

Effect comparison of dark matter annihilation pressure to NFW and pseudo-isothermal profiles of low surface brightness galaxies

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Abstract. We have studied the effect of gas pressure created by electrons and positrons produced from dark matter annihilation for low surface brightness (LSB) galaxies. We have applied 4 different gas and stellar disk models and 2 different dark matter density profiles, i.e. Navarro Frenk and White (NFW) and pseudo-isothermal, to each galaxy. We assume that electrons and positrons are produced from dark matter annihilation and they can lose their energy to photons and the interstellar medium in the galaxies by different loss processes. The pressure of electron and positron gas is a function of the electron-positron spectrum obtained from a diffusion-loss equation which included source term, diffusion coefficient and loss rate. We have added the pressure gradient to the rotation curves of LSB galaxies. We have compared the results with observations by using reduced chi-square. We have found that the pressure from dark matter annihilation provided better fits for several galaxies for NFW profiles but it doesn't play any role for pseudo-isothermal profiles. From these results, we can use NFW profile with pressure from dark matter annihilation to improve the situation of cusp-core problems and to constrain properties of dark matter particles by rotation curves of LSB galaxies for future studies.

1. Introduction

Although NFW profile is widely successful to explain the distribution of dark matter in the large scale structure of the Universe, it fails to explain inner regions of rotation curves of LSB galaxies dominated by dark matter (see e.g. [1]). It has also been shown that pseudo-isothermal profile provided better fits for LSB galaxies than NFW profile [2, 3]. This problem is the so-called “cusp-core” problem.

The idea of “dark matter pressure” has been introduced and studied for the first time by [4]. It was defined as the gas pressure of electrons and positrons produced from dark matter annihilation. It has been shown that dark matter pressure can affect rotation curves of LSB galaxies significantly with NFW profile and certain masses of dark matter particles, i.e. 100 MeV and 1 GeV. In this study, we would like to extend the mass range of dark matter particles to be 10 MeV to 10 TeV in an attempt to find the best fit of models and observations. We would also aim to study the effect of dark matter pressure on the rotation curves of LSB galaxies with pseudo-isothermal profile to compare with NFW profile.



2. Dark matter pressure

We focus on dark matter pressure created by electrons and positrons from dark matter annihilation. The pressure is a function of the electron-positron spectrum $\frac{dn}{d\gamma}(r, \gamma)$ with Lorentz factor γ at a radius r from the centre of the dark matter halo,

$$P_{\text{dm}}(r) = \frac{m_e c^2}{3} \int_1^\infty \frac{dn}{d\gamma}(r, \gamma) \left(\frac{\gamma^2 - 1}{\gamma} \right) d\gamma, \quad (1)$$

where m_e is the rest mass of an electron, and c is the speed of light. The electron-positron spectrum $\frac{dn}{d\gamma}(r, \gamma)$ is the solution of a diffusion-loss equation with a steady state as shown in [4], and is given by

$$\begin{aligned} \frac{dn}{d\gamma}(r, \gamma) &= \frac{1}{b(\gamma)} \frac{\exp\left(-\frac{r^2}{2\Delta\lambda^2}\right)}{(2\pi\Delta\lambda^2)^{\frac{1}{2}}} \\ &\times \left\{ \int_\gamma^\infty d\gamma_s \int_0^\infty dr_s r_s \exp\left(-\frac{r_s^2}{2\Delta\lambda^2}\right) \right. \\ &\times \left[\exp\left(\frac{rr_s}{\Delta\lambda^2}\right) - \exp\left(-\frac{rr_s}{\Delta\lambda^2}\right) \right] Q(r, \gamma_s) \left. \right\}, \end{aligned} \quad (2)$$

where $b(\gamma)$ is loss rate, i.e. by inverse Compton scattering, synchrotron radiation, Coulomb collisions, bremsstrahlung and ionization. In this case, we use the same astrophysical parameters as the canonical model in [4] except the ionization fraction X_{ion} which regulates the energy losses by Coulomb interactions, bremsstrahlung and ionization. Since we aim to see the effect of all loss processes, we use $X_{\text{ion}} = 0.5$ when the interstellar medium (ISM) gas composes of half neutral hydrogen atoms and hydrogen ions, instead of $X_{\text{ion}} = 0$ when the ISM gas entirely composes of neutral hydrogen atoms. r_s and γ_s are the radial distance from the galactic center and the Lorentz factor of dark matter particles which create electrons and positrons. $\Delta\lambda^2$ is the characteristic diffusion length which is defined by $\Delta\lambda^2 = \lambda^2(r) - \lambda^2(r_s)$, where $\lambda^2(\gamma) = \int_\gamma^\infty \frac{2K(\gamma)}{b(\gamma)} d\gamma$ depends on the diffusion coefficient $K(\gamma)$ and loss rate $b(\gamma)$.

