Brackett-\(\gamma\) as a Gold-standard Test of Star Formation Rates Derived from SED Fitting

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**Abstract**

Using a local reference sample of 21 galaxies, we compare observations of the 2.16 \(\mu\)m Brackett-\(\gamma\) (Br\(\gamma\)) hydrogen recombination line with predictions from the Prospector Bayesian inference framework, which was used to fit the broadband photometry of these systems. This is a clean test of the spectral-energy-distribution-derived star formation rates (SFRs), as dust is expected to be optically thin at this wavelength in nearly all galaxies; thus, the internal conversion of SFR to predicted line luminosity does not depend strongly on the adopted dust model and posterior dust parameters, as is the case for shorter-wavelength lines such as H\(\alpha\). We find that Prospector predicts Br\(\gamma\) luminosities and equivalent widths with small offsets (~0.05 dex) and scatter (~0.2 dex), consistent with measurement uncertainties, though we caution that the derived offset is dependent on the choice of stellar isochrones. We demonstrate that even when the Prospector-derived dust attenuation does not well describe, e.g., H\(\alpha\) line properties or observed reddening between H\(\alpha\) and Br\(\gamma\), the underlying SFRs are accurate, as verified by the dust-free Br\(\gamma\) comparison. Finally, we discuss in what ways Br\(\gamma\) might be able to help constrain model parameters when treated as an input to the model, and we comment on its potential as an accurate monochromatic SFR indicator in the era of JWST multiobject near-IR spectroscopy.

**Unified Astronomy Thesaurus concepts:** Galaxy evolution (594); Star formation (1569); Galaxy processes (614)

**1. Introduction**

The modeling of spectral energy distributions (SEDs) is a method for extracting star formation rates (SFRs) and other galaxy properties from photometry and spectroscopy—for reviews, see Walcher et al. (2011) and Conroy (2013). These methods are broadly consistent with other commonly used SFR indicators and now feature Bayesian frameworks with, e.g., nonparametric star formation histories (SFHs), flexible attenuation curves, and nebular emission lines. By folding in all available information about a galaxy, SED fitting attempts to model the complex interplay of galaxy components and constrain, e.g., the dust properties and star formation activity simultaneously and self-consistently. When it comes to SFRs, it is particularly important to disentangle the effects that dust has on its observational signatures, as it influences features across the panchromatic SED (e.g., Spitzer 1978; Calzetti et al. 2000; Buat et al. 2005; Burgarella et al. 2005; Kennicutt & Evans 2012). For example, the ultraviolet (UV) light from young O/B-type stars, which probes the recent star formation, is often heavily attenuated by dust, which reprocesses the light to infrared (IR) wavelengths; however, the total UV+IR luminosity (often considered a probe of the full obscured +unobscured SFR) is impacted by the effect of heating by evolved stellar populations in the infrared (e.g., Cortese et al. 2008; De Looze et al. 2014; Utomo et al. 2014; Leja et al. 2019b; Nersesian et al. 2019). The magnitude of this effect depends strongly on the SFH of the galaxy; thus, only the full modeling of galaxy SFHs on an object-by-object basis can correct for this bias self-consistently.

One such SED-fitting framework is Prospector (Leja et al. 2017; Johnson et al. 2019), which uses stellar population synthesis models from FSPS (Conroy et al. 2009; Conroy & Gunn 2010) to fit photometry and/or spectroscopy. In Leja et al. (2017), the SFRs from Prospector were vetted by comparing the predicted H\(\alpha\) and H\(\beta\) luminosities and equivalent widths with spectroscopic observations for a local reference sample. Hydrogen recombination lines are a useful probe of instantaneous star formation, as they are not significantly affected by heating by evolved stellar populations—though there is evidence for a small contribution (~few \(\AA\) in EW) from post-AGB stars (Byler et al. 2019). Leja et al. (2017) found agreement in the predicted and observed spectral quantities, e.g., H\(\alpha\) luminosities were consistent with an offset of ~0.13 dex and scatter of ~0.19 dex.

However, this comparison is not the most direct validation of Prospector SFRs—the predicted H\(\alpha\) luminosity from Prospector depends not only on the inferred SFR but also on the stellar isochrones adopted (which govern the conversion of SFR to ionizing radiation), as well as on the inferred dust attenuation in each galaxy. Historically, simple functional attenuation curves (e.g., Calzetti et al. 2000; Charlot & Fall 2000), or flexible versions thereof, have been adopted when fitting galaxies, but there is ever-growing evidence for significant variation in galaxy dust attenuation curves in both observations (e.g., Kriek & Conroy 2013; Lo Faro et al. 2017), as well as in cosmological and zoom simulations (e.g., Narayanan et al. 2018; Trayford et al. 2019). It has also been shown that the choice of attenuation law has a significant effect on derived SFRs (for a review, see Salim & Narayanan 2020), and ultimately, any correction for inferred reddening (e.g., via the Balmer decrement) will still be insensitive to the most dust-obscured star formation (e.g., Arp 220), which is simply missed altogether at these wavelengths. Ideally, then, one would compare Prospector emission-line predictions to observations for lines that are as insensitive as possible to the effects of dust, allowing for the cleanest possible probe of the underlying derived SFR.
Such lines exist in the near-infrared (NIR). The optical depth of dust in a galaxy is a strong function of wavelength, because the dust grain-size distribution falls off steeply redward of \( \sim 1 \mu \text{m} \) (e.g., Draine \\& Lee 1984; Mathis 1996). Thus, hydrogen recombination lines at NIR (and longer) wavelengths are better suited for a (nearly) dust-free measurement of the SFR. In particular, the Brackett series—and to a somewhat lesser extent, the Paschen series—provide hope of a line flux measurement that is relatively insensitive to dust attenuation. To illustrate, for a standard Calzetti attenuation curve (Calzetti et al. 2000) assuming \( A_V = 1.86 \) (Price et al. 2014), \( H_\alpha \) is attenuated by \( \sim 75\% \), compared to \( \sim 16\% \) at \( Br_\gamma \) and 41\% at \( Pa_\beta \).

The clear theoretical prediction that \( Br_\gamma \) should be a nearly dust-free probe of a galaxy’s SFR has two important implications: first, that it can be used to test the underlying SFRs and dust predictions from SED-fitting frameworks such as Prospector, and second, that it can be used observationally as a monochromatic indicator of SFR that does not require any corrections for dust.

