SOLVING THE DARK MATTER RIDDLE

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ABSTRACT

Dark matter is considered to be responsible for the unexpectedly high velocities exhibited by the galactic components within the galactic disc and by the galaxies situated within rich galaxy clusters. The velocities are high and the total light output due to visible matter alone cannot account for all the mass and gravity for the overall observed stability. The presence of additional matter in the form of dark matter is required to explain the gravitational stability at such high velocities. I present a theory based on the study of certain characteristics responsible for causing the galaxy rotation problem. Solution to the mentioned problem has been discussed by considering the baryonic matter distribution only. The orbital stability of galaxies at high velocities within rich galaxy clusters has also been taken into account. The theory provides a credible solution without considering dark matter and also without modifying the laws of gravity.

Key words: galaxies: kinematics and dynamics - galaxies: clusters: intracluster medium - gravitational lensing - velocity dispersion - intracluster medium limb darkening - baryonic matter.

1 INTRODUCTION

The search for the mysterious dark matter began almost 84 years ago. In 1933, Swiss astrophysicist Fritz Zwicky while studying the Coma Cluster pointed towards the mass discrepancy after observing that the galaxies within the cluster were moving much faster than their escape velocities calculated with respect to the mass due to the luminous matter that the galaxies contained. The study of the Virgo Cluster (Smith 1936) yielded a similar result of mass discrepancy. Similarly, it was found after the study of numerous galaxies that the rotational or the orbital velocity of the galactic components does not decrease with increasing distance from the centre of the galaxy as shown by Babcock 1939; Rubin & Ford 1970; Roberts & Whitehurst 1975; Rubin et al. 1985. It was observed that instead of exhibiting a declining rotation curve or a Keplerian curve, galaxies exhibited rotation curves that either remained flat or inclined with increasing distance from the centre of the galaxy, this unusual behaviour led to the galaxy rotation problem.

To begin with, we will first consider a large-scale structure such as a galaxy, before moving further to an even more large-scale structure, the galaxy cluster. The galaxy rotation problem arises, especially in the spiral galaxies, where the rotational or the orbital velocity of the galactic components does not decrease with increasing distance from the centre of the galaxy. This indicates that mass of the galaxy is increasing as we move from its centre to the edge. However, since most of the mass of the galaxy is concentrated at its centre as the galactic nucleus and there is no visible matter to account for this anomalous provision of additional mass to the galactic components within the galactic disc and beyond, it gets termed as missing mass in the form of dark matter. We take into consideration only the mass due to the visible matter and the remaining invisible and undetectable matter responsible for providing this additional mass gets termed as dark matter as we cannot detect it. In other words, it is the presence of more mass than the observed luminosity, that is, the mass-to-light ratio is high.

