Photometric Redshift Survey

Abstract

In this project, we perform a photometric survey on a few galaxies, and use a program to convert the calculated magnitudes into redshifts. From the redshift information, we can deduce both the distance and the lookback time. Galaxies with high lookback time can be studied to gain insight into the early universe.

INTRODUCTION

The most common way to determine the distance to a far galaxy or other interstellar object is by determining its redshift. According to Hubble expansion, the universe is expanding at a speed proportional to distance from Earth, meaning that an object will be redshifted much more if it is further away. As light takes time to reach Earth, distant objects provide a lookback into the past.

To determine redshift, we can look at the emitted wavelengths of light. Light will be emitted at certain wavelengths corresponding to the spectral lines of the materials that make up the object we view. These wavelengths will be shifted to the red compared to what we measure on Earth, and by measuring the magnitude of these shifts we get a redshift value.

The most common way to measure redshift is with a spectroscope. By measuring the exact position of the the shifted spectral lines, it is easy to compare how much they have shifted with respect to the unshifted lines. The issue with spectroscopes is that they measure a very narrow band of wavelengths. This means that they acquire much less light than a wide band would. This means that for dim objects, there wont be enough photons gathered for a good measurement. The solution to this is, of course, to use wide bands. By comparing the amount of light in each band, the redshift can be computed that way. This is what is know as photometric redshift.

Our next goal becomes the measurement of the brightness in each of the wide bands. We use a logarithmic magnitude system in which higher numbers indicate dimmer objects. When we take images in different band filters, we want to find the ratio of the pixel brightness (ADU) and the magnitude of stellar objects. We can find this ratio if we known the magnitude of stars in the frame of the image within the correct band.

Once we acquire our magnitudes, we must convert them to redshifts. The spectral distribution is complex, and this cannot be done by hand, and instead we use a program which has been fed known redshift galaxies and can devise a relationship itself.

Historical Background

The first usage of photometric redshift was by Baum in 1962 [1]. The study looked at two clusters of elliptical galaxies through a series of photometric bands and compared the spectral energy distributions to find the redshift of the second cluster. This technique relied on a spectral break and thus could only work on elliptical galaxies, which limits its usefulness.

A more general use technique was first employed by Koo [2]. This method involves finding two color indices and plotting them on a color-color diagram. Then one needs to plot iso-z lines, which have constant spectral type but changing redshift for a variety of galaxy spectral types or models. The point on the line nearest the data is then the redshift for that galaxy. There are a few variations for that method. One of those involves creating two graphs instead of one, one for each color index versus the redshift.

To obtain iso-z lines, one creates models of the spectral output of galaxies. This complex and often requires many approximations in order to get a quantifiable result. However there have been attempts, many have been quite accurate. In fact, some of these models are used in part of the method we will end up using as part of this project, including the one we will talk about following. One of these comes from Brunzal and Charlot [3]. They used a library of stellar spectra and data which models the evolution of stars in order to create models for the spectral evolution of galaxies over time. This gives us figure 1, which can be used to calculate redshift with two indices. There are two main sets of models in their analysis, one that includes rapid starbursts, and one that does not, specifically with starbursts that occur in less than 1GYr. Starbursts are periods of large amounts of star formation, which heavily impacts the spectra of the galaxy. One can think of it almost akin to tree rings, where a tree ring grows wider with more available water, our spectra will change according to starbursts.

We could in theory plot two of color indices on figure 1. and where both intersect the same line at the redshift would be the redshift value. This method also determines which model is the best fit for a galaxy, similarly to the technique we will use. In fact these models

