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Three-Emission-Line Models of Interstellar Dust Attenuation

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ABSTRACT

In this work, we demonstrate an analytic formulation to solve for the parameters of a galactic attenuation curve using a three emission line model. Introduction of the third emission line allows for a model derived from less uncertain parameters than the traditionally used Balmer decrement alone. We choose to investigate the Paschen series of hydrogen as potential candidates for a viable third emission line for the three line model, along with the traditional Hα and Hβ. Paα and Paβ offer the same insensitivity to ISM conditions while probing the same ionized gas, therefore the same star formation timescales. We also consider corrections to the model in the form of covering fractions to compensate for otherwise nonphysical attenuation laws. We conclude by discussing future prospects of three-line attenuation models in future studies with the *James Webb Space Telescope*.

1. INTRODUCTION

Dust attenuation is one of the most prevalent issues in the interpretation of astrophysical measurements. In extragalactic astronomy, understanding how light from the stellar continuum and ionized gases is attenuated by dust in the interstellar medium (ISM) is crucial to properly interpreting measured quantities like star-formation rates (SFRs) and star-formation histories (SFHs), gas-phase metallicities, and ionization parameters.

The most commonly used indicator of nebular attenuation in galactic astronomy is the Balmer decrement, Hα/Hβ. Given a known intrinsic ratio of the Balmer lines, Hα/Hβ = 2.86 assuming case B recombination (Osterbrock 1989), an observed Balmer decrement greater than the known intrinsic ratio indicates the presence of greater attenuation of Hβ than Hα. This observed Balmer decrement is interpreted as a measure of the dust in the ISM of a galaxy.

The Balmer decrement proves very useful in low-redshift and mildly-dusty ISM conditions, but in the moderately- to highly-dusty regime the Balmer decrement begins to lose efficacy. Hα is attenuated by a factor of two at even modest $A_V \approx 1$, and effectively unusable at $A_V \approx 3$, where it is attenuated by a factor of 10. As such, the measurement of the Balmer decrement becomes highly uncertain in moderately dust conditions.

A potential solution to this is the use of a third, longer wavelength emission-line. As the Balmer decrement becomes more uncertain and less viable in dustier galaxies, use of a longer-wavelength emission-line ratio becomes necessary.

For consistency with the Balmer decrement, it is a clear choice to use recombination lines of hydrogen of higher-order transitions (and longer wavelengths). The near-infrared (NIR) Paschen and Brackett series of hydrogen offer the same benefits of the Balmer line ratios, exhibiting relative insensitivity to nuisance conditions in the ISM such as metallicity, temperature, and particle density variations (Osterbrock 1989), while still probing the same regions ionized by massive, young, OB stars. This, in conjunction with the relative insensitivity to dust attenuation when compared to the UV and optical tracers, has led the Paschen and Brackett lines to be crowned "the gold standard" of star formation indicators (Kennicutt & Evans 2012).

Throughout this work, we assume a WMAP9 cosmology with $\Omega_{m,0} = 0.287$, $\Omega_{\Lambda,0} = 0.713$, and $H_0 = 69.3$ km s^{-1} Mpc^{-1} (Hinshaw et al. 2013). We also assume intrinsic line ratios of Hα/Hβ = 2.86 and Hα/Paβ = 17.6, corresponding to Case B recombination at a temperature of $T = 10^4$ K and a density of $n_e = 10^4$ cm^{-3} (Osterbrock 1989).

2. ANALYTIC FORMULATION

In this section, we present an analytic formulation of the three-line model. We also discuss the implications of variable dust attenuation across a galaxy by introducing covering fractions as a further correction to our model.

