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The Relationships Between Dust Attenuation, Stellar Mass, and Star Formation Rate

Daniel Krista-Kelsey[1]

[1] *University of Massachusetts - Amherst*
710 N Pleasant St
Amherst, MA 01003, USA

ABSTRACT

Dust attenuation has become one of the most important factors to consider when exploring galaxy evolution, especially out to cosmic noon z = 3 because dust absorbs optical and UV light very efficiently. In this study, we investigate the redshift evolution of dust attenuation as a function of star formation rate and stellar mass. Using the 3D-HST photometric catalogues modeled by Prospector, we derive polynomial fits and measure galaxy evolution trends from $0 < z < 3.0$ and compare these results to those of similar literature. High dust attenuation A_V is found to be associated with galaxies of higher redshifts. The Mass-A_V-SFR relation is also extended from a previous study of galaxies up to z = 0.7 to a new maximum of z = 3.0, where we confirm a previously proposed anti-correlation of dust attenuation against $M_\star$ that occurs a little below $M_\star = 10^{10}$. The mean A_V in all star forming (SF) galaxies as a function of redshift is explored, including the lower $M_\star$ samples, finding that a slight portion of stellar mass significantly deviates from the generally increasing dust trend.

Keywords: galaxies: evolution — galaxies: formation — dust, attenuation — SFR — redshift — stellar mass

1. INTRODUCTION

One of the most important and impactful factors that modern astronomers have to take into account is the effects of dust attenuation. Attenuation has dramatic effects on obtaining data by obscuring the light from distant galaxies. In other words, the intensity of the light is diminished by the combined geometrical effect of light being scattered into and out of line of sight from dust absorption and scattering. This is represented by: $I_V = I_{V,0}e^{-\tau_V}$, where I_V is the observed intensity of the source in the V-band (5500Å), $I_{V,0}$ is the true intensity of the source, and τ_V is the dust optical depth along the line of sight to the source. This can be further applied to obtain a relation for the absorption in magnitudes in the V-band: $A_V = 2.5\log(e) \times \tau_V \approx 1.086\tau_V$, where A_V is the absorption in magnitudes in the V-band and is the main parameter in this paper. Many astronomers have studied the effects of attenuation in recent history, such as Zahid et al. (2012) looking at the effects of attenuation, derived from the extinction law of Cardelli et al. (1989), on galaxy parameters such as metallicity, stellar mass, and dust extinction. They found strong relationships between these parameters and called it the MDSR (stellar mass, dust, star formation rate) and MZSR (stellar mass, metallicity, star formation rate) relations (the MZSR is also known as the Fundamental Metallicity Relation). In this paper, we explore the so-named MDSR and extend the work of Zahid et al. (2012) to see if dust attenuation effects extends out to further redshifts.

The MDSR relation was explored by Zahid et al. (2012) using a sample of ∼157,000 galaxies from the SDSS DR7 catalogue from 0 < z <0.7. An interesting result of their study is an anti-correlation of A_V to stellar mass $M_\star$ at high $M_\star$ and high star formation rates (SFRs). This paper uses galaxy data from the 3D-HST photometric catalogues, detailed later, to explore this MDSR relation with galaxies from 0.5 < z <3.0; an extreme step in analysis by expanding redshift from $z = 0.7$.

Martis et al. (2016) wrote an interesting paper about the obscured fraction of star forming galaxies noting the importance of dust out to z = 3. They conclude that the median amount of A_V increases and evolves with redshift, while also finding the ratio of the number of dusty star forming galaxies to non dusty star forming galaxies increased with redshift. This important finding is also explored in this paper's analysis of dust attenuation and, by comparing it to other relations brought up here, will be analyzed altogether to bring together conclusions.

To best understand the results drawn on the effects of dust attenuation from data analysis, understanding the data and sample is essential to provide population information so that the work here can be improved if bias shows, while also providing general background to validate findings. In Section 2, we describe the data background and in Section 3, we present our results.

2. DATA AND SAMPLE

2.1. *The 3D-HST Catalog*

As described by Leja et al. (2021), the 3D-HST survey is a photometric catalog consisting of galaxies identified in five well studied fields: AEGIS, COSMOS, GOODS-N, GOODS-S, and UDS (Skelton et al. (2014)). The catalog is additionally supplemented by *Spitzer*/MIPS 24 μm photometry from Whitaker et al. (2014), and later extended by Momcheva et al. (2016) to include grism spectroscopic redshifts. The photometric analysis includes galaxy imaging data at wavelengths $0.3-24\mu$m, where this paper focuses on A_V derived from τ_V in the V-band.