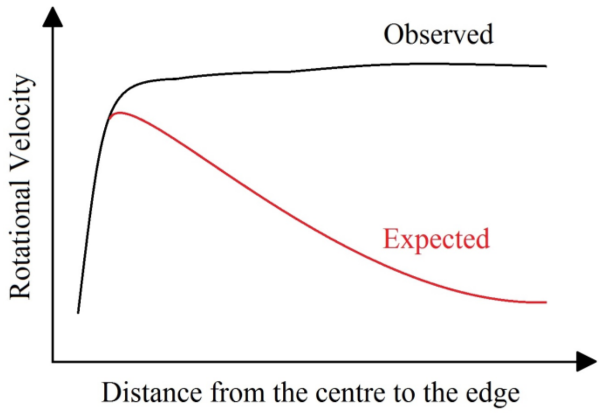

Figure 1. The rotation curve of a galaxy

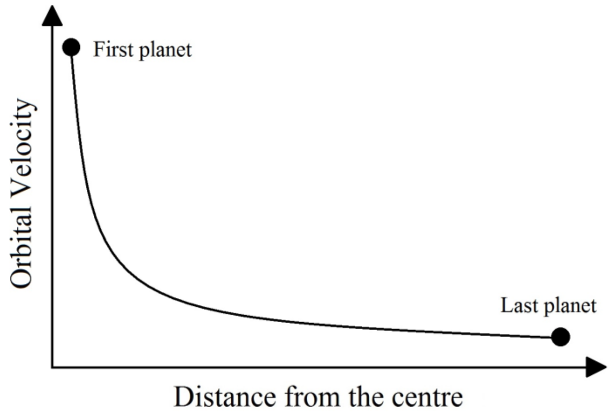

Figure 2. Orbital velocity of planets with distance

In case of the solar system or any other planetary system, the orbital velocity of planets keeps on decreasing with increasing distance from the centre, therefore, the planets exhibit Keplerian motion. However, in case of galaxies, such orbital velocity reduction is not observed even when the distance from the galactic nucleus keeps on increasing towards the edge of the galaxy, as indicated in Fig. 1. The orbital velocity of a star situated along the galactic edge is more than expected which is contrary to Keplerian motion. This unexpected and anomalous behaviour suggests that the mass is increasing with distance beyond the galactic nucleus. Since amount of visible matter decreases with distance from the centre of the galaxy and much of the mass is concentrated within the galactic nucleus, an additional matter (dark matter) is held responsible for providing this additional mass to the galactic components, not only within the visible disc but also further beyond the visible disc. The problem with dark matter is, that it is invisible at all wavelengths and hence undetectable, it only interacts gravitationally, and for this reason it is termed as dark matter. When we consider a more large-scale structure such as a rich galaxy cluster, the effect of dark matter becomes even more prominent. Galaxies are found in clusters, a large cluster such as the Coma Cluster contains thousands of galaxies. The galaxies situated within the cluster exhibit velocities which are higher than expected and the amount of matter or the mass corresponding to visible luminosity is not enough to provide the gravitational stability at such high velocities, that is, at such velocities the galaxies should have flown away from the cluster, however, this does not happen and something provides additional mass and gravity because of which the stability is maintained. Therefore, majority amount of matter within galaxy clusters is considered to be in the form of dark matter. Since, dark matter does not interact with light, it does not emit nor absorb any electromagnetic radiation, therefore, it cannot be detected. The presence of dark matter can only be inferred by its gravitational effect on the galactic components within galaxies and on the overall galaxies present within rich galaxy clusters.

2 IN THE BEGINNING

Before the introduction of non-optical astronomy, the astronomers and astrophysicists relied mostly on the visible photons that made the optical techniques useful during those days, that is, prior to 1950s. Radio techniques became efficient by 1950s and X-ray techniques by 1970s. Observing a rich galaxy cluster optically, that is, in visible wavelength, would just reveal the optically visible features, such as the galaxies and the glowing halo around them. The baryonic intracluster medium (ICM) that shines brightly in X-rays would remain optically invisible, therefore, I believe, that it was the baryonic ICM that got referred to as the dark matter. The total mass of a galaxy cluster in visible wavelength would be according to the mass of luminous matter contained within the galaxies. It is the ICM that causes the high mass-to-light ratio if we observe a galaxy cluster in visible wavelength, or simply, if we consider the optically visible components only. The orbital and the escape velocities of galaxies situated within the cluster would have been less, that is, the said velocities would have been according to the mass of galaxies if the ICM was not present within the cluster.

3 SOLVING THE GALAXY ROTATION PROBLEM

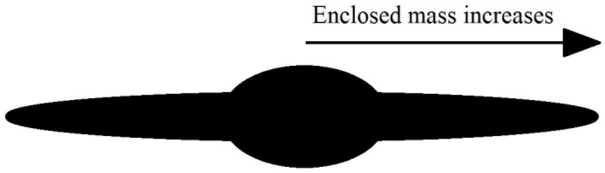

Figure 3. In case of a galaxy, the baryonic enclosed mass increases with distance from the centre of the galactic nucleus.

