Demonstrating the Absence of a Dark Matter Halo in M82 with its Mass-to-Light Ratio

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The search for dark matter has been a central focus in astrophysics since the term was first coined by Zwicky in 1933. This report builds on the pioneering work of Rubin et al. (1980), employing a multi-faceted approach to investigate the dark matter content of the spiral galaxy M82. Through analysis of its rotation curve from HI and CO emission lines, as well as luminosity calculations via CCD photometry in the V-band, we determine the mass-to-light ratio of M82 to be $(0.6 \pm 0.8)\Upsilon_\odot$, an order of magnitude lower than that of Andromeda, and demonstrate that the rotation curve is Keplerian, consistent with that of a galaxy with mass concentrated in the central bulge. We conclude that M82 lacks an extended dark matter halo, challenging prevailing theories of dark matter distributions in spiral galaxies.

I. INTRODUCTION

Hubble, in 1936, classified regular galaxies as either spiral, or elliptical, according to his Hubble Sequence [1]. Spirals are split into sub-classes, but they all feature a bright bulge containing most of the stellar mass, and a thin disk of coiled, spiral arms [2]. The disk is made up of gas clouds, dust and stars, which rotate on nearly circular orbits [3].

The rotation curve of a galaxy is a plot of the rotational velocity, v, of matter on its disk against distance, R, from the galactic centre. Light spectra from different regions of the galaxy are measured, the frequency shift of emission lines, often HI and CO, are recorded, and velocity is obtained via the Doppler shift equation,

$$\frac{v}{c} = \frac{f_e - f_0}{f_0}, \tag{1}$$

where v denotes the rotational velocity of the gas, c the speed of light in a vacuum, f_e the emitted frequency, and f_0 the frequency measured on Earth [4]. Note that this gives the component of velocity parallel to the line joining the galaxy and observer, we can correct for this,

$$v = \frac{c}{\sin\phi_i}\frac{f_e - f_0}{f_0}, \tag{2}$$

where ϕ_i denotes the angle of inclination of the galaxy [5].

Galaxies can also be investigated through optical photometry. Apparent V-band magnitude, m_V, is calculated from photon counts, c, measured by a CCD via the equation

$$m_V = -2.5\log_{10}(c/t_{\text{exp}}) + z, \tag{3}$$

where t_{exp} is the exposure time, and z is the zero-point of the image. From this, absolute V-band magnitude, M_V, is calculated as

$$M_V = m_V + 5 - 5\log_{10}(D(\text{pc})), \tag{4}$$

where $D(\text{pc})$ is the distance to M82 in parsecs. Finally, the V-band luminosity is calculated from the absolute magnitude by

$$L_V = L_{\odot V}10^{(M_{\odot V} - M_V)/2.5}, \tag{5}$$

where $L_{\odot V}$ and $M_{\odot V}$ are the V-band luminosity and absolute magnitude, respectively, of the Sun.

The mass-to-light ratio, Υ, of a galaxy is the ratio of its total mass to its luminosity,

$$\Upsilon = \frac{M}{L}. \tag{6}$$

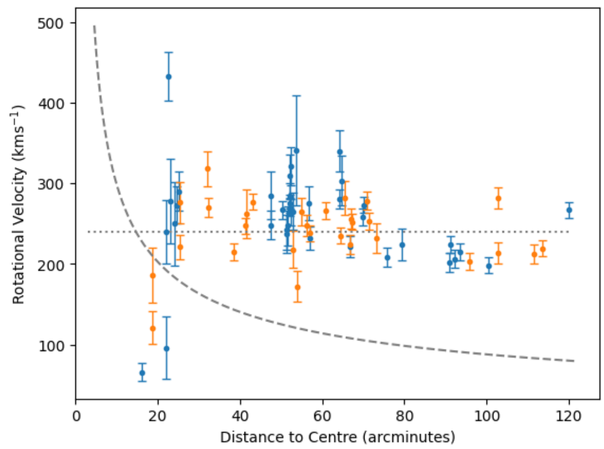

FIG. 1: Rotation curve for Andromeda (M31), as measured by Rubin et al. in 1970 [6], for both positive (blue) and negative (orange) directions from the centre. In both directions, the rotational velocity increases linearly until 30 arcminutes, then remains approximately constant beyond. Rotation curves for a point mass (dashed) and for a mass density $\rho(R) \propto 1/R^2$ (dotted) are indicated.