2.2. *SED Modeling*

The 3D-HST photometry data is modeled by a stellar population synthesis model code **Prospector**, developed by Leja et al. (2017). **Prospector** is a galaxy spectral energy distribution-fitting (SED-fitting) code that derives the galaxy characteristics, of which stellar mass, SFR, attenuation, and redshift are relevant to this paper. A more detailed description of **Prospector** is presented in both Leja et al. (2021) and Leja et al. (2017).

2.3. *Selection*

For this paper, we selected all of the ~63,400 galaxies included in this catalog. Of the characteristics derived from the SED-Modeling data, I specifically utilized stellar mass, SFR, optical depth, and redshift to deep-dive in the dust correlations, or the lack thereof. An important note to make is that this sample is incomplete for $\log M_\star \lesssim 9$, especially at higher z, and is incomplete as low as $M_\star \approx 8.5$ at lower z.

3. RESULTS AND DISCUSSION

3.1. *Stellar Mass and SFR Relation with Dust and Redshift*

Figure 1 shows log(SFR) - log($M_\star$) in bins of increasing A_V on the top panels, and the bottom panels shows log(SFR) - log($M_\star$) with evolving redshift. Focusing on the top panels of Figure 1, there is a clear result - the more dust there is, the higher the SFR is and the higher the $M_\star$. It is reasonable to deduce that with higher SFR, there is more dust production. On the bottom panels of Figure 1, instead of viewing a hex plot, we show a scatter plot color-coded by redshift. To see the evolution with A_V of redshift, we calculate the proportion of galaxies in each bin that have $z > 2$. From left to right, the bins are defined as 17% ($0 < A_V < 0.5$), 17% ($0.5 < A_V < 1.0$), 26% ($1.0 < A_V < 2.0$), and 31% ($A_V > 2.0$). There is an apparent correlation with higher A_V preferentially represented by higher redshifted galaxies.

Both means of analysis of dust evolution show that A_V grows with larger redshifts. Binning by A_V and redshift results in the same qualitative trend as both result in higher SFR. The first A_V bin has a majority of the galaxies at low redshifts, including a few dusty galaxies ($A_V < 2$) that have gone quiescent (log(sSFR < -10)) and some local galaxies with low attenuation, but high SFR.

For a deeper dive into understanding this relation, Figure 2 shows log(SFR) plotted against A_V with redshift. We fit a polynomial to the data in 5 bins of redshift. As shown in Figure 1, the SFR increases with A_V. Figure 2 shows an additional unique trend when fixing A_V: there tends to be an increase in SFR at higher redshifts. This is a very loose observation though due to the polynomial fit only being a 5th-degree function, since another type of fit could be a better fit.

An interesting observation to point out is some of the highest attenuated galaxies in this sample are ones of lower relative redshift. Their SFR is not necessarily completely dead, but it is not very active either. A plausible explanation for these highly attenuated galaxies is feedback via driven interstellar medium winds (Gobat et al. (2018)). If gas (and dust) is cold, star formation can take place, but if the gas is hot, its velocity is too high to be held by gravity. Interstellar winds can explain high temperature gas, where this feedback is caused by an active galactic nuclei. This qualitative extrapolation is purely speculative, and to make a valid claim about this, a more in-depth study would be needed.

3.2. *Extended MDSR Relation*

Figure 3 shows A_V plotted against $M_\star$ with SFR as a third parameter. A 5th-degree polynomial fit was fit to the data for bins of log(SFR) to demonstrate the evolution of SFR and A_V at a fixed $M_\star$. This relation is an extension of Section 3.1 and Figure 2 of Zahid et al. (2012) and will be directly compared to for analysis. In their sample of ~157,000 galaxies out to z = 0.7, they found that there was an anti-correlation at high SFR at $M_\star > 10^{10}\mathrm{M}_\odot$; otherwise, there was a general trend for increasing attenuation with higher $M_\star$. In this paper, the most important difference is that this data has

