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Research

Constraints on the dark matter from the relative motion of the galaxies

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Abstract

The method is considered of deriving the dynamical masses of the neighbouring galaxies from their relative motion. The method allows to constrain the dark matter in galaxies, independently of the model of dark matter. The following pairs of galaxies were studied, the Milky Way and M31, Cen A and M83 as well as the brightest galaxies in the Virgo cluster, M87 and M60, M87 and M89, M87 and M49. The dynamical masses of the galaxies obtained from the relative motion of the galaxies are smaller than the total masses of the galaxies obtained in the ΛCDM model.

Keywords: *Dark Matter; Dynamical Mass; Giant Elliptical Galaxies; Giant Spiral Galaxies; Pairs of Galaxies.*

1. Introduction

The kinematics of tracers in galaxies cannot be explained by the luminous matter (Trimble 1987) and references therein. The dark matter was introduced to fill the gap between the dynamical mass of the galaxies probed by the tracers and the baryonic mass of the galaxies. Alternative explanation is given by the modified Newtonian gravity (Famaey & McGuagh 2012). The galaxy formation can be described in the models with cold dark matter (CDM) (Trimble 1987) and references therein. The ΛCDM model is the standard cosmological model (Ostriker & Steinhardt 1995). Nevertheless, there are several open problems of the ΛCDM model on galaxy scales, e.g. (Weinberg et al. 2015, Kroupa 2012, 2015) and references therein.
Usually, the dynamical masses of individual galaxies are explored. Another way is to probe the dynamical masses of galaxies through the gravitational interaction of the neighbouring galaxies. Determination of the enclosed mass of the pairs of galaxies is a difficult task, because in general only the line-of-sight velocity differences and the projected distances between the galaxies are available. One can estimate the enclosed mass of the pairs of galaxies in a statistical way, e.g. (Nottale & Chamaraux 2020). The radial velocity of M31 toward the Milky Way were estimated in Khokhlov (2020), using the dynamical masses of the Milky Way (Khokhlov 2018) and M31 (Khokhlov 2020) obtained in the model with hot dark matter. In the present paper, we shall consider several pairs of galaxies and derive the dynamical masses of the galaxies from their relative motion, independently of the model of dark matter. Using this method, one can obtain model independent constraints on the dark matter in galaxies. We shall consider the pairs of the Milky Way and M31, Cen A and M83 as well as the pairs of the brightest galaxies in the Virgo cluster, M87 and M60, M87 and M89, M87 and M49.

2. The dynamical masses of the pairs of galaxies

The gravitational interaction of the neighbouring galaxies probes the gravitating matter of the galaxies. One can estimate the dynamical mass of the pair of the galaxies from the gravitational interaction of the galaxies. Consider the method of deriving the dynamical mass of the galaxies in the pair from their relative motion. Let two galaxies be in the relative motion due to gravity. In the frame of the second galaxy, the first galaxy moves toward the second galaxy with the velocity

$$v_1 = \left(\frac{2Gm_{dyn,2}}{R_{12}}\right)^{1/2} \qquad (1)$$

Where G is the Newton constant, $m_{dyn,2}$ is the dynamical mass of the second galaxy, R_{12} is the distance between the galaxies. In the frame of the first galaxy, the second galaxy moves toward the first galaxy with the velocity

$$v_2 = \left(\frac{2Gm_{dyn,1}}{R_{12}}\right)^{1/2} \qquad (2)$$

Where $m_{dyn,1}$ is the dynamical mass of the first galaxy. The relative radial velocity of the galaxies is given by

$$v_{12} = v_1 + v_2. \tag{3}$$

For simplicity, suppose that $m_{dyn,1} = m_{dyn,2}$. In this case, $v_1 = v_2 = v_{12} / 2$. Proceeding from eqs. (1,2), the dynamical masses of the galaxies are given by

$$m_{dyn,1} = m_{dyn,2} = \frac{v_{12}^{\ 2} R_{12}}{8G}. \tag{4}$$

The above considered method constrains the average mass of the galaxies in the pair. The method is meaningful for the galaxies of the comparable masses. Using this method, one can obtain the dynamical masses of the galaxies, independently of the model of dark matter.