Under the assumption that every star in the galaxy is Sun-like, we can express Υ in terms of the solar mass-to-light ratio $\Upsilon_\odot = M_\odot/L_\odot$, giving an approximate ratio of total mass to luminous mass in the galaxy.

By Newton's law of gravitation, the acceleration felt by a test mass R from the centre of the galaxy, assuming a spherical mass distribution, is given by

$$a = \frac{GM_{\text{enc}}(R)}{R^2}, \tag{7}$$

where G denotes the gravitational constant, and $M_{\text{enc}}(R)$ the mass enclosed within R. Assuming the test mass moves in circular orbit about the centre of the galaxy with velocity v, we can equate Equation (7) to its centripetal acceleration,

$$\frac{GM_{\text{enc}}(R)}{R^2} = \frac{v^2}{R}. \tag{8}$$

Multiplying both sides by R, and taking the square root gives us an expression for v,

$$v(R) = \sqrt{\frac{GM_{\text{enc}}(R)}{R}}, \tag{9}$$

the Keplerian model.

Rearranging Equation (9), we can calculate $M_{\rm enc}(R)$ from the rotation curve,

$$M_{\rm enc}(R) = \frac{v^2 R}{G}. \tag{10}$$

As the light from spiral galaxies is centrally concentrated, we can assume that most of the stars are contained in the bulge, so, for distances $R > R_0$ where R_0 is the radius of the bulge, luminous mass is approximately constant and Equation (9) implies we should expect to see velocity scale inversely with $\sqrt{R}$, and decrease quickly outside the bulge as is illustrated by the dashed curve in Fig. 1.

In 1970, Rubin et al. measured Andromeda's rotation curve, see Fig. 1. Instead of following the shape described by Equation (9), rotational velocity beyond R_0 was observed to be essentially constant, as indicated by the dotted line, implying that not all of Andromeda's mass is concentrated in the bulge [6]. In 1980, Rubin et al. published a paper containing the rotation curves of 21 spiral galaxies, each showing a similar shape to that of Andromeda [7]. The mass-to-light ratios for these spiral galaxies were much greater than $\Upsilon_\odot$, $\Upsilon_{\rm M31} = (11.5\pm1.5)\Upsilon_\odot$, which suggested a large fraction of their mass was not luminous [8].

These rotation curves and their associated mass-to-light ratios were verified by subsequent investigations, and so provoked three alternative hypotheses; stellar mass is not distributed as one would expect based on luminosity distribution, our model for gravity requires adjustment, or the disk contains more that just its visible mass [2]. Although physicists have hypothesised modifications of Newtonian dynamics to explain these results, notably the Modified Newtonian Dynamics (MOND hereafter) hypothesis, the theory of 'dark matter', a hypothetical form of matter that interacts with baryonic matter only through gravity , is generally accepted [3] [9]. It is believed that dark matter forms massive, extended 'halos' around spiral galaxies that level out the rotation curves.

This report aims to demonstrate the existence of dark matter by investigating the dark matter content of the spiral galaxy M82, repeating the early experiments of Rubin et al. and calculating its mass-to-light ratio as a function of radius. We conclude, based on its Keplerian rotation curve, Fig. 3, and its mass-to-light ratio, Fig. 4, that M82 appears to have no significant dark matter content, providing no evidence for the existence of dark matter.

II. METHOD

The rotation curve for M82 was obtained by Sofue et al. and Yun et al., and presented as a graph from which the rotational velocities, angular distances from the centre of the galaxy, and their errors were extracted [10][11]. M82 is almost side-on, so inclination did not need to be accounted for in velocity calculations [12].

