GALAXY ROTATION PROBLEM: DARK MATTER, MODIFIED GRAVITY OR JUST BARYONS ?

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ABSTRACT

The deviation of a galaxy from exhibiting a Keplerian curve either indicates the presence of dark matter or the breakdown of Newtonian dynamics. Dark matter still remaining undetected raises a concern whether it exists or not and can the galaxy rotation problem be addressed by modifying the laws of gravity. However, considering the baryonic matter distribution to solve this discrepant behaviour would prove to be a turning point. In this paper I present the theoretical study regarding the kinematics and dynamics of spiral galaxies by considering the distribution of baryonic matter only. The study of Ultra Diffuse Galaxies (UDGs) and Low Surface Brightness (LSB) galaxies which are considered to be dominated by dark matter has also been taken into account. The distribution of baryonic matter throughout a galaxy and its role in influencing both; the nature of galaxy's rotation curve as well as the nature of variation of gravitational acceleration throughout a galaxy has been discussed. We will also compare a planetary system with a galaxy to find out why a planetary system exhibits a Keplerian curve whereas a galaxy deviates from it. The study provides explanation for a galaxy's non-declining rotation curve without considering the presence of dark matter and also without modifying the laws of gravity.

Key words: galaxies: kinematics and dynamics - gravitation - baryonic matter.

1 INTRODUCTION

The galaxy rotation problem is a perplexing mystery that cannot be explained without considering the presence of dark matter or by modifying the laws of gravity. The study of numerous galaxies has revealed a bewildering behaviour according to which the orbital velocities of galactic components do not decrease with increasing distance from the centre of the galaxy as shown by Babcock 1939; van de Hulst et al. 1957; Schmidt 1957; Volders 1959; Rubin & Ford 1970; Roberts & Whitehurst 1975; Rubin et al. 1985. Orbital velocities remain high instead of declining even beyond the visible limit of the galactic edge as revealed by radio telescopes by tracing the HI emission. It has always been observed that the orbital velocity of a galactic component situated far away from the galactic centre is as high as, or sometimes even higher than the orbital velocity of a galactic component situated closer to the galactic nucleus, this is completely contrary to Keplerian dynamics. Since most of the mass of a galaxy (based on observable luminosity) is concentrated at its centre in the form of galactic nucleus, therefore, orbital velocities should decline with increasing distance from the centre according to the Keplerian expectation as observed for a planetary system. Galaxies exhibit rotation curves that either remain flat or incline with increasing distance from the centre of the galaxy. Deviation of a galaxy from exhibiting a declining or a Keplerian curve leads to the galaxy rotation problem. The solution to this anomalous behaviour is to consider the presence of dark matter in the form of a spherical halo surrounding the galaxies or to modify the laws of gravity without involving the presence of additional matter in the form of dark matter.

The galaxy rotation problem turns out to be more serious in galaxies that exhibit very low luminosities; galaxies like Ultra Diffuse Galaxies (UDGs) and Low Surface Brightness (LSB) galaxies. These galaxies possess very few stars as compared to regular galaxies. Furthermore, these galaxies are also devoid of a centrally bright galactic nucleus. The mass-to-light ratio for such galaxies can therefore be very high indicating that these galaxies are dark matter dominated.

Till date, the only solution to galaxy rotation problem remains to consider the presence of dark matter or to modify the laws of gravity. However, I believe that addressing the problem within the framework of Newtonian dynamics by considering the baryonic matter distribution should also be given an equal opportunity.

2 KINEMATICS AND DYNAMICS OF A GALAXY

Figure 1. Spiral galaxy NGC 2841. A galaxy exhibits no empty-space on large-scale. Matter is spread thoroughly throughout the galaxy in the form of gas, dust and stars. The space between the spiral arms is not empty; it is occupied by neutral hydrogen. Neutral hydrogen is also present beyond the visible extent of the galactic edge. The orbital velocity of a galactic component situated along the galactic edge is with respect to the overall enclosed mass present before it right from the centre of the galaxy and not entirely with respect to the centre. Image Credits: Hubble Space Telescope and Subaru Telescope.