The focus of this work is on the first point, but it is worth noting that the primary reason the use of \( Br_\gamma \) as an SFR indicator has not been widely explored to date is that the line shifts redward of the \( K \) band at \( z \sim 0.1 \), making it infeasible to observe in distant systems from the ground. As a result, \( Br_\gamma \), along with other NIR emission lines, has only been measured for small samples of local galaxies (e.g., \( H_\alpha \) et al. 1990; Puxley et al. 1990; Goldader et al. 1995; Calzetti et al. 1996); furthermore, these studies were generally carried out with small apertures compared to the galaxy sizes, and the line fluxes measured were generally not used as direct measures of the total SFR. However, as we discuss further in Section 4, the launch of the James Webb Space Telescope (JWST) will change this picture dramatically and allow for \( Br_\gamma \) measurements in an interesting range of intermediate redshifts.

Nevertheless, even before JWST launches, we can use the benefits of \( Br_\gamma \)’s insensitivity to dust to answer the following question: do Prospector-derived SFRs agree with observations of a nearly dust-free SFR indicator?

The answer to this question has several implications for the SED-modeling framework implemented. Comparing predictions and observations for, e.g., \( H_\alpha \) would miss star formation fully obscured by optically thick dust at 6563 Å, even when applying Balmer decrement corrections. This obscured star formation activity could presumably lack a signature in the broadband photometry used by Prospector to predict \( H_\alpha \) output, particularly when the total bolometric luminosity of the galaxy is not known owing to a lack of far-infrared (FIR) measurements. This lack of “ground-truth” SFR could produce agreement between predicted and observed \( H_\alpha \) luminosities while missing an unknown fraction of highly obscured star formation.

Additionally, Prospector implements a prediction that a significant fraction of the dust heating in galaxies (and thus the resulting IR luminosity) comes from evolved stellar populations, with a strong dependence on SFH (Cortese et al. 2008). This is contrary to the usual assumption that only reprocessed light from young stars contributes to the IR luminosity—and as a result, Prospector-derived SFRs are typically lower than canonical IR SFRs by \( 0.1-0.5 \) dex (Leja et al. 2019b). \( Br_\gamma \) provides a prime opportunity to either validate or challenge this model. Furthermore, the continuity prior on Prospector SFHs tends to produce a smooth recent SFR; thus, significant scatter in the measured \( Br_\gamma \)-SFR relation (beyond measurement uncertainties) could indicate stochasticity in the SFR of these galaxies between \( \sim 100 \) Myr and \( \sim 5-10 \) Myr.

In this work, we repeat the comparative analysis of Leja et al. (2017) using newly obtained \( Br_\gamma \) spectroscopy. The sample obtained here comprises 21 galaxies and was observed with the TripleSpec instrument on the Palomar 200-inch telescope using a specialized force-scanning technique (e.g., Kennicutt 1992; Moustakas et al. 2010) to obtain spatially integrated luminosity-weighted spectra over large apertures, which both mimics the observing scenario at high redshifts and provides measurements that are aperture-matched to available photometry and optical spectroscopy.

Using this sample, we examine whether there is agreement between the \( Br_\gamma \) emission predicted from SED modeling and our measurements, and whether the scatter between them is consistent purely with observational uncertainties. We also discuss the implications for \( Br_\gamma \)-derived SFRs with future surveys, namely, those with JWST, and some model predictions that might allow for \( Br \gamma \) not only to be used as a monochromatic SFR indicator but also to be combined with other spectroscopic and photometric data within an SED-modeling framework to better constrain galaxy properties.

We adopt a \( \Lambda \)CDM cosmology with \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_\Lambda = 0.7 \), and \( \Omega_M = 0.3 \) throughout.

2. Prospector Model Predictions

Prospector\(^6\) is a Bayesian inference framework, which generates stellar population synthesis (SPS) models from FSPS\(^7\) (Conroy et al. 2009; Conroy \\& Gunn 2010) via the python-fspss\(^8\) bindings (Foreman-Mackey et al. 2014) to fit galaxy photometry and/or spectroscopy. The FSPS models feature dust emission (via Draine \\& Li 2007) and attenuation via a flexible attenuation curve (we adopt Kriek \\& Conroy 2013), as well as nebular emission via CLOUDY (Ferland et al. 1998; Ferland et al. 2013, 2017; Byler 2018). Photometry is fit with a seven-component nonparametric SFH within Prospector, using a continuity prior (Leja et al. 2019a). We adopt a Chabrier (2003) initial mass function, with an upper mass limit of \( 120 \ M_\odot \). Markov Chain Monte Carlo sampling is carried out via the dynasty\(^9\) nested-sampling package (Speagle 2020). For a full description of the Prospector framework, see Leja et al. (2017) and Johnson et al. (2019).

The choice of stellar isochrone model bears particular importance in this analysis, as it controls the conversion of a galaxy model’s SFR into the ionizing radiation field that produces nebular emission lines. Nonrotating, nonbinary stellar models have been used to convert \( H_\alpha \) fluxes into SFRs for decades; newer models that include rotation and binarity tend to change this conversion by \( \sim 0.15-0.3 \) dex. One key consequence of this change is that nebular line SFR indicators become inconsistent with other indicators (e.g., Wilkins et al. 2019).

It is yet to be established whether the new models are “correct”; if they are, there must also be a strong explanation for the systematic offset with observations found when using

\(^6\) http://github.com/bd-j/prospector
\(^7\) http://github.com/cconroy20/fspsp
\(^8\) http://dfm.io/python-fspsp/current/
\(^9\) https://github.com/joshspeagle/dynesty
them. In this work, we implement the canonical Padova models (Marigo & Girardi 2007; Marigo et al. 2008), both for consistency with the previous work of Leja et al. (2017), with which we compare results in this study, and because the canonical models are more consistent with SFRs derived using UV and IR fluxes. It is important to note, however, that this choice both is critical to the interpretation of the following analysis and could be reasonably made in another fashion—we thus explicitly discuss the impact of isochrone selection on our results in Section 4.2.