Luminosity data was obtained from the Durham University Physics Department's image database as the conditions were too poor, during our slot, to take our own data. A 20-inch telescope was used to collect data using a CCD detector, with a relatively long exposure time of 90s, chosen to reduce object noise whilst not saturating the image. M82 was selected as it had a high altitude at this time of year, meaning seeing was low, and a low apparent magnitude of 8.41 ± 0.09 [12]. It was important to reduce see-

FIG. 2: Stacked BVR image of M82 taken from Durham on 06/02/2020, each image had an exposure time of 30s. An ellipse is overlaid to demonstrate the type of aperture used to extract luminosity data, R is the semi-major axis.

ing to increase the resolution of our image. The telescope was pointed at M82 by inputting its RA and DEC coordinates into the telescope software. We calibrated the CCD to test which noise source dominated, finding it to be photon noise limited due to the low magnitude of M82, we ensured the signal was linear by taking test images with different exposure times and comparing the relationship between it and intensity. Linearity of the signal was important to ensure Equation (3) applied, and accurate luminosity data was obtained. 120 exposures were taken, corrected by subtracting the dark and bias images and dividing by the flat-field, and stacked to reduce read-out noise. Subtracting the dark image removed noise due to dark currents, subtracting the bias image corrected for the bias level, and dividing by the flat field corrected for any dust on the optics, or shadowing on the detector. During this time period, the rotation of the Earth meant the telescope had to move to keep M82 in sight, this was accounted for by the stacking software. Dark and flat field images were found for the telescope at around the time the images were taken, ideally they would have been taken on the same night to best correct the images.

Gaia software was used to measure the number of photon counts enclosed within elliptical apertures, as illustrated in Fig. 2, with semi-major axes corresponding to the distances to the centre at which the rotational velocities were measured. Background counts were removed by subtracting the sum of counts over a large, circular annulus from the sum of counts over the smaller, elliptical aperture. Counts were converted to apparent magnitude using Equation (3), where the zero-point was calculated by comparing known magnitudes of objects in the image to their background-subtracted counts. The errors in counts were calculated from the signal to noise ratio as

$$\alpha_c = \frac{c}{\sqrt{nct_{\rm exp}}}, \tag{11}$$

where $t_{\rm exp}$ denotes the exposure time, n the number of exposures, and we have assumed that the read-out noise was negligible thanks to stacking.

Luminosity was calculated from apparent magnitude via Equation (4) then (5).

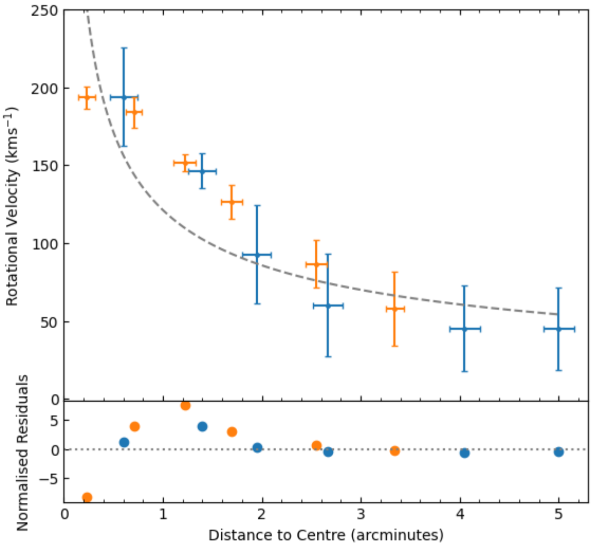

FIG. 3: Rotation curve for M82 obtained from Doppler-shift of HI lines (blue) and CO-lines (orange) as measured by Sofue et al. in 1992 and Yun et al. in 1993 respectively [10][11]. Rotation curve for a point mass (dashed) is indicated, normalised residuals are plotted below.

