

ATLAS. III. Dust Around Little Red Dots: Hydrogen Line Ratios beyond Dust-free Non-Case B Models

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ABSTRACT

We investigate broad hydrogen line ratios in little red dots (LRDs) using five high-redshift ($z > 2$) sources from JWST/NIRSpec medium/high-resolution spectra in the DAWN JWST Archive and fifteen low-redshift sources ($z = 0.1\text{--}0.9$) from the literature, all with broad $H\beta$ detected at $> 5\sigma$. After carefully measuring the broad-line fluxes while accounting for absorption features and neighboring emission lines, we find that the **broad $H\alpha/H\beta$ ratios are very high**, ranging from 6 to 30, **well above the Case B recombination value**. Using plane-parallel CLOUDY photoionization models with the total line emission from both sides of the slab, we investigate the physical origin of the broad hydrogen line ratios beyond Case B, jointly modeling the Balmer and Paschen line ratios for the subset of one high- z and two low- z LRDs with detected broad Paschen lines. We find that one low- z LRD is reproduced by a high gas number density ($\log(n_H/\text{cm}^{-3}) \sim 10\text{--}11$) on the broad-line $H\alpha/H\beta\text{--}Pa\beta/Pa\gamma$ plane, whereas the remaining two LRDs additionally **require substantial dust extinction** of $E(B - V) \gtrsim 0.2\text{--}1.0$, even after accounting for non-Case B effects. Since the narrow $H\alpha/H\beta$ ratios do not indicate such large dust extinction, these results demonstrate that the **obscuring dust is spatially associated with the broad-line region**. Even without Paschen-line measurements, two and eight LRDs in the high- and low-redshift samples, respectively, exhibit $H\alpha/H\beta > 13$, which cannot be reproduced by the non-Case B models, suggesting that **dust obscuration might be common among LRDs**, occurring in at least about half of the population. Such dust may represent a lower-column-density counterpart of the dusty torus in AGNs, reconciling the weak hot-dust emission.

Keywords: Active galactic nuclei (16) — Galaxy evolution (594) — Galaxy formation (595) — High-redshift galaxies (734)

1. INTRODUCTION

Little red dots (LRDs) are among the most striking discoveries enabled by the James Webb Space Telescope (JWST; J. P. Gardner et al. 2023). They are typically spatially unresolved in rest-frame optical JWST images and exhibit V-shaped spectral energy distributions

(SEDs), with blue rest-frame ultraviolet (UV) continua, red rest-frame optical continua, and broad Balmer emission lines (e.g., D. D. Kocevski et al. 2023; Y. Harikane et al. 2023; J. Matthee et al. 2024; J. E. Greene et al. 2024; R. Maiolino et al. 2024; R. E. Hviding et al. 2025; I. Labbe et al. 2025; H. B. Akins et al. 2025; A. de Graaff et al. 2025a; V. Rusakov et al. 2026).

Despite these broad lines, LRDs differ from classical active galactic nuclei (AGNs) in several respects. Many LRDs show weak X-ray emission (e.g., T. T. Ananna

et al. 2024; M. Yue et al. 2024; A. Sacchi & Á. Bogdán 2025; R. Maiolino et al. 2025), a deficit of cold-dust emission relative to classical obscured AGNs or quasars (e.g., C. M. Casey et al. 2025; D. J. Setton et al. 2025; G. C. K. Leung et al. 2025; K. Ronayne et al. 2026, see also I. Delvecchio et al. 2025; M. Brazzini et al. 2026; G. Barro et al. 2026), and weak variability (e.g., M. Kokubo & Y. Harikane 2025; Z. Zhang et al. 2025; C. J. Burke et al. 2026). These properties motivate models in which the physical conditions near the central engine differ from those in classical AGNs.

One promising interpretation is that the accreting black hole is embedded in a dense gas (e.g., R. P. Naidu et al. 2025; A. de Graaff et al. 2025a; K. Inayoshi & L. C. Ho 2025; K. Inayoshi & R. Maiolino 2025; J. Matthee et al. 2026; F. Pacucci et al. 2026; V. Rusakov et al. 2026; A. Sneppen et al. 2026; H. Yanagisawa et al. 2026a). In this picture, the emergent spectrum is shaped by hydrogen radiative transfer in a dense, high-column-density gas, where line optical-depth effects become important. A key clue is that the broad Balmer decrement, especially broad $H\alpha/H\beta$, is often larger than that of the narrow component (e.g., M. Brooks et al. 2025; G. P. Nikopoulos et al. 2026; C.-H. Chen et al. 2026; S. Geris et al. 2026). The narrow-line ratios are generally more consistent with Case B recombination and modest attenuation, whereas the enhanced broad-line decrement suggests that non-Case B processes in the nuclear broad-line gas may contribute. Dust attenuation may also contribute to the observed broad-line ratios (e.g., M. Brooks et al. 2025; G. P. Nikopoulos et al. 2026; Z. Yan et al. 2026; A. Sneppen et al. 2026; S.-J. Chang et al. 2026).

Broad Balmer and Paschen lines provide valuable probes of this central engine. Dust attenuation, collisional excitation, and large line optical depths can modify the observed decrements relative to their Case B values. Balmer lines alone suffer from degeneracies between dust attenuation and non-Case-B physics (e.g., J. Kwan & J. H. Krolik 1981; B. J. Wills et al. 1985); Paschen lines are less sensitive to dust and therefore provide a crucial additional constraint. Joint analyses of broad Balmer and Paschen series can thus test whether the observed line ratios require dense, optically thick gas, dust attenuation, or both.

Complementary evidence for dust is also provided by mid-infrared (MIR) emission. For example, stacked JWST Mid-Infrared Instrument (MIRI; P. Bouchet et al. 2015; G. H. Rieke et al. 2015; G. S. Wright et al. 2023) SEDs of high-redshift LRDs show an excess at $\lambda_{\text{rest}} \sim 3 \mu\text{m}$, which is consistent with dust emission at $\sim 1000 \text{ K}$ (I. Delvecchio et al. 2025, see also M. Brazzini et al. 2026). In addition, X. Lin et al. (2026a) re-

port the Wide-field Infrared Survey Explorer (WISE; E. L. Wright et al. 2010) detections of local LRDs at $z = 0.1\text{--}0.2$ and infer warm/hot dust components from their SEDs. These MIR measurements are consistent with the presence of warm/hot dust, which might be located near the central engines. However, the MIR-emitting dust need not be identical to the material that attenuates the broad-line region along our line of sight. Constraining the dust location, geometry, and its connection to the line-emitting gas, therefore, requires analysis of hydrogen-line ratios.

This paper is the third in the Archival and Theoretical study of LRDs with AGN comparison across Surveys (ATLAS) series. The ATLAS project investigates the LRD population using archival JWST spectroscopy, complemented by theoretical modeling and comparison samples of classical AGNs (H. Yanagisawa et al. 2026a,b, Y. Kageura et al., in preparation). In this paper, we jointly use broad Balmer and Paschen line ratios to assess whether dense, optically thick gas can reproduce the observed decrements without dust attenuation and, where it cannot, to constrain the additional attenuation required within the adopted model framework. We then discuss whether the inferred attenuation is consistent with available MIR constraints. Section 2 describes the sample and the data. Section 3 presents emission-line fitting and photoionization modeling. Section 4 presents the measured line ratios, and Section 5 discusses the implications for the central engines and dust geometry of LRDs. We summarize our conclusions in Section 6. In this paper, we assume a flat Λ CDM cosmology with $H_0 = 67.7 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.31$, and $\Omega_\Lambda = 0.69$ (Planck Collaboration et al. 2020). All magnitudes are in the AB system (J. B. Oke & J. E. Gunn 1983).

2. DATA

We assemble a sample of 20 LRDs, comprising 15 low-redshift ($z = 0.1\text{--}0.9$) and five high-redshift ($z = 2.3\text{--}7.0$) sources. For the primary broad Balmer-decrement analysis, we require broad $H\beta$ to be detected at a signal-to-noise ratio of $S/N \geq 5$. This criterion is applied to both the low- and high-redshift samples. The sample is selected from the literature and available spectroscopy and is not intended to be statistically complete. Its basic properties are summarized in Table 1 and Figure 1. The sample spans $\log(L_{5100}/\text{erg s}^{-1}) = 42.6\text{--}44.5$ as shown in Figure 1.

We additionally identify high-redshift LRDs with suitable spectral coverage of both Balmer complexes but broad $H\beta$ detected at $S/N < 5$. These sources are excluded from the final sample and from the associated statistics because they provide only lower limits

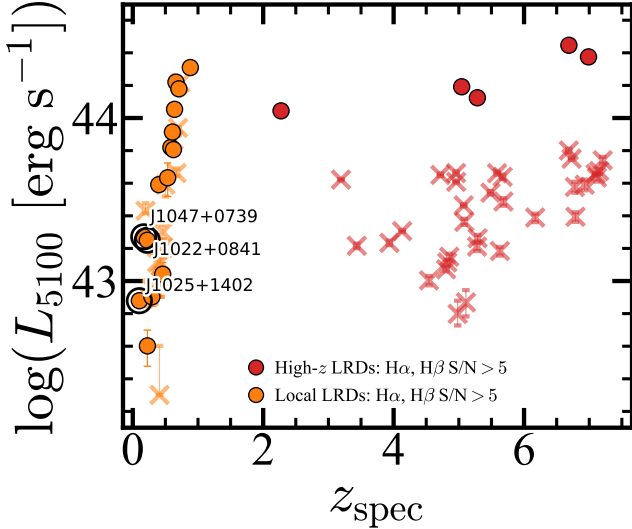


Figure 1. Relation between the rest-frame 5100 Å luminosity and the spectroscopic redshift for the primary sample and the auxiliary high-redshift lower-limit sources. The red and orange symbols show high- and low-redshift LRDs, respectively. The circles indicate sources with both H α and H β detected at S/N ≥ 5 , while crosses indicate sources for which the H β line has S/N < 5. The black circles and labels highlight the three local LRDs reported by X. Lin et al. (2026a). The L_{5100} values are adopted from A. de Graaff et al. (2025a), X. Lin et al. (2026a), and X. Lin et al. (2026b).

on broad H α /H β . We show them separately in Figure 1 and Figure 3. The emission-line fitting and lower-limit calculations are described in Section 3.1.

2.1. Low-redshift LRDs

The low-redshift sample consists of 15 sources: three LRDs reported by X. Lin et al. (2026a) and 12 LRDs from X. Lin et al. (2026b). X. Lin et al. (2026a) report three local LRDs: J102530.29+140207.3, J104755.92+073951.2, and J102208.52+084156.1. Hereafter, we refer to these objects as J1025+1402, J1047+0739, and J1022+0841, respectively. X. Lin et al. (2026a) identified them as local analogs of high-redshift LRDs based on their V-shaped spectral energy distributions (SEDs) and broad Balmer emission lines from the Sloan Digital Sky Survey (SDSS; D. G. York et al. 2000) data. J1025+1402 was also discussed by X. Ji et al. (2026). We adopt the broad Balmer and Paschen line fluxes reported by X. Lin et al. (2026a).