In Leja et al. (2017), UV to mid-infrared (MIR) photometry from the full sample of 129 galaxies from the Brown et al. (2014) atlas was fit with Prospector, and spectral emission lines (Hα, Hβ) were predicted; those predictions were then compared with aperture-matched integrated spectroscopy for those same lines. Of the 129 galaxies in the full sample, we selected ~30 to target spectroscopically for this test based on the prediction of a measurable Brγ line flux ($F \geq 10^{-15}$ erg s$^{-1}$ cm$^{-2}$). Twenty-one of the observed galaxies were used in the final analysis (see Section 3). In Figure 1, we show the derived SFRs and masses for the galaxies in this sample, which contain systems below, on, and above the star-forming main sequence of Salim et al. (2007). The full sample of galaxies from Brown et al. (2014) is shown for reference.

We then fit these galaxies’ UV–MIR photometry, following the procedure of Leja et al. (2017) while making several updates to the Prospector framework as described in Leja et al. (2019a) and Leja et al. (2019b)—the primary difference being the use of a continuity prior between adjacent nonparametric bins of SFR in the SFH prescription. Several model priors were also updated, and an MIR active galactic nucleus (AGN) component was included (see Leja et al. 2018).

At high redshift, it has been found that there is little to no luminosity dependence in the shape of the IR SED (Nordon et al. 2010; Wuyts et al. 2011); this motivates the use of fixed IR SED templates in fits to such systems, as was done in Leja et al. (2019b). Here, however, we adopt a flexible IR SED in the fit, noting that we do not fit any photometry redward of 12 μm, in part because only a small subset of the galaxies in this sample have measured IR photometry, as well as to mimic the observing scenario at higher redshifts, where the MIR (e.g., MIPS 24 μm) is often the reddest band available. The predicted IR SED is thus determined by the UV–NIR SED via energy balance and by direct observations of the MIR bands, allowing for variation in the IR SED shape as has been seen in the local universe (Chary & Elbaz 2001; Dale & Helou 2002).

The relevant model predictions for this study are presented in Figure 2: when conditioned on the far-UV–MIR photometry for the galaxies in this sample, Prospector makes the prediction of a sharp reduction in scatter between emergent Brγ luminosity and recent SFR, as compared with the same comparison for Hα. The relation between SFR and Brγ in Figure 2 is well described by

$$\log \text{SFR} [M_\odot \text{yr}^{-1}] = -6.17 + 1.071 \log L(\text{Brγ}) [L_\odot].$$

(1)

which the modeling predicts has an intrinsic scatter 0.05 dex, compared with ~0.2 dex for the equivalent relation with emergent Hα. We interpret this prediction of the model as stemming primarily from the effects of dust, by which Brγ is far less affected; photoionization models predict little scatter (~0.05 dex) in the ratio of intrinsic, dust-free Br-gamma luminosity to intrinsic, dust-free Hα luminosity. Examples of relations based on this (Kennicutt 1998; Murphy et al. 2011) are overplotted in Figure 2. We caution, however, that even at 2.16 μm some galaxies have been found to be optically thick; Arp 220 is a well-known example of this (Soifer et al. 1999). Still, Brγ should provide some insight into these systems; the bottom left panel of Figure 2 demonstrates that Prospector predicts for galaxies with ~90% attenuation of their Hα luminosity that Brγ is only attenuated by ~30%. We note that all Prospector-derived SFRs used in this work are averaged over the last 30 Myr—this corresponds to the bin width of the most recent bin in the 7-bin nonparametric SFH fit employed. As photometric data alone typically do not strongly distinguish SFRs between 10 and 30 Myr timescales, and the applied continuity prior in the absence of constraining information from bin to bin tends toward retaining the same SFR, we do not introduce finer temporal resolution (i.e., 10 Myr) to the SFH.

Because Brγ is located near the center of the K band, a measurement of Brγ equivalent width (EW)—obtained (essentially) for free with any line flux measurement without the need for absolute calibrations—represents a probe of the K-band continuum of a galaxy. The continuum in this region of the spectrum has been shown to be one of the best probes of the stellar mass of a galaxy, as M/L variations due to young stars present in blueward bands are minimized, while there is not yet emission from polycyclic aromatic hydrocarbons (PAHs), which begin to emit in the MIR. Thus, a direct prediction of the models that follows from the above is that specific star formation rate (sSFR) should be tightly correlated with Brγ-EW. This is presented in the top right panel of Figure 2; a fit to
predicted sSFR and Brγ-EW for the full 129 galaxies produces

$$\log \text{sSFR} \text{ [yr}^{-1}] = 1.1 \log \text{EW(Brγ)} - 10.63 \text{ [Å]} \quad (2)$$

If both the measured Brγ luminosity and equivalent width are consistent with Prospector’s predictions, it would be a strong validation of the Prospector-derived stellar masses and SFRs.

3. Data and Reduction

3.1. Observations

We obtained NIR spectroscopy of this subsample of the Brown et al. (2014) atlas using the TripleSpec instrument (Herter et al. 2008) on the Palomar 200-inch telescope, which has a wavelength coverage of $\sim 1$–2.4 μm in spectral orders roughly corresponding to the J, H, and K bands. Brackett-γ, with a rest-frame wavelength of 2.165 μm, falls in the K band for this local sample. Spectra were obtained via a forced scanning method in which the slit is moved back and forth over
the galaxy using the telescope drive (e.g., Kennicutt 1992; Moustakas et al. 2010), which discards spatial information to produce a luminosity-weighted, spatially integrated spectrum over a large aperture.

This observing mode thus allows for more direct comparisons to high-redshift galaxies, for which apertures are large by necessity, and is designed to produce spectra that are aperture-matched to available photometry. For this study, the spectroscopic apertures were selected to match those of the Moustakas et al. (2010) optical spectroscopic survey that was included in the Brown et al. (2014) analysis. Generally, two scans were needed to do this, because the TripleSpec slit is 1′′ × 30′′, whereas the aperture used in Brown et al. (2014) was 1′ × 2′. A full list of targets used in this analysis is presented in Tables 1 and 2—Table 1 provides Prospector-derived stellar masses, SFRs, and sSFRs used in this work, while Table 2 provides predicted Hα and Brγ line luminosities and equivalent widths. Table 2 also provides measured Brγ line fluxes and equivalent widths derived in this work, as well as Hα luminosities and equivalent widths used here and in Leja et al. (2017), which are part of the Brown et al. (2014) atlas and reproduced here for the reader’s convenience.

The observations were carried out over five nights from 2018 March 29 to 2018 April 03. Weather and seeing for the first three nights were clear, with ∼1″ seeing. The final two nights had similar seeing but variable cloud cover; frames that were disrupted by clouds were identified and removed from the reduction as described below. As the galaxies being observed were typically ~several times larger than the slit, which was being moved across each galaxy, subarcsecond seeing was not a necessity for obtaining usable spectra. Science and sky frames were taken with an exposure time of 300 s, as the NIR sky changes on short (~several minute) timescales. Efforts were made to minimize the time between science and sky exposures.