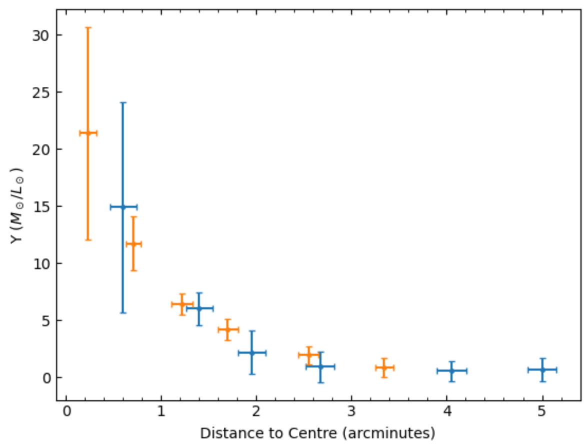

FIG. 4: Mass-to-light ratio against distance to centre, for M82, calculated from HI emission line (blue) and CO emission line (orange).

III. RESULTS

The rotation curve obtained by Sofue et al. and Yun et al. is plotted in Fig. 3.

Angular distance, θ, was converted to linear distance, R, using

$$R = \theta D, \tag{12}$$

where D denotes the distance to M82, $(3.5 \pm 0.3) \times 10^6$ pc, and θ was convert to radians [13].

With the literature values $G = (6.6743 \pm 0.0002) \times 10^{-11}\mathrm{m}^3\mathrm{kg}^{-1}\mathrm{s}^{-2}$ and $c = 299,792,458\mathrm{ms}^{-2}$, Equation (10) was used to calculate the mass enclosed within each R, $M_{\mathrm{enc}}(R)$, from which the mass-to-light ratio, Υ, was calculated using Equation (6) [14].

The mass-to-light ratio for the entire galaxy was determined to be $(0.6 \pm 0.8)\Upsilon_\odot$, and was plotted, in units of $\Upsilon_\odot$, as a function of distance to the centre in Fig. 4. $\Upsilon_\odot$ was calculated as the ratio between the mass of the Sun, $(1.9884 \pm 0.0002) \times 10^{30}$kg, and its luminosity in the V-band, 3.828×10^8 W [15][16]. The values of Υ ranged from $(21 \pm 6)\Upsilon_\odot$ to $(0.6 \pm 0.8)\Upsilon_\odot$.

IV. DISCUSSION

Our calculated mass-to-light ratio of M82 was equal to $\Upsilon_\odot$ within one error. At distances less than 1 arcminute from the galactic centre, Υ is an order of magnitude greater than $\Upsilon_\odot$, but drops off at higher distances. For reference, Rood calculated the mass-to-light ratio of Andromeda as $(11.5 \pm 1.5)\Upsilon_\odot$, significantly greater than that of M82 [8].

At first glance, the high mass-to-light ratio close to the galactic centre seems to imply significant dark matter content in the bulge, but instead can be explained by large clouds of dust in and around the bulge which absorb and scatter light more readily at higher frequencies than lower frequencies via the Tyndall effect, 'reddening' the light from these regions and causing V-band luminosity measured to be lower [17]. Looking at the stacked BVR image in Fig. 2, we can see the centre is significantly redder than the rest of the galaxy. This explanation could be verified by repeating our method for multiple light bands, and comparing the resulting mass-to-light ratios.

Equation (9) was used to fit a Keplerian rotation curve for a centrally concentrated mass to the rotation curve data in Fig. 3. A reduced χ^2 value of 14 was obtained, suggesting the Keplerian model can be used to approximately describe $v(R)$. This implies the mass in M82 is dominated by visible matter, most of which is concentrated centrally, in the galactic bulge, so M82 has no significant extended dark matter halo. Note that χ^2 is still greater than 1, and the residuals are not normally distributed about 0, so the Keplerian model isn't a perfect description.