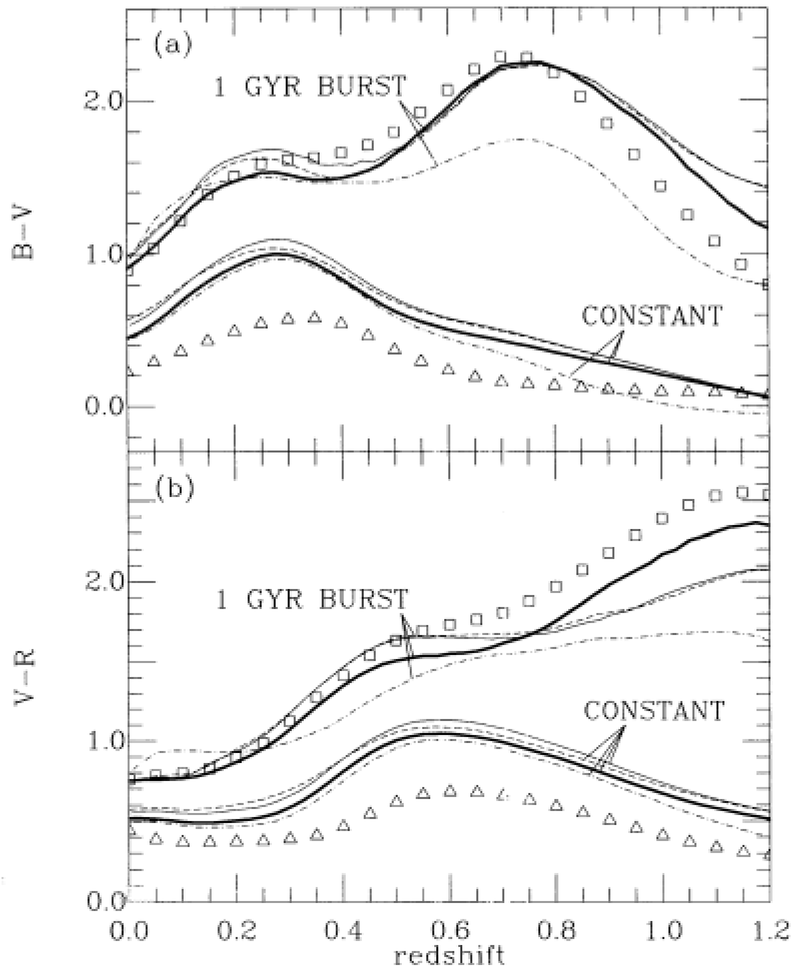

FIG. 1: The isochrone synthesis models from Brunzal and Charlot [3]. These map two color indices to redshift, which was one of the earlier methods for computing it. There are two "sets" of lines distinguishing between the 1 GYr burst models and the constant models.

can be used in that technique.

Modern Techniques

The modern techniques involve using artificial intelligence to find the redshift. One feeds some kind of neural network a training set of data which involves both the photometric data as well as known redshifts from spectroscopy or other methods of calculating distance. Then the program learns to identify redshift from photometric data, so when ones feeds in data from objects with unknown redshifts, the program is able to identify the redshift, and thus the distance. This is our selected method, and although creating the program would be difficult, there are a number of models available readily online.

The method was pioneered by Connoly et. al. [4] Typically, they try to fit the the known values to some kind of function, typically linear or a quadratic. For linear functions:

$$z = a_0 + \sum_{i=1,\ldots,N} a_i m_i$$

Where m_i is the magnitude in a certain filter, N is the number of filters and constants a are linear coefficient. The quadratic version is similar:

$$z = a_0 + \sum_{j=1,\ldots,N} \sum_{i=1,\ldots,N} a_{ij} m_i m_j$$

We can find these constants through a method known as linear regression. Linear regression models the linear relationships through a noise term, something that works very well for physical observations as random uncertainty is all but a guarantee.

Significance

Photometric redshift surveys are still widely used today where objects are too dim to be seen with spectroscopy. Finding the distance to other galaxies lets us solve for many other properties. With their brightness we find their luminosity, which tells us the energy output. The energy output is a window into the composition of the galaxy, an important feature due to the fact that looking far away is a window into the past, since that light will have taken a long time to reach us. We get to learn what the universe was in the past.

Very recently the Cosmic Evolution Early Release Science Survey (CEERS) discovered a galaxy, known as CEERS-93316, which through photometric methods, is estimated to have redshift of z = 16.7 . This would make it one of the highest ever measured redshift as well as the most distant object ever seen, and most importantly the furthest into the past we can see.

The galaxy is awaiting confirmation of the redshift from JWST, which is the other usefulness of the technique. Photometric shift is much quicker and does not require a spectroscope, which makes it perfect for scouting out candidates for more in depth studies.

The Standard Model of Cosmology and Hubble Tension

The standard model of cosmology describes the structure of the universe in general terms. Redshift surveys are one of the ways we construct this model, as they give us insight on how galaxies are distributed as the redshifts tell us the distances. The distribution of galaxies is important as it tells us how mass and energy are distributed across the universe and also is how we discover large scale features such as the Sloan great wall.

Hubble tension is the disagreement in the two main methods of measure the Hubble constant. One of these methods is through using the distances to galaxies and their velocities. One can use the redshift of a galaxy and the distance it is, which can be measured using standard candles or other methods, to determine this measure. The method involves measuring the cosmic background radiation, which is an important part of the standard model of cosmology. There is a disagreement in the late time and early time calculations that is much greater than the uncertainty in the measurements. Redshift surveys are important as a we get high redshift, dim galaxies which are hard to measure spectroscopically, we will see the galaxies which will form the bridge between the early and late universe, and there likely lies the key into understanding the different measures of Hubble's constant.

METHODS

Photometric Magnitudes to Redshift

For the calculation of the redshift from the photometric methods, we employ an empirical method which involves the use of a program. Due to the nature of spectral lines, it is impossible to parameterize the spectral distribution of galaxies, and thus we can only calculate the redshift-color relation from known information. We can use spectroscopic redshift, or other ways of determining distance, to gain a set of data with known redshifts and color information, and use that to determine the pattern.

Our chosen program for this is EAZY (Easy and Accurate Redshifts from Yale) [5], which is an open source photometric redshift code developed at Yale. EAZY works differently to the method discussed earlier in the paper. Instead of creating the relationship between redshift and photometric magnitudes, it finds the best fitting spectral flux template for each redshift value. The best fitting spectral flux template is found by minimizing a parameter,

χ^2, which represents goodness of fit.

$$\chi^2 = \sum_{j=1}^{N} \frac{(T_{z,i,j} - F_j)^2}{(\delta F_j)^2}, \tag{1}$$

Many programs just use the best fitting template, however the complexity and diversity of galaxies means that the best fitting template is not necessarily the best option. Instead, EAZY will calculate a template, using a linear combination of templates, which will give a much more accurate value.

$$T_z \sum_{i=1}^{N_{templates}} \alpha_i T_{z,i}, \tag{2}$$

The coefficients, α_i are all zero or greater. This fit can be done using the minimizing square fit like in equation one, but only if there is one or two templates, for more templates another approach must be taken using an iterative algorithm. Using more than two templates gets a more accurate result but this effect has diminishing returns, the improvement you get falls of above 5 templates and is negligible above 10 [7].