The production rate of electrons and positrons from dark matter annihilation is defined by

$$Q(r, \gamma) = \frac{1}{2} \left[\frac{\rho_{\text{dm}}(r)}{m_{\text{dm}}} \right]^2 \langle \sigma v \rangle_{e^\pm} \frac{dN_{e^\pm}}{d\gamma}(\gamma), \quad (3)$$

where $\langle \sigma v \rangle_{e^\pm}$ is the thermal average of the annihilation cross-section times the dark matter relative velocity, m_{dm} is the mass of dark matter particles, and $\frac{dN_{e^\pm}}{d\gamma}(\gamma)$ is the injection spectrum of electrons and positrons in the final state which equals to 2 since we assume that one electron and one positron are produced per annihilation event. For the dark matter density $\rho_{\text{dm}}(r)$, we will consider NFW and pseudo-isothermal profile.

3. Rotation curves of LSB galaxies

In this study, we have included pressure gradient of electron-positron gas produced by dark matter annihilation to the circular velocity of the galaxies,

$$v_c(r) = \sqrt{\frac{GM(r)}{r} + \frac{r}{\rho_g(r)} \frac{dP_{\text{dm}}(r)}{dr}}, \quad (4)$$

where $\rho_g(r)$ is the gas density at radius r . The mass $M(r)$ of each galaxy is a contribution of dark matter, gas and stellar disk components. We adopt 4 models of gas and stellar disk components from [2].

1. *Minimum disk*. This model considers only dark matter in a galaxy and neglects all visible components.

2. *Minimum disk + gas*. The contribution of dark matter and gas are taken into account but assume that stellar disk is zero.

3. *Constant mass-to-light ratio*. In this case, they have chosen mass:light = 1.4:1.

4. *Maximum disk*. In this case, the rotation curve of the stellar disk component is scaled to the maximum value [5].

For the dark matter component, we have considered NFW and pseudo-isothermal profile. NFW profile is given by [6],

$$\rho_{\text{NFW}}(r) = \frac{\rho_s}{\frac{r}{r_s} \left(1 + \frac{r}{r_s}\right)^2}, \quad (5)$$

where r_s and ρ_s are characteristic radius of LSB galaxies, respectively. Pseudo-isothermal profile is defined by [7],

$$\rho_{\text{ISO}}(r) = \rho_0 \left[1 + \left(\frac{r}{r_C}\right)^2\right]^{-1}, \quad (6)$$

where ρ_0 is the central density of the halo, and r_C is the core radius of the halo.

4. Results

We have adopted data of observed rotation curves, NFW and pseudo-isothermal dark matter profiles of LSB galaxies from [2]. We have added dark matter pressure to 15 LSB galaxies with NFW profile and 11 LSB galaxies with pseudo-isothermal profiles including 4 models of gas and stellar disk components, i.e. minimum disk, minimum disk + gas, constant M/L and maximum disk. For each gas and stellar disk model and each dark matter profile, we have considered 7 masses of dark matter particles, i.e. 10 MeV, 100 MeV, 1 GeV, 10 GeV, 100 GeV, 1 TeV and 10 TeV. In total we have created $(15 + 11 \text{ galaxies}) \times 4 \text{ gas and stellar disk models} \times 7 \text{ masses of dark matter particles} = 728$ modeled rotation curves. In order to find the best fit, we have estimated reduced chi-square χ^2 of observed rotation curves and modeled rotation curves. The masses of dark matter particles that provide the best fit for each gas and stellar disk model of each galaxy are presented with reduced χ^2 in table 1 for both NFW and pseudo-isothermal profiles. χ_{dBB}^2 refers to the original model without dark matter pressure in [2] and χ_{DMP}^2 refers to the models with dark matter pressure. The cases that $\chi_{\text{DMP}}^2 < \chi_{\text{dBB}}^2$ are marked by blue colour.

For NFW dark matter profile, dark matter pressure effects rotation curves of LSB galaxies significantly. For 60 cases of gas and stellar disk models, there are 27 cases that dark matter pressure has improved the fitting of modeled and observed rotation curves. The masses of dark matter particles that provide the best fit are between 10 MeV to 1 GeV since the production rate of electrons and positrons, $Q(r, \gamma)$, with this mass range is higher than the production rate with the larger mass range. Moreover, the electrons and positrons which are produced from dark matter particles with the larger mass range will be more energetic which results in them losing their energy faster than the low energy electrons and positrons which are produced from dark matter particles with the smaller mass. An example of rotation curves of NGC3274 with NFW profile and 4 models of gas and stellar disk are shown in figure 1. Dark matter pressure plays an important role in the inner region of the galaxy in all gas and stellar disk models.