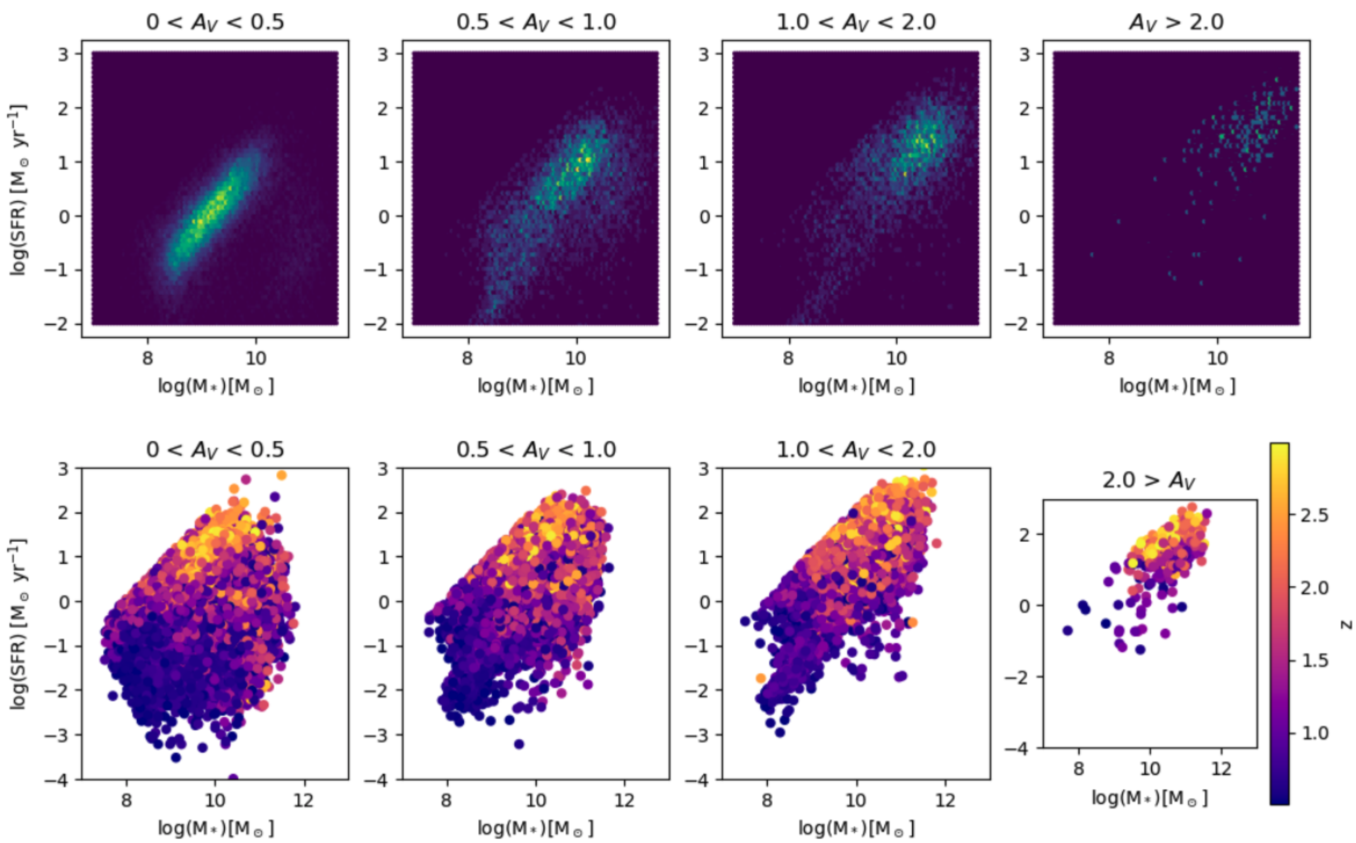

Figure 1. Top: $M_\star$ and SFR tight relation binned by spectral absorbance A_V, where the colormap represents point density. Two vital details is that SFR increases with increasing $M_\star$, and average SFR and $M_\star$ together increases with increasing A_V. Bottom: Same data as top, but point density is replaced by redshift for the colormap. Evolution of redshift is exemplified by these graphs, where there is a slight correlation of redshift with A_V.

a redshift range of $0.5 < z < 3.0$. Our MDSR analysis broadly agrees with the lower redshift study by Zahid et al. (2012), with a general trend for increasing A_V at higher $M_\star$ and at fixed $M_\star$. However, the results are slightly different; at lower $M_\star$, an anti-correlation is present, where at a fixed $M_\star$, higher SFR is attributed with lower A_V until the data gradually flips between $10^9 < M_\star < 10^{10}$. A direct comparison around $10^{10}\mathrm{M}_\odot$ shows that Zahid et al. (2012) result stands true out to $z = 3.0$ - there is an anti-correlation present at the same place that they found, even if it is rough. The difference in the high $M_\star$ range is seen to be up to ~ 0.5 dex in A_V.