These three local LRDs also have mid-infrared photometry from the WISE W1, W2, W3, and W4 bands. X. Lin et al. (2026a) modeled this photometry using fixed-temperature dust templates (J. Lyu & G. H. Rieke 2021) at approximately 90, 300, and 1000 K, together with an additional ~ 2000 K component where required.

We use these warm/hot-dust constraints in Section 5 when discussing the dust properties of LRDs.

In addition, X. Lin et al. (2026b) report a larger sample of local LRDs at $z = 0.2$ – 0.9 (27 sources) from the Dark Energy Spectroscopic Instrument (DESI; DESI Collaboration et al. 2024, 2026) data release 1. From these, we use the sources with both broad H α and H β emission lines detected with S/N ≥ 5 , and the resulting number of sources is 12 from X. Lin et al. (2026b). We utilize the broad Balmer line fluxes of these objects reported in X. Lin et al. (2026b).

2.2. High-redshift LRDs

We construct the high-redshift sample from the LRD compilation of A. de Graaff et al. (2025a), which is based on version 4.4 of the DAWN JWST Archive (DJA; K. E. Heintz et al. 2024; A. de Graaff et al. 2025b; F. Valentino et al. 2025; G. Brammer & F. Valentino 2025)⁷. All spectra in the DJA are reduced with *msaexp* (G. Brammer 2023). In brief, A. de Graaff et al. (2025a) have selected sources with V-shaped SEDs in JWST/Near Infrared Spectrograph (NIRSpec; P. Jakobsen et al. 2022) PRISM spectra and compact morphology in JWST/Near Infrared Camera (NIRCam; M. J. Rieke et al. 2023) F444W imaging.

From this compilation, we retain only sources with available JWST/NIRSpec medium ($R \sim 1000$) or high ($R \sim 2700$) resolution grating spectra. For measurements of the H α /H β ratio, we require both Balmer lines to fall within the wavelength coverage of the grating spectra. For each source, we use the catalog redshift to compute the expected observed-frame line centers, and require the spectra to cover a velocity interval of ± 1000 km s $^{-1}$ around both H α and H β emission lines. This selection yields 37 sources at $z = 2$ – 7 .

For the Paschen line analysis, we additionally identify two objects with multiple Paschen lines in the grating spectra: Rosetta Stone at $z = 2.26$ (JADES-GN-28074; I. Juodžbalis et al. 2024; M. Brazzini et al. 2025) and RUBIES-BLAGN-1 (catalog ID RUBIES-UDS-40579) at $z = 3.10$ (B. Wang et al. 2025). The Rosetta Stone is already included in the H α /H β -selected sample, while RUBIES-BLAGN-1 is only used specifically for the Paschen-line analysis. For the 37 selected sources, we downloaded the publicly available JWST/NIRSpec grating spectra from DJA version 4.4 and used these spectra for the emission-line measurements described in Section 3.1. The primary high-redshift sample therefore comprises five sources with both broad H α and broad H β detected at S/N ≥ 5 . RUBIES-UDS-40579 is included

⁷ <https://dawn-cph.github.io/dja/>

Table 1. LRD sample in this study.

ID	R.A. (deg)	Decl. (deg)	Redshift	L_{5100}	Broad line			Narrow line			References	
					H α	H β	P $\alpha\alpha$	P $\alpha\beta$	P $\alpha\gamma$	H α		H β
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
J102530.29+140207.3	156.37622	14.03586	0.101	$0.809^{+0.033}_{-0.033}$	$87.6^{+2.56}_{-2.56}$	$5.75^{+0.35}_{-0.35}$	$22.7^{+0.26}_{-0.26}$	$4.49^{+0.42}_{-0.42}$	$3.03^{+0.13}_{-0.13}$	$21.2^{+0.21}_{-0.21}$	$6.20^{+0.05}_{-0.05}$	L26a
J104755.92+073951.2	161.98302	7.66423	0.168	$2.00^{+0.057}_{-0.057}$	$293.6^{+6.19}_{-6.19}$	$30.1^{+1.62}_{-1.62}$	$88.4^{+0.59}_{-0.59}$	$67.0^{+0.93}_{-0.93}$	$30.6^{+0.43}_{-0.43}$	$201.3^{+1.60}_{-1.60}$	$62.1^{+0.52}_{-0.52}$	L26a
J102208.52+084156.1	155.53552	8.69892	0.223	$1.90^{+0.033}_{-0.033}$	$554.4^{+13.7}_{-13.7}$	$16.5^{+0.51}_{-0.51}$	$125.0^{+3.05}_{-3.05}$	$79.3^{+2.84}_{-2.84}$	$21.0^{+1.16}_{-1.16}$	$30.3^{+7.68}_{-7.68}$	$15.4^{+0.21}_{-0.21}$	L26a
J132137.00+021417.04	200.40417	-2.23807	0.224	$0.4^{+0.1}_{-0.1}$	$41.0^{+0.60}_{-0.60}$	$2.60^{+0.40}_{-0.40}$	...	...	...	$13.0^{+0.30}_{-0.30}$	$5.10^{+0.20}_{-0.20}$	L26b
J134317.81+393418.07	205.82421	39.57169	0.293	$0.8^{+0.1}_{-0.1}$	$66.4^{+1.50}_{-1.30}$	$5.50^{+0.80}_{-0.80}$	...	...	...	$54.8^{+0.70}_{-0.70}$	$17.3^{+0.40}_{-0.40}$	L26b
J082921.37+131237.44	127.33904	13.21040	0.399	$3.9^{+0.2}_{-0.2}$	$443.2^{+62.6}_{-34.1}$	$20.4^{+2.30}_{-1.90}$	...	...	...	$180.7^{+2.30}_{-2.00}$	$57.0^{+1.10}_{-0.90}$	L26b
J024337.99+034915.97	40.90829	3.82110	0.458	$1.1^{+0.2}_{-0.2}$	$175.2^{+3.70}_{-3.70}$	$11.6^{+1.80}_{-1.80}$	...	...	...	$53.1^{+1.40}_{-1.50}$	$17.9^{+0.60}_{-0.60}$	L26b
J164102.65+070806.47	250.26104	7.13513	0.535	$4.3^{+1.1}_{-1.1}$	$635.4^{+32.4}_{-32.4}$	$30.1^{+3.10}_{-3.10}$	...	...	...	$57.3^{+1.50}_{-1.50}$	$13.0^{+0.80}_{-0.80}$	L26b
J212725.88+044808.92	321.85783	-4.80248	0.584	$6.6^{+0.6}_{-0.5}$	$485.5^{+48.9}_{-36.0}$	$76.6^{+13.6}_{-11.5}$	...	...	...	$42.7^{+3.90}_{-3.90}$	$13.2^{+1.10}_{-1.10}$	L26b
J104242.43+372147.63	160.67679	37.36323	0.608	$8.2^{+0.6}_{-0.6}$	$1435^{+34.8}_{-37.2}$	$105.1^{+8.50}_{-8.00}$	...	...	...	$69.0^{+31.2}_{-20.8}$	$14.7^{+1.10}_{-1.10}$	L26b
J142337.59+520216.05	215.90662	52.03779	0.624	$6.4^{+0.2}_{-0.3}$	$795.0^{+21.4}_{-28.3}$	$72.5^{+11.2}_{-10.0}$	...	...	...	$45.7^{+1.70}_{-2.40}$	$15.0^{+0.60}_{-0.70}$	L26b
J165450.36+033741.74	253.70983	3.62826	0.641	$11.3^{+0.6}_{-0.5}$	$1731^{+72.1}_{-68.4}$	$140.5^{+23.3}_{-16.0}$	...	...	...	$71.0^{+14.1}_{-14.4}$	$19.2^{+1.20}_{-1.30}$	L26b
J094411.31+024908.65	146.04712	-2.81907	0.662	$16.6^{+0.6}_{-0.5}$	$3262^{+90.2}_{-122.9}$	$297.5^{+10.1}_{-8.40}$	...	...	...	$87.1^{+12.4}_{-14.2}$	$18.8^{+1.50}_{-1.70}$	L26b
J164637.91+142648.62	251.65796	14.44684	0.707	$15.1^{+0.7}_{-0.7}$	$2794^{+183.4}_{-77.1}$	$259.3^{+17.9}_{-17.9}$	...	...	...	$182.5^{+11.2}_{-11.2}$	$56.8^{+2.90}_{-3.40}$	L26b
J102553.75+502843.24	156.47396	50.47868	0.882	$20.4^{+1.5}_{-1.5}$	$5850^{+75.9}_{-75.9}$	$441.7^{+87.2}_{-50.8}$	...	...	...	$170.7^{+24.9}_{-27.2}$	$32.8^{+2.90}_{-2.60}$	L26b
JADES-GN-28074	189.06459	62.27382	2.260	$11.6^{+0.0213}_{-0.0254}$	$2782^{+27.8}_{-27.2}$	$200.7^{+6.29}_{-5.31}$	...	$473.1^{+10.8}_{-13.1}$	$208.3^{+11.4}_{-8.9}$	$426.3^{+13.2}_{-16.9}$	$93.1^{+3.39}_{-3.67}$	This work, J24, dG25
JADES-GN-68797	189.22914	62.14619	5.039	$16.2^{+0.120}_{-0.098}$	$6285^{+205.6}_{-219.3}$	$403.6^{+43.2}_{-43.9}$	...	...	...	$533.6^{+200.3}_{-144.9}$	$105.3^{+19.8}_{-22.7}$	This work, dG25
RUBIES-EGS-42046	214.79537	52.78885	5.276	$13.9^{+0.119}_{-0.120}$	$5552^{+369.9}_{-263.1}$	$551.2^{+54.8}_{-58.6}$	...	...	...	...	...	This work, dG25
RUBIES-EGS-49140	214.89225	52.87741	6.685	$29.1^{+0.217}_{-0.235}$	$6983^{+137.6}_{-62.2}$	$825.6^{+36.3}_{-38.1}$	...	...	...	...	...	This work, dG25
RUBIES-EGS-55604	214.98303	52.95600	6.983	$24.7^{+0.209}_{-0.209}$	$8370^{+210.6}_{-210.6}$	$658.3^{+32.2}_{-32.2}$	...	...	...	...	...	This work, dG25
RUBIES-UDS-40579	34.24420	-5.24587	3.104	$14.3^{+0.0653}_{-0.0614}$	$3021^{+178.4}_{-178.4}$	...	...	$815.1^{+30.2}_{-29.1}$	$556.4^{+97.6}_{-112.3}$	$225.0^{+140.1}_{-142.4}$	...	This work, dG25, W25

NOTE— Primary LRD sample and a supplementary Paschen-line source. For the primary LRD sample, sources with both broad H α and broad H β detected with $S/N > 5$ are shown. $L_{5100} \equiv \lambda L_{\lambda}(5100\text{\AA})$ is in units of $10^{43} \text{ erg s}^{-1}$. The line luminosities are in units of $10^{40} \text{ erg s}^{-1}$. The line luminosities of the low-redshift LRDs are taken from X. Lin et al. (2026a) and X. Lin et al. (2026b). For the high-redshift LRDs whose narrow H α and H β are not constrained in the fitting, we show no measurements. As a reference, RUBIES-UDS-40579 is included separately as a supplementary source with multiple Paschen lines but without H β coverage. All luminosities and their uncertainties, including values taken from the literature, are rescaled to the cosmology adopted in this work. L26a: X. Lin et al. (2026a); J24: I. Joudzbali et al. (2024); W25: B. Wang et al. (2025); dG25: A. de Graaff et al. (2025a).

only as a supplementary Paschen-line source and is not counted among the 20 primary-sample LRD (Table 1).

