IRANIAN JOURNAL OF PHYSICS RESEARCH

Iranian Journal of Physics Research, Vol. 24, No. 3, 2024
DOI: 10.47176/ijpr.24.3.91755

Review of the measurements and results of the Coma cluster dark mass

M Ramazanoghly[*] and A Shariati
Department of Physics, Faculty of Physics and Chemistry, Alzahra University, Tehran, Iran

E-mail: mallaliramazan@gmail.com
a.shariati@alzahra.ac.ir

(Received 19 September 2023 ; in final form 12 February 2024)

Abstract
We have examined data from 852 Coma cluster galaxies from three different catalogs and grouped them according to their velocity and magnitude in two fields to survey the core (Coma1) and the periphery (i.e. southwest of the core and centered on NGC4839; Coma3). We have identified a group of these galaxies that appear to be a dense cluster (main cluster) of 545 galaxies (430 in Coma1 and 115 in Coma3) at a distance of 104 Mpc. Furthermore, we have calculated their kinetic energy ($10^{54 \pm 0.6}$ J) and potential energy ($10^{54 \pm 0.7}$ J) using observational data. Then we calculated the total mass ($10^{45 \pm 0.3}$ kg) using luminosity and from the virial theorem, we obtained the virial mass ($10^{47 \pm 0.4}$ kg), that the virial mass was greater than the total mass of the galaxies in the cluster. These galaxies cover the range of $12.7 < R < 22.7$, which corresponds to, $-22.5 < M_R < -12.5$ ($H = 67.4 \pm 0.5$ km s^{-1} Mpc^{-1}) and the velocity of this set is in this range (1000 km s^{-1} < v < 10000 km s^{-1}). Our sample is 95% complete in redshift up to a magnitude $b_{26.5} = 18.0$ mag.

Keywords: Coma cluster, dark Matter, galaxies, Coma galaxy cluster

1. Introduction

The Coma cluster is a group of galaxies centered in the constellation Coma Berenice, Some of these galaxies are so close together, that they form a gravitational bounded set. In this article, i estimate the dark matter mass of the Coma cluster using galaxy luminosity and virial mass. Fritz Zwicky was the first to investigate the mass of the Coma cluster. In [1], He showed that the virial mass of galaxy clusters is much larger than their total mass, indicating the presence of dark matter in galaxy clusters and its impact on their mass and size. In [2], a list of the velocities of 305 masses in the Coma cluster in its central regions is provided. This list includes two areas; The center of Coma1, which includes the galaxies (NGC4889 and NGC4874) with a number of 271 galaxies, and the outskirts of Coma3, which includes the galaxy (NGC4839) with a number of 34 galaxies, with the coordinates in the range α = [12h 57.3m], δ = [28° 14.4′] is presented and table 1, shows a sample line from this catalog. In [3], examine the spectroscopic and photometric properties of dwarf and giant galaxies in the Coma cluster. Two fields were selected for spectroscopic observations, one in the Coma1 core with 302 masses and another in the southwestern outskirts of the core with center (NGC4839), containing 188 masses. The information from these catalogs is presented in table 3. In [4] To investigate the members of the Coma cluster, the special structural and kinematic differences between early and late-type galaxies, and between dwarf and giant galaxies were considered. As a result, this study 187 masses in the Coma cluster with the coordinates in the range α = [12h 57.3m], δ = [28° 14.4′] is presented, which are a sample list in table 2.

2. The catalogue

By merging the data (tabales 1, 2, 3) which includes 852 galaxies in Coma1 (NGC4889 and NGC4874) and Coma3 (NGC4839) regions, table 4 shows an example of this data.

1. Date, Catalog of these years.
2. GMP number, when available; an asterisk indicates that the number corresponds to the unpublished star catalogue of the same authors.
3. NGC/IC/D number.
4. Right ascension in degrees [J2000].
5. Declination in degrees [J2000].
6. Magnitude b26.5 from the GMP catalogue.
7. Color (b-r) from the GMP catalogue.
8. Heliocentric velocity, cz, in km s^{-1}.
9. Comment, displays cluster membership.

Table 1. A list of Coma Clsuter data [2].

GMP	N-gxy	X	Y	m	b-r	cz	Comm
3561	NGC4865	335	409	14.54	1.83	4809	C1

Note: Units of right ascension and declination are arcsec in [B1950].