The program also has an empirically calculated error. This done by comparing the photometric values to the spectroscopic values, and the difference between them ($\Delta z = z_{\text{phot}} - z_{\text{spec}}$) will give us the uncertainty, as per equation #.

$$\sigma = 1.48 * \text{median}(|\frac{\Delta z - \text{median}(\delta z)}{1 + z_{\text{spec}}}|) \tag{3}$$

The article accompanying the program has already calculated sigma far a data set with a large number of galaxies. The uncertainty is nearly flat for z ¡ 1.5, which is the range that we are working in. The error in the area is $\sigma = 0.034$, which is notably high for the expected range of redshifts we are working in. This is for certain the biggest source of uncertainty, and all other sources will likely be insignificant when compared to it.

Redshift and Distance Relation

The doppler effect is characterized in terms of frequency and source or receiver velocity by the following equation:

$$f = \frac{c \pm v_r}{c \pm v_s} f_0$$

If the source is receding from the receiver, then the frequency is reduced, leading the longer wavelengths, which in the visible spectrum shifts it towards the red. We can defined a parameter which defines the magnitude of the redshift, "z".

$$z = \frac{\lambda_r - \lambda s}{\lambda_s} \tag{4}$$

We can parameterize the universe by the Robertson-Walker (RW) metric, which describes the expanding universe. This leaves us, with adequate approximation, with equation 4.

$$cz \approx H_0 d \tag{5}$$

Here we equate the speeds given by the redshift and the Hubble constant. If the object in question exists further than a hypothetical sphere known as the Hubble sphere, then it will appear to recede faster than the speed of light. As objects cannot move faster than that, there must be additional relativistic effects. Furthermore, the Hubble constant is not constant, and for far off objects we see light that represents a Hubble parameter in the distant past. From that metric we derive a more complex version of the redshift distance conversion:

$$d = \frac{c}{H_0} z[1 - \frac{1 - q_0}{2} z] \tag{6}$$

In the limit small z, that is $z << 2/(1 + q_0)$, we return equation 4, since the term linear in z will dominate at that range.

Another parameter we may be interested in the lookback time, which is the amount of time we see back when looking at a distant galaxy. The lookback time is equal to t_0 - t_e, and we find that as part of the derivation for equation 5.

$$t_0 - t_e \approx H_0^{-1}[z - \frac{1 - q_0}{2} z^2] \tag{7}$$

Just like equation 4., for low z the relationship can be approximated as roughly linear.

$$t_0 - t_e \approx H_0^{-1} z \tag{8}$$

[I possibly will go a little more in depth here at some point]

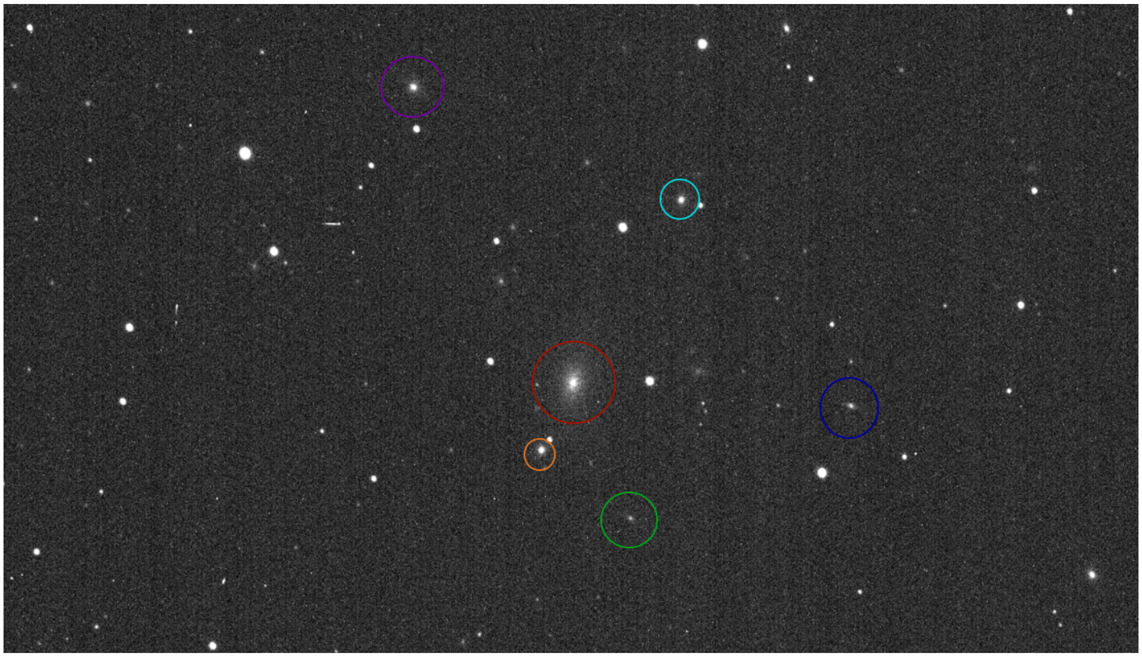

FIG. 2: Photo centered on the galaxy NGC 1650, circled in red, taken in the i' filter. This image contains many galaxies, but only the brightest ones could be used for the project, since this filter band appeared the brightest. In orange just below and to the left of NGC 1650 is 2MASX J04451370-1553151, and in green below and right of that is LEDA 904935. To the right of NGC 1650 in blue is 2MASX J04445318-1552381, in cyan above is 2MASX J04450420-1549191, and to the far upper left in purple is 2MASX J04452168-1547268.