### 3.2. Spectroscopic Reduction

The spectra obtained with TripleSpec were first sky-subtracted using adjacent blank sky frames. In some cases where sky subtraction was poor owing to time delays in observing (e.g., intermittent clouds, telescope drive faults), the closer adjacent sky exposure was used for subtraction. All sky-subtracted frames were assessed by eye for quality, and those with poor subtraction were removed; the rest of the science frames were then combined. Galaxies for which B Pfely exactly on a particularly strong skyline were also removed, as were several observations that exhibited detector persistence issues caused by bright telescope pointing calibration stars. These cuts eliminated nine observed galaxies, leaving a final sample of 21.

Due to the force-scan observing mode, emission is present across the entire width of the slit for the observed galaxies; thus, residual skyline subtraction could not be performed using pixels near the edges of the slit. This is the reason for the uncharacteristically strong skyline residuals in the spectra presented in Figure 3; however, the final reduced sample comprises the systems with skylines separable enough from the emission line that they could be easily masked when measuring.

| Name       | D_{r}^a(Mpc) | R.A.^a(J2000) | Decl.^a(J2000) | Stellar Mass \((\log M_{\odot})\) | SFR \((\log M_{\odot} \, yr^{-1})\) | sSFR \((\log yr^{-1})\) |
|------------|--------------|---------------|----------------|-------------------------------------|---------------------------------|-----------------|
| Arp 220^b  | 85.2         | 15:34:57.2    | +23:30:11      | 10.64±0.07                         | 1.14±0.12                        | −9.70±0.38      |
| IC 0691    | 23.7         | 11:26:44.3    | +59:09:20      | 9.26±0.09                          | −0.28±0.08                       | −9.62±0.12      |
| Mkr 3      | 22.9         | 10:32:31.9    | +54:24:03      | 9.29±0.06                          | −0.28±0.09                       | −9.50±0.13      |
| Mkr 1450   | 20.0         | 11:38:55.6    | +57:52:27      | 7.8±1.16                           | −1.47±0.08                       | −9.21±0.16      |
| Mkr 1490^b | 115.5        | 11:49:14.3    | +49:14:12      | 10.27±0.13                         | 0.94±0.22                        | −9.49±0.16      |
| NGC 3310   | 20.1         | 10:38:45.8    | +53:30:12      | 9.74±0.09                          | 0.63±0.08                        | −9.25±0.09      |
| NGC 3627^b | 9.4          | 11:20:15.0    | +12:59:30      | 10.31±0.04                         | −0.43±0.26                       | −10.61±0.16     |
| NGC 3690^b | 50.6         | 11:28:31.7    | +58:33:44      | 10.71±0.15                         | 1.48±0.09                        | −9.44±0.13      |
| NGC 4088   | 19.8         | 12:05:34.2    | +50:32:21      | 10.61±0.05                         | 0.57±0.08                        | −10.05±0.11     |
| NGC 4194^b | 41.5         | 12:14:09.6    | +54:31:36      | 9.83±0.09                          | 1.03±0.17                        | −9.41±0.10      |
| NGC 4254   | 16.5         | 12:18:49.6    | +14:24:60      | 10.3±0.05                          | 0.29±0.18                        | −9.95±0.13      |
| NGC 4321   | 14.3         | 12:22:54.8    | +15:49:19      | 10.27±0.04                         | 0.04±0.13                        | −10.13±0.12     |
| NGC 4536   | 14.4         | 12:34:27.0    | +02:11:17      | 10.21±0.04                         | −0.08±0.13                       | −10.18±0.17     |
| NGC 4826^b | 7.5          | 12:56:43.6    | +21:40:59      | 10.4±0.05                          | −0.7±0.17                        | −10.90±0.26     |
| NGC 5055   | 7.8          | 13:15:49.3    | +42:01:46      | 10.92±0.03                         | −0.15±0.16                       | −10.30±0.12     |
| NGC 5194^b | 7.6          | 13:29:52.7    | +47:11:43      | 10.09±0.04                         | −0.01±0.08                       | −10.14±0.14     |
| NGC 5653   | 58.7         | 14:30:10.4    | +31:12:56      | 10.67±0.07                         | 0.91±0.12                        | −9.77±0.15      |
| NGC 5953^b | 34.6         | 15:34:32.4    | +15:11:38      | 10.43±0.04                         | 0.38±0.12                        | −10.05±0.10     |
| NGC 6052   | 74.8         | 16:05:12.8    | +20:32:32      | 10.18±0.07                         | 0.96±0.07                        | −9.24±0.16      |
| NGC 6090   | 130.2        | 16:11:40.9    | +52:27:27      | 10.66±0.04                         | 1.19±0.04                        | −9.31±0.16      |
| UGC 08696^b| 165.9        | 13:44:42.11   | +55:53:12      | 10.86±0.06                         | 1.25±0.15                        | −9.86±0.28      |

Notes. Quoted values and uncertainties for all Prospector-derived quantities are calculated using the 16th, 50th, and 84th percentiles of the posterior distribution, weighted by each sample’s respective weight (see Speagle 2020). Observed quantities are provided in Table 2.

^a Brown et al. (2014).

^b Galaxy marked as either AGN or SF/AGN in Brown et al. (2014) BPT classification. Of the sample, only Arp 220 and UGC 08696 are categorized as AGNs; the rest are all composite. Due to the large spectrophotometric apertures used in this work, we expect the fractional AGN contribution to our measurements to be minimal.
line fluxes—this is more clearly visible in the 2D cutouts of the science spectra.

Wavelength calibration and spectral extraction were carried out using the Palomar TripleSpec mode of the SpexTool\(^{10}\) IDL package (Cushing et al. 2004, version 5.1 (via private correspondence)). Reductions, with the exception of the spectrophotometric standard, were carried out using the “A” single-image mode, as sky subtraction had already been performed. The spectrophotometric standard was observed in the “A-B” observing mode and was extracted with that setting. We used SpexTool’s calibration panel to derive flat-field corrections and wavelength calibrations using dome flats and sky images taken during observations (SpexTool fits the order shapes from the flat fields and determines wavelength calibration by fitting known atmospheric emission lines). Spectra were extracted over the entire width of each spectral order in order to remain aperture-matched to the previous observations.