A key fundamental difference between Zahid et al. (2012) and our data is that they used $M_\star$ bins where I used 5th-degree continuous bins, which can highly vary the comparison. The assumption here is that the relation is one like a polynomial, but could easily be better represented by any other fit, or no fit at all such as Zahid et al. (2012) they simply observed the trend in the median A_V.

Zahid et al. (2012) concluded that the twist may represent a physical process which leads to the shutdown of star formation. If this is assumed to be true, then the physical process happens even earlier than cosmic noon as the "flip" is already present in this higher z study.

Despite the lack of total agreement in the comparison, this result confirms what Zahid et al. (2012) found. They did a low redshift comparison, whereas I explored the relation out to cosmic noon. Galaxies out at cosmic noon have a lot higher SFR than now (Whitaker et al. (2014)), and there's a lot more dust to explain for the high SFR. It is no surprise that what is drawn from Figure 3 accurately represents cosmic SF history.

3.3. *Obscurity by Dust*

Figure 4 shows the average A_V as a function of redshift, binned by $\log(M_\star)$ in around $10^{0.3}$-wide bins of redshift. This figure is near identical to Martis et al. (2016), but with distinct differences which leads to a new observation not mentioned in the other paper. Martis et al. (2016) also used the 3D-HST catalogues to produce this, but what is included here and not in that