Telescope and Filters

The telescope we use for this is the Las Cumbres Observatory SBIG 0.4m telescope [8]. This telescope allows us to see objects up to a magnitude of approximately 17. We want to stay at the top of this range because far galaxies are dim and far galaxies have a higher redshift, and a bigger redshift is easier to measure.

The telescope has an FOV of 29.2 x 19.5 arcmin, and a pixel size of 0.571 arcsec. There is a read noise of 14.5 e- and a dark current of approximately .03 e-/pix-s. The telescope has a gain of 1.6 e-/ADU.

All images are automatically processed through the BANZAI pipeline. During this process a number of calibrations are made. This includes: bad pixel masking, bias subtraction, dark subtraction, and flat field correction. These help suppress noise and cancel the effects of image artifacts.

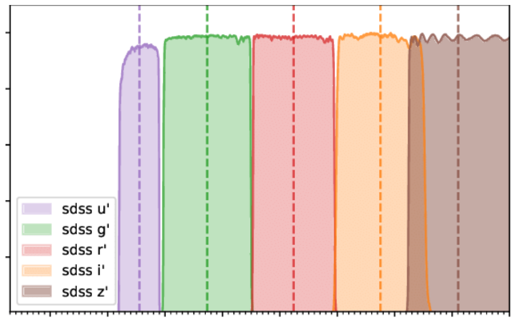

FIG. 3: These are the filter bands that we used. Note not only the low overlap, but also that they also cover the entire spectrum [9]

For the filters, we initially intended to use the four (ugri) SDSS prime filters as they give us a wide band with little overlap. The LCO telescope has 4 of these filters, which gives us a decent amount of color information for the scope of the experiment.

However, having done the experiment the ultraviolet (u) filter has two major issues that made it impossible, at least for the first two pictures taken, to use it for our project. One, I had given it the same exposure time with only one exposure, like the rest of the data. This is an issue because the atmosphere blocks UV light, and there is a high noise on the image, which means the S/N ratio is visibly low, and it is hard to resolve the galaxy in the image, let alone stars. Even if we had taken a stack of exposures, we would have issues. There is a notable lack of photometric data for the stars around our chosen galaxies in the ultraviolet range, so it would be impossible to use our chosen photometry technique which we will discuss in the following section.

Instead, we went with g'r'i' and BV filters. This gives a reasonable number of filters, and the S/N ratio is high enough as long as we use sufficient time for the B filter, which tends to transmit less signal.

Photometry

There are two main methods of photometry. The first of which is aperture photometry. Aperture photometry involves the counting of photons incident on detectors and how that translates into the resulting image. Of course, there are countless parameters involved in the computation of this. It is called aperture photometry, becomes we are counting light that passes through the optical aperture.

In aperture photometry, one must perform corrections to account for the opacity of the Earth's atmosphere, as it is more or less transparent for certain wavelengths. The correction for this is known as the K-correction. The K-correction is very difficult to model as the atmosphere is very complex, it changes with altitude and includes a number of tiny dust particles which makes it hard to find wavelength dependence. Atmospheric influence is also determined by weather, cloudy days will block more light. Nevertheless, there are many approximations which give a good correction. One parameter with big effect is the airmass, which is basically how much air one is looking through. At low angles near the horizon, one looks through much more atmosphere than straight up.

Another method is known as relative photometry. Say that you have already done aperture photometry on one or more stars that are in the same frame as the object you want to measure. The stars will have the same atmospheric influence as the object you want to measure across the filter band. You can then relate the pixel brightness (ADU) to the measured magnitude of that star. From that you get a ratio of the ADU to the filter magnitude, which you can then apply to the object, in this case galaxy, whose magnitude you want to measure. This method will automatically cover for weather and atmospheric effects, and since we can use photometric data from other surveys we do not have to do any aperture photometry. This method is best used will multiple reference stars, as that will help account for any random noise effects.

To do relative photometry, we must look at a star in frame with known brightness in that spectral band and compare, and one thing to note with filters is that many stars are only in UBVR filter data, since those filters are older than SDSS filters and more surveys have been conducted as a result. We use the conversions from Jester et. al. [10], Jordi et. al [11], as well as ugri to prime conversions from the SDSS website, in order to convert the stars in frame from UBVR to u'g'r'i' so that we may use them in our photometric calculations These were only used for three of the images, one for each filter of a certain target. To find the magnitudes we use various online databases, SIMBAD is excellent for identifying nearby stars and providing their magnitudes based on various catalogs which we cite in the works cited, and there are many other databases tailored for photometry.

