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Analysis of Dust Extinction using Reddening Map

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ABSTRACT

When observing celestial objects in the sky, one factor that needs to be taken into account is the dust. The effect of dust on the light when we are detecting from distant stars includes extinction (distant objects look dimmer) and reddening (objects look redder). Extinction is the combined effect of absorption and scattering by dust (Tatum n.d.), and reddening occurs as light rays with longer wavelengths (bluer colors) get less absorbed than the ones with shorter wavelengths (redder colors), making stars appear redder than they are. The main task is examining how brightness measurement gets corrected by dust extinction (change in magnitude) under the constraint of the limiting behavior of Hubble Space Telescope (HST) and James Webb Space Telescope (JWST), and using reddening dust map and converting reddening to extinction in a given filter (Landolt V band). The used dustmaps include Bayestar19 data and a dustmap (Lenz et al. 2017) that does not contain distance related data. The obtained results suggest that the positive distance-extinction correlation is only proven for small distances (some hundred parsecs) at the coordinates we work with.

Keywords: Dust — Reddening — Extinction — Limiting magnitude

1. INTRODUCTION

Interstellar dust consists of small grains of carbon, silicon, iron, aluminium and other heavier elements (UCPH 2018). The phenomenon of the dimming of distant objects due to the presence of dust is called extinction[1]. Robert Trumpler discovered that distant star clusters appeared dimmer than expected based on their distance alone (COSMOS 1999), which should be a manifestation of the effect of the dust on stellar object imaging. The incoming blue light is either scattered or absorbed by the dust grains, removing the shorter wavelengths from the light reaching us. The objects observed along the line of sight appear dimmer (extinction) and redder (reddening) than they really are (Theuns 2002). The main tasks are (1) numerically computing the extinction magnitude using a reddening dustmap (Lenz et al. 2017), and (2) investigating the effect of extinction on the limiting magnitudes of the chosen telescopes (HST and JWST) with respect to distance to an observed object using Bayestar dustmap.

2. THEORY

When the light (radiation) interacts with an atom (dust grain), the atom may be excited to a higher energy level. The atom then "immediately" (in the scale of nanoseconds) drops down to its original level and emits a photon with the same frequency as the one it absorbed (Tatum n.d.). This temporary absorption that is followed by re-emission (without change in wavelength) is scattering in this context (Tatum n.d.). Then the task is to analyze how the absorption affects the magnitude. Suppose there is a ray of light from distant stars with intensity I. The amount of light of this ray absorbed per unit distance obeys $dI/dr = -Br$. In other words, each distance dr will contribute a reduction of a constant fraction $dI/I = -B\,dr$ of the light(Theuns 2002). The solution to this equation is $I = I_0 exp(-Br)$ (using integration). The coefficient B will depend on the size and the distribution density of the dust grains. Taking the log of both sides of the previous equations lead to $A\,r$, which is the effect on the magnitude (Theuns 2002). The extinction in terms of brightness magnitude is given by:

[1] There is also extinction due to gas, which is beyond the scope of this project

$$m - M = 5log(d) - 5 + A \quad (1)$$

where A is the extinction magnitude and d is the distance between the chosen telescope and the observed object in kpc ($A = Br, d = r$), m and M being the apparent and absolute magnitude respectively. HST is said to have a "limiting magnitude" +31.5 while JWST's limiting magnitude is +34.

The absorption of the photons will in different color band which differs from one another. The B band (450nm) and V band (550nm) are used to estimate the effect of reddening, with $A_v \neq A_B$ (different absorption and scattering). The absorption in different bands leads to a color change (reddening, as the longer wavelengths get less absorbed than the shorter ones)(Theuns 2002). Applying Eq. 1, we obtain:

$$E_{B-V} = (m_B - m_V) - (M_B - M_V) = A_B - A_V \quad (2)$$

The change in color excess (reddening) can be rewritten as:

$$E_{B-V} = (B - V) - (B - V)_o = A_B - A_V \quad (3)$$

where $(B - V)$ is the observed color index and $(B - V)_o$ denotes the intrinsic color index value. Using the empirical data, the relation between A_V and the color excess, transformed from Eq. 3, is found to be:

$$A_V = R_V \cdot E_{B-V} \quad (4)$$

R_V is the reddening parameter or the proportionality constant, in general with a value of 3.1 (SBU Astron. n.d.).