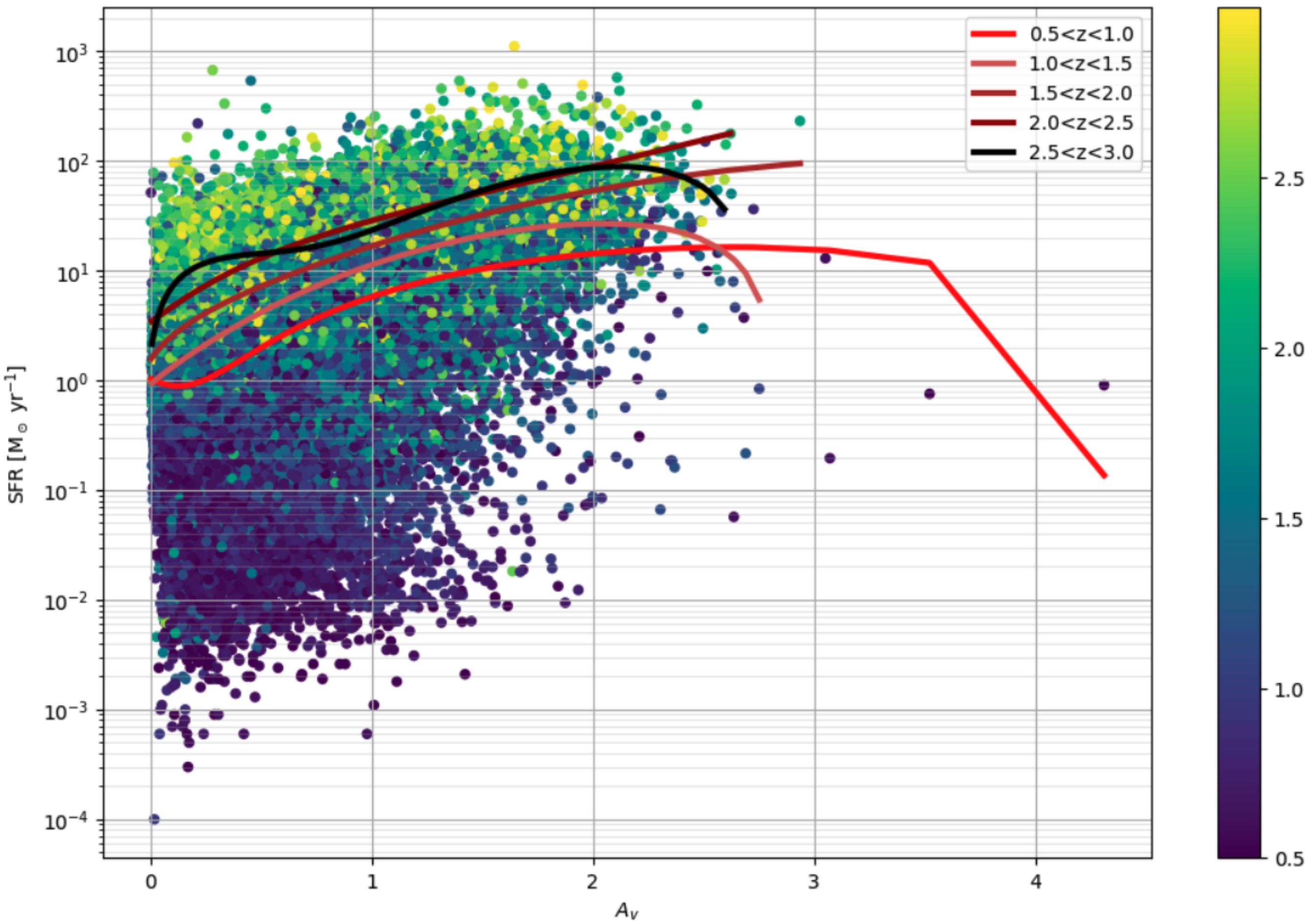

Figure 2. SFR plotted against A_V with a z colormap. SFR and A_V relation polyfitted, binned by z shown on plot legend. As displayed by the fitted curves, SFR increases with higher amounts of A_V, and at larger redshifts.

paper is the extension of the lower end of $M_\star$, where there is a present anti-correlation in the higher redshift - low mass range, creating a new relation. Our results corroborate those in Martis et al. (2016). Namely; the increase in dust attenuation with increasing $M_\star$ is inconsistent with the mass-metallicity relation, suggesting that there is vital missing information with metallicity in the high redshift obscured range.

The lower end range from $10^{7.512} < M_\star < 10^{8.625}$ was completely missing from Martis et al. (2016) due to the sample not being complete. Again, there is an anti-correlation at lower-relative redshifts, starting at the turnaround point $M_\star = 10^{10.492}$M$_\odot$ and any higher mass has lower attenuation. This is a key observation, and one that is also explained. Higher mass galaxies tend to be quiescent in the local universe but are seen to be vigorously more active the farther back in time looked at.

Something to keep in mind from the additional lower end $M_\star$ trends is that $M_\star \sim 10^{7.843}$ has gone rogue from the general trend followed by all of the other $M_\star$ bins. It strongly increases to have higher dust than some of the most massive galaxies up to z = 2.5. We saw from Figure 2 that there is no unusual observation made in the $2.0 < z < 2.5$ range relating to SFR, with an increase of more than 1.25 dex in A_V within $\Delta z = 0.2$. This is due to this sample being incomplete - only a handful of galaxies exist in this stellar mass range.

4. CONCLUSIONS

By comparing dust attenuation to SFR and stellar mass out to cosmic noon, we have built upon previous literature to further understand known relations. We used the 3D-HST catalog to derive correlations and fits to further understand the impact dust attenuation has on galaxies. Overall, the key takeaways include:

1. We found strong evolution of A_ν on the stellar mass and SFR relation, with indication of evolution of an increasing fraction of high redshift with increasing A_ν.