The study of a distant galaxy through a ground based optical telescope would reveal the galaxy to an observer in such a way that the massive luminous mass would appear to be concentrated at the centre and stars orbiting around it, this would be a scenario similar to a planetary system. Much of the non-luminous mass in the form of neutral hydrogen would remain optically invisible while still adding mass to a galaxy. High-resolution space-based optical telescopes have revolutionized astronomical techniques to such an extent that by just looking at Fig. 1 it becomes quite clear that luminous mass is indeed concentrated at the centre, however, it can also be seen that the actual or the overall mass of a galaxy is spread thoroughly throughout the galaxy mostly because of the gas. Therefore, a galaxy contains significant amount of baryonic matter in the form of gas, dust and stars distributed thoroughly throughout the galaxy from the nucleus onwards, such that a galaxy exhibits no empty-space (perfect void) on large-scale.

If we observe any spiral galaxy carefully, the spiral arms contain most of the stars and hence the gas is luminous along the spiral arms. The space between the spiral arms appears dark, this however does not imply that this space is empty; the space between the spiral arms contains neutral hydrogen. Furthermore, neutral hydrogen is also present beyond the visible boundary of the galactic edge as traced out by radio telescopes. Therefore, the galaxy rotation curve should remain flat, and indeed it does remain flat for this gaseous distribution present even beyond the galactic edge, because the overall enclosed mass keeps on increasing with increasing distance from the centre of the galaxy. Matter distributed radially throughout the galactic disc from the centre of the galaxy to any large distance beyond becomes part of the galaxy's enclosed mass. Gravity will act along this radial direction since maximum amount of matter is distributed along this radial direction.

Since the baryonic mass keeps adding to the previous mass with increasing distance from the centre of the galaxy, therefore, the gravitational acceleration decreases at a very gradual rate (insignificant rate) throughout the galaxy. This can be visualized by considering a galaxy as a disc having an initial diameter of 1 kpc. At this moment it would be correct to consider that the mass of this disc is the only enclosed mass. Now, the diameter of this disc keeps on increasing gradually from 1 kpc to 2 kpc before finally becoming 30 kpc. What would happen to the mass of the disc? Would the mass still remain concentrated as was before when the disc had an initial diameter of 1 kpc? Of course not, the mass will increase as well. This happens because the mass keeps adding to the previous mass with increasing diameter or the radius of the disc. This can further be understood by considering a planetary model for a galaxy. If the radius of a planet keeps on increasing, then its mass will also increase accordingly, gravitational acceleration will therefore decrease at a very gradual rate for such planet; this is how a galaxy behaves. A galaxy is therefore, just like a disc or a planet whose baryonic enclosed mass keeps on increasing with increasing distance from the centre. This is as simple as the galaxy growing bigger than before with increasing distance from the centre.

This further suggests that with increasing distance from the centre of the galaxy the massive centre gets extended along. The galactic nucleus is not the massive centre for all galactic components, that is, for a galactic component situated closer to the galactic nucleus, the galactic nucleus is the massive centre, and on the other hand, for a galactic component situated along the galactic edge, the entire galaxy is the massive centre. This implies that there will be more mass enclosed interior to the galactic edge as compared to the mass enclosed interior to the galactic nucleus. A galactic component therefore orbits with respect to the overall enclosed mass present before it and not entirely with respect to the central mass. Considering that orbital velocities of all galactic components are entirely with respect to the luminous galactic centre only seems to give rise to the galaxy rotation problem. If a galaxy was completely devoid of gas and dust then the orbital velocities of stars would have been with respect to the central mass, that is, the galactic nucleus, and the orbital velocities would have declined according to the Keplerian expectation as observed for a planetary system. Therefore, any galaxy exhibiting a flat, inclined or slightly declined rotation curve is perfectly the expected behaviour and does not seem to be a problem. A galactic component must orbit at suitable velocity in order to balance itself against the inward gravitational pull due to the mass enclosed by it.