Consider the pair of the Milky Way and M31 which are the largest galaxies in the Local Group. Both the Milky Way and M31 are giant spiral (late type) galaxies. Estimate the dynamical masses of the Milky Way and M31 from eq. (4). The observational radial velocity of M31 toward the Milky Way is 109.3 ± 4.4 km s^{-1} (van der Marel et al. 2012) at the distance 770 kpc. Calculation gives the dynamical masses of the Milky Way and M31, $m_{dyn,MW} = m_{dyn,M31} = 2.7 \times 10^{11}$ $m_\odot$.

The observational stellar masses of the Milky Way and M31 are $m_{*,\,MW} = (5 \pm 1) \times 10^{10}$ $m_\odot$ (Bland-Hawthorn & Gerhard 2016) and $m_{*,M31} = 1.3 \times 10^{11}$ $m_\odot$ (Corbelli et al. 2010) respectively. The dynamical-to-stellar mass ratio for the pair of the Milky Way and M31 is $m_{dyn,\,MW+M31} / m_{*,\,MW+M31} = 2.9$.

Compare the dynamical masses of the Milky Way and M31 obtained from their relative motion with those obtained from the rotation curves of the galaxies. In the ΛCDM model, the total mass of the Milky Way within the virial radius 282 kpc is $m_{vir,MW} = 1.3 \times 10^{12}$ $m_\odot$ (Bland-Hawthorn & Gerhard 2016), the total mass of M31 within the virial radius 270 kpc is $m_{vir,M31} = 1.3 \times 10^{12}$ $m_\odot$ (Corbelli et al. 2010). The total masses of the Milky Way and M31 obtained in the ΛCDM model are 5 times larger than the dynamical masses of the Milky Way and M31 obtained from their relative motion.

Consider the pair of Cen A and M83 which are the central galaxies of the subgroups of the complex CenA/M83 group. Cen A is a giant elliptical (early type) galaxy, and M83 is a giant spiral (late type) galaxy. Estimate the dynamical masses of Cen A and M83 from eq. (4).

The observational radial velocity of Cen A outward M83 is 35 km s^{-1} (Karachentsev et al. 2007) at the distance 1.73 Mpc. Calculation gives the dynamical masses of Cen A and M83 due to the radial motion, $m_{dyn,rad,CenA} = m_{dyn,rad,M83} = -\,0.6 \times 10^{11}$ $m_\odot$. The observational relative tangential velocity of Cen A and M83 is 69 km s^{-1} (Karachentsev et al. 2007). For the tangential motion, one should replace the factor 1/8 in eq. (4) by the factor 1/4. Calculation gives the dynamical masses of Cen A and M83 due to the tangential motion, $m_{dyn,tan,CenA} = m_{dyn,tan,M83} = 4.8 \times 10^{11}$ $m_\odot$. The total dynamical masses of Cen A and M83 are $m_{dyn,CenA} = m_{dyn,M83} = 4.8 - 0.6 = 4.2 \times 10^{11}$ $m_\odot$.

The stellar masses of Cen A and M83 can be obtained from their luminosities in the K-band taken from 2MASS, $L_{K,CenA} = 1.5 \times 10^{11}$ $L_\odot$ and $L_{K,M83} = 0.7 \times 10^{11}$ $L_\odot$. The stellar mass-to-light ratio, $m_{*,\odot} / L_{K,\odot} = 1$, gives the stellar masses of Cen A and M83, $m_{*,CenA} = 1.5 \times 10^{11}$ $m_\odot$ and $m_{*,M83} = 0.7 \times 10^{11}$ $m_\odot$, respectively. The dynamical-to-stellar mass ratio for the pair of Cen A and M83 is $m_{dyn,CenA+M83} / m_{*,CenA+M83} = 3.8$. This is larger than the value 2.9 for the pair of the Milky Way and M31.