Table 2. A list of Coma Cluser data [5].

GMP	N-gxy	X	Y	m	b-r	cz	Comm
2374	NGC4911	16.15	-10.85	13.91	1.67	7987	C1

Note: Units of right ascension and declination are arcmin in[B1950].

Table 3. A list of coma cluster data [7].

GMP	N-gxy	RA	Dec	m	b-r	cz	Comm
2149		13 0 25.16	27 33 7.89	16.08	1.53	7230	C1

Note: Units of right ascension are hours, minutes, seconds and units of declination are degrees, arcminutes, arcseconds in [J2000].

Table 4. A list of coma cluster data that I sorted.

Date	GMP	N-gxy	RA	Dec	m	b-r	cz	Comm
1995	3201	NGC4876	194.93	28.91	15.51	1.91	6629	C1
2001	57916		194.83	27.97	17.04	1.53	7200	C1
2004	3400	IC 3973	194.88	28.88	15.32	1.88	4722	C1

Note: Units of right ascension and declination are degrees.

Now, from the data in table (4), we plot a diagram of right ascension and declination of galaxies. The right ascension represents the distribution of galaxies in our line of sight, while the declination represents their dispersion in space. Figure1a, shows the distribution and scatter of galaxies in our line of sight, using the data in table(4), which includes two separate fields. Two galaxies (NGC4889 and NGC4874) are located in the central region of Coma1 and one galaxy (NGC4839) is located in the outskirts of Coma3, marked in red. Figure 1b, shows the right ascension and declination of galaxies in a certain range of velocities (main cluster), with the majority of galaxies located in the center of Coma1.

3. Analysis of recessional velocity distribution from a terrestrial perspective

Based on table (4), we have a number of databases whose velocity distribution we want to obtain. In Fig 2a between 2000 km s^{-1} and 175000 km s^{-1} the distribution of the recessional velocities are drawn, where the solid curve is the continuous distribution being fit using the [histogram] algorithm. It is seen that the distribution is the superposition of two separate almost-Gaussian distributions. In figure 2b the distribution of galaxies with recessional velocity less than 10000 km s^{-1} is drawn. The dotted red curve is the best fit Gaussian with parameters

$$\bar{v} = 6979 kms^{-1}, \sigma = 1085 kms^{-1}, \qquad (1)$$

Assuming that all 545 galaxies in the Coma cluster are at approximately the same distance from us, we estimated their distance based on the peak of their velocity distribution function, which also gave us their mean velocity(1). According to Hubble's law, v represents the radial velocity of a galaxy, d represents the distance of the galaxy from Earth in units of (Mpc), and H_0 is the Hubble's constant (67.4 ± 0.5 km s^{-1} Mpc^{-1}) [5], which is estimated to be around

$$v = H_0 d, \qquad (2)$$

the velocity of these galaxies is proportional to their distance, which shows that they are all at the same distance from us [6]. Using the Hubble formula, we can estimate this distance to be about 104 Mpc. However, if we interpret the other velocities of this group as Hubble's velocity, it turns out that this set of galaxies is located at a distance of

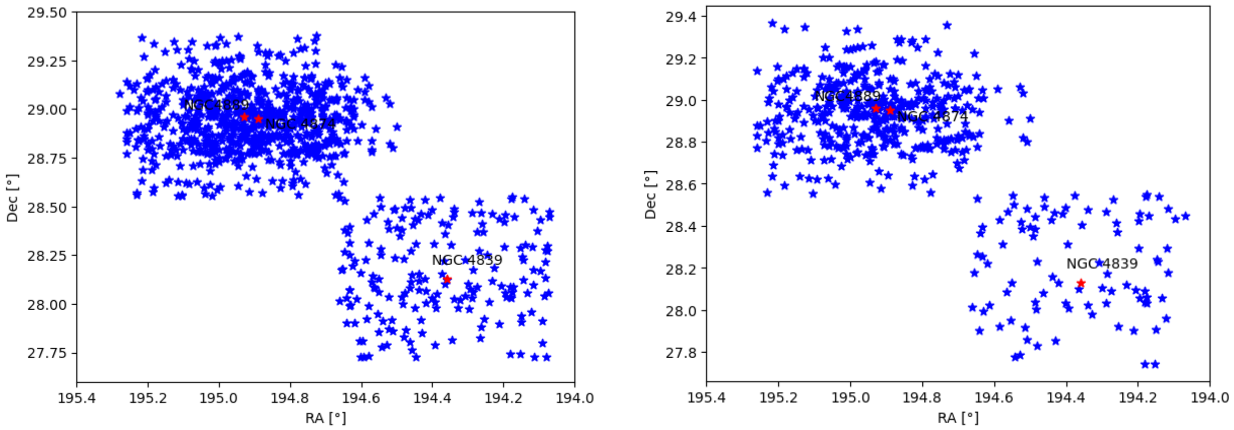
$$v_{\max} = 9889 kms^{-1}, d_{\max} = 98 h_{100}^{-1} Mpc, \qquad (3)$$