Corrections for the response curve of the TripleSpec instrument, as well as for telluric lines, were carried out using the O\(\lambda V\) standard star BD +75°325. As no catalog spectra for this star could be found that extended past 1 \(\mu m\), a blackbody fit was performed to the available spectrum from CALSPEC (Bohlin et al. 2014) and extrapolated to 2.5 \(\mu m\). We also, for redundancy, located an O\(\lambda V\) star from the Pickles (1998) catalog that was relatively well matched with BD +75°325 in the optical but that had NIR coverage; the two methods produced consistent calibrations when used.

We then tied our spectra to known values by performing synthetic photometry, convolving the observed spectra with the Two Micron All Sky Survey \(\mathcal{K}_s\) filter curve to derive the scaling factor that produced the bandpass magnitude quoted in Brown et al. (2014). The median Prospector continuum model spectra for each galaxy were then scaled to the same photometry as were the observed spectra (though we note that this correction was minor).

Final science spectra were then obtained by subtracting the matched, median Prospector continuum spectra from our observed spectra for each galaxy. We estimated uncertainties in the \(\mathcal{B}\gamma\) flux extraction by performing “false extractions” over 700 km s\(^{-1}\) windows spread throughout the \(\mathcal{K}\) band in regions consisting of no emission lines (either from the galaxy or from the sky), taking the 1\(\sigma\) biweight spread in measured fluxes across those extractions as the flux uncertainty. We note that with 5-minute individual exposures with TripleSpec, we are sky limited rather than read-noise limited.

For equivalent width measurements, the Prospector stellar continuum model was adopted (see Leja et al. 2017, Section 2.2). Equivalent width measurements do not include uncertainties from the assumed Prospector continuum model.

\footnote{\url{http://irafweb.ifa.hawaii.edu/~cushing/spextool.html}}

### Table 2

| Name           | Equivalent Widths | Luminosities |
|----------------|-------------------|--------------|
| Arp 220\(^a\)  | \((\mathcal{H}_\alpha, \mathcal{B}_\gamma)\) \((\mathcal{H}_\alpha, \mathcal{B}_\gamma)\) \((\mathcal{H}_\alpha, \mathcal{B}_\gamma)\) | \((\mathcal{H}_\alpha, \mathcal{B}_\gamma)\) \((\mathcal{H}_\alpha, \mathcal{B}_\gamma)\) \((\mathcal{H}_\alpha, \mathcal{B}_\gamma)\) |
| IC 0691        | \(68.56 \pm 6.89\) | \(7.34 \pm 0.02\) |
| Mrk 33         | \(136.13 \pm 25.8\) | \(7.43 \pm 0.01\) |
| Mrk 1450       | \(253.59 \pm 28.53\) | \(6.69 \pm 0.26\) |
| NGC 3310       | \(197.56 \pm 20.96\) | \(5.99 \pm 0.04\) |
| NGC 3624\(^d\) | \(127.1 \pm 21.37\) | \(4.29 \pm 0.00\) |
| NGC 3690\(^d\) | \(129.33 \pm 16.62\) | \(4.78 \pm 0.00\) |
| NGC 4088       | \(58.88 \pm 12.29\) | \(6.58 \pm 0.19\) |
| NGC 4194\(^d\) | \(178.01 \pm 16.64\) | \(6.58 \pm 0.19\) |
| NGC 4254       | \(66.15 \pm 18.44\) | \(6.58 \pm 0.19\) |
| NGC 4321       | \(44.57 \pm 10.01\) | \(6.58 \pm 0.19\) |
| NGC 4536       | \(35.3 \pm 18.48\)  | \(6.58 \pm 0.19\) |
| NGC 4826\(^d\) | \(7.24 \pm 2.92\)  | \(6.58 \pm 0.19\) |
| NGC 5055       | \(33.84 \pm 8.15\)  | \(6.58 \pm 0.19\) |
| NGC 5194\(^d\) | \(57.58 \pm 8.97\)  | \(6.58 \pm 0.19\) |
| NGC 5653\(^d\) | \(75.9 \pm 16.26\)  | \(6.58 \pm 0.19\) |
| NGC 5954\(^d\) | \(42.44 \pm 6.64\)  | \(6.58 \pm 0.19\) |
| NGC 6052       | \(188.57 \pm 19.4\) | \(6.58 \pm 0.19\) |
| UGC 08696\(^d\)| \(83.29 \pm 11.37\) | \(6.58 \pm 0.19\) |

Notes.

\(^a\) Prospector-derived line luminosity or equivalent width predicted from fits to photometry. Reported values are calculated using the 16th, 50th, and 84th percentiles from 3000 samples drawn from the posterior. Note that Prospector-derived luminosities and equivalent widths presented here are the predicted observable quantities, i.e., they include dust attenuation, and are thus directly comparable to the corresponding quantities measured from spectra.

\(^b\) Brown et al. 2014.

\(^c\) Galaxy marked as either AGN or SF/AGN in Brown et al. (2014) BPT classification. Of the sample, only Arp 220 and UGC 08696 are categorized as AGNs; the rest are all composite. Due to the large spectrophotometric apertures used in this work, we expect the fractional AGN contribution to our measurements to be minimal.

\(^d\) BROWN ET AL. 2014.
values; however, we note that the 1σ spread in Prospector model spectra at 2.16 μm for this sample is ∼3%. Spectra were inspected visually to ensure that continuum models and spectra were consistent. We do not include uncertainty in luminosity distance in our calculations, but we find that on average quoted uncertainties for these galaxies in the literature (see, e.g., Moustakas et al. 2010) are ≤5%, resulting in a line luminosity uncertainty of ≤10%. We note that this uncertainty component does not strongly affect the following analysis, as the EWs measured are distance independent and in the direct comparisons of line luminosities the distance falls out.

4. Results

4.1. Scatter between Observed and Predicted Brγ

For the 21 galaxies in the sample, we fit the photometry to constrain our physical model, which then predicted Brγ and Hα emission. We then compared the predicted Brγ and Hα line luminosities and equivalent widths with the observations taken with TripleSpec (Figure 4). Measurements of Brγ are from this study, while Hα measurements are from Brown et al. (2014), as used in Leja et al. (2017).