3. ANALYSIS

3.1. Emission-line Fitting and Flux Measurements

We measure the Balmer and Paschen emission-line fluxes in the high-redshift sample. For each spectral region, we first determine the maximum-likelihood solution by minimizing χ^2 with the Levenberg–Marquardt algorithm implemented in `lmfit` (version 1.3.4; M. Newville et al. 2025). We then use the best-fitting parameters to initialize Markov chain Monte Carlo (MCMC) sampling with `emcee` (D. Foreman-Mackey et al. 2013). We adopt a Gaussian likelihood based on the flux-density uncertainties. The $H\beta$ + $[O\text{ III}]$ complex, the $H\alpha$ + $[N\text{ II}]$ complex, and each Paschen-line region are fitted separately. All rest-frame wavelengths used in the emission-line fitting are in vacuum (e.g., 5008.240 Å for $[O\text{ III}]\lambda 5007$), although we follow the long-standing nomenclature based on their air wavelengths.

For the $H\beta$ + $[O\text{ III}]\lambda\lambda 4959, 5007$ complex, our baseline model contains narrow Gaussian components for $H\beta$ and $[O\text{ III}]\lambda\lambda 4959, 5007$, a broad $H\beta$ component modeled with an exponential profile, and a linear continuum. The narrow $H\beta$ and $[O\text{ III}]$ components are constrained to have the same velocity widths and redshifts, while their fluxes are allowed to vary independently. The $[O\text{ III}]$ doublet flux ratio is fixed to $f_{[O\text{ III}]\lambda 5007}/f_{[O\text{ III}]\lambda 4959} = 2.98$ (P. J. Storey & C. J. Zeppen 2000).

We also consider an additional Gaussian outflow component for $[O\text{ III}]$ emission lines. We define the difference in the Bayesian Information Criterion (BIC; G. Schwarz 1978) as $\Delta\text{BIC} = \text{BIC}_{\text{no outflow}} - \text{BIC}_{\text{outflow}}$, where $\text{BIC}_{\text{no outflow}}$ ($\text{BIC}_{\text{outflow}}$) is the BIC without (with) the outflow component, which shares redshift, velocity width, and their flux ratio to be fixed to the same theoretical value. We include the outflow component when $\Delta\text{BIC} > 15$. In these cases, we also include an $H\beta$ outflow component whose velocity center and width are tied to those of the $[O\text{ III}]$ outflow component, while its flux is allowed to vary freely.

We fit the $H\alpha$ + $[N\text{ II}]$ complex with narrow Gaussian components for $H\alpha$ and $[N\text{ II}]\lambda\lambda 6548, 6584$, a broad exponential $H\alpha$ component (e.g., J. Scholtz et al. 2026), and a linear continuum. The narrow components share a redshift and velocity width. The $[N\text{ II}]$ doublet flux ratio is fixed to $f_{[N\text{ II}]\lambda 6584}/f_{[N\text{ II}]\lambda 6548} = 3.05$ (P. J. Storey & C. J. Zeppen 2000). The $H\alpha$ outflow component is also included using the same procedure as for the $H\beta$ + $[O\text{ III}]$, and its kinematics are tied to those measured from $[O\text{ III}]$ emission lines.

We also perform fits to the $H\alpha$ + $[N\text{ II}]$ complex, including an absorption component described by a partial-covering absorption model,

$$T(\lambda) = 1 - C_f + C_f e^{-\tau(\lambda)}, \quad (1)$$

where C_f is the covering factor and $\tau(\lambda)$ is the optical-depth profile (e.g., J. Scholtz et al. 2026). This absorption component attenuates the broad component and continuum. We model the optical-depth profile as a Gaussian in velocity space,

$$\tau(\lambda) = \tau_0 \exp \left[-\frac{1}{2} \left(\frac{v(\lambda) - \Delta v}{\sigma_v} \right)^2 \right], \quad (2)$$

where τ_0 is the central optical depth, Δv is the absorber velocity shift from the systemic redshift, and σ_v is its velocity dispersion. The absorption component is included when the absorption model is favored over the no-absorption model by $\Delta\text{BIC} > 15$. The same procedures are independently applied to the other Balmer ($H\beta$) and Paschen series to measure absorption features.

We model each covered Paschen region with a narrow Gaussian component, a broad exponential component, and a local linear continuum. An absorption component is added when favored by the same $\Delta\text{BIC} > 15$ criterion. Because broad $\text{He I}\lambda 10830$ overlaps $\text{Pa}\gamma$, the two lines are fitted simultaneously with separate broad exponential components.

The full model is convolved with the wavelength-dependent line-spread function (LSF). We adopt an effective resolving power of $R_{\text{eff}}(\lambda) = 1.8 \times R_{\text{doc}}(\lambda)$, where $R_{\text{doc}}(\lambda)$ is the wavelength-dependent resolving power from the JWST/NIRSpec documentation⁸, to account for the compact morphology of LRDs (A. de Graaff et al. 2024). This corresponds to an instrumental full width at half maximum (FWHM) of $\text{FWHM}_{\text{inst}}(\lambda) = \lambda/R_{\text{eff}}(\lambda)$. The LSF is assumed to be Gaussian in the fitting. Figure 2 shows examples of the fitting results for the $H\beta$ + $[O\text{ III}]$ and the $H\alpha$ + $[N\text{ II}]$ complex.

We report the median posterior line fluxes, with uncertainties given by the 16th and 84th percentiles of the posterior distributions. For objects in which the broad $H\beta$ component was not detected at $S/N \geq 5$, we refitted the $H\beta$ using the broad $H\alpha$ profile as a template. Specifically, exponential width and redshift are fixed at those of $H\alpha$, while the $H\beta$ normalization was allowed to vary. The uncertainty in the $H\alpha$ broad-line profile is propagated in the $H\beta$ MCMC approach. We define the

⁸ <https://jwst-docs.stsci.edu/jwst-near-infrared-spectrograph/nirspec-instrumentation/nirspec-dispersers-and-filters>

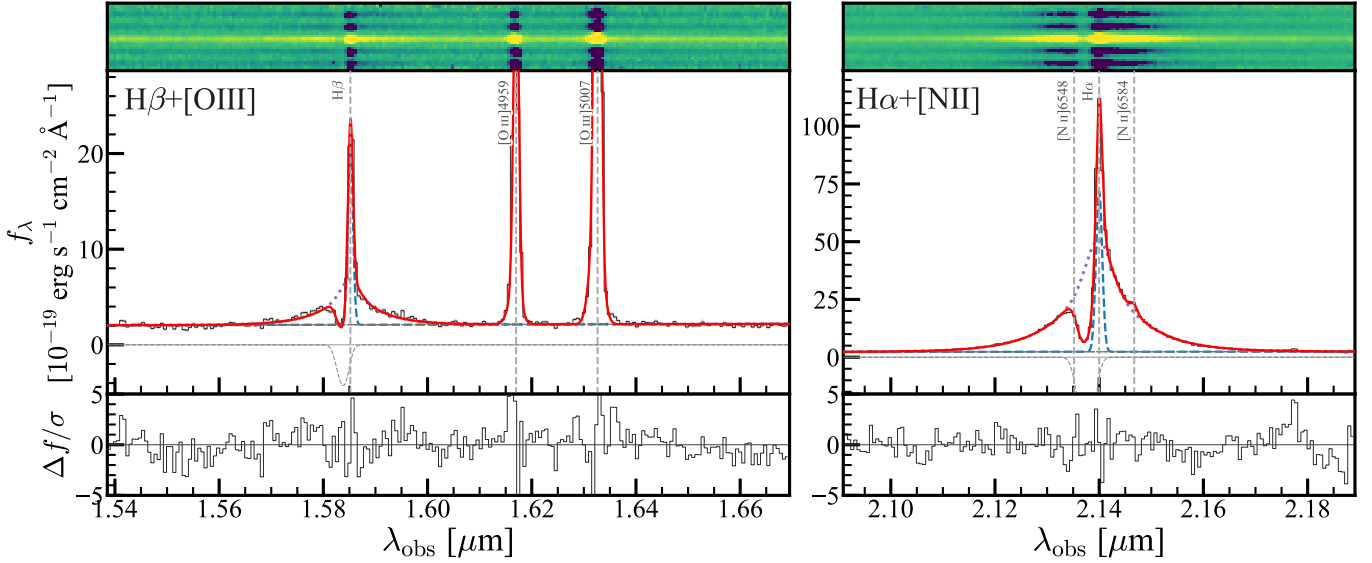


Figure 2. Example of the spectral fitting. The JWST/NIRSpec spectra around $H\beta + [O\text{III}]\lambda 4959, 5007$ (left) and $H\alpha + [N\text{II}]\lambda 6548, 6584$ (right) for JADES-GN-28074. The top, middle, and bottom panels show the two-dimensional spectrum, the one-dimensional spectrum, and the residuals between the observed spectrum and the best-fit model normalized by the 1σ uncertainties, respectively. In the middle panel, the black histogram and the gray-shaded region show the observed spectrum and the associated 1σ uncertainties, respectively. The red curve shows the best-fit model, while the dashed curves show the individual fitted components (blue: narrow line, purple: broad exponential, gray: absorption). The vertical gray dashed lines mark the wavelength of the labeled emission lines.

3σ upper limit on the broad $H\beta$ flux as the 99.865th percentile of the posterior flux distribution. We calculate line-ratio posteriors from the relevant line-flux posteriors.

3.2. Cloudy Modeling

We model the hydrogen-line ratios with photoionization calculations using CLOUDY version c23.01 (G. J. Ferland et al. 1998; C. M. Gunasekera et al. 2023). The purpose of this modeling is to identify the range of physical conditions capable of reproducing the observed Balmer and Paschen line ratios. The models are not intended to determine a unique gas density, column density, or ionization parameter for each source. Instead, they provide a feasibility grid to assess whether the observed broad-line ratios can be reproduced by high-density and optically thick gas without dust attenuation.

We use constant-density, plane-parallel slab models over the $\Phi(\text{H})-n_{\text{H}}$ plane, where $\Phi(\text{H})$ is the incident ionizing photon flux and n_{H} is the hydrogen number density (e.g., K. T. Korista & M. R. Goad 2004; A. Schnorr-Müller et al. 2016). The incident photon flux $\Phi(\text{H})$ is defined as

$$\Phi(\text{H}) = \frac{Q(\text{H})}{4\pi R^2}, \quad (3)$$

where $Q(\text{H})$ is the ionizing-photon production rate and R is the distance between the ionizing source and the

illuminated cloud face. The corresponding ionization parameter at distance R is

$$U = \frac{\Phi(\text{H})}{n_{\text{H}}c}, \quad (4)$$

where c is the speed of light. The $\Phi(\text{H})-n_{\text{H}}$ plane is widely used to parameterize AGN broad-line-region (BLR) gas (e.g., K. T. Korista & M. R. Goad 2004; A. Schnorr-Müller et al. 2016; D. Kim & M. Im 2018).