$$v_{\min} = 4732 kms^{-1}, d_{\min} = 47 h_{100}^{-1} Mpc, \qquad (4)$$

The size of this galaxy cluster is about 51 Mpc, and if so, the gravitational effect of these galaxies is very small, and there is almost no connection between them.

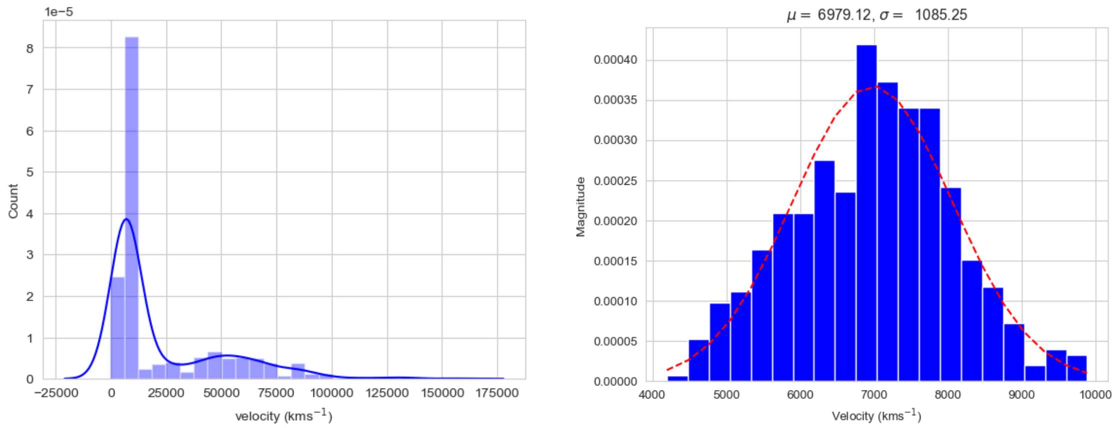
Now, we will plot the magnitude versus recessional velocity for different ranges of galaxies velocities. In figure 3a, displays the distribution of galaxies velocities from (0 − 200, 000 km s^{-1}), where numerous scattered and distant galaxies can be observed. In figure 3b, depicts the velocities of the galaxies in the range of (3, 000 − 12, 000 km s^{-1}), which corresponds to the main cluster of this galaxy group and includes 545 galaxies known as the main cluster.

In figure 3b, the points are uniformly distributed in a vertical rectangle. If we interpret all velocities as Hubble's law (Internal velocity of the cluster), we conclude that as the galaxies in this cluster move farther away from us, the distribution and average apparent magnitude of the galaxies do not change, although we must accept that more distant galaxies are brighter. Accepting this fact is not an easy task. A simpler argument is that this collection of approximately 545 galaxies is at a uniform distance of 1 Mpc from us, forming a primary cluster of galaxies. If we imagine the image of this collection of galaxies, it would appear as a circle with a diameter of 0.7° = 0.012rad in the sky, which corresponds to a 1Mpc diameter circle at a distance of 104Mpc. This is a very reasonable assumption.