3. METHOD OF ANALYSIS

Some python packages such as dustmaps and healpy are used for analysis. In the first part of the project, the "Bayestar19" dustmap data will be used for computing A_V with using Eq.4. Both A_V (using query() method) and E_{B-V} (using bayestar() method) changes with distance according to the dustmaps documentation (Green n.d.), the dust correction should then depend on the distance. The empirically estimated R_V for Landolt V band used for calculating A_V, which is 2.742 according to the reference (Schlafly & Finkbeiner 2011).

Four sets of coordinates are selected from the plotted region below and the distance dependent/independent analysis will be performed based on the data that are retrieved from the dust map at these points.

A similar analysis is done for the dustmap (Lenz et al. 2017) based on all-sky observations of Galactic HI emission by the HI4PI Survey, except that this map does not need distance as a parameter[2].

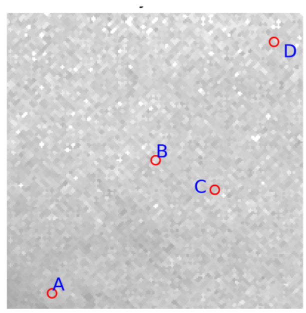

Figure 1. Region in the bayestar dustmap that is used for investigation, with longitude in the range [95,105] degrees and latitude in [25,35] degrees. The distance is set to be 100kpc for this visual representation. The coordinates of A,B,C,D can be found in Table 1.

4. RESULTS AND DISCUSSIONS

The extinction magnitude A_V based on Bayestar19 data is plotted against distance (fig 2) at four coordinates (specified in Table 1). It is observed that the value of A_V reaches a constant "plateau" at certain distances at all the

[2] This map (Lenz et al. 2017) is plotted with low HI column density, which is related to the interstellar medium composed of neutral atomic hydrogen (HI), which is not included in our analysis.

chosen coordinates, which means the effect of distance on A_V is only observed at close distance (with scale of 0.1kpc, i.e. mostly less than 1kpc) in our cases. The existence of plateau is probably due to the limitation of the Bayestar data, or there is no more dust detected over that distance. A_V at the coordinates of point A has a slower rising rate with respect to the evolution of distance before reaching the plateau comparing to that at B. The values of A_V at plateau are also different, which is realistic as the dust distribution is not uniform in the universe. There is also an extinction graph shown in Appendix A that the galactic coordinates are set to be both zero degree. The values of A_V at 50kpc and 100kpc are shown in Table 1(not covered by fig 2, but are more appropriate in analysis considering the scale of the limiting magnitude of the telescopes in fig 3). Some other investigations on the behavior of A_V with changing distance can be found in Appendix A.

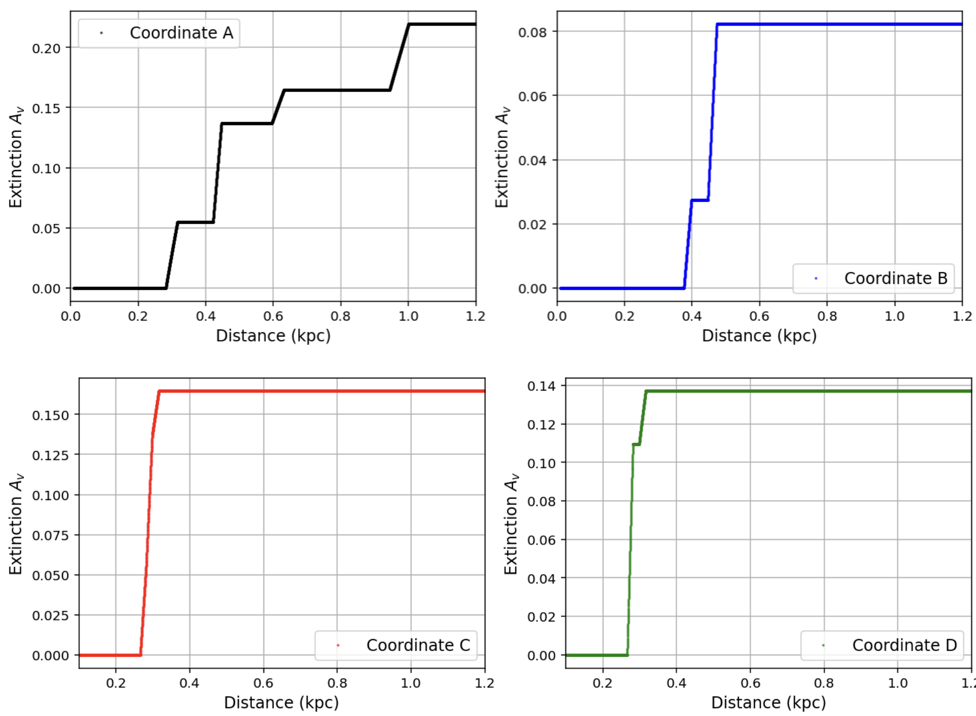

Figure 2. The extinction in V band with respect to distance at coordinates of A, B, C and D. The extinction only changes approximately between 0.2 kpc and 1 kpc. The value of A_v is obtained by using Eq.4 with $R_V = 2.742$.