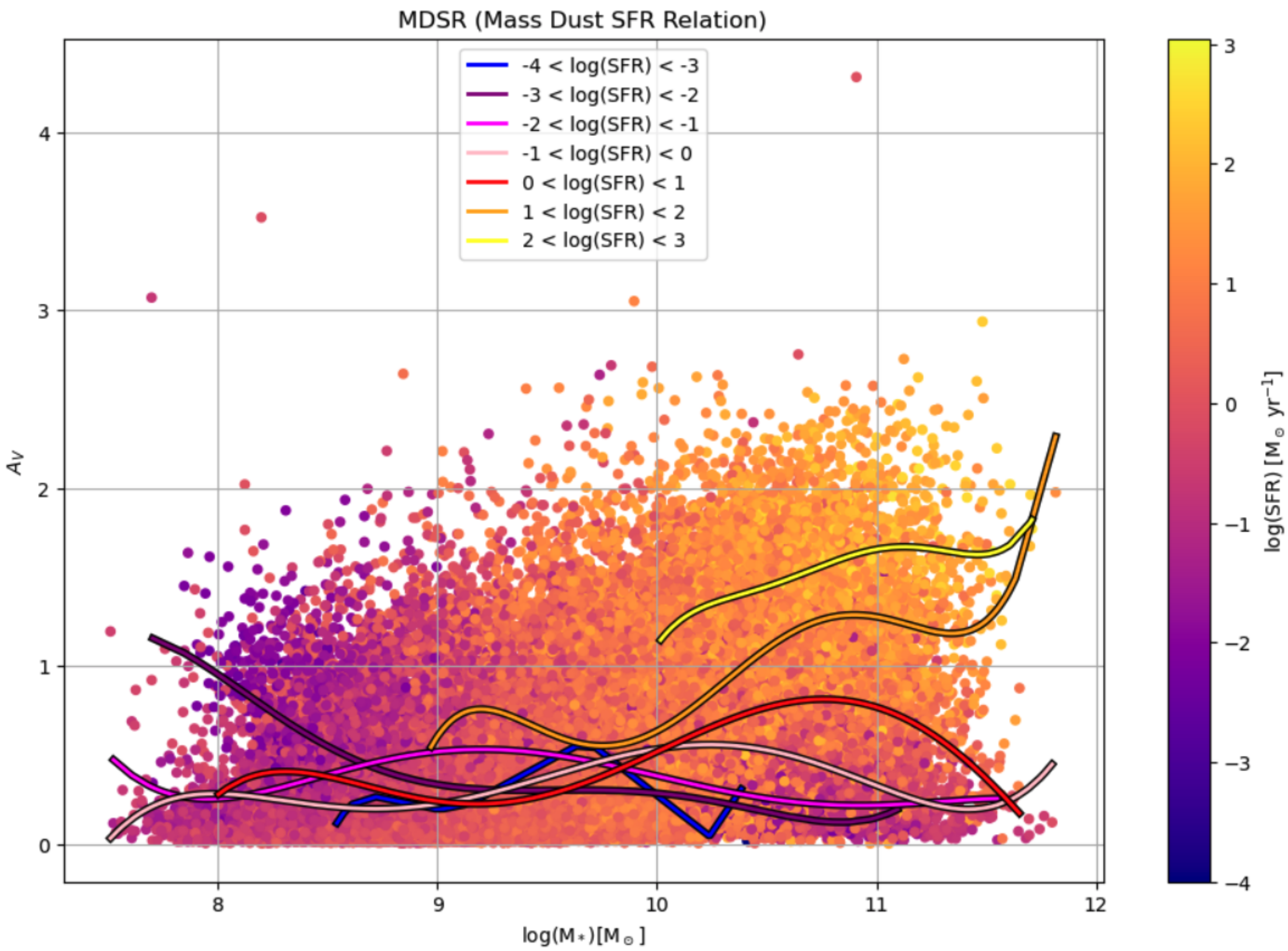

Figure 3. A_V plotted against $M_\star$, with SFR colormap. A_V and $M_\star$ relation plotted by bins of SFR, where the color key is shown by the plot legend. The larger the log(SFR) bin, the larger the A_V present. There is also a subtle "flip" in correlation around $10^{10}M_\star$, just as Zahid et al. (2012) found.

2. There is an increase in the SFR rate at evolving redshifts with higher dust content.

3. Our results detailing the MDSR relation out to z = 3 agree with Zahid et al. (2012) relatively local universe of z < 0.7 claims of an anti-correlation at, loosely, around $10^{10}\mathrm{M}_\odot$ and supports their claim that there may be some unknown physical process causing the twist.

4. The general relation of higher obscurity due to dust at higher $M_\star$ with increasing redshift stands positively correlated, but suffers a high deviation at one specific $M_\star$ of $M_\star = 10^{7.843}\mathrm{M}_\odot$ that remains unexplained and open for further interpretation.

Modern astronomers have realized for the past decade that the most important step for the future of galaxy evolution is investing heavily into the infrared to pierce the highly dense and obscured regions by dust. This will allow all of the relevant relations discussed here to be expanded upon to further redshifts via the infrared, to smaller $M_\star$ via larger telescopes at further redshifts, and to unveil new and improved relations to better describe star formation history and galaxy evolution.