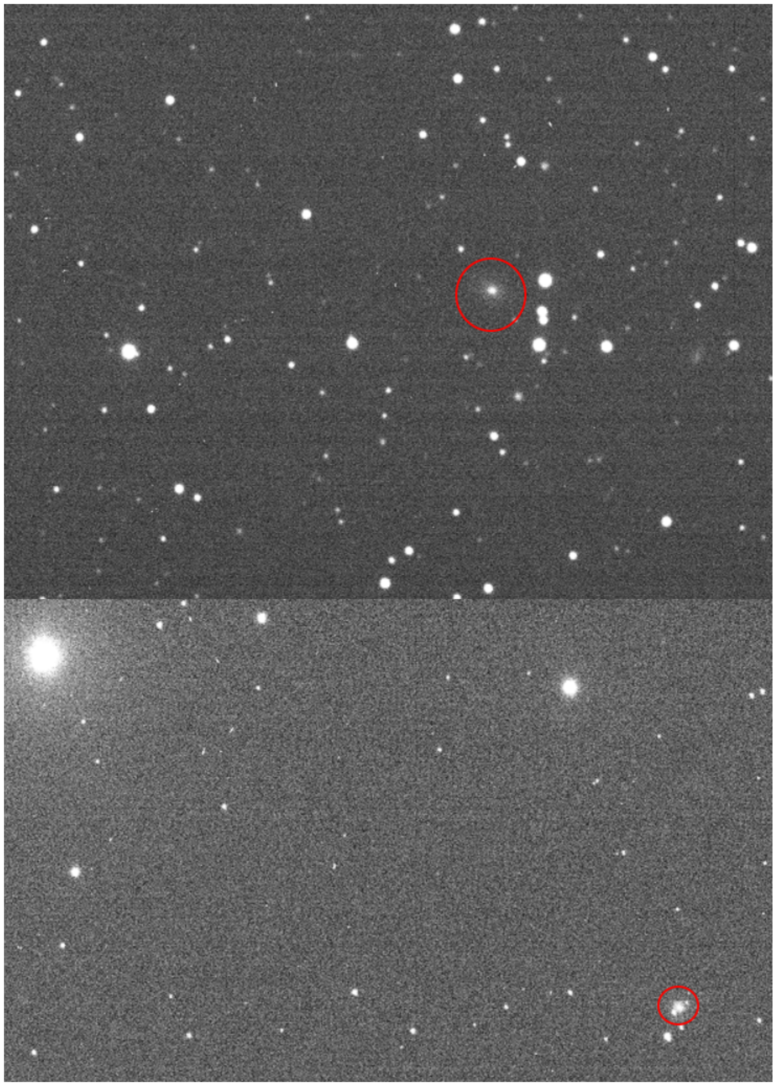

FIG. 4: Pictured here are two galaxies captured in the g' filter. Picture above is NGC 1661 and below is NGC 1585. The two images where taken at different observatories which may explain the difference in noise visible, as there may have been different airmass or weather. Also pictured alongside NGC 1585 in the top left corner is a particularly bright variable star, whose light may affect background noise levels. Note that for both galaxies the core is significantly brighter than the surrounding parts.

RESULTS

Photometric Results

We use the program AstroArt 8 and its photometry and aperture tools to extract the magnitudes for each galaxy. The photometric catalouges used for the reference stars are

FIG. 5: Both pictures depict NGC 1600 with two of its satellite galaxies, NGC 1601 and NGC 1603. On the left is the i' filter and on the right is the g' filter. It is clearly visible that the galaxies are brighter in the infrared rather than the green.

listed in their own section in the works cited. We did photometry on 14 galaxies, but only 12 were able to be used in calculations due to missing images.

For the reference stars, we chose the ones which had both enough photometric data, and also were significantly bright. Many stars were missing either photometric data or were too dim to the point they were either hard to resolve from background noise or would have provided weaker information, as they would have significantly smaller number of photons, increasing the effects of random errors. This is why there is a varying amount of reference stars. For NGC 1585, using many reference stars caused great variance (4 magnitudes) in the r' filter when compared to the g' and i' filters, when it was visually clear this was not the case. When only a single reference star was used, this was not the case. Typically there are more reference magnitudes in the B and V filters than in the prime filters, which were mostly limited to one.

The program wants the data inputted in units of F_ν. To convert to these, we use the zero points, the prime filters are in AB magnitudes while the B and V filters are in Vega magnitudes. The conversion here depends on the flux zero point, which occurs at the same point for the AB magnitudes and different points for Vega magnitudes.

For uncertainty, we first say that the galaxy may be treated as a point source for the purposes of calculating the SNR. This will mean that we overestimate our SNR since galaxies

Identifier	B	V	g’	r’	i’
NGC 1661	14.259	14.803	13.998	13.255	13.43
6dFGS gJ044701.0-020847	16.457	16.592	14.89	14.409	14.334
NGC 1585	13.297	14.391	13.92	13.24	12.721
NGC 1600	13.414	12.37	12.804	12.098	11.258
NGC 1603	15.705	14.861	15.231	14.667	13.69
NGC 1601	14.637	14.626	14.879	14.297	13.439
NGC 1650	14.175	13.717	14.13	13.206	12.9
MASX J04452168-1547268	15.62	14.864	15.361	14.447	13.972
2MASX J04451370-1553151	15.899	15.356	15.863	15.13	14.373
2MASX J04445318-1552381	16.67	16.007	16.484	15.684	15.131
LEDA 904935	17.263	16.585	17.333	16.272	15.729
2MASX J04450420-1549191	16.576	14.99	15.67	14.69	14.433
NGC1	N/A	N/A	13.71	13.145	12.547
NGC2	N/A	N/A	14.778	14.141	13.755

TABLE I: Table of measured photometric magnitudes. The uncertainty is equal to the inverse of the SNR, which was calculated for each value using either expected or measured magnitudes as available. The program requires 5 filter bands which is why NGC1 and NGC2 were not redshift calculated as the images in B and V were unable to be acquired, however the photometry was done in the remaining bands for completeness

are extended sources, this leads to an underestimation of error. We then say that the uncertainty in magnitude is as in the following equation:

$$\sigma_m = 1/SNR \tag{9}$$

We then used the percentage error from the magnitude as the error in the flux density which was used as the input values. This is another underestimation, however. Small fluctuations will in magnitude will be amplified to be large fluctuations in the flux density due to the fact it is a magnitude scale.