This differs greatly from the conclusions Rubin et al. drew from their measurements of other spiral galaxies. Sofue et al. came to the same conclusion as us, they explained the absence of dark matter in M82 as a result of interaction with its larger neighbour, the spiral galaxy M81. They theorised that M82 was once a much larger galaxy with an extensive dark matter halo, but had its disk truncated during a close encounter with M81 leaving little left but the central bulge. They simulated such an interaction, and succeeded in reproducing the unusual features of M82 we observed in this report [4].

The errors in our calculated mass-to-light ratio were very high; the dominant source of error was in rotational velocity, a systematic error. These errors were large, and their contribution was especially high as velocity is raised to a power of 2 in Equation (10). As these errors were associated with the data from literature, the only way we could improve precision would be to take our own rotation curve data via spectroscopy. This data is 30 years old, so it is possible that technology has improved and we could obtain more precise results.

In calculating the mass-to-light ratio, we made two significant assumptions: that all stars in M82 have the same mass-to-light ratio as the Sun, and that the matter in M82's disk orbits the centre following circular paths. The first assumption is somewhat reasonable; spiral galaxies typically contain a range of different classes of stars with a range of mass-to-light ratios, which could average out roughly to

$\Upsilon_\odot$. It is almost certain, however, that the mean mass-to-light ratio for stars in M82 isn't equal to $\Upsilon_\odot$. Our investigation could therefore be made more accurate by investigating the stellar population of M82, testing this assumption and, if it isn't accurate, adjusting it to establish a better guess of the mean mass-to-light ratio. The second assumption, again, is somewhat reasonable, however, taking a close look at Fig. 3, we can see it is flawed. For distances greater than roughly 2.6 arcminutes, the rotation curve v drops below the Keplerian model, $v_K \propto 1/\sqrt{R}$, implying v^2 decreases faster than R. Substituting this into Equation (10), we see that our calculated $M_{\rm enc}(R)$ decreases with increasing R in this region. Enclosed mass cannot decrease with radius, so our assumption must be failing here, causing us to underestimate $M_{\rm enc}(R)$ and therefore Υ. This effect is difficult to reduce, as a more accurate model would be mathematically complicated, however we could try modifying our assumptions and allowing for elliptical orbits in Equations (7 - 10).

In the introduction, we considered an alternative theory to dark matter, MOND. Whilst the rotation curve of M82 can be explained with just Newtonian Dynamics, we must look elsewhere to explain the rotation curves of other spirals, such as Andromeda. Both MOND and dark matter theories have been successful in explaining such curves, but rotation curves are not the only applications of dark matter, and MOND fails to explain the velocity dispersions of galaxies within galaxy clusters [9].

V. CONCLUSION

In this report, we investigated the mass-to-light ratio and rotation curve of M82. We found that the mass-to-light ratio had the same order of magnitude as the solar mass-to-light ratio, and that the rotation curve was consistent with the Keplerian model for a centrally concentrated mass, leading us to conclude that M82 lacks an extended dark matter halo. From this, we could not provide any evidence for the existence of dark matter.

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ERROR APPENDIX

The errors in distance from the centre of the galaxy, α_R, were calculated by multiplying the fractional error in distance to M82, approximately 7%, from literature, α_D, by the distance from the centre,

$$\alpha_R = R\left|\frac{\alpha_D}{D}\right|. \tag{13}$$

The errors in apparent magnitude, α_{m_V}, were calculated using the calculus-based approximation; taking the derivative with respect to counts, c, of both sides of Equation (3) gives

$$\frac{\mathrm{d}m_V}{\mathrm{d}c} = \frac{1}{\ln(10)}\frac{1}{c} \tag{14}$$

[18]. Provided the errors in m_V and c are sufficiently small, they were approximately $10^{-6}\%$, we rearrange to get

$$\alpha_{m_V} = \frac{1}{\ln(10)}\left|\frac{\alpha_c}{c}\right|, \tag{15}$$

where α_c are the errors in counts taken from Gaia, which were similarly small.