Table 1. Table of A_v values computed using Eq.4 with $R_V = 2.742$ and numerically computed Bayestar E_{B-V}. The galactic coordinates of the points A,B,C,D (in fig. 1) are listed below.

Coordinate (longitude/latitude)	Av (50kpc and 100kpc)
A (96.5, 25.5)	0.22
B (100, 30)	0.08
C (102, 29)	0.16
D (104, 34)	0.14

The evolution of the limiting magnitude before and after applying the dust correction is demonstrated in fig 3, with an input distance range of 100pc to 1Mpc. The distance-dependent relation (Eq.1) is used for the data at point A. For larger distances (from 45Mpc to 230Mpc), a redshift-dependent plot of magnitude demonstrates the results (fig 4, where the values of the redshifts are converted to luminosity distances). From those plots, it can be observed that the limiting magnitude of both telescopes is smaller after being corrected with dust extinction. By observing the magnified plot (fig 3 (b)), it is noticed that the effect of the distance on the dust correction is imperceptible at the current scale, which matches with the earlier discussion on the A_V magnitude obtained with query() method.

Table 2. Limiting absolute magnitude with dust correction using A_V from Table 1 with $R_V = 2.742$. The coordinates of each point are found in Table 1.

(coordinates\dist)	JWST (50kpc)	HST (50kpc)	JWST (100kpc)	HST (100kpc)
A	15.29	12.79	13.78	11.28
B	15.42	12.92	13.92	11.42
C	15.34	12.84	13.84	11.34
D	15.37	12.87	13.86	11.36

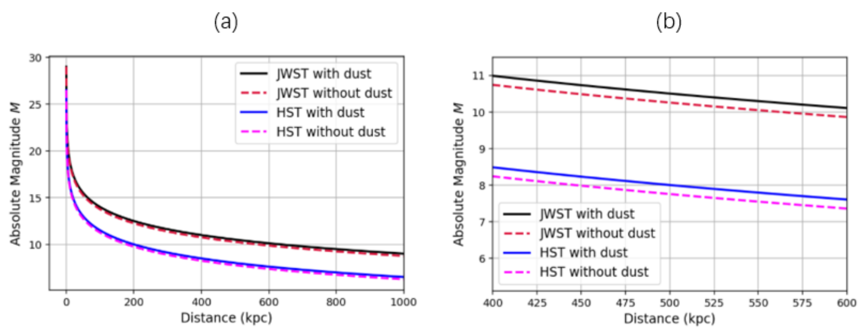

Figure 3. Limiting absolute magnitude at different distances for JWST and HST with\without dust correction (point A). The range of distances: (a) 100pc to 1Mpc, (b) (magnified plot with distance range of) 400kpc to 600kpc.

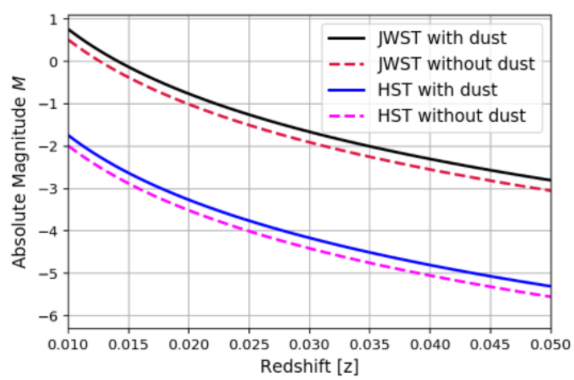

Figure 4. Limiting absolute magnitude with\without dust correction (point A) using luminosity distances corresponding to redshift z = 0.01 (luminosity distance of 45Mpc) to z = 0.04 (230Mpc).

The data at the points A and C are not covered by the reddening map (Lenz et al. 2017). See the codes in the jupyter notebook for details. The A_V value at point B is 0.11, and the value is about 0.12 at point D. The distances related to the data retrieved from the map (Lenz et al. 2017) are unknown. By comparing the values of A_V in Table 1, the data should be taken at distances larger than 100kpc (A_V here larger than the value in Table 1 for both coordinates of B and D), assuming that the dust extinction behavior becomes more intense as distance increases. However, it is also noticed that the extinction for the Bayestar data only changes at a few hundred parsecs away from the observer (Appendix A). It is unclear whether there is a correlation between the HI density and the distance in terms of their influence on the dust extinction. One thing we can tell is that the choice of R_V value of 2.742 for Landolt V band in equation 4 applied here is appropriate (A_V obtained for both Lenz map and the Bayestar data have order of magnitude of 10^{-1}).