As compared to the solar system or any other planetary system, a galaxy contains significant and continuous distribution of matter in the form of gas and dust from the nucleus onwards. Mostly it is the gas (ionized and neutral hydrogen) that makes the distribution of matter significant and continuous throughout the galaxy right from the centre. Therefore, the baryonic "enclosed mass" keeps on increasing with distance from the centre of the galaxy (With increasing distance from the centre of the galaxy, the baryonic mass keeps adding to the previous mass, hence the baryonic "enclosed mass" increases with distance from the centre of the galaxy. Since the enclosed mass is increasing with distance, therefore, the gravitational acceleration decreases gradually and not rapidly throughout the galaxy). If this matter distribution was not present, then the orbital velocity of galactic components would have declined with distance in a similar manner as observed in case of a planetary system.

For example, the Sun situated at a distance of 8 kpc from the centre of the galaxy, exhibits an orbital velocity of 220 km s^{-1}, thereby giving us an enclosed mass of 8.952×10^{10} $M_\odot$ (1.7904×10^{41} kg), the gravitational acceleration due to this enclosed mass is 1.9605×10^{-10} m s^{-2}, which is extremely low, however, since the mass of the Sun is 2×10^{30} kg, therefore, the gravitational force between the Sun and the enclosed mass becomes 3.921×10^{20} N (this is the weight of the Sun with respect to this enclosed mass. At this magnitude of the force involved, Newtonian dynamics must be obeyed).

Now, we will consider that there is no matter distribution between the Sun and galactic centre. The mass of the galactic centre (supermassive black hole) is 4×10^6 $M_\odot$ (8×10^{36} kg), the orbital velocity of Sun at 8 kpc would then be 1.47 km s^{-1}, the gravitational acceleration due to the galactic centre at this distance would be 8.7603×10^{-15} m s^{-2} and the gravitational force between the Sun and the galactic centre would be 1.7520×10^{16} N (this is the weight of the Sun with respect to the galactic centre when matter distribution is not present between them). We can see how the orbital velocity of an object situated far away from the centre is influenced by the presence or the absence of matter distribution between them. Therefore, the orbital velocity of the galactic components depends upon the enclosed mass, and it is this enclosed mass with respect to which the galactic components orbit. The gravitational acceleration due to the enclosed mass is extremely low throughout the galaxy with values ranging between 10^{-10} to 10^{-11} m s^{-2}, however, it is the mass of the celestial object situated along the perimeter of this enclosed mass that determines the overall gravitational force between them.

The visible galaxy terminates at the edge of the galactic disc, however, gas (neutral hydrogen) is still present beyond the galactic edge, we can say that the matter distribution present beyond the galactic edge is more homogeneous, since it is mostly gas, therefore, as the distance from the centre of the galactic nucleus keeps on increasing in the direction of the galactic edge and beyond, the enclosed mass keeps on increasing and for this reason the rotation curve either remains steady or in some cases it keeps rising even beyond the galactic edge. The increasing enclosed mass with distance from the centre of the galactic nucleus to the galactic edge and beyond enhances the galaxy's rotation curve. Therefore, an additional mass in the form of dark matter is not required to explain the unexpected rotational velocity of the galactic components within the galactic disc and beyond.

In case of the solar system, significant matter distribution between the Sun and planets is not present, therefore, the planets exhibit Keplerian motion and the orbital velocity of planets keeps on decreasing with increasing distance from the centre. A planetary system is devoid of enclosed mass that increases with distance, the mass remains constant and concentrated at the centre, therefore, the gravitational acceleration due to the massive central star decreases rapidly with increasing distance from the centre, for example, in the solar system the gravitational acceleration due to the Sun decreases rapidly from 10^{-2} m s^{-2} to 10^{-6} m s^{-2} (Mercury to Pluto) and this happens within a radius of 5.9×10^{12} m. We can compare the size of the Milky Way galaxy to an 80 m dish, whereas, the solar system at this scale would correspond roughly to the size of 1 μm. Therefore, the amount of matter present in the form of gas within the solar system is highly insignificant to form an efficient enclosed mass since it is a small-scale structure as compared to the amount of matter distribution present in the form of gas within a large-scale structure such as a galaxy.

