be a part of a series of terms which fully describe its function. Therefore, one possible modification is by allowing some general function of the torsion scalar to take place in the Lagrangian, leading to what is called $f(T)$ gravity.

This modification results in changing the description of how the force of gravity works. Changing the Lagrangian results in a change in the equations of motion of the system. By doing so allows us to consider alternative ways to explain the aspect of dark energy without dark energy, completely through a manifestation of torsion of space-time and hence as a by-product of how gravity works.

Various models on this theory of gravity have been proposed (and are still being studied) as means to explain the expansion history of the universe; some of the most prominent candidates include power-law $f(T) = \alpha T^n$ by Bengochea and Ferraro (2009), exponential $f(T) = \alpha T_0 \left[1 - \exp\left(-p\sqrt{\frac{T}{T_0}}\right)\right]$ by Linder (2010) and logarithmic $f(T) = \alpha T_0 \sqrt{\frac{T}{qT_0}}\, \ln\left(\frac{qT_0}{T}\right)$ by Bamba, Geng, Lee and Luo (2011) (other competing models can be found in Nesseris, Basilakos, Saridakis & Perivolaropoulos, 2013), where $\alpha$, $p$ and $q$ are model parameters, whilst $T_0$ is the torsion scalar evaluated at current times.

Although such models do prove to be successful in describing an expanding dark energy filled universe, this does not imply that everything is solved. Some models are good in describing specific phenomena, whilst others are good in describing others. A good model is one that is able to describe the various phenomena, whilst retaining the same Lagrangian. Therefore, it must be able to describe the various other problems found in the universe.

One such problem lies in the earliest stages of the universe, the Cosmic Microwave Background (CMB) radiation, discovered by Penzias and Wilson (1965). This radiation originates from the earliest moments of the universe's lifetime, where the universe was still extremely hot with photons colliding into each other continuously. As the universe expanded, it cooled down, leading to the formation of heavier elements. This resulted in a decrease in the number of collisions, allowing some photons to freely roam the space. This moment, called photon decoupling, leaves us an image of how the universe looked like when it was only 380,000 years old. It is this process that resulted in the CMB imprint today.

The first images of the CMB temperature distribution seemed to indicate that it was homogeneous and isotropic in every direction. However, advancements in technology allowed us to study temperature variations in the scale of µK. Thanks to WMAP, and more recently Planck, the temperature distribution was in fact found to be anisotropic. Furthermore, it was found that the suggested expansion history of the universe did not agree with the size of the CMB spectrum, as the size of the universe at the CMB imprint suggests it is much larger.

How is this possible? Is there another unexplained mechanism causing this discrepancy? Various theories were proposed, however the most accepted one so far is that the universe undergoes an inflationary period, a stage where the size of the universe expanded $e^{60}$ orders of magnitude. The true source which caused inflation is unknown (theory suggests a scalar field known as the inflaton field with an associated particle called the inflaton), however it is not attributed to standard matter and radiation, and is one which exhibits negative pressure in the same way as dark energy (Baaquie & Willeboordse, 2015; Dodelson, 2003). Whether a such field and particle truly exist is still unknown, the other possibility is that it can simply be a manifestation of gravity at such an early stages, which has not been explained so far. Therefore, the role of teleparallel gravity can be important as a possible alternative to explain this epoch.

*Gabriel Farrugia*

## 3 Galactic Rotation Dynamics in Modified Gravity

In the last hundred years, general relativity has proven to be an invaluable theory for explaining many properties of the universe. That being said, just as Newton's theory of gravity has its limits, so does general relativity. There are some areas where general relativity alone does not agree with observational data. Such an area is that of galactic rotation curves. Some of the most abundant formations in the observable universe are galaxies. Galaxies are accumulations of billions of stars, gasses and dust held together by gravity. When directly observing the multitude of galaxies surrounding our own, we notice that for general relativity to explain their behaviour, these galaxies would need far more mass then what can currently be observed.

Masses tend to orbit the center of their galaxy. Both theory and observation confirm that the orbital velocities of these masses tends to increase with radial distance from the galaxy's center until some point along the line a maximum orbital velocity is reached. It is here that a problem crops up. General relativity predicts that after this maximum velocity, these orbital velocities should start to diminish in magnitude until eventually going to zero. This dissipation of velocities is in conflict with what we actually observe when examining the behaviour of galaxies. According to our observational data (Chemin, Renaud & Soubiran, 2015), on various galaxies the orbital velocity of masses generally tends to plateau soon after reaching this maximum orbital velocity.