For traditional two-emission-line measurements, such as for the Balmer decrement, a galaxies nebular attenuation law can be constrained in terms of the slope and normalization parameters. For the simplest case, assume no slit losses or other observational constraints of the spectroscopy. We can parameterize the attenuation law using the optical depth as a function of wavelength, scaled to the V-band optical depth τ_V. Similarly to the literature (Charlot & Fall 2000):

$$\tau_\lambda = \tau_V \left(\frac{\lambda}{5500\text{Å}} \right)^{-n} \quad (1)$$

where the slope of the attenuation law is given by the parameter n. τ_V can be expressed in terms of the optical continuum attenuation A_V as $A_V = 1.086\tau_V$ in magnitudes.

Each emission line has an observed flux given by the flux-luminosity relation

$$F = \frac{Le^{\tau_\lambda}}{4\pi d_L^2} \quad (2)$$

where d_L is the luminosity distance to the galaxy at a given redshift. For the ratio of two fluxes (for lines we will generically refer to as i and j), we have

$$\frac{F_i}{F_j} = \frac{L_i e^{\tau_{\lambda_i}}}{L_j e^{\tau_{\lambda_j}}} \quad (3)$$

implementing the relation in equation 1, we have

$$\frac{F_i}{F_j} = \frac{L_i e^{\tau_V \left(\frac{\lambda_i}{5500\text{Å}}\right)^{-n}}}{L_j e^{\tau_V \left(\frac{\lambda_i}{5500\text{Å}}\right)^{-n}}}$$

We can divide by the luminosity ratio to isolate the optical depths and attenuation law slopes

$$\frac{F_i/F_j}{L_i/L_j} = \exp\left(-\tau_V \left[\left(\frac{\lambda_i}{5500\text{Å}}\right)^{-n} - \left(\frac{\lambda_j}{5500\text{Å}}\right)^{-n}\right]\right) \quad (4)$$

If we now consider the case of three emission-lines, i, j, and k, we can use the relationship shown in Equation 7 for two sets of line ratios to get an equation solely in terms of the measured fluxes and luminosities and the attenuation law slope n. This takes the form

$$\frac{\ln\left(\frac{F_i/F_j}{L_i/L_j}\right)}{\ln\left(\frac{F_k/F_i}{L_k/L_i}\right)} = \frac{\left(\frac{\lambda_j}{\lambda_i}\right)^{-n} - 1}{1 - \left(\frac{\lambda_k}{\lambda_i}\right)^{-n}} \quad (5)$$

This formalism does not impose any restriction on the analysis of the dust attenuation law derived from the three line model other than the normalization and slope being non-negative. In the following subsection, we will introduce a correction, the covering fraction, to the model in order to accommodate observations which may not directly fit with this most simple case of the three-line model.

2.1. *Covering Fractions*

We now consider a correction to our three-line model where the attenuation of light from the observed galaxy is spatially variable. We introduce the notion of a covering fraction, which implies that some regions of the galaxy are opaque to bluer light. In this implication, the bluer light is only observable for the subset of sightlines with low attenuation.

We adjust our analytic solution by assuming that all sightlines are either dusty or free of dust, and that all emission from the three lines is observed in the dust free regions, while the light from the dusty portions is attenuated according to the derived attenuation model. The notion of the covering fraction, f_{cov}, indicates the fraction of the galaxies which lies in a dusty region. In this notation, $f_{cov} = 0$ implies no dust in the galaxy, and $f_{cov} = 1$ implies that the entire galaxy is in a dusty region. The observed line flux of equation 2 with the covering fraction correction becomes

$$F_\lambda = \frac{(1 - f_{cov})L_\lambda + f_{cov} L_\lambda e^{-\tau_\lambda}}{4\pi d_L^2} \quad (6)$$

where the first term in the numerator represents the light from dust-free sightlines, and the second term represents the light from dusty sightlines, attenuated in the same manner as in Equation 2.