Compare the dynamical masses of Cen A and M83 obtained from their relative motion with those obtained in the ΛCDM model. The total masses of Cen A and M83 in the ΛCDM model can be obtained from the stellar mass - halo mass relation (Behroozi et al. 2013). We shall take the halo masses in the low limit. Then, the halo masses of Cen A and M83 are $m_{h,CenA} = 1.5 \times 10^{13}$ $m_\odot$ and $m_{h,M83} = 3.0 \times 10^{12}$ $m_\odot$, respectively. The total masses of Cen A and M83 obtained in the ΛCDM model are larger than the dynamical masses of Cen A and M83 obtained from their relative motion by factors of 36 and 7 respectively.

Consider the gravitational interaction of the brightest galaxies in the Virgo cluster. We shall consider the motion due to gravity of the galaxies M60, M89, M49 toward M87 situated in the centre of the Virgo cluster. All the galaxies are giant elliptical (early type) galaxies.

Consider the pair of M87 and M60. Estimate the dynamical masses of M87 and M60 from eq. (4). The radial velocity of M60 toward M87 obtained from the X-ray data analysis is 1030 km s^{-1} (Wood et al. 2017) at the distance 0.97 Mpc. Calculation gives the dynamical masses of M87 and M60, $m_{dyn,M87} = m_{dyn,M60} = 3.0 \times 10^{13}$ $m_\odot$.

The stellar masses of M87 and M60 can be obtained from their luminosities in the V-band taken from NED, $L_{V,M87} = 1.34 \times 10^{11}$ $L_\odot$ and $L_{V,M60} = 1.05 \times 10^{11}$ $L_\odot$. Taking the stellar mass-to-light ratio, $m_{*,\odot} / L_{V,\odot} = 6$, the stellar masses of M87 and M60 are estimated to be $m_{*,M87} = 8 \times 10^{11}$ $m_\odot$ and $m_{*,M60} = 6.3 \times 10^{11}$ $m_\odot$ respectively. The dynamical-to-stellar mass ratio for the pair of M87 and M60 is $m_{dyn,M87+M60} / m_{*,M87+M60} = 42$.

Consider the pair of M87 and M89. Estimate the dynamical masses of M87 and M89 from eq. (4). The radial velocity of M89 toward M87 obtained from the X-ray data analysis is 1680 km s^{-1} (Machacek et al. 2006) at the distance 0.35 Mpc. Calculation gives the dynamical masses of M87 and M89, $m_{dyn,M87} = m_{dyn,M89} = 2.9 \times 10^{13}$ $m_\odot$.

The stellar mass of M89 can be obtained from the luminosity in the V-band taken from NED, $L_{V,M89} = 4.39 \times 10^{10}$ $L_\odot$. Taking the stellar mass-to-light ratio, $m_{*,\odot} / L_{V,\odot} = 6$, the stellar mass of M89 is estimated to be $m_{*,M89} = 2.6 \times 10^{11}$ $m_\odot$. The dynamical-to-stellar mass ratio for the pair of M87 and M89 is $m_{dyn,M87+M89} / m_{*,M87+M89} = 55$.

Consider the pair of M87 and M49. Estimate the dynamical masses of M87 and M49 from eq. (4). The radial velocity of M49 toward M87 obtained from the kinematics analysis is 750 km s^{-1} (Gavazzi et al. 1999) at the distance 1.35 Mpc. Calculation gives the dynamical masses of M87 and M49 due to the radial motion, $m_{dyn,rad,M87} = m_{dyn,rad,M49} = 2.2 \times 10^{13}$ $m_\odot$. The observational relative tangential velocity of M49 and M87 is 310 km s^{-1} (Smith et al. 2000). For the tangential motion, one should replace the factor 1/8 in eq. (4) by the factor 1/4. Calculation gives the dynamical masses of M87 and M49 due to the tangential motion, $m_{dyn,tan,M87} = m_{dyn,tan,M49} = 0.7 \times 10^{13}$ $m_\odot$. The total dynamical masses of M87 and M49 are $m_{dyn,M87} = m_{dyn,M49} = 2.2 + 0.7 = 2.9 \times 10^{13}$ $m_\odot$.