The errors in absolute magnitude, α_{M_V}, were calculated as the sum in quadrature of the errors in apparent magnitude and the error the logarithmic term in Equation (4). As above, the error in the logarithmic term was calculated using the calculus-based approximation, valid as all errors were at least an order of magnitude smaller than the values, this time with the error in distance to M82, α_D,

$$\alpha_{M_V} = \sqrt{\left(\frac{\alpha_{m_V}}{m_V}\right)^2 + \left(5\frac{\alpha_D}{\ln(10)D}\right)^2}. \tag{16}$$

The errors in luminosity, α_L, were calculated by making the substitution

$$u = \frac{M_{\odot V} - M_V}{2.5}, \tag{17}$$

then applying the calculus-based approximation to Equation (5). Making this substitution, Equation (5) becomes

$$L = L_\odot 10^u, \tag{18}$$

taking the derivative with respect to u of both sides and rearranging, the errors in luminosity are given by

$$\alpha_L = \ln(10)\alpha_u|L|, \tag{19}$$

where the errors in u, α_u, are given by $1/2.5$ times the sum in quadrature of the error in the absolute V-band solar magnitude, $\alpha_{M_{\odot V}}$, and the errors in our determined absolute V-band magnitude values, α_{M_V},

$$\alpha_u = \frac{1}{2.5}\sqrt{\left(\frac{\alpha_{M_\odot}}{M_\odot}\right)^2 + \left(\frac{\alpha_{M_V}}{M_V}\right)^2}. \tag{20}$$

This is valid as the percentage errors in Solar mass and magnitude are sufficiently small, 0.01% and 3% respectively. The percentage errors in luminosity were roughly 3%.

The errors in enclosed mass, $\alpha_{M_{\mathrm{enc}}(R)}$, were calculated using the functional approach as the errors in velocity, α_v, and the errors in distance from the centre of the galaxy, α_R, both were too significant, they ranged from 8% to 60% and from 3% to 23% respectively, to apply the calculus approximation [18]. Here, the dominant errors were the errors in velocities from the rotation curve, due to both their high magnitude and the fact that $M_{enc}(R)$ depends on v^2.

$$\alpha_{M_{\mathrm{enc}}(R)} = \left|f(v,R) - f(v+\alpha_v, R+\alpha_R)\right|, \tag{21}$$

where $f(v,R)$ is given by Equation (10). These errors were large, ranging from 17% to 170%.

The errors in mass-to-light ratio, α_Υ, were calculated again with the functional approach detailed above, as the errors in $M_{enc}(R)$ were so high. This resulted in percentage errors ranging from 14% to 160%.

The Keplerian rotation curve model, described by Equation (9), was fit to the rotation curve data by varying the constants to minimise χ^2, where

$$\chi^2 = \sum_R \frac{(v(R) - v_K(R))^2}{v_K(R)}. \tag{22}$$

To measure of how well the model fit the data,

$$\chi^2_{\mathrm{red}} = \frac{\chi^2}{\mathrm{d.o.f.}} \tag{23}$$

was calculated, $\mathrm{d.o.f.}$ denotes the number of degrees of freedom in the data.

LAY SUMMARY

Matter is everywhere: the Sun is made of matter, the device you're reading this on is made of matter, even you are made of matter. There are two distinct types of matter: one, visible matter, is understood reasonably well by physicists, the other, dark matter, we don't understand at all. Dark matter is, as its name suggests, impossible to see. Even worse, it doesn't interact with visible matter in any way but through gravity; this makes it very difficult to investigate. The theory of dark matter, which dates back to the 1930s, exists predominantly to explain peculiar phenomena observed in, and around, galaxies. One phenomenon that can be explained by dark matter is the, otherwise, inexplicably fast rotation of spiral galaxies. How fast a spiral galaxy rotates is, loosely, governed by its mass, and how many stars a galaxy contains is, again loosely, indicated by its brightness in the night sky. In this report, we compare these two features for the Cigar galaxy, M82, and attempt to determine how much of this galaxy's mass does not belong to stars: roughly the amount of dark matter it contains. We find that M82 contains very little, if any, dark matter.