The adopted model setup, parameter ranges, and grid spacing are summarized in Table 2. At each point in the $\Phi(\text{H})-n_{\text{H}}$ plane, we calculate models over a range of total hydrogen column densities (N_{H}), stopping each calculation at the specified N_{H} . We adopt gas metallicities of $Z/Z_{\odot} = 0.01, 0.1$, and 1.0 . The incident continuum is the AGN SED implemented in CLOUDY (W. G. Mathews & G. J. Ferland 1987), with its normalization set by $\Phi(\text{H})$. We include no microturbulence in the fiducial models.

For each model, we calculate Balmer and Paschen line ratios directly from the line intensities reported by CLOUDY, rather than measuring them from the synthetic model SEDs (e.g., Z. Yan et al. 2026). This approach avoids additional dependencies on the assumed spectral resolution, line profile, continuum placement, and integration windows. The synthetic spectra around $H\beta$ contain numerous blended emission features, including iron lines and a structured pseudo-continuum. Mea-

measuring $H\beta$ directly from the model SEDs would introduce an unnecessary dependence on the adopted models. We compare the intrinsic model line ratios with the observed flux ratios measured in Section 3.1. We discuss the comparisons in Section 5 and show the model grid results in Appendix A.

We note that there are other choices for geometries and line-output conventions. For the fiducial calculations, we adopt plane-parallel geometry and obtain the line ratios using the CLOUDY “total” line intensity, $I_{\text{total}} = I_{\text{inward}} + I_{\text{outward}}$. This quantity represents the total two-sided line emission from the slab, usually used in AGN studies, rather than the directional line flux seen by an observer from one side. We adopt this convention because it provides an approximate reproduction of the observed $L_{\text{bol}}-L_{\text{broad, H}\alpha}$ scaling relation of LRDs (H. Yanagisawa et al. 2026a).

We also repeat representative calculations using the CLOUDY `sphere` command, which approximates closed geometry. The qualitative dependence of the Balmer and Paschen ratios on gas density, ionizing photon flux, and column density does not change. Detailed comparisons among geometries and line-output conventions are presented in Appendix B. We note that Z. Yan et al. (2026) derive their predicted Balmer line ratios from the outward line-emission component. We also discuss them in Appendix B.

4. RESULTS

4.1. Broad and Narrow Balmer Decrements

We combine the high-redshift line measurements from Section 3.1 with the published low-redshift fluxes described in Section 2.1. We first examine the broad Balmer decrements, which are widely observed and linked to the central engine of LRDs.

Figure 3 shows the relation between the broad $H\alpha/H\beta$ ratio and the broad $H\alpha$ luminosity ($L_{H\alpha, \text{broad}}$). The red and orange circles show high- and low-redshift LRDs, respectively, with both broad $H\alpha$ and broad $H\beta$ detected at $S/N \geq 5$. The red arrows indicate lower limits on the broad $H\alpha/H\beta$ ratio for high-redshift LRDs with broad $H\beta$ to have $S/N < 5$. The gray points show a comparison sample of SDSS AGNs ($z < 0.35$; H.-Y. Liu et al. 2019). For reference, unobscured Type-1 AGNs typically have intrinsic broad $H\alpha/H\beta$ ratios of $\sim 2.7-3.1$, close to the Case B value (X. Dong et al. 2008; C. M. Gaskell 2017).

In Figure 3, most LRDs have broad $H\alpha/H\beta$ ratios above the intrinsic Case B recombination value ($= 2.87$ for $n_e = 10^2 \text{ cm}^{-3}$ and $T_e = 10^4 \text{ K}$; e.g., P. J. Storey & D. G. Hummer 1995), and several reach $H\alpha/H\beta \gtrsim 13$. These extreme values exceed the maximum ratio in our adopted dust-free CLOUDY grid shown as the red line

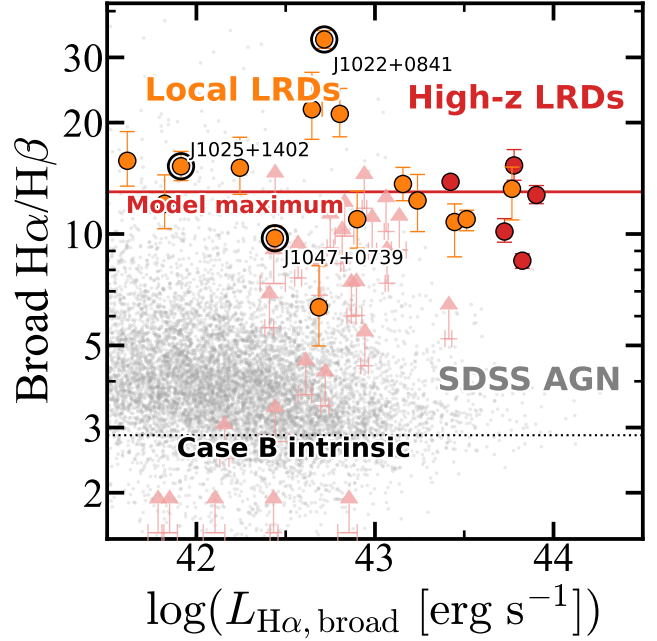


Figure 3. Relation between the broad $H\alpha/H\beta$ ratio and the broad $H\alpha$ luminosity. The red and orange circles show high-redshift and low-redshift LRDs with both $H\alpha$ and $H\beta$ $S/N \geq 5$ listed in Table 1, respectively. The red arrows show the high-redshift LRDs without $\geq 5\sigma$ broad $H\beta$ detections. The gray points show the SDSS AGNs at $z < 0.35$ (H.-Y. Liu et al. 2019). The Case B intrinsic value ($= 2.87$) is shown as a black dotted line. The red line indicates the maximum ratio (~ 13) obtained in the dust-free CLOUDY grid (Section 5). The three low-redshift LRDs with available Paschen-line and MIR data are highlighted with black circles.

in Figure 3. The implications of this comparison, including the possible role of attenuation, are discussed in Section 5. LRDs also tend to have higher broad $H\alpha/H\beta$ values than the SDSS comparison sample (gray; H.-Y. Liu et al. 2019) (see also S. Geris et al. 2026). Some SDSS AGNs also show $H\alpha/H\beta > 13$. A detailed analysis of these SDSS AGNs with high $H\alpha/H\beta$ is beyond the scope of this study and will be presented in a forthcoming paper. We briefly discuss them in Appendix C, together with comparisons to LRDs.

Comparison between the broad line ratio and the narrow one provides insight into the physical properties of LRDs. Figure 4 compares the broad and narrow $H\alpha/H\beta$ ratios. The main symbols are the same as in Figure 3. For reference, we also show the corresponding $E(B-V)$ values based on the $H\alpha/H\beta$ ratio as black arrows, assuming the Small Magellanic Cloud (SMC) attenuation curve (K. D. Gordon et al. 2003) implemented in the `dust_extinction` package (K. D. Gordon 2024). The different extinction curves (e.g., D. Calzetti et al. 2000, the Large Magellanic Cloud, and the Milky Way) show

Table 2. Fiducial CLOUDY models.

Parameter	Adopted value or range	Description
Geometry	Plane-parallel slab	Constant-density gas geometry
Incident continuum	AGN	Ionizing radiation field
Metallicity	0.01, 0.1, and 1.0 $Z_{\odot}$	Gas-phase metallicity
$\log(n_{\text{H}}/\text{cm}^{-3})$	5–16, in steps of 0.5 dex	Hydrogen number density
$\log(\Phi(\text{H})/\text{cm}^{-2} \text{ s}^{-1})$	16–24, in steps of 0.5 dex	Incident ionizing photon flux
$\log(N_{\text{H}}/\text{cm}^{-2})$	21–26, in steps of 0.5 dex	Stopping hydrogen column density
Dust grains	None	Intrinsic, dust-free line-ratio calculation
Microturbulence	None	Turbulence

NOTE—The incident AGN continuum is based on [W. G. Mathews & G. J. Ferland \(1987\)](#). Although the full calculations extend to $\log(n_{\text{H}}/\text{cm}^{-3}) = 16$, Figures 5 and 6 display only $\log(n_{\text{H}}/\text{cm}^{-3}) \leq 12$ for clarity.

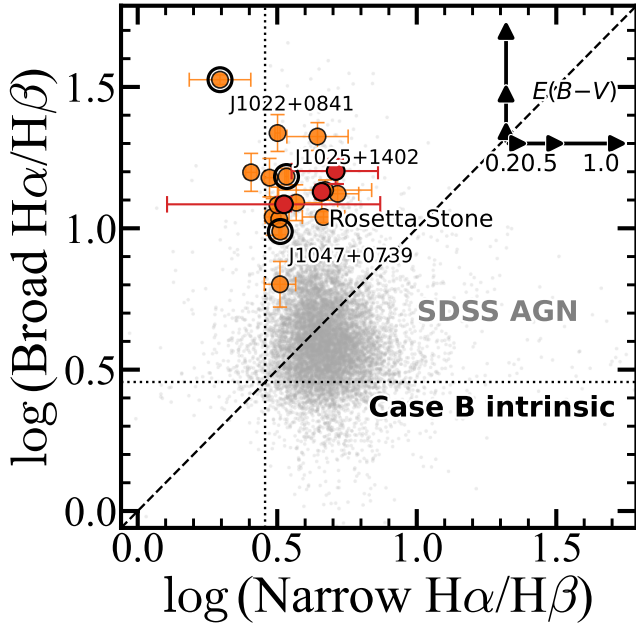


Figure 4. Relation between the broad $\text{H}\alpha/\text{H}\beta$ ratio and the narrow $\text{H}\alpha/\text{H}\beta$ ratio. The red and orange circles show high-redshift and low-redshift LRDs with both $\text{H}\alpha$ and $\text{H}\beta$ $\text{S/N} \geq 5$, respectively. The arrows show the $E(B - V)$ values (0.2, 0.5, and 1.0) assuming the Small Magellanic Cloud (SMC) extinction curve. The black dashed line shows equality between the broad and narrow ratios. The Case B intrinsic value ($= 2.87$) is shown as the black dotted lines. The other symbols are the same as in Figure 3. The Rosetta Stone (JADES-GN-28074) is also labeled.

different $E(B - V)$ values for the Balmer and Paschen decrements, but changing the extinction curve affects the inferred values of $E(B - V)$ but not the qualitative trends discussed below. In the following of this paper,

we use the SMC law ([K. D. Gordon et al. 2003](#)) as a fiducial extinction curve.

In Figure 4, for both high- and low-redshift samples, the broad-line ratios are generally larger than the corresponding narrow-line ratios (see also [X. Lin et al. 2026a](#); [G. P. Nikopoulos et al. 2026](#); [M. Brooks et al. 2025](#)). The narrow $\text{H}\alpha/\text{H}\beta$ ratios almost follow the Case B intrinsic value ($= 2.87$). This trend demonstrates that the broad-line emitting region has some non-Case B effects and/or dust extinction, while the narrow-line emitting region generally follows no/little dust conditions.