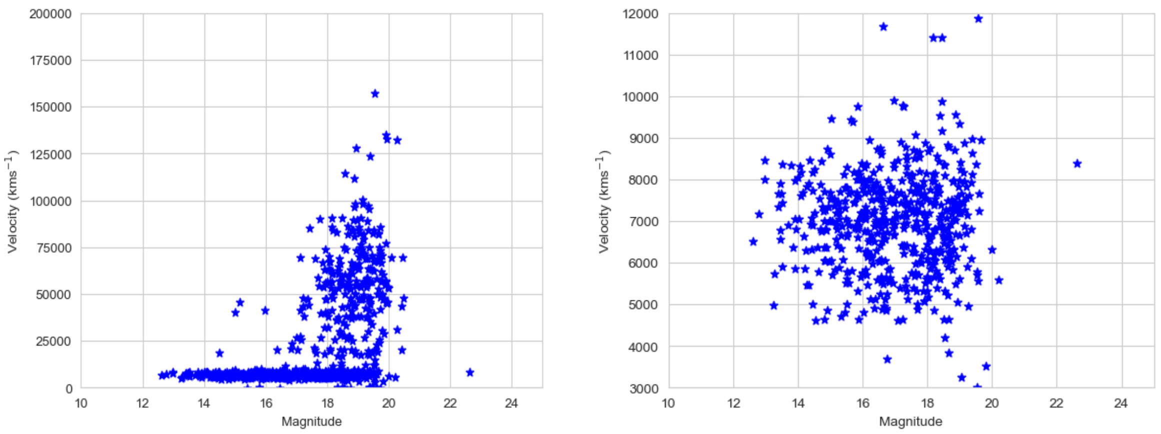
a b

Figure1. In figure (a), the horizontal axis shows the distribution of galaxies in our line of sight, and the vertical axis shows their spatial distribution based on the data in table 4. It shows two separate fields, with two galaxies (NGC4874 and NGC4889) at the center of Coma1 and one galaxy (NGC4839) at the center of Coma3, shown in red star. Figure (b) shows the right ascension and declination of galaxies in the Coma cluster within a certain range of velocities (3000 − 10000 km s^{-1}), with two galaxies (NGC4874 and NGC4889) at the center of Coma1 and one galaxy (NGC4839).



a b

Figure 2. The distribution of velocities in the Coma cluster galaxies is shown in figure (a), where each line represents a galaxy, and the position of the line on the horizontal axis indicates the recession velocity of that galaxy. Some galaxies appear to be very far apart, while others are close together, and a few appear to be concentrated at a certain distance. In figure(b) shows the distribution of the main subset of galaxies in the velocity range of (3000 − 10000) km s^{-1} where a Gaussian curve is fitted with a red line. The mean velocity of this subset is v_{mean} = 6979 km s^{-1} and its standard deviation is σ = 1085 km s^{-1}.



a b

Figure 3. The horizontal axis represents the apparent magnitude, while the vertical axis represents the recessional velocity from the ground observer. If we interpret this recessional velocity as a Hubble, the vertical axis will be a multiple of the distance from the galaxy to us. figure (a) in the velocity range (0 − 200000 km s^{-1}), which are moving away from us at a very high velocity. Figure (b) is drawn in the velocity range (3000 − 12000 km s^{-1}), which is the main set (main cluster).

In figure 3b, the points are uniformly distributed in a vertical rectangle. If we interpret all velocities as Hubble's law (Internal velocity of the cluster), we conclude that as the galaxies in this cluster move farther away from us, the distribution and average apparent magnitude of the galaxies do not change, although we must accept that more distant galaxies are brighter. Accepting this fact is not an easy task. A simpler argument is that this collection of approximately 545 galaxies is at a uniform distance of 1 Mpc from us, forming a primary cluster of galaxies. If we imagine the image of this collection of galaxies, it would appear as a circle with a diameter of 0.7º = 0.012rad in the sky, which corresponds to a 1 Mpc diameter circle at a distance of 104 Mpc. This is a very reasonable assumption.

4. Analysis of galaxies luminosity

Galaxy luminosity measures the amount of radiation emitted by galaxies, including visible light. It depends on the radiation from stars and hot gases and dust within them. The luminous energy flux of a celestial body on Earth is represented by L, and distance from us d

$$\phi = \frac{L}{4\pi d^2}, \quad (5)$$

We have the maximum and minimum distance using Hubble's formula (2)

$$d_{\max} = 105 Mpc, d_{\min} = 103 Mpc \quad , \quad (6)$$

Therefore, it is reasonable to consider this set for all galaxies according to the distance model and calculate the average, minimum and maximum absolute value, which is equal to

$$\overline{M} = -18.2, M_{\max} = -12.49, M_{\min} = -32.86 \quad , \quad (7)$$

In the above, we obtained the mean, minimum, and maximum absolute magnitude, and using these values, the corresponding values of luminosity were determined