Table 1. Orbital velocities remaining constant with increasing distance (Flat rotation curve)

Radius (kpc)	Orbital velocity (km s^{-1})	Baryonic enclosed mass (gas + dust + stars) ($M_\odot$)	Gravitational acceleration (m s^{-2})
5	220	5.5950×10^{10}	3.1370×10^{-10}
6	220	6.7140×10^{10}	2.6141×10^{-10}
7	220	7.8330×10^{10}	2.2406×10^{-10}
8	220	8.9520×10^{10}	1.9606×10^{-10}
9	220	1.0071×10^{11}	1.7427×10^{-10}
10	220	1.1190×10^{11}	1.5684×10^{-10}
11	220	1.2309×10^{11}	1.4259×10^{-10}
12	220	1.3428×10^{11}	1.3071×10^{-10}
13	220	1.4547×10^{11}	1.2065×10^{-10}
14	220	1.5666×10^{11}	1.1203×10^{-10}
15	220	1.6785×10^{11}	1.0456×10^{-10}
16	220	1.7904×10^{11}	9.8032×10^{-11}

Table 2. Orbital velocities increasing with increasing distance (Inclined rotation curve)

Radius (kpc)	Orbital velocity (km s^{-1})	Baryonic enclosed mass (gas + dust + stars) ($M_\odot$)	Gravitational acceleration (m s^{-2})
5	220	5.5950×10^{10}	3.1370×10^{-10}
6	230	7.3385×10^{10}	2.8572×10^{-10}
7	240	9.3220×10^{10}	2.6666×10^{-10}
8	250	1.1560×10^{11}	2.5317×10^{-10}
9	260	1.4066×10^{11}	2.4341×10^{-10}
10	270	1.6855×10^{11}	2.3625×10^{-10}
11	280	1.9939×10^{11}	2.3097×10^{-10}
12	290	2.3333×10^{11}	2.2711×10^{-10}
13	300	2.7051×10^{11}	2.2436×10^{-10}
14	310	3.1106×10^{11}	2.2245×10^{-10}
15	320	3.5513×10^{11}	2.2124×10^{-10}
16	330	4.0285×10^{11}	2.2057×10^{-10}

Baryonic enclosed mass increasing with distance causes the gravitational acceleration to decrease at a very gradual rate (insignificant rate) throughout a galaxy. As compared to Table 1, the rate at which the baryonic enclosed mass is increasing with distance (per kpc) is greater in Table 2, and as a result the gravitational acceleration decreases at more gradual rate. Therefore, the nature of galaxy's rotation curve as well as the nature of variation of gravitational acceleration throughout a galaxy depends upon the rate at which the baryonic enclosed mass is increasing with distance.

2.1 Influence of baryonic matter on the nature of rotation curve and gravitational acceleration variation throughout a galaxy

As already discussed that the baryonic enclosed mass keeps on increasing with distance from the centre of the galaxy, the nature of galaxy's rotation curve therefore depends upon the rate at which this enclosed mass is increasing with distance. If the enclosed mass is increasing at a faster rate throughout the galaxy then the rotation curve will incline, gravitational acceleration decreases at very gradual rate (insignificant rate) in this case. Increase of enclosed mass at moderate rate will keep the rotation curve flat and gravitational acceleration will decrease at a moderate rate, whereas, if the enclosed mass increases at slower rate, the rotation curve will be slightly declined and gravitational acceleration in this case will decrease at comparatively faster rate.

It is believed that low magnitude of gravitational acceleration encountered at galactic scale renders Newtonian dynamics inapplicable, however, it must be noted that the mass present along the perimeter of the enclosed mass is not minuscule, the product of gravitational acceleration due to the enclosed mass and the mass of a galactic component situated along the perimeter of this enclosed mass yields a value of gravitational force whose magnitude should bring the galaxy back to the regime of Newtonian dynamics, because the magnitude of force involved is equal to the magnitude of force between the planets and the central star in planetary systems.

