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Vipin Kumar Sharma and Murli Manohar Verma

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A NEW EXPLANATION OF DARK MATTER-PLASMA SHIFT IN BULLET CLUSTER BY MODIFICATION OF GRAVITY

Vipin Kumar Sharma* and Murli Manohar Verma†
*,† *Department of Physics, University of Lucknow, Lucknow 226 007, India*
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The explanation of the cluster dynamics in the Einstein's theory of gravity via gravitational lensing observation of the Bullet Cluster (1E0657-558) at a redshift, z 0.296 presumably invokes the evidence for dark matter. This is revealed by the Hubble Space Telescope (HST) / Advanced Camera Survey (ACS) images of the cluster cores of the stellar component and the fluid-like X-ray emitting plasma (the most dominant baryonic component) by the Chandra Space Satellite. It is observed from such images that the k-map (a measure of the curvature or convergence of spacetime through gravitational lensing) and the Σ-map (a measure of the surface mass density of the hot intercluster medium (plasma) through King β model have the different peaks. However, the peak value of the k-map does not trace the dominant component (plasma) but rather traces the galaxies (stellar component). In the present work, we attempt to explain this cluster scale anomaly without the need of any dark matter of the standard form but by modifying the Einstein's law of gravity in a way that under the weak field limit the theory satisfies the galactic dynamics as well as the local gravity constraints via a chameleon mechanism. We work with the modified Einstein - Hilbert action using $f(R) = R^{1+\delta}/R_c^{\delta}$, δ <<1 shows the deviation from Einstein's gravity theory. We obtain the gravitational lensing angle formula in the modified gravity background and use it to calculate the gravitational lensing potential and convergence or the scaled surface mass density, k (as Σ / $\Sigma_{(critical)}$) for the Bullet Cluster. We claim that this modified convergence may be held responsible for the observed shifting of the peak of the gravitational potential from the dominant plasma component of the Cluster.

* vipinastrophysics@gmail.com
† sunilmmv@yahoo.com

I. INTRODUCTION

Precision cosmology is imperfect without the precise physical observations of systems at different scales. For precise observations, the physical system must be completely known. Unfortunately, the major portion of our observable universe is not completely known to us in Einstein's General Relativity (GR) framework. Also, Einstein's gravity theory with a positive cosmological constant (Λ) based on GR supported by observations still can not be regarded as an ultimate gravity theory because of the recent stronger than before Planck's observation of an accelerating universe (having the shifted w from -1) and its inability to reconcile with the quantum theory completely and also, more importantly, the fundamental properties of the dark sector (dark energy and cold dark matter) is still unknown besides its distribution. Thus, the observational evidences at different redshifts nurture the concept of modified gravity theory instead of the Einstein's physical gravity theory of GR with Λ (positive) and cold dark matter (CDM) [1–8]. The investigation of deviation in Einstein's GR theory has become an active area of research under the study of precision concordance cosmology. Therefore, it is the need of precision concordance cosmology to opt for an alternative theory of gravity.

We attempt to explain the dynamics of the special cluster (a Bullet Cluster- formed due to the collision of two galaxy clusters of different sizes) without invoking any particulate dark matter profile by working with modified gravity theory (gravity) [9–12].

In the present work, we study the deviations in GR in the form $R^{1+\delta}$ (with δ being the dimensionless physical observable quantity) and instead of investigating the Yukawa-like correction potential as others did [13, 14], we explore the bare modified $f(R)$ effects in the form of δ for different observations without including any versions of the dark sector. The present paper is organized in different sections as follows. In Section (II), we mathematically discuss the Jordan frames dynamical $f(R)$ field equations by obtaining the $f(R)$ potential and deflection angle. In Section (III), we discuss the convergence map for the Bullet Cluster dynamics. We end with the discussion and concluding remarks of results on the constraints in Section (IV).

Throughout the paper, we follow the signature of the spacetime metric as $(-, +, +, +)$ and indices μ (or ν) = (0, 1, 2, 3).

II. $f(R)$ GRAVITY AND CONFORMALLY RELATED FIELD EQUATIONS

Recently, in our work, we attempted to explain the dark matter and dark energy issue for the gravity model. gravity is a generalization of the Einstein's Riemannian geometric theory of gravity. Here,

$$f(R) = \frac{R^{1+\delta}}{R_c^{\delta}}, \tag{1}$$

with δ as a free parameter and R_c is the weight constant. A mild deviation in the Einstein theory of gravity may also explain the dynamics at the galactic and cluster scales without invoking any particulate dark matter components. We therefore obtain the equation of motion for such model through the variation of action integral approach. The solution, i.e., the scale factor in the homogeneous and isotropic universe is :

$$a(t) = a_0 \left[\frac{1-\chi}{(\frac{H}{H_0})^{\frac{1+2\delta}{1+\delta}} - \chi} \right]^{\frac{1+\delta}{2+4\delta}}, \tag{2}$$

where $\chi = \frac{R_0}{12{H_0}^2}$ and a_0 is the present value of the cosmological scale factor.