$$\overline{L} = 2.4 \times 10^{12} L_{sun}, \quad (8)$$

$$L_{\max} = 1.2 \times 10^{14} L_{sun}, \quad (9)$$

$$L_{\min} = 7.0 \times 10^{8} L_{sun}, \quad (10)$$

5. Estimation of kinetic energy in the center-of mass reference frame

The motion of galaxies and matter within clusters is related to their kinetic energy, which can be calculated based on their radial velocity and total mass. To determine the kinetic energy in the center-of-mass reference frame, we measure the radial velocities of galaxies relative to the center of mass and determine the total mass using the luminosity of galaxies. Then the kinetic energy can be calculated using the following equation [7]

$$K = \frac{1}{2} MN\sigma^2, \quad (11)$$

In the above equation, M represents the mass of the galaxy, σ represents the radial velocity, and k represents the kinetic energy of the galaxy. The mass-to-luminosity ratio is constant for galaxies, using this assumption, we can estimate the mass of the galaxies in our catalog based on their absolute

magnitude. For galaxies, this ratio is roughly equal to $M_{sun}/L_{sun} = 5\times10^3$, So the mass of galaxies is

$$M = 2.1\times10^{45} \pm 0.3 kg \quad , \quad (12)$$

The total kinetic energy of the 545 galaxies can be estimated by summing their masses, approximately 3.7 × 10^{57} J. So the mean kinetic energy is

$$\bar{k} = 3.2\times10^{54} \pm 0.6 \quad , \quad (13)$$

Now, we estimate the kinetic energy with another method. The mean squared velocity in the center of mass frame for the 545 galaxies is approximately $3 \times \sigma^2 \simeq 3 \times 10^{12}\ m^2 s^{-2}$. Assuming the mean mass of the galaxies based on their luminosity to be $M \simeq 2.4 \times 10^{12}$ Msun$\simeq 4.4 \times 10^{42}$ kg, we can calculate the mean kinetic energy

$$\bar{k} = 6.6\times10^{54} \pm 0.6 \quad , \quad (14)$$

Certainly, This value is approximately the numerical result we obtained. Given these two numbers

$$\bar{k} = 10^{54} \pm 0.6 \quad , \quad (15)$$

it is a reasonable estimation.

6. Estimation of potential energy

Estimating the potential energy of galaxies is crucial for understanding the distribution of mass within them and their gravitational impact on other galaxies and matter. This calculation involves determining the total mass of the galaxies (MN), their distances from each other (R), and the gravitational constant

$$U = -\frac{2}{5}\frac{G(MN)^2}{R} \quad , \quad (16)$$

We have the total mass MN = $1.0 \times 10^{45} \pm 0.3$ kg. now we assume that it is uniformly distributed in a sphere with a diameter of 1 Mpc, that the total potential energy is equal to $U \simeq -3.5\times10^{57}$ J using the above equation (16). So the average potential energy is equal to

$$\overline{U} = -3.7\times10^{54} \pm 0.7 \quad (17)$$

The very interesting thing about this cluster is that the amount of kinetic energy is slightly higher than the amount of potential energy. In other words, this galaxy cluster works in a limited way, and if the distance between the galaxies increases too much, the cluster may not merge anymore, which is very strange. This result is strange because it shows that the Coma galaxy cluster is not a finite system

$$T = 500 My \quad , \quad (18)$$

In [8] over time, the radius of the Coma galaxy cluster nearly doubles. Simply put, this galaxy cluster rotates around its center but is not confined to its cosmic background. It moves around without changing its shape. On the other hand, several hundreds of galaxies within this cluster have been thrown to different parts of the universe and are not gravitationally connected to each other. However, after a while, they all gather in one place, which is a very rare occurrence in the world. In other words, this galaxy cluster appears to be tightly bounded and in a state of dynamical equilibrium. Based on these features, we can conclude that this galaxy cluster was probably in a similar state in the past, and that its deformation was much

less than what we observe now. Therefore, this cluster should be strictly limited.