4.2. Broad Balmer and Paschen Line Ratios

A subset of the LRD spectra covers broad Paschen emission lines. In this subsection, we summarize the broad Balmer and Paschen line ratios. Figure 5 compares broad $\text{H}\alpha/\text{H}\beta$ with broad $\text{Pa}\beta/\text{Pa}\gamma$. The usable measurements comprise two low-redshift LRDs (J1022+0841 and J1047+0739) and one high-redshift LRD, the Rosetta Stone ([I. Juodžbalis et al. 2024](#)). Although $\text{Pa}\beta$ is covered for the local LRD J1025+1402, strong telluric absorption prevents a reliable measurement ([X. Lin et al. 2026a](#)). We therefore exclude this source from the $\text{Pa}\beta/\text{Pa}\gamma$ comparison.

The LRDs have broad $\text{Pa}\beta/\text{Pa}\gamma$ ratios spanning ~ 1.5 –4. In the $\text{H}\alpha/\text{H}\beta$ – $\text{Pa}\beta/\text{Pa}\gamma$ plane, the position of J1047+0739 is consistent with the direction expected for a simple SMC foreground screen, assuming the adopted intrinsic ratios. The remaining LRDs do not lie along this simple reddening locus. Because broad-line intrinsic ratios can depart from Case B, this comparison alone does not uniquely determine the attenuation. For comparison, we also show the local AGN sample selected by the hard X-ray Swift-Burst Alert Telescope (BAT) AGN

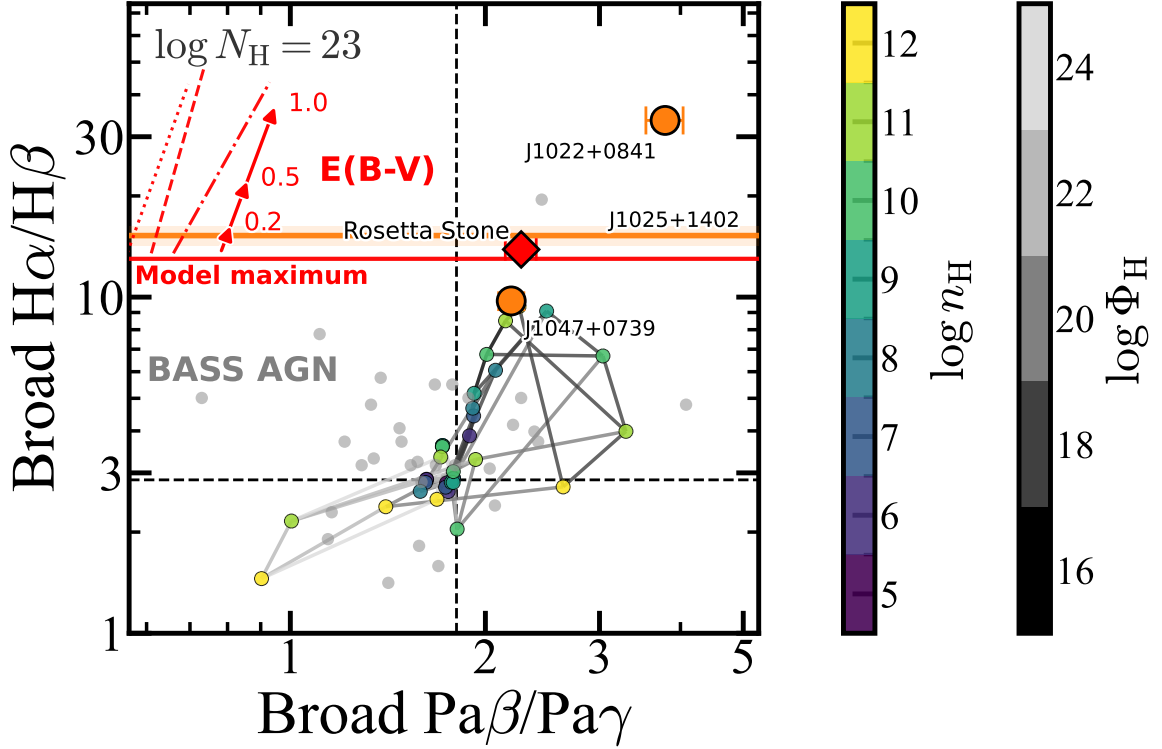


Figure 5. Relation between the broad $H\alpha/H\beta$ ratio and the broad $Pa\beta/Pa\gamma$ ratio. The red diamond and orange circles show the high-redshift and low-redshift LRDs, respectively. The orange line shows the $H\alpha/H\beta$ of J1025+1402, which has no reliable $Pa\beta$ flux. The gray circles show local AGNs from the Swift Burst Alert Telescope (BAT) AGN Spectroscopic Survey (BASS; I. Lamperti et al. 2017; J. S. den Brok et al. 2022; J. E. Mejía-Restrepo et al. 2022). The colored points show the dust-free CLOUDY models with $\log(n_H/\text{cm}^{-3}) = 5\text{--}12$, as indicated by the color bar. The gray lines connect models with $\log(\Phi(H)/\text{cm}^{-2} \text{ s}^{-1}) = 16, 18, 20, 22$, and 24. The models assume $\log(N_H/\text{cm}^{-2}) = 23$ and $Z/Z_\odot = 0.1$. The red line shows the maximum $H\alpha/H\beta$ values in our model framework. The red arrow indicates the reddening vector for the SMC attenuation curve ($E(B-V) = 0.2, 0.5$, and 1.0). The dotted, dashed, and dash-dotted lines, from left to right in the top left of this figure, show the $E(B-V) = 1.0$ in the case of the Milky Way, the Large Magellanic Cloud (LMC), and the D. Calzetti et al. (2000) law, respectively. The horizontal and vertical dashed lines show the Case B intrinsic value for $H\alpha/H\beta$ and $Pa\beta/Pa\gamma$, respectively.

Spectroscopic Survey (BASS; I. Lamperti et al. 2017; J. S. den Brok et al. 2022; J. E. Mejía-Restrepo et al. 2022) as gray circles. A subset of the BASS AGNs overlaps with the LRDs in the broad Balmer and Paschen line-ratio diagram. This overlap suggests that some local AGNs may share similar line-forming conditions, such as high density, large line optical depths, and/or differential attenuation (see also F. Ricci et al. 2022).

Figure 6 compares broad $Pa\beta/Pa\gamma$ with broad $Pa\alpha/Pa\beta$. Only J1022+0841 and J1047+0739 are shown because they are the only LRDs in our sample with reliable measurements of all three broad Paschen lines. The symbols and model grids have the same meanings as in Figure 5. Both sources have broad $Pa\alpha/Pa\beta$ ratios below the adopted Case B value. A standard foreground attenuation screen would instead increase this ratio, because $Pa\beta$ is more strongly attenuated than $Pa\alpha$. The observed ratios therefore cannot be explained by foreground attenuation alone under the Case B as-

sumption. We note that RUBIES-UDS-40579, which is not shown in Figures 5 and 6 because it lacks broad $H\beta$ coverage, has $Pa\beta/Pa\gamma = 1.46$. If it also has a large $H\alpha/H\beta$ ratio, the two ratios may challenge the models or indicate dust extinction, motivating future $H\beta$ spectroscopy. The implications of the CLOUDY model comparison in Figure 5 and Figure 6 are discussed in Section 5.

5. DISCUSSION

In this section, we interpret the observed hydrogen-line ratios using the CLOUDY calculations described in Section 3.2. We first assess whether optically thick, high-density line-forming gas can reproduce the observed ratios without attenuation. We then examine whether additional line-of-sight attenuation is required within the assumptions of our model framework. The implications for the dust distribution are discussed together with the MIR comparisons in the following subsections.

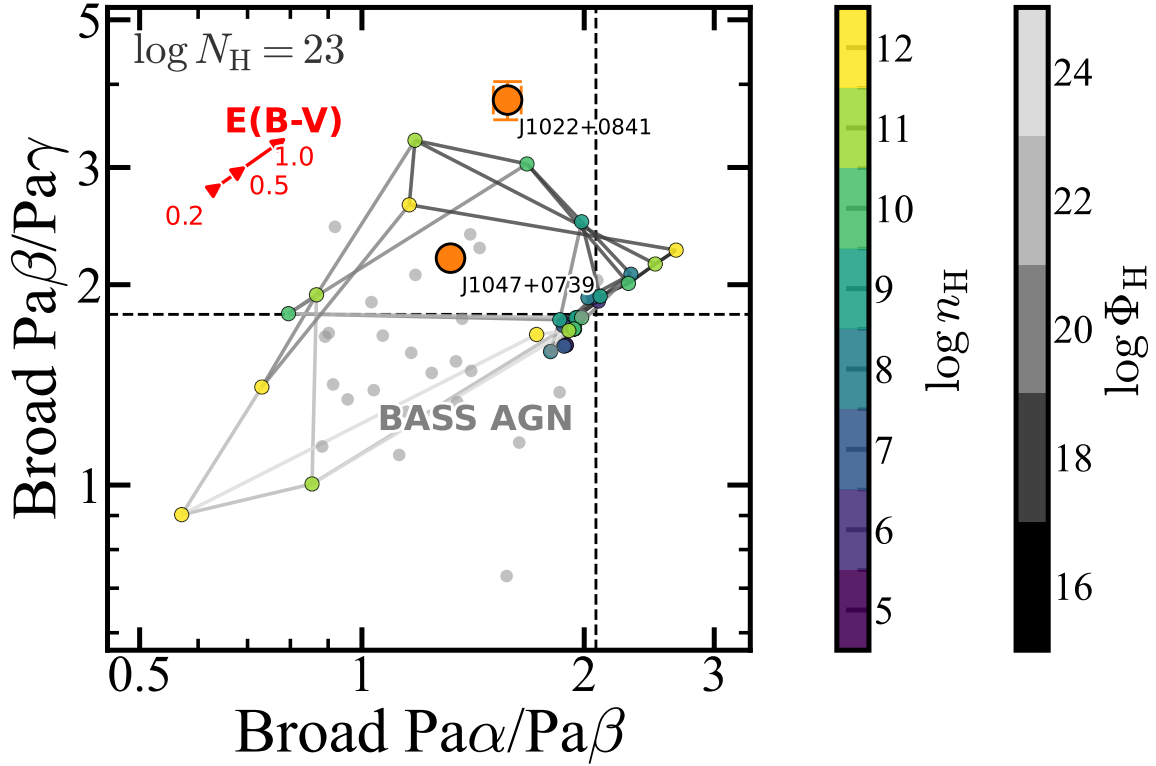


Figure 6. Relation between the broad $\text{Pa}\beta/\text{Pa}\gamma$ ratio and the broad $\text{Pa}\alpha/\text{Pa}\beta$. The symbols and the dust-free CLOUDY model grids are the same as in Figure 5.