The line ratios analogous to Equation 7 is now

$$\frac{F_i/F_j}{L_i/L_j} = \frac{(1 - f_{cov}) + f_{cov}\exp\left[-\tau_V \left(\frac{\lambda_i}{5500\text{Å}}\right)^{-n}\right]}{(1 - f_{cov}) + f_{cov}\exp\left[-\tau_V \left(\frac{\lambda_j}{5500\text{Å}}\right)^{-n}\right]} \quad (7)$$

This formalism with the covering fraction correction allows us to model the attenuation laws of some galaxies which would otherwise be deemed unphysical by other models. Further discussion of the benefits of introducing a covering fraction correction can be seen in Prescott, Finlator, Cleri et al. in prep.

3. APPLICATION TO PASCHEN AND BALMER LINES

In observations, we are limited to a relatively small set of emission lines from which to form the three-line attenuation model of a galaxy. Given the ubiquitous use of the well-established Balmer decrement, Hα/Hβ, we choose a third emission line with similar properties. The Paschen lines of hydrogen are a viable choice as they probe the same ionized gas and are similarly insensitive to metallicity, temperature, and particle density variations in the ISM (Kennicutt & Evans 2012; Osterbrock 1989).

The addition of a Paschen recombination line of hydrogen to the three-line model offers

A small sample of 29 Paβ-emitting galaxies has been studied using *Hubble Space Telescope* (*HST*) WFC/G102 slitless grism spectroscopy in Cleri et al. (2020). Cleri et al. (2020) also includes a subsample of 11 galaxies with matching optical spectroscopy from the Team Keck Treasury Redshift Survey (TKRS, Wirth et al. (2004)). In the following subsections, we specify a three-line model using Paβ, Hα, and Hβ, and compare with the subsample of 11 galaxies from Cleri et al. (2020). We also discuss the potential for issues with comparing the space-based slitless grism spectroscopy and ground-based slit spectroscopy.

3.1. *Three-Line Model with* Paβ*, Hα, and* Hβ

The following formalism is derived in full in Prescott, Finlator, Cleri et al. in prep. In the context of Paβ, Hα, and Hβ, the formalism of equation 5 becomes

$$\frac{\ln\left(\frac{F_{H\alpha}/F_{H\beta}}{L_{H\alpha}/L_{H\beta}}\right)}{\ln\left(\frac{F_{Pa\beta}/F_{H\alpha}}{L_{Pa\beta}/L_{H\alpha}}\right)} = \frac{\left(\frac{\lambda_{H\beta}}{\lambda_{H\alpha}}\right)^{-n} - 1}{1 - \left(\frac{\lambda_{Pa\beta}}{\lambda_{H\alpha}}\right)^{-n}} \tag{8}$$

This formalism allows us to calculate the slope of the attenuation law for any galaxy given just the Paβ, Hα, and Hβfluxes in addition to the redshift. We will discuss the implications of adding the covering fraction correction in the following section.

These ratios rely on the well-studied relative abundances of the three emission lines, with the intrinsic ratios of Paβ/H$\alpha \approx 1/17.6$ and Hα/H$\beta \approx 2.86$ (Osterbrock 1989).

3.2. *Comparison with Observations*

In this subsection we compare the measurable quantities of the three-line model with data from the Cleri et al. (2020) sample. For the eleven objects which have Paβ with Balmer lines from TKRS, we plot the Paβ/Hα to Hα/Hβ relation in Figure 1. We show the iYH-band composite images for each object, which indicates several galaxies with extended morphologies and steep color gradients. We discuss potential issues in measuring the Balmer decrement in these types of galaxies in the following section.

We note several of the objects lie well above the predictions from the Calzetti et al. (2000) (blue), Fitzpatrick (1999) (green), or Gordon et al. (2003) (orange) attenuation models. One of these is well explained (in the upper right) by the prominent dust lane, where we expect a large covering fraction, with most of the galaxy being completely opaque to Balmer emission. These galaxies are where the addition of the Paβ/Hα ratio proves extremely valuable in the determination of the attenuation model of the galaxy. Future studies of higher redshift samples with *JWST* will offer Paschen-line detections for a larger sample of highly dusty objects.