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) (kg)	Gravitational acceleration (m s^{-2})
5	220	1.1190×10^{41}	3.1370×10^{-10}
6	220	1.3428×10^{41}	2.6141×10^{-10}
7	220	1.5666×10^{41}	2.2406×10^{-10}
8	220	1.7904×10^{41}	1.9606×10^{-10}
9	220	2.0142×10^{41}	1.7427×10^{-10}
10	220	2.2380×10^{41}	1.5684×10^{-10}
11	220	2.4619×10^{41}	1.4259×10^{-10}
12	220	2.6857×10^{41}	1.3071×10^{-10}
13	220	2.9095×10^{41}	1.2065×10^{-10}
14	220	3.1333×10^{41}	1.1203×10^{-10}
15	220	3.3571×10^{41}	1.0456×10^{-10}
16	220	3.5809×10^{41}	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) (kg)	Gravitational acceleration (m s^{-2})
5	220	1.1190×10^{41}	3.1370×10^{-10}
6	230	1.4677×10^{41}	2.8572×10^{-10}
7	240	1.8644×10^{41}	2.6666×10^{-10}
8	250	2.3120×10^{41}	2.5317×10^{-10}
9	260	2.8133×10^{41}	2.4341×10^{-10}
10	270	3.3710×10^{41}	2.3625×10^{-10}
11	280	3.9878×10^{41}	2.3097×10^{-10}
12	290	4.6666×10^{41}	2.2711×10^{-10}
13	300	5.4102×10^{41}	2.2436×10^{-10}
14	310	6.2213×10^{41}	2.2245×10^{-10}
15	320	7.1027×10^{41}	2.2124×10^{-10}
16	330	8.0571×10^{41}	2.2057×10^{-10}

Gravitational acceleration decreasing at a gradual rate throughout the galaxy as the baryonic enclosed mass keeps on increasing with distance. 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. The nature of rotation curve therefore depends upon the rate at which the baryonic enclosed mass increases with distance.

4 HIGH VELOCITIES OF GALAXIES WITHIN A RICH GALAXY CLUSTER

Figure 4. Galaxies around NGC 4874 within the Coma Cluster. Image credit: Hubble Space Telescope.

The galaxies situated within a rich cluster exhibit velocities which are anomalously higher than expected. To explain this discrepant anomaly we will focus upon the Coma Cluster.

Now, just as an example, we will consider the radius of the Coma Cluster to be 6 Mpc (1.8514 x 10^{23} m). A galaxy situated along the edge of the cluster exhibiting an orbital velocity of 1000 km s^{-1} around the cluster gives an enclosed mass of 1.3872 x 10^{15} $M_\odot$ (2.7744 x 10^{45} kg), the gravitational acceleration due to this enclosed mass is 5.4011 x 10^{-12} m s^{-2}, if the mass of a galaxy situated along the edge of the cluster (which is also the edge of this enclosed mass), is assumed to be 2 x 10^{11} $M_\odot$ (4 x 10^{41} kg), then the gravitational force between this galaxy and the enclosed mass will be 2.1604 x 10^{30} N (this is the weight of the galaxy situated along the edge with respect to the enclosed mass) and the escape velocity of this galaxy with respect to this enclosed mass is 1414.19 km s^{-1}. In this case we have considered the presence of matter distribution in the form of ICM that forms the enclosed mass.