5.1. Comparison with CLOUDY Models

Figures 5 and 6 show representative CLOUDY model grids with $Z/Z_{\odot} = 0.1$ and $\log(N_{\text{H}}/\text{cm}^{-2}) = 23$. The colored points span $\log(n_{\text{H}}/\text{cm}^{-3}) = 5\text{--}12$, and the gray curves show models with $\log(\Phi(\text{H})/\text{cm}^{-2} \text{ s}^{-1}) = 16\text{--}24$.

The models predict elevated $\text{H}\alpha/\text{H}\beta$ ratios at $\log(n_{\text{H}}/\text{cm}^{-3}) \sim 10$ and $\log(\Phi(\text{H})/\text{cm}^{-2} \text{ s}^{-1}) \sim 18$, where $\text{H}\alpha/\text{H}\beta$ can reach ~ 10 (see also Appendix A for the full model grids). In this regime, the hydrogen-line ratios are modified by the combined effects of large line optical depths, radiative trapping, and collisional processes, which alter the level populations and emergent line emissivities relative to the Case B approximation (e.g., B. J. Wills et al. 1985; D. Ilić et al. 2012; A. J. Ruff et al. 2012; J. Wu et al. 2023; S. Son et al. 2025; Z. Yan et al. 2026; S.-J. Chang et al. 2026). While Case B assumes efficient trapping of Lyman-series photons but optically thin Balmer and Paschen transitions, the present models can also become optically thick in the Balmer lines. In particular, repeated absorption and re-emission of trapped $\text{H}\beta$ photons can alter the branching of the $n = 4$ level. A photon initially emitted as $\text{H}\beta$ ($4 \rightarrow 2$) may instead follow the $4 \rightarrow 3 \rightarrow 2$ cascade, producing $\text{Pa}\alpha$ and $\text{H}\alpha$. In addition, collisional excitation ($2 \rightarrow 3$) and de-excitation at high density may further contribute to the departure from the Case-B ratios.

Such mechanisms can preferentially modify $\text{H}\alpha/\text{H}\beta$ (see also e.g., J. Kwan & J. H. Krolik 1981; S.-J. Chang et al. 2026).

The $\text{Pa}\alpha/\text{Pa}\beta$ ratio (Figure 6) provides a complementary constraint. A foreground attenuation screen increases $\text{Pa}\alpha/\text{Pa}\beta$, because $\text{Pa}\beta$ is more strongly attenuated than $\text{Pa}\alpha$. In contrast, in optically thick, high-density gas, the $\text{Pa}\alpha$ ($4 \rightarrow 3$) transition can become optically thick before $\text{Pa}\beta$ ($5 \rightarrow 3$). The escape probability of $\text{Pa}\alpha$ is then reduced more strongly by photon trapping and radiative or collisional redistribution, allowing the emergent $\text{Pa}\alpha/\text{Pa}\beta$ ratio to fall below its Case-B value. Therefore, a ratio below the adopted Case B value cannot be produced by foreground attenuation alone if the intrinsic ratio is assumed to be Case B. Both J1022+0841 and J1047+0739 have broad $\text{Pa}\alpha/\text{Pa}\beta$ ratios below this value (Figure 6). This result supports non-Case-B hydrogen-line formation in their broad-line-emitting gas and is consistent with the optically thick, high-density regime (e.g., B. J. Wills et al. 1985; S. A. Drake & R. K. Ulrich 1980; E. Glikman et al. 2006; H. Landt et al. 2008; B. T. Soifer et al. 2004).

We note that J1022+0841 is still deviating from the CLOUDY model grids. This might reflect the dust extinction at least in the line of sight (indicated by the red arrow in Figure 6) from the high-density condi-

tions. Especially, $H\alpha/H\beta$, $Pa\alpha/Pa\beta$, and $Pa\beta/Pa\gamma$ ratios of J1022+0841 is simultaneously explained by $\log(n_H/\text{cm}^{-3}) \sim 10\text{--}11$, $\log(\Phi_H/\text{cm}^{-2} \text{ s}^{-1}) \sim 18$ and $E(B - V) \sim 1$ in Figures 5 and 6. These line ratios of another local LRD, J1047+0739, is explained by $\log(n_H/\text{cm}^{-3}) \sim 10\text{--}11$ and $\log(\Phi_H/\text{cm}^{-2} \text{ s}^{-1}) \sim 18$ and no information of dust extinction (Figures 5 and 6). These results also highlight that non-Case B physics alter Balmer and Paschen line ratios, but some objects still require additional attenuation toward the broad-line-emitting gas. We mention that the $H\alpha/H\beta$ - $Pa\beta/Pa\gamma$ of Rosetta Stone are roughly close to the $\log(n_H/\text{cm}^{-3}) \sim 9$, $\log(\Phi_H/\text{cm}^{-2} \text{ s}^{-1}) \sim 18$, and $\log N_H = 25$ model grids with $E(B - V) \sim 0.2$. More generally, two high-redshift and eight low-redshift LRDs have $H\alpha/H\beta > 13$, exceeding the maximum of the fiducial dust-free grid (Figure 3). Within the adopted geometry and line-output prescription, these extreme decrements favor additional attenuation. Except for the Rosetta Stone and J1022+0841, however, these sources lack usable Paschen-line constraints.

We also note that these trends remain largely unchanged even when we choose other high column densities ($\log(N_H/\text{cm}^{-2}) = 22\text{--}25$) and metallicities ($Z/Z_\odot = 0.01$ and 1.0). The column-density dependence becomes weak once the cloud is ionization-bounded. Beyond the hydrogen ionization front, additional deeper gas contributes little to the main Balmer-line-emitting region, causing the line ratios to saturate with increasing N_H . The Balmer decrements primarily depend on hydrogen level populations and line optical depths and show only a weak net dependence on metallicity. Figure 7 shows the relation between the number density $\log n_H$ and the $H\alpha/H\beta$ ratio obtained from the models. At fixed $\Phi(H)$, the ratio increases toward the intermediate densities, reaches a maximum, and then declines at higher densities. The turnover occurs as $Pa\alpha$ also becomes optically thick, reducing the efficiency of the $H\beta \rightarrow Pa\alpha + H\alpha$ conversion. At still higher densities, collisional excitation and de-excitation drive the excited-state populations toward LTE, and the $H\alpha/H\beta$ ratio lower than the maximum value. The maximum values of $H\alpha/H\beta$ ratios in our grid are ~ 13 , and even if we choose a different column density, the general trend of the maximum $H\alpha/H\beta$ does not change.

To further test the effects of column densities, we also show the relation between the column density $\log N_H$ and the $H\alpha/H\beta$ ratio in Figure 8. Figure 8 shows the maximum $H\alpha/H\beta$ ratios for each column density, indicating that the $H\alpha/H\beta$ ratio is almost saturated for high column density. Thus, we find that $H\alpha/H\beta \sim 13$ is the threshold that can be achieved without dust, accounting

for the non-Case B effects in the CLOUDY model framework. We show the resulting full grid $H\alpha/H\beta$ ratio of the $\Phi(H)$ - n_H plane in Appendix A. We note that at higher column density ($\log(N_H/\text{cm}^{-2}) > 24$), CLOUDY calculation sometimes become unstable, but general trend does not change and the main discussion of this paper remain unchanged.

5.2. Comparison with Mid-infrared Constraints

Broad $H\alpha/H\beta$ ratios that exceed the dust-free CLOUDY grid can require additional differential attenuation within the model framework. As for local LRDs, Paschen line ratios (Figure 6) also suggest additional extinction. MIR emission provides complementary evidence for dust around the central engine, but does not by itself identify the material responsible for broad-line attenuation.

X. Lin et al. (2026a) fit the WISE SEDs of the three local LRDs with the fixed-temperature dust templates of J. Lyu & G. H. Rieke (2021). The left panel of Figure 9 shows the luminosity of each fitted dust component (L_{dust}), normalized by the rest-frame optical pseudo-blackbody luminosity ($L_{\text{pseudo-BB}}$). X. Lin et al. (2026a) report the optical pseudo-blackbody temperature of 5019 K, 5013 K, and 5558 K for J1025+1402, J1047+0739, and J1022+0841, respectively (Table D1 of X. Lin et al. 2026a). Thus, the left panel compares the relative strengths of the $T_{\text{dust}} \sim 90$, 300, and 1000 K dust templates. It does not directly measure dust mass, covering factor, or line-of-sight extinction. The ~ 2000 K component fitted for J1022+0841 by X. Lin et al. (2026a) is included in the figure.

For reference, we estimate a characteristic dust-heating scale by assuming that the $T \sim 5000$ K optical pseudo-blackbody emission illuminates the surrounding dust. Setting the luminosity of the heating source as $L_{\text{heat}} = L_{\text{pseudo-BB}}$, radiative equilibrium of a single dust grain gives

$$r_{\text{BB}} = \left(\frac{L_{\text{heat}}}{16\pi\sigma_{\text{SB}}T_{\text{dust}}^4} \right)^{1/2}, \quad (5)$$

where σ_{SB} is the Stefan Boltzmann constant. The upper axis of the left panel shows this quantity. It is an order-of-magnitude heating scale, not a direct size measurement or a globally energy-balanced estimate. Dust at $T_{\text{dust}} \sim 300\text{--}2000$ K is commonly associated with the warm and hot circumnuclear component of classical AGN tori ($r_{\text{BB}} \sim 0.01\text{--}1$ pc scale), whereas the ~ 90 K component can include more extended polar, narrow-line-region, or host-galaxy dust (e.g., J. Lyu & G. H. Rieke 2021). J1025+1402 (red) and J1022+0841 (green) have their strongest fitted components near 300 K,