We find strong agreement between the predicted and observed Brγ luminosities and equivalent widths across a wide range in stellar masses and SFRs. We find a scatter between predicted and measured EW(Brγ) and L(Brγ) of 0.17 ± 0.08 dex and 0.24 ± 0.07 dex, respectively (Figure 4), with uncertainties determined via bootstrap resampling. The mean observational uncertainties in these quantities are 0.13 and 0.213 dex, respectively, which implies that the intrinsic scatter is small and consistent with zero, i.e.,

\[
\sigma(\text{EW})_{\text{intr}} = 0.109_{-0.104}^{+0.104} \text{ dex} \quad (3)
\]

\[
\sigma(L)_{\text{intr}} = 0.111_{-0.111}^{+0.114} \text{ dex}, \quad (4)
\]

where this calculation does not include any uncertainty in the observational uncertainties.

It is interesting to note that the scatter could in principle be large, not due to any shortcoming of the models but rather due to large variations in the SFR between ∼100 and ∼5 Myr timescales. Differences in SFR on these timescales leave few signatures in broadband photometry; where such variation is most visible is in comparing, e.g., UV+IR luminosities (which trace the longer timescale) with emission lines (which trace the instantaneous SFR).

In general, any analysis of, e.g., \(L(\text{UV}+\text{IR})/L(\text{Hα})\) has to contend with both SFR variations and dust effects as sources of scatter. With Brγ, the latter is largely eliminated, so in principle it is possible to place fairly tight constraints on the variability in SFR in this sample—which, given these results, shows little evidence for large variability on these timescales. However, in practice one would prefer significantly reduced observational uncertainties to probe this effect. In a future work, we will present deeper, high-S/N measurements of Brγ in a sample selected to have available Herschel photometry, in order to investigate these effects observationally, as well as within the modeling framework.

4.2. Observed Offsets and the Impact of Isochrone Selection

While the measured scatter appears consistent with purely observational uncertainties, the measured offsets require
slightly more interpretation. As previously discussed, the predicted line fluxes from Prospector are subject to the chosen conversion between SFR and ionizing radiation. This conversion depends on several factors within the stellar isochrones being used in the fit. For example, MIST (Choi et al. 2016; Dotter 2016)—one of five other available isochrones in FSPS—includes stellar rotation, which has been shown to predict a factor of $\sim 2$ more ionizing photons at fixed SFR compared with models without rotation (e.g., Choi et al. 2017; Wilkins et al. 2019). It has also been shown that stellar binarity can produce additional ionizing photons with respect to single-star nonrotating models (e.g., BPASS; Eldridge & Stanway 2009; Stanway & Eldridge 2018).

To test for dependencies on isochrone selection, we fit the galaxies in this sample using both MIST and Padova isochrones and find agreement with the previous results; the MIST isochrones predict $\sim 0.15$ dex higher emission-line luminosities at fixed SFR, resulting in a zero-point offset in the relation between SFR and $\text{Br}\gamma$ by 0.15 dex.

This result appears to provoke some tension with the treatment of ionizing photon production within newer isochrone models. We caution that further detailed analysis is required to investigate this point; for example, dust attenuation uncertainties within HII regions has been invoked to explain such offsets. While this should not be a major factor at the wavelength of $\text{Br}\gamma$ in emission, it has also been hypothesized that ionizing photons themselves may be absorbed by dust, which could result in a decrement in all nebular emission lines and increased infrared output. In these fits, such an effect might not be captured, as our SEDs do not extend to the FIR. Though it is beyond the scope of this work, an interesting test of this possibility would be to compare Prospector-derived SFRs to those derived from extinction-free radio continuum measurements (e.g., Murphy et al. 2011; Tabatabaei et al. 2017).

Figure 4. Model predictions from Prospector (abscissa) vs. measurements from spectra (ordinate). The top panels compare measurements and predictions for the equivalent width of $\text{Br}\gamma$ and $\text{H}\alpha$, respectively, while the bottom panels compare line luminosities between the two. Summary statistics are presented for the full sample with $\text{H}\alpha$ measurements with $S/N > 3$ (gray), as well as for the observed sample (blue). $\text{Br}\gamma$ shows reduced offset from the 1:1 relation with respect to $\text{H}\alpha$ and shows similar or reduced scatter that is dominated by measurement uncertainties. As a note, the Prospector-derived luminosities and equivalent widths are the predicted observable quantities, i.e., they include dust attenuation, and are thus directly comparable to the corresponding quantities measured from spectra.
which provide an independent probe of the massive star formation activity—though, of course, this is still a challenging prospect, involving the simultaneous solving for stellar physics effects (e.g., rotation, binaries) and dust absorption of ionizing photons.

Additionally, there is a dependence on stellar metallicity and an assumed Lyman escape fraction that can influence this zeropoint. Particularly given the considerable observational uncertainties, we intend to revisit this topic in a future work with tighter $\gamma$ constraints and a more detailed battery of tests to the photoionization models, before determining whether $\gamma$ strongly constrains them. For example, jointly fitting photometry and $\gamma$ with MIST and BPASS should force the offset to 0, allowing us to interrogate the origin of the offsets seen here.

This noted difference in ionizing photon productions means that the reported offsets in this work must be treated as isochrone dependent. However, in comparing $\gamma$ to $\alpha$, we find that the relative offset between the two is consistent across fits made with different isochrones. That is, for this sample, $\alpha$ luminosities are offset from the 1:1 relation ~0.1 dex higher than $\gamma$ luminosities, and $\alpha$ equivalent widths are offset ~0.2 dex higher than $\gamma$ EWs, as calculated by differenting the mean offsets for the observed sample (i.e., top two and bottom two panels of Figure 4), regardless of the absolute offset.

Even in the Padova fits, which predict the $\gamma$ measurements with ~0.2 dex offset, $\alpha$ luminosities and equivalent widths tend to be overpredicted by the modeling fits. As a note, though we find the magnitude of the offsets and scatters to be marginally larger than what was reported in Leja et al. (2017), this is primarily a sample selection effect rather than a result of updates to the model; this is illustrated in Figure 4 by the gray points in the left panels, which show galaxies from the full sample in Brown et al. (2014), which have $\alpha$ measurements with $S/N > 3$. The mean offsets and scatters calculated using all of these points are ultimately consistent with the previously reported values.