We chose to use the scale of kpc (in fig.3) because the distance d in Eq.1 has units of kpc. This scale is not very appropriate for dust correction analysis (and Mpc in fig.4 is even worse). The distance depedent behavior is only found in the small distance regime.

5. CONCLUSION

Our results show that the effect of dust extinction on the brightness magnitude of light rays is larger as the distance to the source object is larger, but this conclusion is only certain within specific distances (up to 1 kpc for coordinates at A and 30 kpc when the longitude and latitude are both zero degree). The order of magnitude of A_V is generally 10^{-1} at a few hundred parsecs from us with our coordinates. The choice of 2.742 as the estimate of R_V (ratio of A_V and color excess) is good enough to keep the scale of extinction to be 10^{-1} for both maps that are used. One thing to notice is that there is not only one factor (distance) for the effect of extinction. We could possibly improve our results by incorporating the effect of other parameters (like the density of HI in the line of sight).

APPENDIX

A. DISTANCE DEPENDENT EXTINCTION MAGNITUDE A_V

This graph shows that the extinction value in V band comes to plateau around 30 kpc, which is the estimate of the radius of Milky Way.

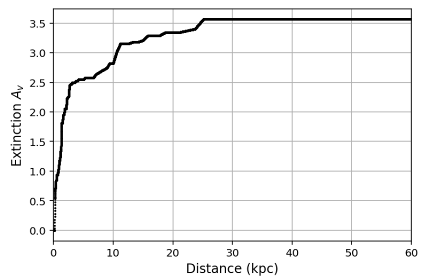

Figure 5. Extinction magnitude A_V at (0,0) in (longitude, latitude) with respect to distances.

The screenshots of following the results of A_V (coordinates of point A in Table 1) obtained using query() method for small large scale distances are found as follows. It is apparent that for large scale distances (scale of kpc), A_V has no change (or its change is insignificant as the values, rounded to the fifth digital place after the decimal point, are the same at different distances). Only at small scales with small distances (close to us), the A_V change is apparent (as shown in fig 6).

```
d = np.arange(450,460,0.5)
l0, b0 = (100., 30.) #longitude,latitude
l, b = np.meshgrid(l, b)
coords = SkyCoord(l0*u.deg, b0*u.deg, distance= d*u.pc, frame='galactic')
bayestar = BayestarQuery(max_samples=1)
Av_bayestar = 2.742 * bayestar(coords)
```

```
print(Av_bayestar)
```

```
[0.03446697 0.0355249  0.03658166 0.03763725 0.03869167 0.03974492
 0.04079702 0.04184795 0.04289772 0.04394634 0.0449938  0.04604011
 0.04708528 0.0481293  0.04917217 0.05021391 0.05125451 0.05229397
 0.05333231 0.05436951]
```

Figure 6. Extinction magnitude A_V at coordinates with distances from 450pc to 460 pc using Bayestar data (with query() method).

```
d = np.arange(10,100,1)
l0, b0 = (100., 30.) #longitude,latitude
l, b = np.meshgrid(l, b)
coords = SkyCoord(l0*u.deg, b0*u.deg, distance= d*u.kpc, frame='galactic')
bayestar = BayestarQuery(max_samples=1)
Av_bayestar = 2.742 * bayestar(coords)
```

```
print(Av_bayestar)
```

```
[0.08226 0.08226 0.08226 0.08226 0.08226 0.08226 0.08226 0.08226 0.08226
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```

Figure 7. Extinction magnitude A_V at coordinates with distances from 10kpc to 100 kpc using Bayestar data (with query() method).

```
d = np.arange(10**5,10**5+100,1)
l0, b0 = (100., 30.) #longitude,latitude
l, b = np.meshgrid(l, b)
coords = SkyCoord(l0*u.deg, b0*u.deg, distance= d*u.pc, frame='galactic')
bayestar = BayestarQuery(max_samples=1)
Av_bayestar = 2.742 * bayestar(coords)
```

```
print(Av_bayestar) # see distance dependent effect of A_V in appendix A
```

```
[0.08226 0.08226 0.08226 0.08226 0.08226 0.08226 0.08226 0.08226 0.08226
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 0.08226]
```

Figure 8. Extinction magnitude A_V at coordinates at distances 100pc starting from 100 kpc using Bayestar data (with query() method).

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