This further suggests the importance of gravitational acceleration and mass, that is, for planets the gravity of the nearby star is significant as planets are not extremely massive to be influenced by the feeble gravitational acceleration of a galaxy, whereas for stars and gas clouds which are extremely massive, even the feeble gravitational acceleration of galaxy becomes significant.

Now, the gravitational force acting upon a galactic component due to the mass enclosed by it can vary randomly throughout a galaxy, it is not necessary that the gravitational force acting upon a galactic component situated along the galactic edge will be less than the gravitational force acting upon a galactic component situated somewhere in the middle of the galactic disc or may be somewhere closer to the galactic centre. As discussed before that the gravitational acceleration decreases at a very gradual rate throughout a galaxy, therefore, it is quite obvious that gravitational acceleration along the galactic edge will be comparatively less than the gravitational acceleration near the galactic centre. However, if the mass of a galactic component situated along the galactic edge is more than the mass of a galactic component situated closer to the galactic centre, then the magnitude of gravitational force acting upon the galactic component situated along the galactic edge will be more comparatively. Since, stars and gas clouds are distributed randomly irrespective of their own mass throughout a galaxy's gradually decreasing gravitational acceleration gradient, therefore, the magnitude of gravitational force acting upon a galactic component depends much upon the mass of the galactic component itself.

2.2 Galaxy rotation curve vs. planetary or Keplerian curve: the reason for the difference

When we compare a planetary system and a galaxy, some of the obvious questions that arise are, why do orbital velocities of planets decline with increasing distance from the centre? Why does a planetary system exhibit Keplerian curve whereas a galaxy does not? Even though a planetary system is present within a galaxy, they still do not exhibit similar characteristics. One of them obeys Keplerian dynamics while the other deviates from it.

It must be noted that the area occupied by any planetary system is extremely small as compared to the gigantic area occupied by a galaxy, therefore, the amount of matter present in the form of gas within the small area of the planetary system is highly insignificant to form an efficient enclosed mass so that the orbital velocities of its planets may be enhanced, the orbital velocities therefore decline. In case of the solar system the Sun is the only enclosed mass since the mass of galactic gas present within the small area occupied by the solar system is negligible. Therefore, the gravitational acceleration due to the Sun decreases very rapidly throughout the solar system. For a planetary system to exhibit similar flat rotation curves, either the density of gas within the small area of the planetary system must be many times greater than the actual gas density, or a planetary system needs to occupy an area as big as a galaxy so that even a low density gas distributed across a large distance is able to form an effectively massive and hence an efficient enclosed mass.

2.3 Do Ultra Diffuse Galaxies (UDGs) and Low Surface Brightness (LSB) galaxies indicate the presence of dark matter?

It is believed that Ultra Diffuse Galaxies and Low Surface Brightness galaxies are dark matter dominated. Luminosity exhibited by such galaxies is extremely low as they contain few stars and do not show the presence of a bright galactic nucleus, conditions like these are unable to illuminate or ionize the gaseous distribution present within such galaxies; hydrogen remains in the neutral state. An Ultra Diffuse Galaxy (the very well-known Dragonfly 44) or a Low Surface Brightness galaxy as big as the Milky Way but still unable to exhibit orbital velocities of its galactic components in excess of 100 km s^{-1} suggests that the gaseous or the overall baryonic enclosure in such galaxies is not that massive as compared to the gaseous or the overall baryonic enclosure found in regular spiral galaxies. The enclosed mass due to the baryonic matter distribution is not sufficient to enhance the orbital velocities of the galactic components present within such galaxies; velocities hardly reach 100 km s^{-1}. For comparison, the orbital velocity of Sun situated at a distance of 8 kpc from the centre of the Milky Way Galaxy is 220 km s^{-1}; this gives us an enclosed mass of 8.952×10^{10} $M_\odot$ (1.7904×10^{41} kg). The presence of dark matter in such discussed dark matter dominated galaxies should have enhanced the orbital velocity of the galactic components. Low orbital velocities of galactic components do not seem to indicate the presence of dark matter in these galaxies. Considering the presence of a dark matter halo around such galaxies just enhances the dark matter mass many times over the actual baryonic mass, whereas, the actual mass or the baryonic mass of such galaxies can be obtained from the orbital velocities of the galactic components with respect to their distance from the centre; after all, the orbital velocities of galactic components will always be with respect to the overall baryonic enclosed mass present before them right from the centre.