Now, we will consider that the matter distribution or the ICM is not present within the cluster (this is similar to observing the cluster in visible wavelength). A galaxy situated along the edge of the cluster at the same distance of 1.8514 x 10^{23} m from a central massive galaxy whose assumed mass is 10^{13} $M_\odot$ (2 x 10^{43} kg), will then exhibit an orbital velocity of 84.90 km s^{-1}. The gravitational acceleration due to the central massive galaxy at this distance will be 3.8936 x 10^{-14} m s^{-2}, if the mass of a galaxy situated along the edge is 2 x 10^{11} $M_\odot$ (4 x 10^{41} kg), then the gravitational force between this galaxy and the central massive galaxy will be 1.5574 x 10^{28} N (this is the weight of the galaxy situated along the edge with respect to the central massive galaxy, when the matter distribution or the ICM is not present within the cluster), the escape velocity of this galaxy with respect to the central massive galaxy will then be 120.07 km s^{-1}.

On comparing these two situations we can see how the presence or the absence of matter distribution in the form of ICM influences the physical parameters. In the first case, the weight of the galaxy along the edge is 140 times greater than the weight of the same galaxy in the second case. Similarly, the escape velocity of the galaxy along the edge in the first case is 12 times greater than the escape velocity of the same galaxy in the second case. This makes it clear that the orbital and the escape velocities of the galaxies situated within the cluster depends upon the enclosed mass (non-luminous baryonic ICM visible in X-rays) and not just upon the mass of the galaxies.

The baryonic ICM within the cluster forms the enclosed mass, and it causes the galaxies situated within the cluster to weigh more. The galaxies therefore behave as if their mass has increased above their luminous mass (This results into an anomaly, since the ICM which forms the enclosed mass was invisible and its presence remained unknown before space-based X-ray astronomy gained importance. Therefore, the only solution to this anomaly was to consider that either the galaxies or the cluster possessed more mass than the optically visible luminous mass). However, if ICM is not present within the cluster, then the orbital and the escape velocities of the orbiting galaxies will be according to the mass of the galaxies only.

Observing a galaxy cluster in visible wavelength is similar to observing it without considering the presence of ICM, since the ICM would only be visible through a space-based X-ray telescope, therefore, with respect to what is optically visible to us, as it appears in Fig. 4, we expect the galaxies within the cluster to exhibit velocities that would be consistent with the mass due to the visible luminous matter contained within the galaxies only.

The orbital velocities of galaxies situated within the cluster are higher than expected because of the ICM that forms the enclosed mass between the central galaxy and the galaxies situated far away from the centre, therefore, the orbital velocity of galaxies within the cluster remains higher even for the galaxies situated far away from the central galaxy. If this matter distribution in the form of ICM was not present between the central galaxy and a galaxy situated along the edge of the cluster, then the orbital velocity of such galaxy situated far away from the centre would have comparatively been extremely less, and less would have been its escape velocity too.

5 THE INTRACLUSTER MEDIUM, ITS DENSITY AND THE X-RAY EMISSION

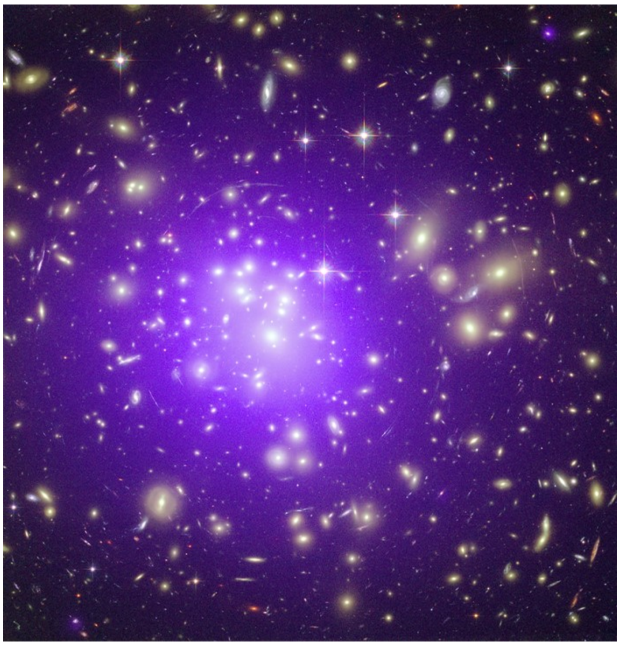

Figure 5. Galaxy cluster Abell 1689 in visible (yellow) and X-ray (purple) wavelengths. The extremely hot, X-ray emitting ICM is visible in X-ray telescope in the form of purplish glow engulfing the galaxy cluster. Image credits: Hubble Space Telescope (optical) and Chandra X-ray Observatory (X-ray).