7. The Virial theorem

The Virial theorem relates the kinetic and gravitational potential energy of objects within a galaxy cluster. If the kinetic energy is less than the gravitational potential energy, the cluster collapses and reaches a state called ”virial”. The virial mass represents the mass required for dynamic equilibrium. This theorem applies to a system of masses in dynamic equilibrium that relates their average kinetic energy and potential. And the virial theorem [9] is

$$K=-\frac{1}{2}U, \tag{19}$$

If we assume that a cluster of Coma galaxies (545 galaxies) are in dynamic equilibrium, we can assign a specific mass to the cluster using the virial theorem. This mass is known as viral mass. If M_{vir} represents the mass of the cluster and N the number of galaxies in the cluster, the average mass of each galaxy is M_{vir}/N . If σ represents the standard deviation of the radial velocities, the standard deviation of the velocities at the center of the frame will be 3 σ. Let’s assume that N galaxies are located within a sphere of radius R, and their distribution is uniform. So

$$M_{vir}=2.3\times10^{47}\pm0.4kg=1.1\times10^{17}\pm0.4M_{sun} \quad , \tag{20}$$

The Coma cluster galaxies are not uniformly distributed, with a higher density towards the center. The average mass of the 545 galaxies is estimated to be around 10^{45} kg = 10^{15} Msun, based on their luminosity. This difference is due to the presence of dark matter, which has a much greater mass than observable matter and contributes to the cluster’s weight through its gravitational effect. Some of this matter is visible and includes cold hydrogen clouds, dwarf galaxies, low-luminosity stars, or even non-baryonic matter.

8. Dark matter density

Given the estimated viral mass of 10^{47} kg, for the 545 galaxies in the Coma cluster, which are distributed in a sphere with a radius of 1Mpc, the volume of the sphere is approximately 10^{68} m^3 [10]. The mean density becomes almost equal

$$\bar{\rho}=10^{-21}kgm^{-3}, \tag{21}$$

Dark matter has a lower density than ordinary matter, and its particles are composed of fundamental particles that have a mass one hundred times that of a proton. Due to their low abundance per unit volume, detecting these elusive particles in terrestrial laboratories is challenging. This challenge requires sensitive and precise instruments for detection. Despite the difficulties, extensive efforts have been made to detect and identify dark matter in terrestrial experiments, including the use of sensitive detectors, particle accelerator experiments, and the analysis of observational data on the gravitational effects of dark matter in galactic systems. The use of telescopes and spacebased observational systems is also of great importance in studying and investigating dark matter and its role in the structure and motion of galaxy clusters.

9. Summary and Conclusion

Based on the velocities of the galaxies, we isolated about 852 galaxies in the Coma cluster, according to their velocity distribution, 545 galaxies have a Gaussian velocity distribution. Which is the mean velocity v_{mean} = 6979 km s^{-1} and standard deviation σ = 1085 km s^{-1}. We interpret the mean velocities as hobble’s, so the cluster is approximately at this distance 104 Mpc. Not only that, but we consider the velocity deviation at the center of the mass frame, from which we obtained the kinetic energy (10^{54}±0.6 J) and estimated the potential energy (10^{54}±0.7 J). Then, By using the total luminosity, we obtained the total mass $10^{45} \pm 0.3$ kg $\simeq 10^{15}$ Msun and estimated the virial mass $10^{47} \pm 0.4$ kg $\simeq 10^{17}$ Msun using the Virial Theorem. As a result, the virial mass is greater than the total mass, suggesting that the components of this cluster may be cold hydrogen or non-baryonic matter.

References

1. F Zwicky, “*A Source Book in Astronomy and Astrophysics*”, Harvard University Press (1979).
2. A Biviano, et al., *Astron. Astrophys. Suppl.* **111**, 265 (1995) .
3. B Mobasher, et al., *Astrophys. J. Suppl. Ser.* **137**, 2 (2001) 279.
4. C M Gutiérrez, et al., *Astrophys. J.* **602**, 2 (2004)664.
5. N Aghanim, et al., *Astronom. Astrophys*. **641**, A6. (2020).
6. A Liddle, “*An introduction to modern cosmology*”, John Wiley & Sons (2015).
7. B Ryden, “*Introduction to cosmology*” Cambridge University Press (2017).
8. A Shariati, The dark mass of the coma cluster, (2010).
9. H Goldstein, C Poole, and J Safko, “*Classical mechanics. American association of physics teachers*” (2002).
10. B W Carroll and D A Ostlie, “*An introduction to modern astrophysics*” Cambridge University Press (2017).