4. POTENTIAL ISSUES WITH THE THREE-LINE MODEL

The primary issues of the three-line model arise from observational concerns. The first of which, particular to the three hydrogen lines chosen in this work to derive the three-line model, is a concern of detectability of all three lines. The Paschen lines are significantly fainter than the Balmer lines, with the intrinsic Paβ/H$\alpha \approx 1/17.6$. Future work with deeper spectroscopy will give significantly larger sample of well-detected Paβ-emitting galaxies.

The second major concern of the three-line model, in the case of the Cleri et al. (2020) sample, is the comparison of emission lines from different instruments. The *HST* grism-based slitless spectroscopy of the Paβ-detections in the Cleri et al. (2020) sample are matched with ground-based slit spectroscopy from TKRS for the Balmer line fluxes (Wirth et al. 2004). This has potential issues in the assumptions of the TKRS measurements, where the equivalent widths of the emission lines are assumed constant across the galaxy. This implies that there may be issues with slit losses and slit placement, rendering the comparison of slit to slitless measurements dubious in some cases.

We note in Figure 1 that several of the objects which are not well modeled by the Calzetti et al. (2000), Fitzpatrick (1999), or Gordon et al. (2003) curves are those with extended morphologies and steep color gradients, along with one object with a prominent dust lane which can be well explained by virtue of it being the dustiest in the sample by far. The other objects which are not well modeled by the predictions may fall victim to the assumptions and potential slit losses of the TKRS measurements, causing uncertainties in the Balmer decrements. In the Summary and Conclusions we discuss the implications of future studies with *JWST* NIRCam slitless grism spectroscopy which will resolve the issues of comparing slit to slitless line fluxes.

5. SUMMARY AND CONCLUSIONS

In this work, we have presented a formulation to derive the slope and normalization parameters of an ISM attenuation model using a three emission line approach. This has significant benefits over the standard two-line models, such as those derived from the Balmer decrement, in that three-line models are more generalizable to a broader range of ISM conditions.

We specifically consider the case of adding a Paschen recombination line of hydrogen to the Balmer lines Hα and Hβ to construct our three-line model. The choice of Paβ, Hα, and Hβ for the three-line model offers consistency in the timescales of the star formation traced by each line, along with each of the three being relatively insensitive to nuisance parameters in the ISM such as metallicity, temperature, and density.

Future work will greatly expand both the need and means for these such analyses. The *James Webb Space Telescope* will give Paschen and Balmer line flux measurements to redshift $z \sim 3$ with the NIRCam grism and NIRSpec spectrograph. This will offer "gold standard" star formation rates and attenuation estimates past the peak of cosmic star formation at $z \sim 2$ (Madau & Dickinson 2014).

JWST will give access to all three of these lines from space-based spectroscopy from the same instruments, alleviating the issues of comparing space-based grism spectroscopy to ground-based slit spectroscopy. This practice of combining measurements from different instruments proves potentially dangerous, as discussed above. The paramount advantage of slitless grism spectroscopy is the lack of a need to consider slit losses, which are the source of such issues.