However, for pseudo-isothermal dark matter profiles, dark matter pressure barely affects the rotation curves of LSB galaxies. There are only 9 cases in 60 cases that the models with dark matter pressure slightly improved the fitting and there is no difference between various masses

Table 1. Reduced χ^2 and dark matter mass for NFW and pseudo-isothermal profile of LSB galaxies. χ_{dBB}^2 refers to the original model without dark matter pressure in [2], χ_{DMP}^2 refers to the models with dark matter pressure and m_{dm} refers to the mass of dark matter particles that provided the best fit for each gas and stellar disk model, i.e. minimum disk (Min D), minimum disk + gas (Min D + G), constant mass-to-light ratio (Const. M/L) and maximum disk (Max D). The cases that $\chi_{\text{DMP}}^2 < \chi_{\text{dBB}}^2$ are marked by blue colour.

NFW												
Name	χ_{dBB}^2	Min D χ_{DMP}^2	m_{dm}	χ_{dBB}^2	Min D + G χ_{DMP}^2	m_{dm}	χ_{dBB}^2	Const. M/L χ_{DMP}^2	m_{dm}	χ_{dBB}^2	Max D χ_{DMP}^2	m_{dm}
DDO47	0.320	0.293	100 MeV	0.250	0.224	100 MeV	0.307	0.293	100 MeV	0.455	0.519	100 MeV
DDO185	2.677	3.067	1 GeV	2.326	2.930	1 GeV	2.269	2.823	100 MeV	2.137	2.679	100 MeV
DDO189	0.171	0.159	10 MeV	0.119	0.117	10 MeV	0.099	0.101	10 MeV	0.156	0.162	10 MeV
UGC1230	1.143	1.111	10 MeV	1.244	1.211	10 MeV	1.091	1.069	10 MeV	0.724	0.725	10 MeV
UGC3371	0.287	0.303	10 MeV	0.273	0.295	10 MeV	0.278	0.303	10 MeV	0.980	0.791	10 MeV
UGC4173	0.058	0.063	10 MeV	0.116	0.116	10 MeV	0.129	0.144	10 MeV	0.993	0.254	10 MeV
UGC4325	1.330	1.386	1 GeV	1.132	1.179	1 GeV	1.157	1.217	1 GeV	1.225	1.330	100 MeV
UGC5005	0.191	0.225	10 MeV	0.191	0.192	10 MeV	0.170	0.170	10 MeV	0.557	0.405	10 MeV
UGC5750	3.288	6.232	10 MeV	3.129	5.637	10 MeV	3.110	6.423	10 MeV	3.118	9.544	10 MeV
NGC1560	2.969	2.994	1 GeV	2.630	2.647	1 GeV	2.243	2.258	1 GeV	8.859	7.010	1 GeV
NGC2366	2.154	2.116	1 GeV	2.240	2.205	1 GeV	1.932	1.829	100 MeV	1.245	1.968	100 MeV
NGC3274	0.894	0.791	1 GeV	0.830	0.735	1 GeV	0.928	0.873	1 GeV	1.804	1.680	1 GeV
NGC4395	0.762	0.739	1 GeV	0.733	0.711	1 GeV	0.646	0.629	1 GeV	0.994	0.850	1 GeV
NGC4455	0.452	0.450	1 GeV	0.393	0.393	1 GeV	0.630	0.666	1 GeV	1.495	1.692	100 MeV
F5631	0.343	0.336	10 MeV	0.358	0.352	10 MeV	0.360	0.358	10 MeV	0.373	0.377	10 MeV
Isothermal												
DDO47	0.205	0.208	all masses	0.173	0.175	all masses	0.152	0.098	all masses	0.101	0.098	all masses
DDO64	0.423	0.428	all masses	0.423	0.428	all masses	0.413	0.437	all masses	0.439	0.437	all masses
DDO189	0.064	0.074	all masses	0.053	0.125	all masses	0.042	0.047	all masses	0.047	0.047	all masses
UGC4173	0.066	0.070	all masses	0.041	0.040	all masses	0.062	0.116	all masses	0.118	0.116	all masses
UGC4325	0.017	0.018	all masses	0.015	0.021	all masses	0.006	0.126	all masses	0.076	0.126	all masses
NGC1560	4.343	4.304	all masses	4.306	4.373	all masses	4.298	4.301	all masses	2.445	4.301	all masses
NGC3274	0.918	2.296	all masses	0.906	0.964	all masses	0.787	1.132	all masses	1.064	1.132	all masses
NGC3371	0.003	0.005	all masses	0.009	0.012	all masses	0.016	0.543	all masses	0.080	0.543	all masses
NGC4395	0.601	0.602	all masses	0.513	0.507	all masses	0.478	0.464	all masses	0.454	0.464	all masses
NGC4455	0.299	0.309	all masses	0.283	0.333	all masses	0.225	0.458	all masses	0.400	0.458	all masses
F5631	0.203	0.205	all masses	0.217	0.259	all masses	0.261	0.424	all masses	0.427	0.424	all masses