4.3. Implications for Modeling Dust Attenuation

The offsets found in this work are systematically higher for $\alpha$ than for $\gamma$ for both the Padova and MIST fits, even when comparing to the full sample of $\alpha$ measurements from Brown et al. (2014). This has potential implications for the dust models in Prospector: since the ionizing radiation is the same in both cases, the offsets seen here are presumably due to insufficient flexibility in the dust attenuation model (which is already more flexible than many generally adopted in the literature).

Another possible explanation for the higher $\alpha$ offsets is related to sample selection, which for this study was primarily driven by the prediction of a measurable $\gamma$ line flux. This means that, in some sense, surface brightness was selected on more strongly than luminosity; indeed, comparing this sample to the full Brown et al. (2014) atlas, we find that the systems in this study lie preferentially toward the lower-luminosity end, which exhibit increased offsets in the full sample presented in Leja et al. (2017) compared with higher-luminosity systems. This motivates further studies of the high-luminosity end of the parameter space—in general a more challenging endeavor due to the average distances involved being larger and surface brightnesses being lower.

Whatever the cause, the derived fraction of light attenuated by dust at 6563 Å appears to be systematically underpredicted by roughly 0.1 dex (for the isochrones used here), which in turn affects the $\alpha$ line flux prediction without affecting $\gamma$. This
effect can be seen in Figures 5, 6, and 7: while no galaxies in the sample are significantly removed from the relevant relations in SFR or sSFR (Figures 5 and 7), several galaxies are dramatic outliers in reddening (Figure 6), with significantly underestimated reddening between H_α and Br_γ.

These four systems (labeled in Figure 6) represent an excellent “rogues gallery” of galaxies where we might expect our dust models to be inadequate: Arp 220 is the classic example of a galaxy optically thick owing to dust even at 2 μm, NGC 4254 is an edge-on disk, Mrk 1490 contains an AGN, and NGC 4536 is a central starburst (Davies et al. 1997)—all of which have complex dust configurations. This, once again, indicates that more flexible dust attenuation laws are needed if we want to model these types of systems well. This finding is in agreement with, e.g., recent observations of dusty submillimeter galaxies (Chen et al. 2020) that also find current dust models insufficiently complex to describe very dusty, star-forming systems.

While there is evidence that additional flexibility (or constraining information) is needed in our dust modeling in order to correctly predict optical spectral lines from photometry for some galaxies, the derived SFRs—the ultimate quantity of interest—are validated by this study (Figure 5). For reference, we show the standard H_α calibrations (Kennicutt 1998) against both H_α and Br_γ luminosities. The four outlier galaxies in reddening are also shown in Figure 5, where they do not stand out significantly—highlighting that even when the reddening between H_α and Br_γ is severely underpredicted, the derived SFRs are sound.

As expected, H_α luminosities fall below the relation and would require, e.g., a Balmer decrement correction before being used to infer an SFR. On the other hand, we find that those same dust-free relations fit the observed Br_γ luminosities with virtually no offset. The Br_γ version of the calibrations was derived by shifting the H_α relations by the expected dust-free atomic ratio between H_α and Br_γ, assuming case B recombination, n_e = 100 cm⁻³ and T = 10,000 K (Osterbrock & Ferland 2006). Ultimately, the right panel of Figure 5 removes the ambiguity introduced by uncertain dust corrections to, e.g., using H_α as a means for vetting SFRs. Here, we find that the instantaneous SFRs derived by Prospector and the (largely) dust-free measurement via Br_γ agree strongly with the theoretically predicted dust-free relation between the two.

4.4. Observational Implications

The tightness of the relation in Figure 5 speaks to Br_γ’s effectiveness observationally as a monochromatic SFR indicator. As discussed in Section 1, the limitation of Br_γ to date has primarily been its inaccessibility at z > 0.1 from the ground. Thus, for observers, the launch of the JWST (Gardner et al. 2006) will change this picture dramatically, with a multiobject spectrograph (NIR-Spec; Bagnasco et al. 2007; Birkmann et al. 2010) with coverage from 0.6 to 5.6 μm. With this instrument, Br_γ will be readily observable out to z ∼ 1.4. Even for extragalactic surveys not directly targeting this, and other, NIR lines, it has been shown that there will be many serendipitous emission-line detections with NIR-Spec (Maseda et al. 2019).

The amount of legacy information available on extragalactic sources observed with JWST will vary greatly, ranging from full far-UV–FIR photometry to nearly no information. While the theoretical prediction that Br_γ would be an efficient and nearly dust-free probe of ionizing radiation in galaxies has been discussed since the 1970s, prior to this work no sample of galaxies with spatially integrated Br_γ-derived global SFRs has
been assembled. A supplementary implication of this work is that a standard line luminosity–SFR calibration (e.g., Murphy et al. 2011) can indeed convert measured Brγ to an accurate SFR without the need for any additional information about a galaxy. Put another way, the consistency found in this analysis implies that for galaxies with available panchromatic photometry, Brγ is not needed as a constraint in Prospector to accurately predict SFRs, but in systems with less-constraining photometry, Brγ alone can be a powerful probe of the SFR.

Critically, the uncertainty in the conversion of ionizing luminosity to an SFR in this work is driven almost entirely by measurement uncertainty. From the ground, that uncertainty is always considerable for weaker lines such as Brγ, due to, e.g., atmospheric molecular absorption (skylines) and their correction, weather, and air-mass variability. However, many of these sources of uncertainty will be eliminated for JWST, which will make observations in an extremely clean environment (namely, L2). This pristine observing environment is of course also well suited for further tests of SED modeling using Brγ, for which the current 0.24 dex scatter can ideally be reduced substantially in order to probe a wider range of galaxy types—in particular, systems with very low EW(Brγ) for which the Prospector assumptions about dust heating dramatically affect the derived SFRs.

In addition to probing the instantaneous SFR of a galaxy, there is evidence that Brγ (indirectly) probes the stellar mass as well. In Figure 7, we show the observed Brγ equivalent widths as a function of Prospector-derived sSFR. Once again, we find a near-perfect agreement, with a negligible offset and scatter consistent with measurement uncertainties. Such a tight relation is possible because EW(Brγ) divides line flux (i.e., SFR) by the K-band continuum—known to be a relatively stable spectral region for estimating stellar mass, as it is not subject to scatter owing to variations in M/L ratios in blueward bands from young stars or by dust emitting at redward MIR wavelengths. It is also a measurement that can be made without any absolute calibration of the data gathered. In some sense, then, Brγ encodes information about both the SFR and sSFR of a galaxy—though it is important to note that the latter requires the detection of both the emission line and continuum, in general a more challenging and time-consuming measurement. In cases where both are detected, however, these two quantities can be used to probe stellar mass.