The photometric values can be seen in table I.

Object	Redshift	Proper Distance (Mpc)	Lookback Time (yr)
NGC 1661	0.006754745	28.9288	$9.43659*10^7$
6dFGS gJ044701.0-020847	0.06281053	269.001	$1.39226*10^9$
NGC 1585	0.006859928	29.3793	$9.58353*10^7$
NGC 1600	0.07120691	304.961	$9.94782*10^8$
NGC 1603	0.08084199	346.225	$1.12939*10^9$
NGC 1601	0.07798261	333.979	$1.08944*10^9$
NGC 1650	0.08880502	380.329	$1.24063*10^9$
MASX J04452168-1547268	0.08368757	358.412	$1.16914*10^9$
2MASX J04451370-1553151	0.0878702	76.325	$1.22757*10^9$
2MASX J04445318-1552381	-1	N/A	N/A
LEDA 904935	0.0996583	426.811	$1.39226*10^9$
2MASX J04450420-1549191	0.0996583	426.811	$1.39226*10^9$

TABLE II: The redshift calculated from the program as well as the proper distance and lookback time using the small z limit formulae and a hubble constant of 70 km$\cdot$s$^{-1}\cdot$Mpc^{-1}. We utilized a z step size of .001 and minimum z of .001 as well as a maximum z of 0.1. One calculated value superseded this limit, and returned an error value of -1. This is likely due to errors in the input data. The uncertainty for the redshift was .0091. This gives an uncertainty of 38.973Mpc in distance and $1.2713 * 10^8$ years in time. For the two values which appear as outliers in the calculated redshift, the uncertainty appears larger than the value itself, suggesting a large issue with those values.

Redshift and Distances

Results can be seen in table II.

We receive a given uncertainty as part of the results. This arises from both the uncertainty from SNR that we input as well as the uncertainty from how deviant our results are from the spectroscopic redshifts. We expect that if our uncertainty is all from random error sources, that one standard deviation of our points, which is approximately 6, will be withing one sigma of the $z_{spec} = z_{phot}$ line.