We now consider a spherically symmetric source (a typical spheroidal massive galaxy) of mass M in the modified spacetime background in the complete absence of any other gravitating source. We construct the effective potential of the system i.e., the potential due to a source (as galaxy) and the potential of the modified spacetime itself in the weak field limit as:

$$V_{effective} = -\frac{GM}{r} - \frac{{H_0}^2}{2r^2} \left[\chi r^{\frac{2+4\delta}{1+\delta}} - (\chi - 1) {r_0}^{\frac{2+4\delta}{1+\delta}} \right]^{\frac{2(1+\delta)}{1+2\delta}}, \tag{3}$$

where r_0 is the $f(R)$ background galactic length scale parameter measured in kpc and H_0 is the present hubble parameter.

Modifying the geometric theory of gravity will affect the light deflection angle. Therefore, the deflection in the path of photon propagating in z-direction in $f(R)$ gravity background having a gravitating source (typical galaxy as lens) of mass M with an effective potential, $V_{effective}$ is:

$$\hat{\alpha}_{Net} = \frac{2}{c^2}\int_{-\infty}^{+\infty} \nabla_{\perp} V_{effective}\, dZ. \tag{4}$$

Now, on making use of $r^2 \equiv x^2 + y^2 + z^2 = \xi^2 + z^2$ with $\nabla_{\perp} = \frac{\partial}{\partial \xi}$ and ξ is a two dimensional impact parameter, we get after some algebraic calculations

$$\hat{\alpha}_{Net} = \frac{4G_N M}{c^2 \xi} - 2\frac{H_0^2}{c^2}\sqrt{\pi}\xi^2 \left(\frac{1}{2}\right)^{\frac{2+2\delta}{1+2\delta}} \times \left[\left(\frac{r_0}{\xi}\right)^4 \frac{\sqrt{\pi}}{2} - 2\frac{\Gamma(-\frac{1}{2}+\frac{1}{1+\delta})}{\Gamma(\frac{1}{1+\delta})}\left(\frac{r_0}{\xi}\right)^{\frac{2}{1+\delta}}\right]. \tag{5}$$

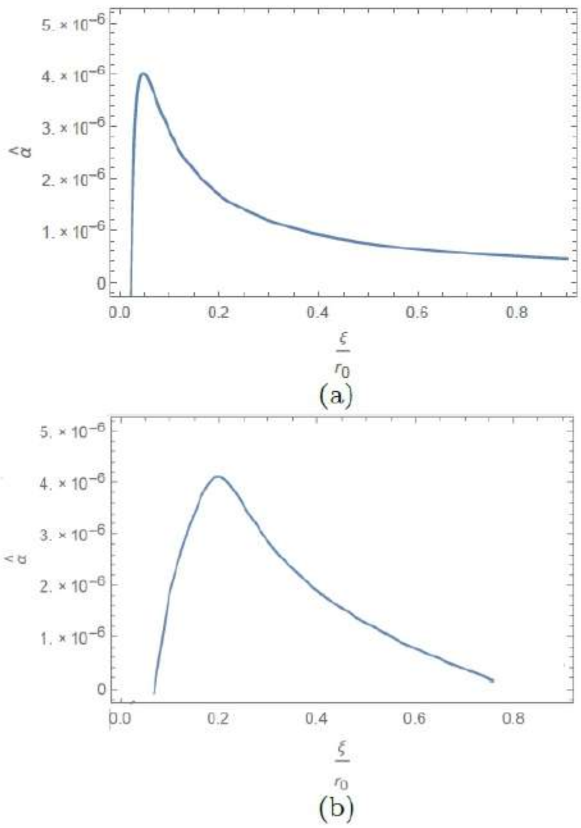

FIG. 1: The plot is obtained for galactic plasma of NGC 5533 with $\delta \approx O(10^{-6})$ and $r_0 = 10^{2.650}$ kpc . From the sub figures 1(a) and 1(b), it become clear that lensing peak due to galaxy plasma lies much beyond the galaxy centre in Einstein gravity theory due to the pseudo isothermal dark matter model of galaxy (Fig. 1(b)) as compared to the modified gravity theory without dark matter (Fig. 1(a)). Because the density of plasma (baryonic content) in a galaxy decreases with distance, so the light deflection angle peak lies close to the centre of galaxy.