A galaxy cluster is engulfed by an extremely hot gas (10^8 K) that forms the intracluster medium (ICM). The temperature of the ICM is so high that the gas is in the plasma phase and emits X-rays. A space-based X-ray telescope reveals the presence of the extremely hot gas or the plasma distributed throughout the cluster. In X-ray wavelength the ICM is visible as purplish glow that surrounds the entire galaxy cluster and engulfs all the galaxies within the cluster.

By knowing the brightness of the X-ray emission it is possible for us to know the density of the ICM, as X-ray emission is proportional to the square of ICM's density. ICM possesses maximum density at the centre as indicated by the strong X-ray emission observed from the central region. However, with increasing distance from the centre, the density of the ICM decreases as X-ray brightness keeps on decreasing towards the edge of the ICM. This is clearly visible in Fig. 5, where the ICM exhibits maximum X-ray brightness in the central region which then decreases gradually with increasing distance from the centre along the edges.

Now, there is a property associated with spherical, self-luminous celestial objects, a property which in case of the ICM would make us infer that the density of ICM is decreasing as we move from its centre to its edge. This property is the ICM limb darkening (analogous to the stellar limb darkening), this effect causes the ICM to exhibit maximum X-ray brightness in the central region, the brightness then decreases gradually with increasing distance from the centre to the edge of the ICM.

According to the ICM limb darkening effect, the X-ray photons from the central region of the ICM reach the detector (X-ray telescope) along straight line of sight, therefore, the X-ray brightness is maximum from the central region and hence the density appears to be maximum there. However, with increasing distance from the centre, the X-ray photons travel out of sight (X-ray photons emerging from the edge of the ICM do not reach the detector that effectively as compared to those X-ray photons that reach the detector from the central region along straight line of sight. Therefore, the ICM appears comparatively more opaque at the centre than it appears along the edges, where it is more transparent. When X-ray photons travel along straight line of sight, the X-ray glare is maximum and ICM appears opaque and more dense, on the other hand, when X-ray photons travel out of sight, the X-ray glare is minimum and the ICM appears more transparent and less dense). The ICM limb darkening effect keeps on increasing with increasing distance from the centre as the spherical curvature of the ICM makes the X-ray photons to travel more and more out of sight. Therefore, the X-ray brightness keeps on decreasing with increasing distance from the centre of the cluster as the X-ray photons continue to travel out of sight. As a result of this effect, it appears that the density of ICM is decreasing on the account of decreased X-ray photon reception by the detector with increasing distance from the centre along the edges of the ICM. Based upon this we obtain a density deficit and hence underestimate the actual mass of the ICM which is more than what is observed, thereby requiring the presence of dark matter to explain the observed mass discrepancy.