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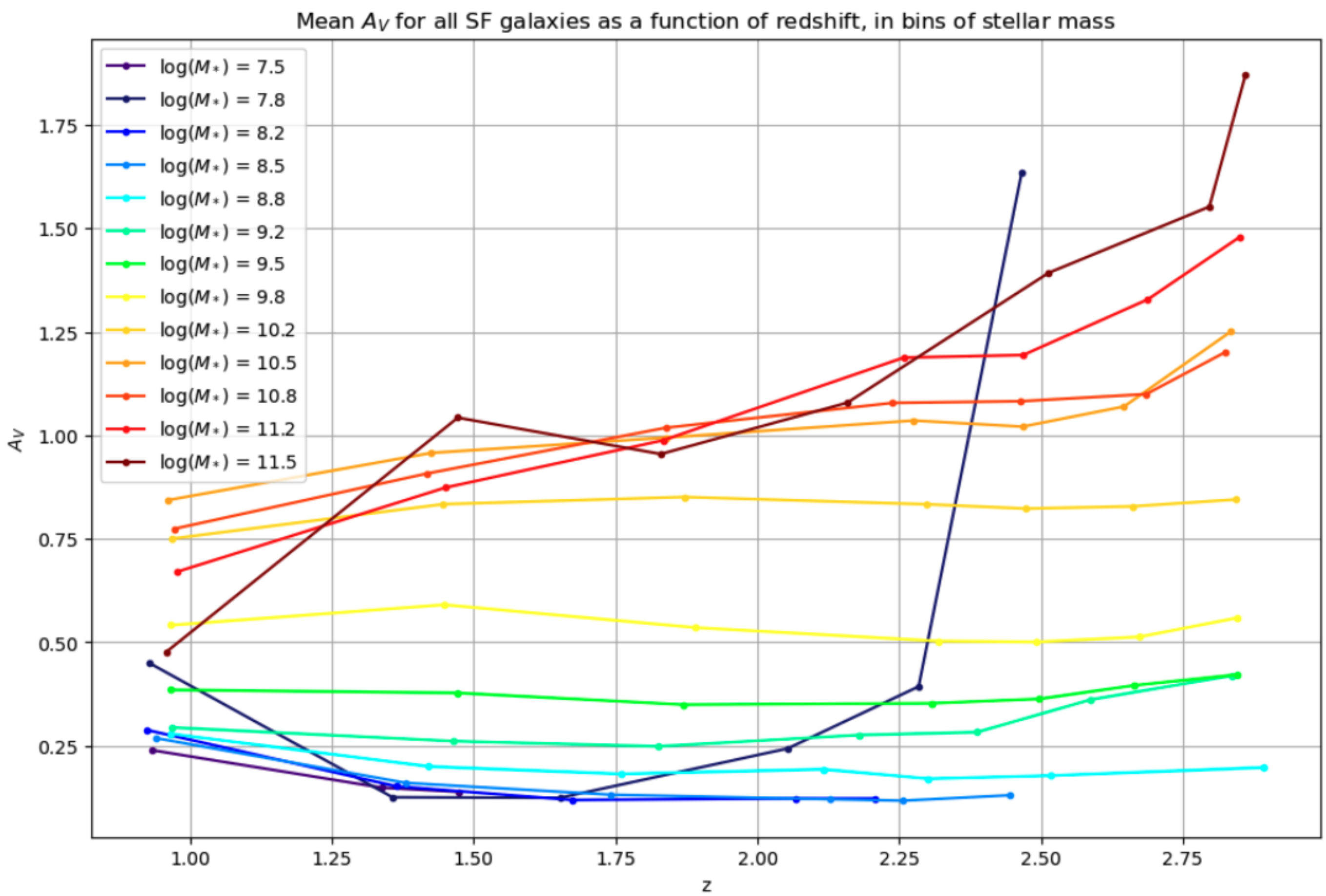

Figure 4. The average A_ν as a function of redshift. Redshift is binned by $M_\star$. $M_\star < 8.505$ fits fall short of the z = 3 extent the other fits achieve due to a lack of low $M_\star$ data at high z. The general trend is A_V increases with redshift, and more-so at larger stellar masses.

based on data collected by the 3D-HST Treasury Program (GO 12177 and 12328) with the NASA/ESA HST.

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