III. MODIFIED SPACETIME CONVERGENCE MAP AND SHIFTED PLASMA PEAKS OF BULLET CLUSTER

We consider the Bullet Cluster system as a lens and obtain the surface mass density of the system in modified spacetime background through gravitational lensing angle. The Einstein's lens potential generated through the deflection angle in vector form in general relativity framework is:

$$\psi_{Einstein} = \frac{1}{\pi\Sigma_c}\int\int \Sigma \ln|\xi - \acute{\xi}| d^2\acute{\xi}. \tag{6}$$

Here $\Sigma_c = \frac{1}{4\pi G}\frac{D_S}{D_L D_{SL}}$ is the critical surface mass density of the system with D_S, D_L and D_{SL} are the distances between the observer to source plane, observer to lens plane and lens to source plane respectively. So, for the effective source mass obtained from the modified lensing angle equation, we have the corresponding modified effective lens potential as:

$$\bar{\psi} = \frac{1}{\pi\Sigma_c}\int\int \bar{\Sigma} \ln|\xi - \acute{\xi}| d^2\acute{\xi}. \tag{7}$$

Here

$$\bar{\Sigma} = \Sigma - 2\Sigma \times \frac{H_0^2}{c^2}\sqrt{\pi}\xi^2\left(\frac{1}{2}\right)^{\frac{2+2\delta}{1+2\delta}}$$
$$\left\{\left(\frac{r_0}{\xi}\right)^4\frac{\sqrt{\pi}}{2} - 2\frac{\Gamma(-\frac{1}{2}+\frac{1}{1+\delta})}{\Gamma(\frac{1}{1+\delta})}\left(\frac{r_0}{\xi}\right)^{\frac{2}{1+\delta}}\right\}$$

is an effective mass per unit surface area with,$\Sigma(=\int_{-x}^{+x}\rho dz)$ is the projected volume mass distribution of the lens plane. The actual profile of volume mass distribution is given by isothermal king beta model, which is:

$$\rho = \rho_0\left[1 + \left(\frac{r}{r_c}\right)^2\right]^{\frac{-3\beta}{2}}. \tag{8}$$

Here,$r_c = r_{core}$ is the core radius in a typical cluster system, ρ_0 is the central density for a given X- ray peak and r is the radial extent of the cluster with β is the free parameter used to fit with the observations. Hence, we have:

$$\begin{aligned}\bar{\Sigma} = \int_{-z}^{+z}&\Big[\rho_o\left(1 + \left(\frac{\xi^2+z^2}{r_core}\right)^2\right)^{\frac{-3\beta}{2}} \times \\ &\Big(1 - 2\frac{H_0^2\xi^2}{4GM}\left(\frac{1}{2}\right)^{\frac{2+2\delta}{1+2\delta}} \times \\ &\left(\left(\frac{r_0}{\xi}\right)^4\frac{\sqrt{\pi}}{2} - 2\frac{\Gamma(-\frac{1}{2}+\frac{1}{1+\delta})}{\Gamma(\frac{1}{1+\delta})}\left(\frac{r_0}{\xi}\right)^{\frac{2}{1+\delta}}\right)\Big)\Big]\end{aligned} \tag{9}$$

The parameters r_o, β, and δ is used for fitting while r_{core},ρ_o, M, G and H_o are the usual standard known parameters for the given system. Thus, the modified k-map is reconstructed from the gravitational lensing profile according to, $\bar{k} = \frac{\bar{\Sigma}}{\Sigma_{critical}}$. Such modified k-map can explain the observed Plasma shift.

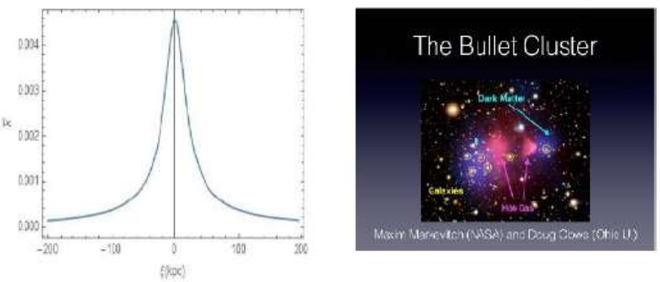

FIG. 2: The existence of the central lensing peak located on the gas is a natural outcome of the baryonic matter.

IV. CONCLUSION

Under the $f(R)$ gravity background, the gravitational lensing behaviour due to the intra galactic plasma (dominant baryonic component of galaxy) is different from the Einstein gravity theory with dark matter, which is clear from Fig. 1. The constructed modified spacetime convergence, k map for the collisional cluster system can shift the inter-galactic plasma in a way that the X-ray observations is explained within the certain limit of accuracy without demanding any dark matter. The existence of the central lensing peak located on the gas is a natural outcome of the baryonic matter (Fig. 2). As a future possible study, we constrain our model parameters to further investigate the offset of the lensing peaks from the central gas, due to the baryonic content and modified gravity background. Under this approach, we may also modify the standard cold dark matter model behaviour, i.e., from non-interacting to interacting dark matter.

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