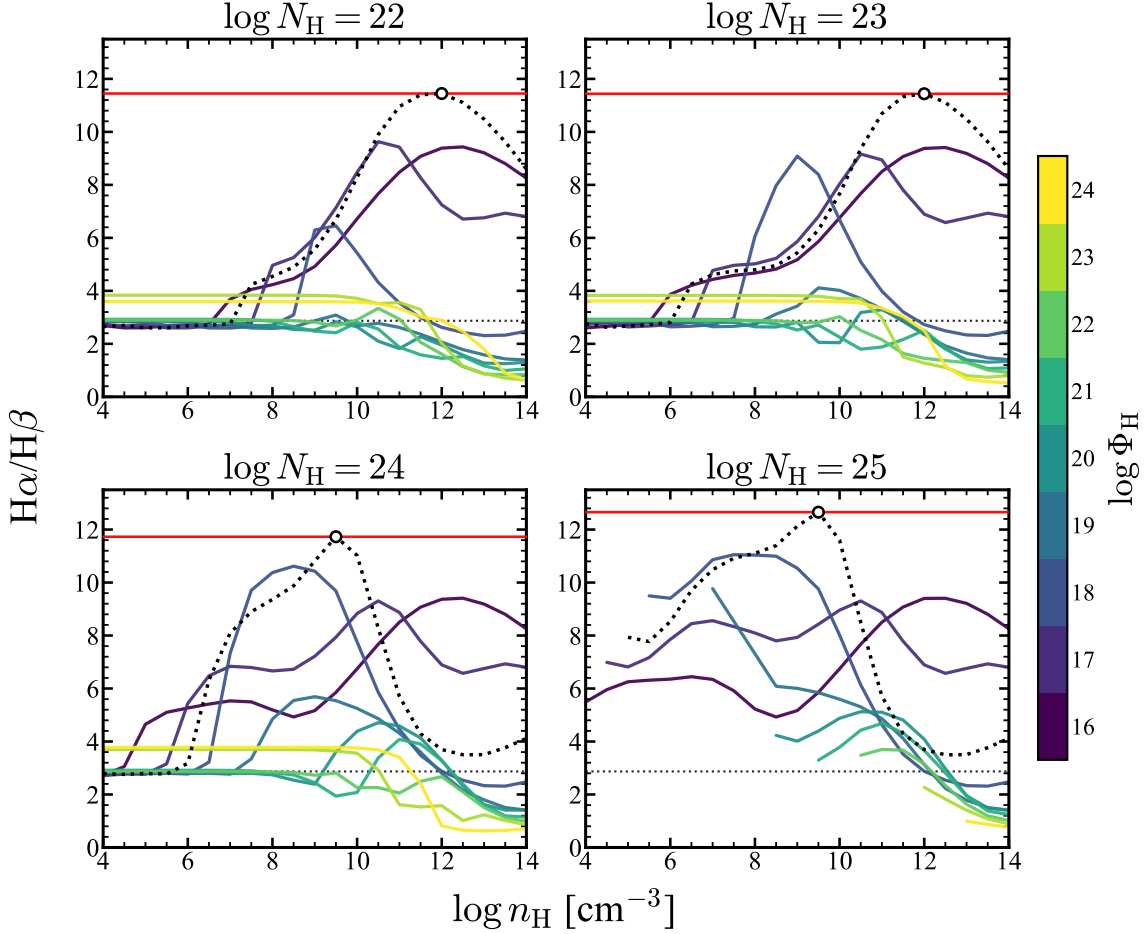


Figure 7. Relation between the $H\alpha/H\beta$ ratio and the hydrogen number density ($\log n_H$) obtained from the CLOUDY modeling. The different lines show the different hydrogen column densities ($\log(N_H/\text{cm}^{-2}) = 22\text{--}25$). In this figure, we fix the ionizing photon flux $\Phi(H)$ indicated by the color bar. The horizontal black dotted line shows the Case B intrinsic value. The black dashed curve shows the case for the highest $H\alpha/H\beta$ ratio in each column density at a fixed $\Phi(H)$. The red lines show the maximum $H\alpha/H\beta$ in each column density.

which might indicate the presence of dust around tori in the case of the classical AGNs. On the other hand, the ~ 90 K component is strongest in J1047+0739 (blue), which might suggest a narrow-line region and/or host galaxy-scale dust is dominant.

The right panel of Figure 9 compares the narrow- and broad-line attenuation estimates with the $H\alpha$ FWHM. The narrow-line values are taken from X. Lin et al. (2026a). For broad lines, we derive the minimum additional SMC attenuation after adopting the maximum intrinsic ratio in our dust-free CLOUDY grid, $H\alpha/H\beta \simeq 13$; the inferred values are therefore model-dependent lower limits. J1025+1402 (red) and J1022+0841 (green) require $E(B - V)_{\text{broad}} \gtrsim 0.2$ to the dust-free CLOUDY models. Their prominent $\sim 300\text{--}2000$ K components (left panel of Figure 9) are qualitatively consistent with warm circumnuclear dust contributing to the broad-line attenuation, although the MIR-emitting and attenuat-

ing dust need not be the same component. The dust-free grid reproduces J1047+0739 and hence has no positive lower limit on additional broad-line attenuation. ~ 90 K emission of J1047+0739 (blue) may instead trace more extended dust compatible with its narrow-line attenuation ($A_{V,\text{narrow}} \sim 0.8$ for J1047+0739; X. Lin et al. 2026a).

In addition, summing the fitted dust components relative to the pseudo-blackbody luminosity, J1022+0841 has the largest total relative warm/hot dust luminosity ($T_{\text{dust}} = 300\text{--}2000$ K) among the three local LRDs. This result is qualitatively consistent with the large broad-line attenuation inferred for J1022+0841 (green) in the right panel of Figure 9. However, the dust luminosity traces global reprocessed emission, whereas the broad-line attenuation is line-of-sight dependent.

We note that there are some degeneracies and uncertainties in decomposing the IR luminosity of each

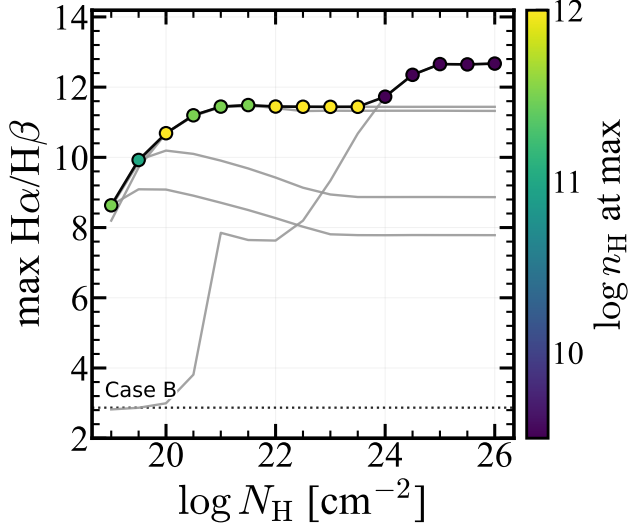


Figure 8. Relation between the $H\alpha/H\beta$ ratio and the hydrogen column density ($\log N_H$) obtained from the CLOUDY models. At each column density, we plot the maximum $H\alpha/H\beta$ value obtained among the model grids. The color of each data point indicates the hydrogen number density that yields this maximum ratio, as shown by the colorbar. The gray curves show the $H\alpha/H\beta$ ratios as a function of $\log N_H$ at fixed $(\log n_H, \log \Phi(H))$ for the models that reach the maximum at one or more column densities. The horizontal black dotted line denotes the Case B recombination value.

temperature, also mentioned in X. Lin et al. (2026a). The general trend of the detection in MIR remains unchanged, but future MIR observations, such as JWST/MIRI spectroscopy for local LRDs (e.g., JWST GO-12316), will further probe these components.

At high redshift, individual rest-frame MIR measurements remain limited (e.g., I. Delvecchio et al. 2025; I. Juodžbalis et al. 2024; M. Brazzini et al. 2026; P. G. Pérez-González et al. 2026). However, stacked JWST/MIRI data show a continuum excess to $\lambda_{\text{rest}} \sim 3 \mu\text{m}$ that is consistent with hot, AGN-heated dust (I. Delvecchio et al. 2025). This population-level result is consistent with dust near at least some LRD central engines, but it neither requires nor localizes the dust responsible for any individual broad-line decrement. In addition, the MIRI SED of the Rosetta Stone has been interpreted as containing a warm or hot dust component (I. Juodžbalis et al. 2024; M. Brazzini et al. 2026). Taken together, the line ratio and MIR constraints support a picture in which an optically thick gas shapes the intrinsic broad hydrogen-line ratios, while additional dust attenuation may be required along some lines of sight.

5.3. Possible Type-2-like LRDs

Although our analysis is restricted to the broad Balmer/Paschen line objects, possible narrow-line counterparts provide an external test of the sightline-dependent dust geometry. If the circumnuclear dust column increases along some viewing directions, the same underlying central engine could appear without a detectable BLR.

In previous studies, some LRD candidates have compact morphologies and V-shaped continua but lack a detectable broad $H\alpha$ component. Using NIRSpect medium- or high-resolution spectra, Z. Zhang et al. (2026) identified five such narrow-line LRDs among 32 LRDs with $H\alpha$ coverage ($\sim 16\%$). These sources could be dusty, compact star-forming galaxies, but they may also include obscured AGNs. In the latter case, dust associated with circumnuclear material could attenuate BLR emission along our line of sight, making them Type-2-like counterparts of broad-line LRDs (e.g., C. M. Urry & P. Padovani 1995).

This interpretation is not yet unique. R. E. Hviding et al. (2025) find broad Balmer emission in all compact spectroscopically V-shaped point sources for which the data allowed robust broad-line measurement. The remaining cases are inconclusive due to spectral limitations. Longer-wavelength spectroscopy, including Paschen lines, will help to test whether narrow-line LRDs contain a dust-obscured BLR. If confirmed, these narrow-line LRDs may provide complementary views of central engines seen along more obscured sightlines. Together with the broad-line ratios and MIR constraints, they motivate the illustrative circumnuclear dust geometry discussed in the following subsection.

5.4. Possible Dust Geometry

Figure 10 presents an illustrative multiphase geometry of an LRD motivated by the hydrogen-line ratios and MIR constraints. The left (right) panel of Figure 10 shows the simplified view of a Type-1 AGN (LRD). In LRDs, dense, optically thick ionized gas near the central engine (blue in Figure 10) can produce non-Case-B broad hydrogen-line ratios, while warm or hot circumnuclear dust (brown in Figure 10) may additionally attenuate the broad-line-emitting gas along some lines of sight. The optical continuum temperature inferred for LRDs ($\sim 5000 \text{ K}$; e.g., A. de Graaff et al. 2025a) exceeds the dust sublimation temperature ($\sim 1500\text{--}2000 \text{ K}$; e.g., R. Barvainis 1987; A. Baskin & A. Laor 2018), implying that dust is unlikely to survive in the innermost line-emitting region. As the incident radiation field decreases and shielding increases with distance from the central engine, conditions may favor cooler,