CONCLUSIONS

In this paper we have addressed the galaxy rotation problem by considering the baryonic matter which is thoroughly spread throughout the galaxy. The galaxy rotation problem does not seem to be a problem; it is the expected behaviour. The role of baryonic matter in influencing the nature of galaxy's rotation curve and the nature of variation of gravitational acceleration throughout the galaxy with increasing distance from the centre has been discussed.

The high mass-to-light ratio exhibited by Ultra Diffuse Galaxies and Low Surface Brightness galaxies does indicate the presence of dark matter, however, the low velocity dispersion of galactic components in these galaxies do not seem to indicate its presence. A massive dark matter halo surrounding a galaxy just enhances the dark matter mass many times over the actual baryonic mass.

Dark matter still remaining undetected raises a concern regarding its existence. On the other hand modifying gravity does not seem to be a credible solution since the magnitude of gravitational force between the enclosed mass and the galactic component should make the system obey Newtonian dynamics. The presence of baryonic matter has therefore been considered for the observed non-declining galaxy rotation curves.

It seems that the galaxy rotation problem and hence the need for dark matter and modified gravity arise due to the reason that the orbital velocities of galactic components are considered to be entirely with respect to the luminous galactic centre.

The paper has been summarized with the following conclusions.

(1) Baryonic matter present throughout a galaxy from the nucleus onwards in the form of gas, dust and stars accounts for the observed non-declining galaxy rotation curves; the contribution is mostly because of gas.

(2) With increasing distance from the centre of the galaxy the baryonic mass keeps adding to the previous mass, the baryonic enclosed mass therefore keeps on increasing with increasing distance from the centre of the galaxy and for this reason the orbital velocities of galactic components do not decline according to the Keplerian expectation.

(3) The orbital velocities of galactic components are not entirely with respect to the luminous centre, but with respect to the overall enclosed mass present before them right from the centre. If such high orbital velocities were entirely with respect to the galactic centre only, then the galactic components would have not remained gravitationally bound to the galaxy.

(4) The mass enclosed by a galactic component becomes the massive centre for that galactic component. Therefore, with increasing distance from the centre of the galaxy the massive centre gets extended along.

(5) Since the baryonic enclosed mass keeps on increasing with distance from the centre of the galaxy, the gravitational acceleration therefore decreases very gradually (insignificantly) throughout the galaxy.

(6) The nature of galaxy's rotation curve (whether flat, inclined or slightly declined) depends upon the rate at which the baryonic enclosed mass is increasing with distance. A faster rate will cause the galaxy rotation curve to incline, a moderate rate will keep the rotation curve flat, and a slower rate will make the curve slightly declined.

(7) The rate at which the baryonic enclosed mass increases with distance further governs the rate at which the gravitational acceleration varies with distance throughout the galaxy. A faster rate will make the gravitational acceleration to decrease very slowly (inclined rotation curve), a moderate rate moderately (flat rotation curve), whereas a slower rate will make the gravitational acceleration to decrease comparatively faster (slightly declined rotation curve).

(8) Since galactic components (stars and gas clouds) are distributed randomly irrespective of their own mass throughout a galaxy's gradually decreasing gravitational acceleration gradient, therefore, the gravitational force acting upon a galactic component can vary randomly throughout a galaxy.

(9) The orbital velocity of a galactic component yields a value of enclosed mass for which the value of escape velocity is greater than the orbital velocity, therefore, the galactic components should not escape the system.

(10) Since the distance between galactic components within galaxies is quite large, therefore, even a low density gas distributed across such large distance should form an effectively massive and hence an efficient enclosed mass.

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