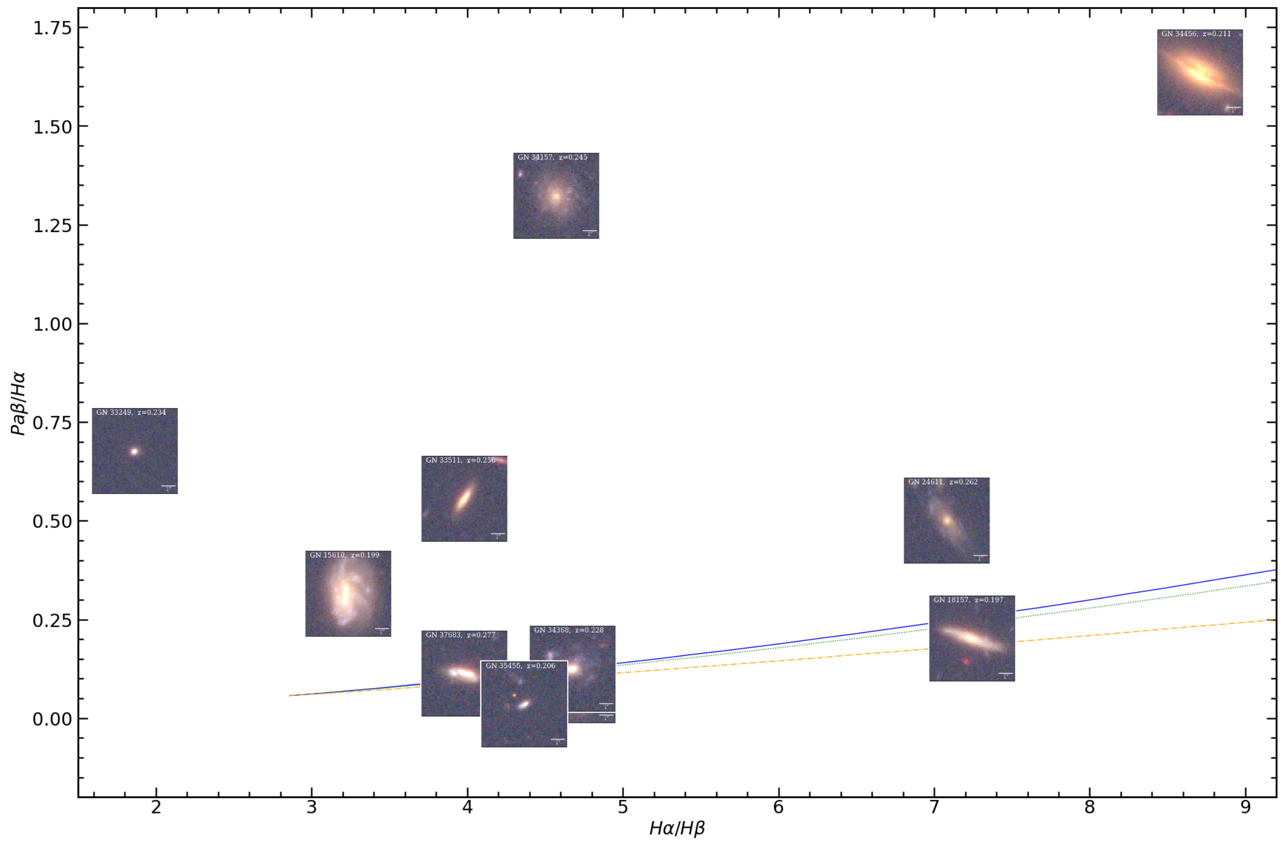

Figure 1. The relation between the Paβ/Hα to Hα/Hβ ratios for the subsample of 11 galaxies with matching optical spectroscopy from the Cleri et al. (2020) sample. Each point on the figure is plotted using the iYH-band composite image of the galaxy. The three models show the expected attenuation curves assuming Calzetti et al. (2000) (blue), Fitzpatrick (1999) (green), or Gordon et al. (2003) (orange) attenuation models. The galaxy in the upper right has a prominent dust lane, which explains the extremely high Paβ/Hα ratio compared to the predictions. Several of the other galaxies which lie well above the models are larger in radius, which makes them more susceptible to slit losses in the TKRS Balmer line measurements.

The *JWST* surveys in the future will be probing higher redshifts, thus dustier objects. This regime is where a three-line model with Paschen lines will prove the most valuable. *JWST* will also offer sample sizes orders of magnitude greater than those currently in the literature for similar work.

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This work is inspired by the analyses in an upcoming paper, Prescott, Finlator, Cleri et al. in prep, along with the work in Cleri et al. (2020).

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