5. Discussion

Having demonstrated that Prospector largely predicts Brγ luminosities accurately, and thus produces robust SFRs, we turn to the question of what information, if any, Brγ might add to the modeling framework. While this will be be explored in greater depth in a future work, a simple, informative question we can ask is whether the models predict that Brγ adds more constraining information to UV–NIR modeling than, e.g., rest-frame MIR photometry—the standard observational approach for roughly constraining L(IR) and breaking modeling degeneracies, particularly when FIR photometry is not available. To this end, we refit the galaxies in this sample using only the UV–NIR (λ ≤ 2.5 μm) photometry and then compared the joint posteriors between L(Brγ), L(8 μm), and L (12 μm) with model SFR (i.e., the IRAC and WISE bands; Fazio et al. 2004; Wright et al. 2010). This is presented for the 21 galaxies in this observational sample in Figure 8.

We find that, as expected, the joint posterior between Brγ and SFR is extremely tight. In contrast, the joint posterior between the MIR luminosity and SFR shows significant dispersion, with several galaxies exhibiting contours that deviate significantly from the central relation defined by the other galaxies. This increased dispersion in MIR-band luminosity at fixed SFR is primarily driven by the sensitivity of the model’s MIR energy output to the fraction of dust in PAHs, i.e., higher PAH fractions lead to significantly increased luminosity in the MIR bands at fixed SFR. Additionally, while the galaxies in this sample are generally best fit by models with small fractional AGN contributions, we find evidence that, for those models with larger AGN fractional contributions, the MIR output is also generally higher. In general, both of these correlations seem to contribute to the large spread in the MIR luminosity–SFR relation, when constrained only by UV–NIR data.

An observational counterpoint to this model-space analysis is presented in Figure 9. Here, we show the measured WISE 12 μm luminosity density for the galaxies in this sample versus the most constrained SFR for each system, that is, SFRs derived from Prospector fits to the full UV–IR photometry. The observed L(MIR)–SFR relation shows somewhat less scatter than the model-only analysis above; this is unsurprising, given the wide prior on PAH fraction adopted in the models and the fact that these galaxies represent a relatively homogeneous sample of ~L* galaxies near the star-forming main sequence. It is also worth noting that there is a small but irreducible scatter in the observed L(MIR)–SFR relation presented for this sample due to the change in rest-frame wavelength coverage resulting from the inhomogeneous redshift of the sample. For comparison, the derived power-law conversion presented in Figure 9 has a best-fit slope of 1.248, which is consistent with the independent calibration derived by Senarath et al. (2018) using Balmer-decrement-corrected Hα observations, which finds a slope of 1.24 ± 0.08. This provides a complementary indication that Prospector-derived SFRs are consistent with multiple gold-standard calibrations.

Nevertheless, we find that the scatter in the observed L (MIR)–SFR relation is somewhat larger than that of L(Brγ)–SFR; additionally, the MIR photometric uncertainties are considerably lower, contributing to a larger χ² value in the relation—illustrating the impact of secondary effects beyond SFR on the MIR flux of even these galaxies. The L(Brγ)–SFR relation, of course, has a secondary sensitivity to the selection of stellar isochrones as discussed above—but this dependence has the advantage of being a fixed offset for all objects, whereas variations in PAH fraction or AGN power are galaxy-specific and difficult to constrain.

6. Conclusion

The Brγ hydrogen recombination line is a clean, “gold-standard” probe of the SFR of a galaxy, as the effects of dust on the conversion from line luminosity to SFR are minimal at 2.16 μm. This makes Brγ an ideal diagnostic for vetting the SFRs from the fitting of panchromatic SEDs.

We obtained NIR spectroscopy of Brγ for a local sample of galaxies from the Brown et al. (2014) atlas that had available aperture-matched photometry and optical spectroscopy, using the forced scanning technique of, e.g., Kennicutt (1992) and Moustakas et al. (2010) to obtain luminosity-weighted, spatially averaged spectra. We then compared the line
luminosities and equivalent widths with predictions from the Prospector inference framework, which was used to fit the (aperture-matched) UV–MIR photometry of each galaxy to derive SFRs and in turn line fluxes and equivalent widths.

We find that Prospector successfully predicts both the line luminosity and equivalent width of Brγ to within measurement uncertainties, with predicted intrinsic scatters that are small and consistent with zero. We find that Brγ provides reduced offset and scatter compared with Hα predictions and measurements for the same systems, potentially pointing to insufficiently flexible dust attenuation models. We find four cases where this certainly appears to be the case: Arp 220, NGC 4254, NGC 4536, and Mrk 1490—all of which are systems known to have very complex dust morphologies and for which Prospector significantly underestimates the reddening between Hα and Brγ. Despite this, we show that these galaxies still lie relatively close to the predicted SFR–Brγ relation, indicating that Prospector-derived SFRs are considerably insulated from detailed issues in the dust modeling.

Additionally, the measured Brγ equivalent widths not only were well predicted by Prospector but also were found to follow a tight relation with Prospector-derived sSFR, indicating that in addition to Brγ closely tracing the instantaneous SFR, the K-band continuum is accurately tracing the stellar mass of these galaxies.

Finally, we note that our Brγ observations are well described by standard dust-free SFR calibrators from the literature, in contrast with the well-known decrement seen in Hα due to dust attenuation. We thus conclude that for JWST, which will make NIR measurements in a clean environment without atmospheric absorption, Brγ luminosities will tightly trace SFR and the overall ionizing radiation field in a galaxy without the need for any dust corrections or additional information—though we caution that there will always be a caveat to this statement for the universe’s dustiest systems.

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Software: Python (Rossum 1995), numpy (van der Walt et al. 2011), scipy (Jones et al. 2001), astropy (Astropy Collaboration et al. 2013), matplolib (Hunter 2007), prospect (Johnson & Leja 2017), python-fsps (Foreman-Mackey et al. 2014), fsps (Conroy & Gunn 2010), MIST (Choi et al. 2016; Dotter 2016), dynesty (Speagle 2020), cloudy (Ferland et al. 1998; Ferland et al. 2013, 2017; Byler 2018), emcee (Foreman-Mackey et al. 2013), pandas (Reback et al. 2020), seaborn (Waskom et al. 2014), makecite (Price-Whelan et al. 2018).

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