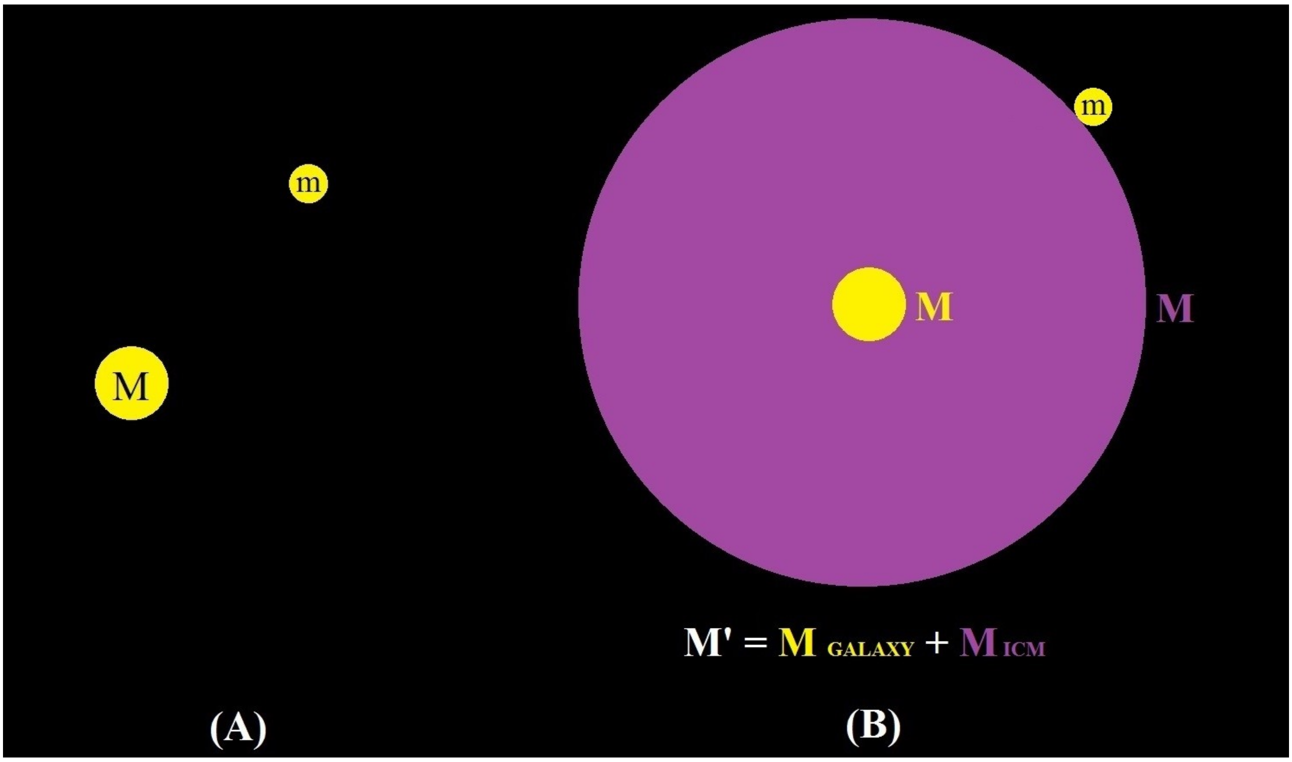

Figure 6. (A) Galaxy cluster in visible wavelength. ICM remaining invisible, the only optically visible components are M and m. The orbital and escape velocity of m is therefore expected to be with respect to the mass M, since it is the only optically visible enclosed mass. However, the orbital velocity of m is more than expected, thereby resulting into a mass discrepancy. The presence and role of ICM as enclosed mass was not known before the introduction of space-based X-ray astronomy. **(B)** Galaxy cluster in visible and X-ray wavelengths. The enclosed mass constituted by the central galaxy and ICM is visible. The orbital and escape velocity of m is therefore with respect to the entire enclosed mass M', constituted by $M_{\text{GALAXY}} + M_{\text{ICM}}$.

6 CONCLUSIONS

(1) The matter distribution in the form of gas is highly significant on large-scale throughout a galaxy, therefore, a galaxy exhibits no empty space on large-scale.

(2) The galaxy rotation curve does not decline, because the baryonic enclosed mass keeps on increasing with distance from the centre of the galactic nucleus to the galactic edge and beyond. Since the enclosed mass is increasing with distance, the gravitational acceleration decreases gradually throughout the galaxy and not rapidly as in case of the solar system. Therefore, with respect to the increasing enclosed mass, the rotation curve either remains steady or in some cases it keeps rising (depending upon the rate at which the enclosed mass is increasing with distance). The attribute of enclosed mass increasing with distance enhances the galaxy's rotation curve, such attribute is not exhibited by a planetary system, and therefore, the orbital velocities of planets decline with increasing distance from the centre.