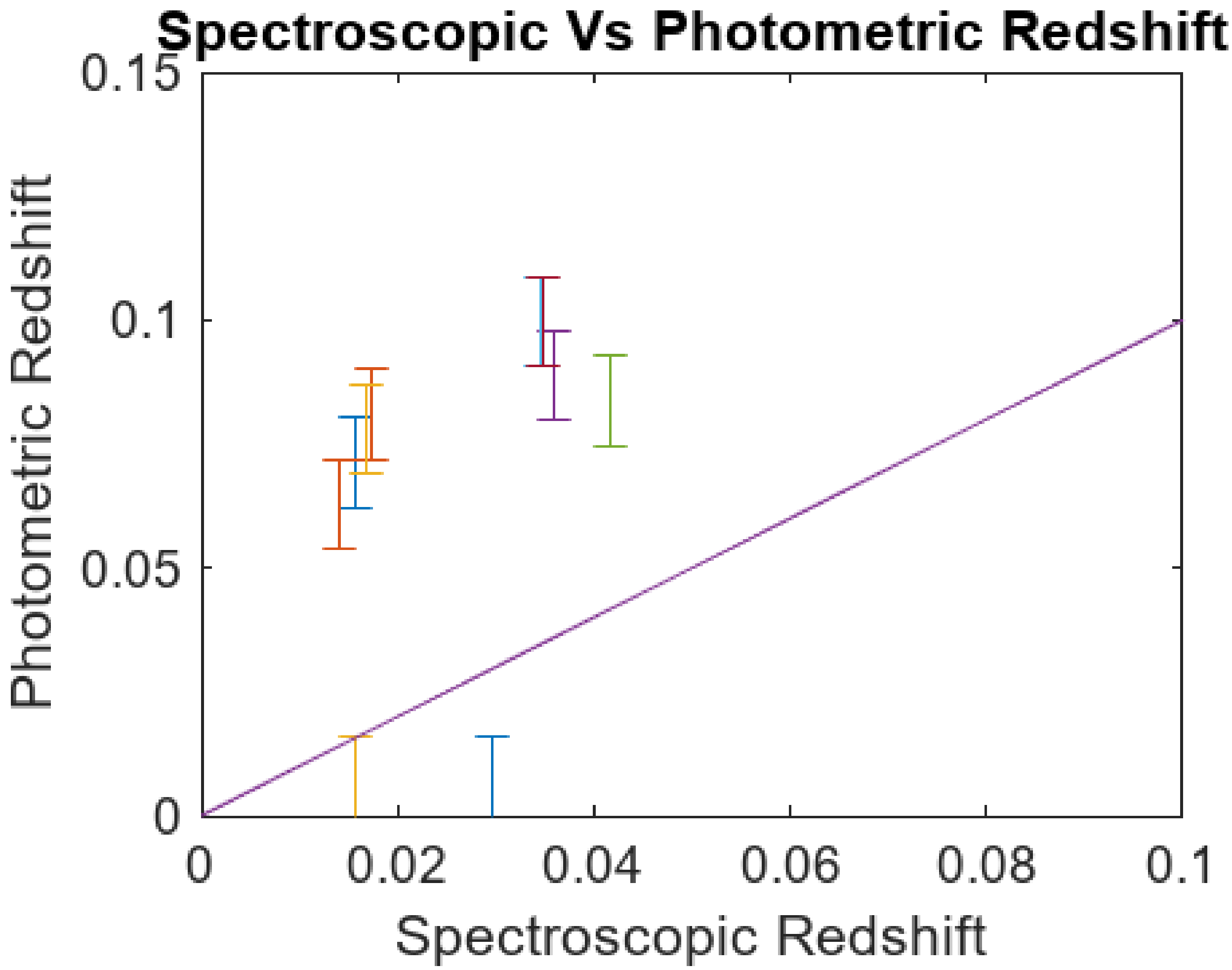

FIG. 6: This figure depicts a plot of our photometrically calculated redshift and the currently accepted value for the redshift. The line plotted represents where the two values are equivalent. Here we can clearly see that aside from two outlier values, the linear behavior is there but shifted, likely due to systematic error. One of the points which had readable photometric redshift is not graphed here because it does not have known spectroscopic redshift (LEDA 904935)

DISCUSSION

Our calculated results were not close to the accepted values. Naturally, in photometric redshift, there will be some level of uncertainty that is inherent in the method. It is impossible to find an exact formula for the spectrum of a galaxy, as it is not only hard to parameterize spectral line but galaxies are complex structures comprised of billions of stars, each with their own emission patterns, as well as many other galactic objects. Thus, to find

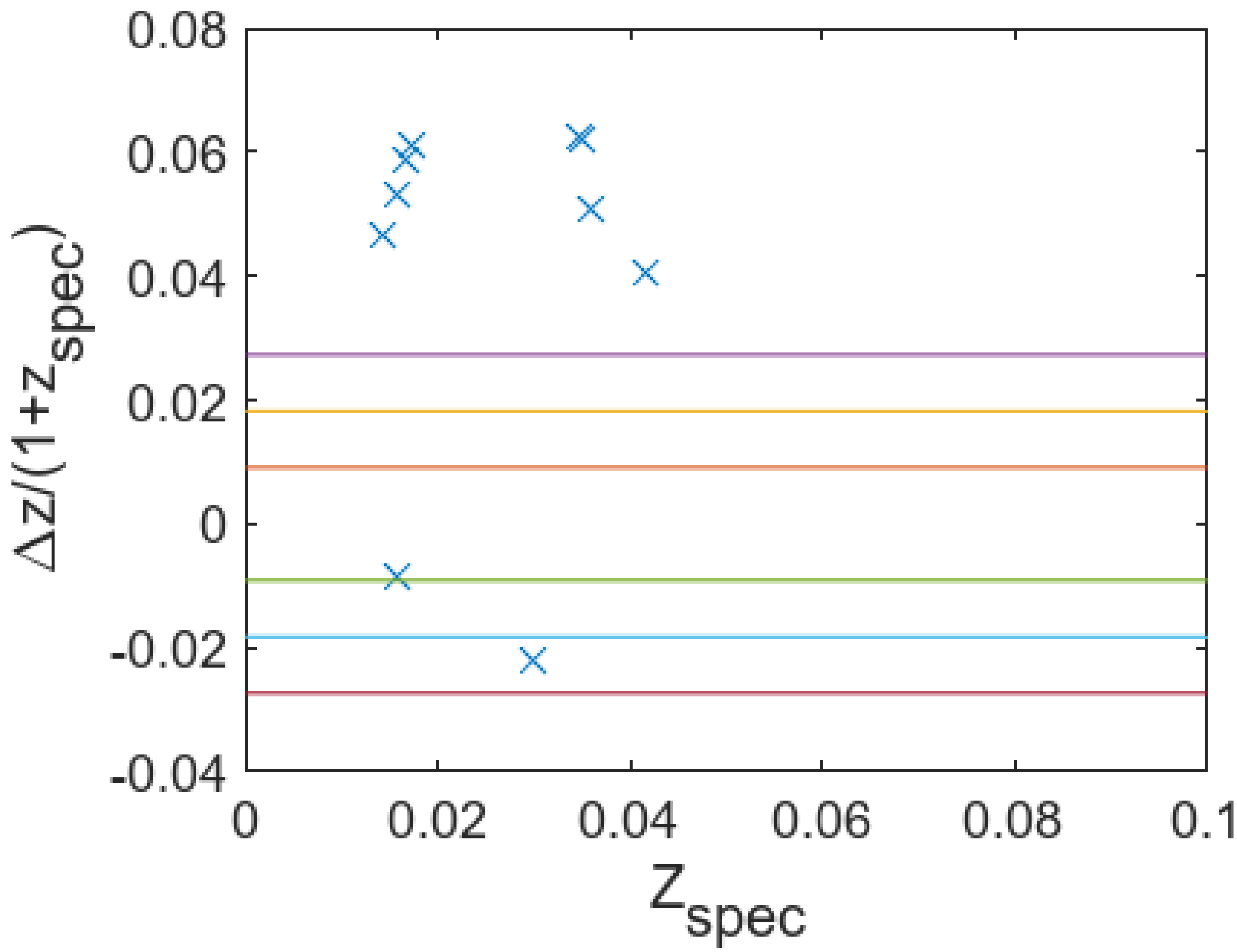

FIG. 7: Similar to the prior image, but rotated, the z equivalency line occurs in this image horizontally at 0. Each graphed line here represents one σ. One can clearly see that everything is shifted vertically, and that if the values were downward shifted, one would see a standard deviation of the values falling withing one σ.

the photometric redshift relationship, we have to model on best fit approaches. These methods are by no means inaccurate, but compared to spectroscopic redshift there will always be a somewhat significant difference between the calculated values from the two.