The stellar mass of M49 can be obtained from the luminosity in the V-band taken from NED, $L_{V,M49} = 1.78 \times 10^{11}$ $L_\odot$. Taking the stellar mass-to-light ratio, $m_{*,\odot} / L_{V,\odot} = 6$, the stellar mass of M49 is estimated to be $m_{*,M49} = 10.7 \times 10^{11}$ $m_\odot$. The dynamical-to-stellar mass ratio for the pair of M87 and M49 is $m_{dyn,M87+M49} / m_{*,M87+M49} = 31$.

Compare the dynamical mass of M87 obtained from the motion of M60, M89, M49 toward M87 with that obtained from the rotation curve of M87 in the ΛCDM model. Oldham & Auger (2016) used kinematics of the globular clusters and satellite galaxies to explore the mass distribution in M87. They considered ΛCDM model with four dark matter profiles as well as isotropic and anisotropic stellar profiles. For NFW dark matter profile and isotropic stellar profile, the total mass of M87 within the virial radius $R_{vir} = 1.6$ Mpc is $m_{vir,M87} = 2.5 \times 10^{14}$ $m_\odot$. The total mass of M87 within the radius 0.35 Mpc (distance to M89) is ~ 4.5×10^{13} $m_\odot$, within the radius 0.97 Mpc (distance to M60) ~ 1.5×10^{14} $m_\odot$, within the radius 1.35 Mpc (distance to M49) ~ 2.0×10^{14} $m_\odot$. The total mass of M87 obtained in the ΛCDM model is larger than the dynamical mass of M87 obtained from the motion of M60, M89, M49 toward M87 by a factor of 1.5 at 0.35 Mpc, by a factor of 5 at 0.97 Mpc and by a factor of 7 at 1.35 Mpc.

The total mass of M87 can be estimated from the X-rays data of the Virgo Cluster centered on M87. Simionescu et al. (2017) presented X-rays mapping of the Virgo Cluster based on the Suzaku data. Within the framework of the ΛCDM model with NFW dark matter profile, they obtained a virial mass of $m_{200} = 1.05 \times 10^{14}$ $m_{\odot}$ within the radius $R_{200} = 0.97$ Mpc. This mass exceeds that obtained from the motion of M60 toward M87 by a factor of 3.5 (the distance from M87 to M60 is the same as $R_{200} = 0.97$ Mpc).

The dynamical mass of M87 obtained from the relative motion of the galaxies is smaller than the total mass of M87 obtained in the ΛCDM model from the rotation curve and from the X-rays data. The dynamical mass of M87 obtained from the relative motion of the galaxies does not vary with the radius in the range 0.35-1.35 Mpc. Also, it does not vary with the stellar masses of the galaxies in the range $m_* = (2.6 - 10.7) \times 10^{11}$ $m_{\odot}$. The results obtained may evidence for the existence of two types of dark matter, the first in the galaxies Milky Way, M31, Cen A, M83, and the second in the galaxies M87, M60, M89, M49.

3. Conclusion

We have derived the dynamical masses of the neighbouring galaxies from their relative motion. The method applied is independent of the model of dark matter and allows to constrain the dark matter in galaxies. We have considered several pairs of galaxies. For simplicity, we have supposed that the galaxies in a pair are of the same mass. The dynamical masses obtained in this way constrain the average mass of the galaxies in the pair.

We have considered the pairs of the Milky Way and M31, Cen A and M83, and derived the dynamical masses of the galaxies from their relative motion. The dynamical-to-stellar mass ratio for the pair of the Milky Way and M31 is 2.9 and for the pair of Cen A and M83 is 3.8. The dynamical masses of the galaxies obtained from the relative motion of the galaxies are smaller than the total masses of the galaxies obtained in the ΛCDM model.

We have considered the pairs of the brightest galaxies in the Virgo cluster, M87 and M60, M87 and M89, M87 and M49, and derived the dynamical masses of the galaxies from their relative motion. The dynamical masses of the galaxies obtained are $(2.9\text{-}3.0) \times 10^{13}$ $m_{\odot}$ in the range of the distances between the galaxies 0.35-1.35 Mpc. The dynamical-to-stellar mass ratio for the galaxies are in the range 31-55. The dynamical mass of M87 obtained from the relative motion of the galaxies is smaller than the total mass of M87 obtained in the ΛCDM model.

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