(3) Similarly, a galaxy cluster contains huge amount of hot X-ray emitting gas or the plasma that forms the ICM. The orbital and the escape velocities of the galaxies within a rich cluster without the ICM would be according to the mass of the galaxies and in this case the said velocities would be governed by the mass of the central massive galaxy present within the cluster, however, since ICM is present within the cluster, therefore, it is the ICM that forms the enclosed mass and governs the orbital and the escape velocities of the galaxies within the cluster. The orbital and the escape velocities of galaxies depend upon the enclosed mass (non-luminous baryonic ICM visible in X-rays) and not just upon the mass of the galaxies.

(4) In case of the ICM, the X-ray brightness is maximum from its central region since the X-ray photons travel towards the detector along straight line of sight, however, with increasing distance from the centre towards the edge of the ICM, the X-ray photons travel more out of sight due to the

surface curvature of the ICM, thereby reducing the X-ray brightness along the edges of the ICM. The edges of the ICM therefore appear faint and transparent. This effect is attributed to the ICM limb darkening which is analogous to the stellar limb darkening effect.

(5) The ICM limb darkening effect causes an underestimation of ICM's density and hence the mass on account of reduced X-ray brightness reception by the X-ray detector with increasing distance from the centre of the ICM.

(6) The mass obtained from gravitational lensing and from the known orbital velocities of galaxies within the cluster (velocity dispersion of galaxies) may be giving us the actual mass of baryonic matter present within the cluster that cannot be determined accurately from the mass corresponding to the observable luminosity.

(7) Since the galaxies within the cluster are clustered quite closely together, therefore, it is possible that the gravitational potential well of an individual galaxy within the cluster may merge with the gravitational potential well of another nearby galaxy so as to form a collective gravitational potential well. This may cause the formation of gravitationally lensed arcs that are longer than usual, thereby overestimating the cluster's actual mass.

(8) Only dense, massive and spherically symmetric celestial objects such as black holes, neutron stars, quasars and elliptical galaxies can cause gravitational lensing. Therefore, the gravitational lensing observed in galaxy clusters is mostly because of massive elliptical galaxies.

(9) Observing a rich galaxy cluster in visible wavelength makes us believe that the galaxies are only held by the mutual gravitation between them, and as a result, the orbital and escape velocities of galaxies within the cluster are expected to be with respect to the mass that is optically visible. Since the baryonic ICM remained invisible before the introduction of space-based X-ray astronomy, therefore, the presence and the role of ICM as enclosed mass remained unknown.

(10) The galaxies within the cluster are not only held by the mutual gravitation between them, but also because of the baryonic ICM that forms the enclosed mass.

(11) Since the distance between the galactic components within galaxies and the distance between galaxies within galaxy clusters is quite large, therefore, no matter how less dense the gaseous baryonic matter distribution is, because, at such large distances, even a low density gas should form an effectively massive and hence an efficient enclosed mass.

(12) The galactic components within a galaxy and the galaxies within a rich cluster orbit with respect to the total enclosed mass present before them right from the centre. The orbital and escape velocities are therefore not with respect to the centre, but with respect to the overall enclosed mass.

(13) The escape velocity of an orbiting object is always greater than its orbital velocity with respect to the enclosed mass obtained from the known orbital velocity. Therefore, if the orbital velocity is with respect to the baryonic enclosed mass, then the escape velocity is too.

(14) The enclosed mass that we obtain from the known orbital velocity, yields a very small value of gravitational acceleration, a dark matter dominated system should not yield such small values of gravitational acceleration if the orbital velocities are because of dark matter.

(15) The baryonic matter distribution explains the anomaly or the discrepancy without considering the presence of dark matter in galaxies and in galaxy clusters.

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