Figures 6 and 7 show us whether or not our project values follow the general trend of what we expect. We expect each point to form something that looks at 45-degree line on the graph, or a horizontal line in the case of figure 7. If they follow that line roughly, that means our experiment was somewhat successful in being a prediction the redshift. The figure show us that despite the values being far, if one neglects the two outlier values the linear behavior is visible, yet has been shifted upwards. This indicates that there is systematic error present.

We were unable to locate the source of this systematic error, otherwise it would have been fixed. Due to the way we calculate redshift, a systematic error which affected all filter bands equally would not have an effect on the results as it would act as if the object were simply dimmer or brighter, since we are measuring differences in magnitudes and flux densities. This means that the issue is only affecting one or two filters, and since it is above the line of fit it is likely the redder end is too bright or the bluer end is too dim. As for what would cause this, it is unknown.

There are also the two outlier values. Their measured values are smaller than the uncertainty, and we know for certain galaxies other than Andromeda and its satellites should always be receding and thus redshifted, so there is a clear issue with both of those values. The issue likely stems from a bad photometric measurement. Photometric measurements would vary by a little in magnitude depending on where the aperture is centered, which would be enlarged when measured as flux density. Furthermore, despite differing exposure times depending on the magnitude, the SNR varied by a noticeable amount between different filters. As a galaxy consists of a bright core and a dimmer outer region, the angular size would appear to vary by SNR, as the dimmer outs would be more visible against the noise for high SNR than low SNR. However, it is worth noting that if one did not choose the aperture size correctly, the dim outer parts would still numerically exist (but not visually) and would add or not add depending on weather the aperture was large enough. This could cause error. The data was worse until a second go at the photometry in some of the filter bands was attempted, which may have alleviated this issue, but possibly this issue still remains.

Another limiting aspect in the project is the fact the photometric redshift works more accurately on high redshift galaxies, as the redshift is more pronounced and thus easier to measure. This can clearly be seen in EAZY's provided uncertainty, which is large compared to the redshift ranges of the galaxies we work in. This is mainly limited in the light gathering power of our telescope, as even in the dimmest magnitudes the redshift of the galaxies are still relatively low. Furthermore, since galaxies are not point sources and their magnitudes assume that they are, you cannot see as high as magnitude as you can with stars. Many of the templates may also be more accurate when working in this high z environment. The default step for z for instance is 0.03, which is as high as or higher than some of our expected redshifts. Working in a higher redshift regime may lead us to not have the vertical shift we see on our results.

If we were to repeat the experiment, we would pay very close attention to what photometric data is available in the frame of the target galaxy. Most stars do not have complete filter magnitudes, which can make it difficult to calculate certain filter band magnitudes using relative photometry. Aperture photometry is much more complex and harder to perform since it does not account for any atmospheric distortions like relative photometry, so having good photometric references is important.

We would also use as many filters as possible. Having more filters provides more data which allows the program to get a better fit for the spectrum. It also reduces the chances of random or unanticipated effects, such as weather, as they may not affect all filter bands. If one or two filters are for instance, slightly off, it has much much greater effect on the final results if there are only five filters as opposed to many more.

The relevance of our results to the current astrophysical climate is that it demonstrates the techniques that are still used today, and helps demonstrate the advantages and disadvantages of it. There is a large part of the universe's history, the first galaxies, which we have not yet been able to study. Instead of looking at many galaxies with a spectroscope, we can find potential high redshift galaxies using photometric redshift which takes a fraction of the time since you can integrate for less. Even at small redshifts, we do still see the correct relation between spectroscopic redshift and photometric redshift. This is useful as if we for example knew the distance to one of our galaxies, we could use that to calibrate out the vertical shift we have in our results. Once we factor out the vertical shift, either through that or just by fixing the source of the systematic error, we could use known distances to make a measurement for the late universe Hubble constant. Of course, we chose to work backwards in this case, using the Hubble constant to calculate distances. If we noticed a galaxy with high redshift, we would also have found a galaxy who could be used to study the earlier universe.

The more we are able to do photometric redshifts, the more we may be able to alleviate the issue of Hubble tension. There is still a "dark" area of galaxies in our universe's timeline we have yet to be able to see which lies between the galaxies we routinely observed and cosmic microwave background, and there may lie the solution to the tension between the two values. After all, it lies between them in time. Those galaxies are the dimmest, and thus the only way to measure them would be with either a supremely powerful telescope, or through photometric redshift. Photometric redshift can tell us if these dim galaxies lie within this dark zone and mark them for further study. Photometric redshift is the portal through which we can gaze into the unknown frontiers of the universe's history.

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