This phenomenon can be explained in General relativity by the introduction of non-luminous matter, dark matter. In order for dark matter to produce the required effect, it has to vastly outweigh the contribution of the luminous matter in a galaxy by a factor of roughly six. Although the addition of such a field is very successful in producing the correct rotation curves, dark matter itself has never been successfully directly observed. This discrepancy between theory and observation could also be an expression of the failure of general relativity to correctly describe the dynamics of the system in question. If this is so, our standard picture of gravity must change, thus making it necessary to construct alternative theories of gravity in the hopes of accounting for such a discrepancy (Mannheim & O'Brien, 2013).

One such alternative theory is that of torsional gravity. Apart from not treating gravity as a force, gravity in general relativity is curvature dominated. In torsional gravity, we treat gravity as a force manifesting from the torsion of the spacetime fabric. Since torsional gravity on its own reproduces the results of general relativity exactly, modifications of the theory are considered. Such theories are called $f(T)$ gravity theories. Here $f(T)$ represents functions dependant on $T$ which is called the torsion scalar. Since galaxies consist of different parts with different geometric profiles, multiple expressions for the velocity profiles must be formulated in order to cater for these profiles. Various possible $f(T)$ functions will finally be tested in order to determine which can be solved and which are good candidates for further study.

The models constructed will be developed with the intention that they incorporate the observed velocity profiles of galactic rotation curves while still agreeing with other observational data with which general relativity is in agreement. It is only in the galactic regime where enough data exists to vigorously test these hypotheses, as well as have a strong enough field to allow for the appearance of deviations from the standard theory. It is for this reason that torsional gravity is being tested in this area. The work is being conducted in the hope of developing an $f(T)$ gravity theory to such a point that it can be employed in constraining its parameter set through observational data that is available freely.

*Andrew Finch*

## 4 Exotic Stars

Looking up at the night sky, you can't help but wonder at the vastness and endlessness of space. Countless stars dust the night sky in a symphony of light and spectacle. That is the romantic side to astrophysics. The amazing thing is that we have barely begun to scratch the surface on understanding what is really out there. Everyday new stars are being discovered. What we mostly work on are exotic types of stars. These are stars which were first theorized and later observed through sophisticated techniques.

Neutron stars are one of the most extreme objects in the Universe. They provide some of the best bases upon which we may test theories of gravity. They are like giant atom cores, kilometres in diameter, very dense, and violent. But how can something like this even exist? First, we shall take a look at the life of a star and how a neutron star is born.

The life of a star is a constant battle to keep two forces in balance - its own gravity and the radiation pressure propagated by its fusion reaction. In the core of a star, hydrogen atoms fuse together to form heavier elements. Heavier and heavier atomic nuclei fall and build up in the centre of the star. When the fusion reaction stops, the radiation pressure drops rapidly and the star would no longer be in balance. The outer layers of the star would be catapulted into space, in a violent explosion called *supernova*. The remnants of this explosion may form a neutron star depending on the residual core mass.

A neutron star's mass is nominally between $1\,M_\odot$–$3\,M_\odot$, but compressed to a celestial object about 25 km in diameter. A neutron star is very dense, so much so that one cubic centimetre of a neutron star contains the same mass as an iron cube 700 m, across roughly $10^9$ tonnes. That is the same as having the mass of Mount Everest in the size of a sugar cube.

Since the density is so large, the gravity is bound to be very impressive, if one were to drop an object 1 m over the surface, it would hit the star in 1 µs and the object would reach a velocity of up to $2 \times 10^6\,\mathrm{m\,s^{-1}}$. The surface is very close to being perfectly flat, with irregularities of $\pm 5$ mm maximum. The surface temperature of a neutron star is about $10^6$ K, as compared to 5800 K for our Sun.

The closer we get to the core, the more neutrons and fewer protons we see, until there's just an incredibly dense soup of indistinguishable neutrons. The cores of neutron stars are very unusual. We are still not sure what their properties are, but our closest guess is a *super-fluid neutron degenerate matter* or some kind of *ultra-dense quark matter, called quark-gluon-plasma.* This may only exist in such an ultra-extreme environment. In many ways, a neutron star is similar to a giant atom core. The difference is that while atom cores are held together by strong interactions, neutron stars are held together by gravity.

A few other extreme properties include the fact that neutron stars spin very fast. A younger neutron star would spin faster, and if there is a regular star nearby to feed it, it can rotate the neutron star up to several hundreds times per second.

An example is the neutron star PSR J1748-2246ad spins at approximately $252\,\mathrm{km\,h^{-1}}$ or 716 Hz. So fast that the star has a rather strange shape. We call these objects *pulsars* because they emit a strong radio signal. The magnetic field of a neutron star is roughly a trillion times stronger than the magnetic field of the Earth, so strong that atoms get bent when they enter its sphere of influence.

It is estimated that there are $10^8$ neutron stars within our galaxy alone. Thus far, we have only observed about 1000 of these neutron stars ever since their discovery in 1960s.

*Mark Pace*

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