of dark matter particles. It is because pseudo-isothermal profile is a core profile that provide a much lower density of dark matter than NFW profile. The production rate $Q(r, \gamma)$ of dark matter annihilation is not high enough to produce electrons and positrons that can create strong pressure to make any changes for the rotation curves. An example of unchanged rotation curves of NGC4455 are shown in figure 1.

5. Conclusions

We have studied the effects of dark matter pressure created by electrons and positrons from dark matter annihilation to rotation curves of LSB galaxies. We have added dark matter pressure to rotation curves with 4 models of gas and stellar disk components and NFW and pseudo-isothermal dark matter profile. Dark matter pressure effects rotation curves of LSB galaxies with NFW profile significantly but it barely affects the rotation curves with pseudo-isothermal profile. These results indicate that we can apply dark matter pressure to improve the situation of cusp-core problems by using only NFW profile. This might lead to an agreement of a universal dark matter profile for all scales in the Universe.

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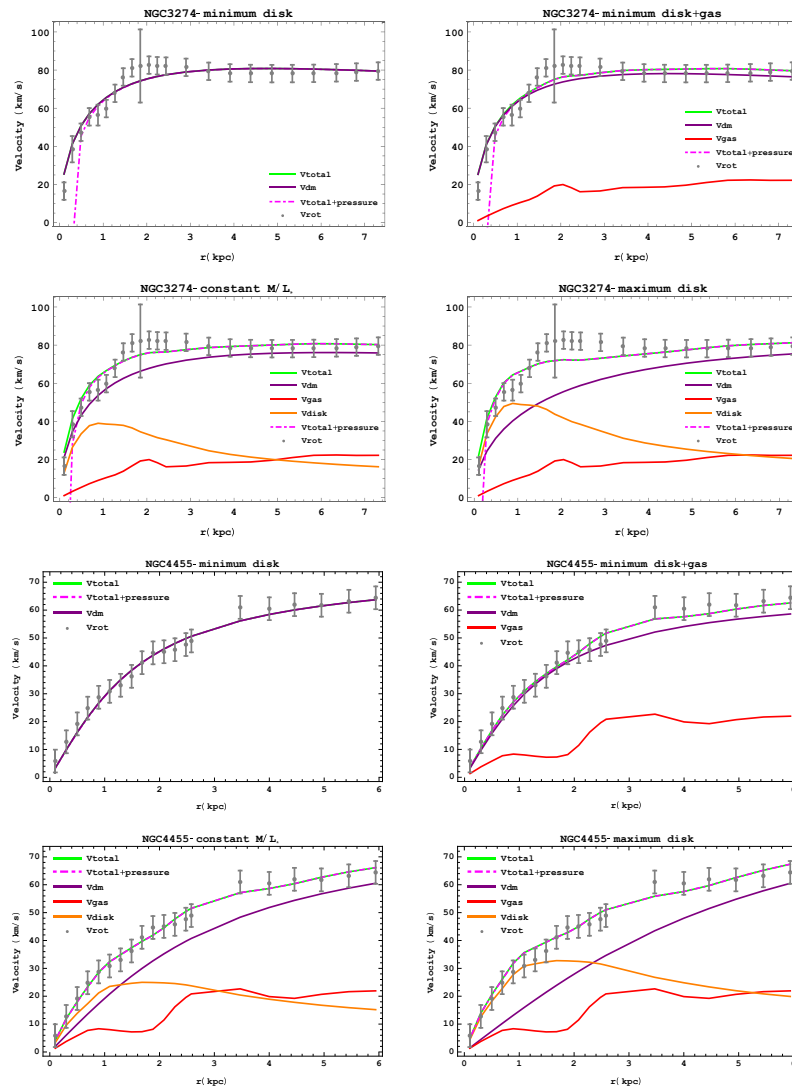


Figure 1. Observed rotation curves (data points with error bars) compared to model predictions for galaxy NGC3274 with NFW profile and galaxy NGC4455 with pseudo-isothermal profile for minimum disk, minimum disk + gas, constant M/L and maximum disk. Solid dark purple lines, solid orange lines, solid red lines, solid green lines and dot-dashed magenta lines are rotation curve due to dark matter, stellar disk, gas, dark matter + stellar disk + gas (from [2]) and dark matter + stellar disk + gas + dark matter pressure (our model), respectively.

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