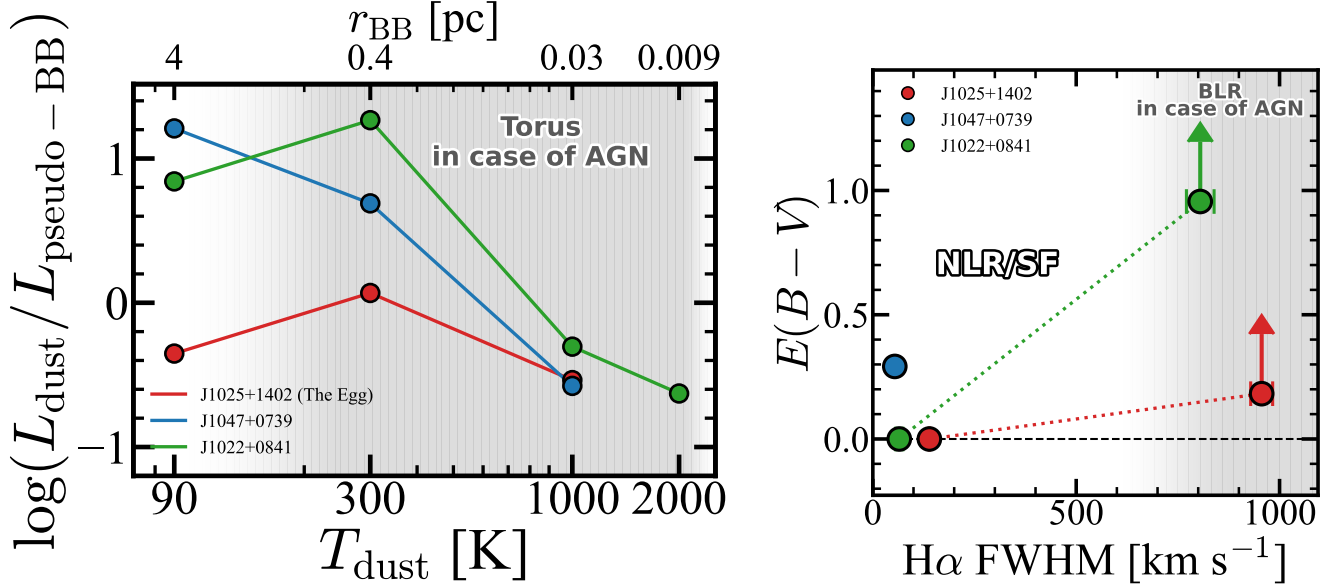


Figure 9. Left: Relation between the dust luminosity normalized by the pseudo-blackbody luminosity, $L_{\text{dust}}/L_{\text{pseudo-BB}}$, and the dust-template temperature for the local LRDs studied by X. Lin et al. (2026a). L_{dust} denotes the luminosity assigned to each fixed-temperature dust template in the SED decomposition of X. Lin et al. (2026a). The red, blue, and green symbols show J1025+1402, J1047+0739, and J1022+0841, respectively. The upper axis shows the corresponding blackbody-equilibrium heating radius (r_{BB}) estimated from the $L_{\text{pseudo-BB}}$ as an illustrative scale. The shaded regions indicate the approximate temperature ranges commonly associated with circumnuclear tori and extended polar or narrow-line-region dust in AGNs (e.g., J. Lyu & G. H. Rieke 2021). Right: Relation between the $E(B-V)$ and the $\text{H}\alpha$ FWHM. The narrow-line $E(B-V)$ values are taken from X. Lin et al. (2026a), which are estimated from multiple narrow Balmer lines. The broad-line $E(B-V)$ values show the minimum additional SMC-like attenuation required when the observed $\text{H}\alpha/\text{H}\beta$ ratio exceeds the maximum value in our dust-free CLOUDY grid. The narrow-line FWHM values of J1025+1402 and J1047+0739 are slightly shifted for visualization. J1047+0739 (blue) falls within the CLOUDY model grids (Figures 5 and 6), and we have no constraints on the extinction of broad lines.

low-ionization, molecular, and dusty gas ($T_{\text{dust}} \sim 300\text{--}2000$ K) phases. The narrow-line emission may probe more extended regions and different sightlines and can therefore experience less attenuation.

Additional spectral features support the presence of such multiphase/stratified gas structures in at least some LRDs (e.g., X. Lin et al. 2026a; B. Wang et al. 2026; V. Kokorev et al. 2026; A. Torralba et al. 2026). For example, the local LRD J1025+1402 shows strong Ca II triplet, Na D, and K I absorption, suggesting cool, metal-enriched, low-ionization/atomic gas (green in Figure 10; X. Lin et al. 2026a). B. Wang et al. (2026) reported a rest-frame $\sim 1.4\ \mu\text{m}$ absorption feature consistent with H_2O absorption in two LRDs, indicating a cool ($T \lesssim 3000$ K), molecular gas component (brown in Figure 10; see also H. Liu et al. 2026). The LRD schematic view qualitatively resembles the stratified Type-1 AGNs (left panel of Figure 10), mainly determined by the distance from the central engine and hence gas/dust temperature. If its circumnuclear gas redistributes angular

momentum, an LRD could develop a flatter, classical AGN-like dusty structure.

We refer to this putative circumnuclear dust component as a “proto-torus,” while emphasizing that its geometry, column density, and evolutionary relation to classical AGN tori remain unconstrained. Among the four high-redshift LRDs with luminous broad $\text{H}\alpha$ ($\log(L_{\text{H}\alpha, \text{broad}}/\text{erg s}^{-1}) > 43.5$), one has $\text{H}\alpha/\text{H}\beta > 13$ (Figure 3). Since our fiducial CLOUDY total-emission models cannot reproduce such a large decrement, this object could require additional dust attenuation. The observed incidence (1/4) is suggestive, but cannot yet be converted directly into a dust-covering factor due to the small, heterogeneous sample. Larger homogeneous samples with Balmer and Paschen spectroscopy will be needed to constrain the geometry of circumnuclear dust in LRDs. Cold-dust (~ 30 K) constraints from the Atacama Large Millimeter/submillimeter Array (ALMA) (e.g., C. M. Casey et al. 2025; D. J. Setton et al. 2025) probe a different component and do not by themselves

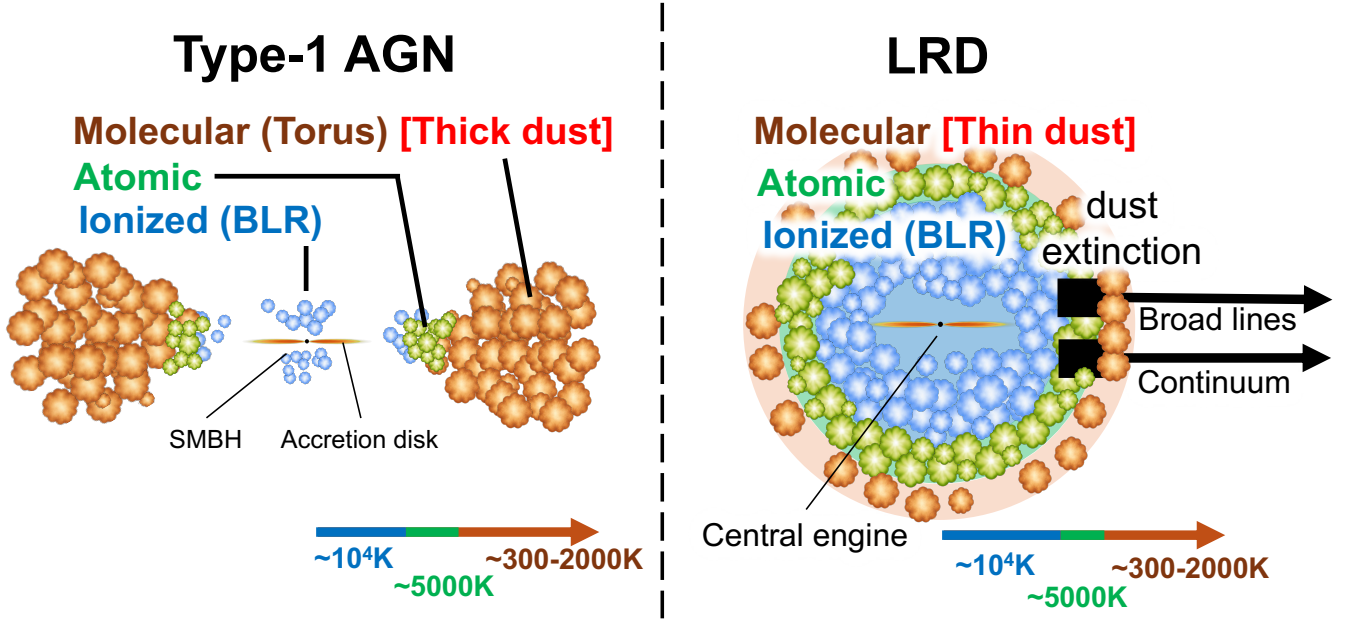


Figure 10. Simplified schematic view of a classical Type-1 AGN (left) and an LRD (right). The blue, green, and brown clouds denote dense ionized gas, cooler low-ionization/atomic gas, and possible molecular and dusty gas, respectively. In the LRD schematic, dust along the illustrated line of sight can attenuate the broad-line and continuum emission. The bottom arrows indicate the temperature structure ($\sim 10^4$ K for ionized gas, ~ 5000 K for atomic gas/low ionization gas, and $\sim 300\text{--}2000$ K for molecular gas or dust temperature).

rule out this hot/warm dust scenario (i.e., Dust-poor on the galaxy scale, but dust is in LRDs).

An additional speculative possibility is in-situ dust formation within the dense gas surrounding the central engine. R. P. Naidu et al. (2026) proposed that LRDs may share similarities with Type II supernovae, in which shocks within a dense circumstellar envelope can produce favorable conditions for dust formation (e.g., M. Shahbandeh et al. 2025). If analogous processes operate in LRDs, they could provide a pathway for producing circumnuclear dust around the broad-line-emitting gas. Although this scenario is not tested with the present data, the dust-production mechanism itself is an intriguing avenue for future studies of LRD central engines.

6. SUMMARY AND CONCLUSION

We investigate broad Balmer and Paschen line ratios in a sample of 20 LRDs, comprising 15 low-redshift ($z = 0.1\text{--}0.9$) and five high-redshift ($z = 2.3\text{--}7.0$) sources. Our sample requires both broad $H\alpha$ and broad $H\beta$ to be detected at $S/N \geq 5$. By comparing the measured line ratios with dust-free CLOUDY calculations, we assess the relative roles of optically thick gas and dust attenuation in shaping the broad hydrogen-line emission. Our main results are summarized as follows.

1. Broad $H\alpha/H\beta$ ratios ($\sim 6\text{--}30$) are generally larger than the corresponding narrow-line ratios ($\sim 3\text{--}5$) and the Case B value ($= 2.87$ for $n_e = 10^2 \text{ cm}^{-3}$

and $T_e = 10^4$ K). In contrast, the narrow $H\alpha/H\beta$ ratios are broadly consistent with the Case B recombination value. This broad-narrow contrast indicates that the physical conditions and/or attenuation affecting the broad-line-emitting gas differ from those affecting the narrow-line-emitting gas.

2. The two local LRDs with reliable broad $\text{Pa}\alpha$, $\text{Pa}\beta$ measurements (J1022+0841 and J1047+0739) have $\text{Pa}\alpha/\text{Pa}\beta$ ratios (~ 1.5) below the adopted Case B value ($= 2.0$). Because a foreground attenuation screen would increase this ratio, the Paschen measurements support non-Case-B hydrogen-line formation processes in an optically thick, high-density gas.
3. The dust-free CLOUDY grid (assuming plane parallel geometry and adopting total line intensity outputs) reproduces elevated broad Balmer decrements through radiative-transfer and collisional effects, with the largest $H\alpha/H\beta$ ratios reaching ~ 13 at $\log(n_H/\text{cm}^{-3}) \sim 10$ and $\log(\Phi/\text{cm}^{-2} \text{ s}^{-1}) \sim 18$. Broad $H\alpha/H\beta$ ratios above this model would require additional differential attenuation, or physical conditions not included in the present grid.
4. Among the three LRDs with joint Balmer–Paschen constraints for objects with reliable Paschen lines, J1047+0739 can be approximately reproduced by

dust-free dense-gas models. J1022+0841 and Rosetta Stone remain outside the dust-free grid and require additional attenuation within the model framework.

5. Two high-redshift and eight low-redshift LRDs in the sample have broad $H\alpha/H\beta$ ratios above the maximum value of our grid (> 13). If these extreme decrements are interpreted as additional dust attenuation, they imply that dust preferentially attenuates the broad-line emission along some lines of sight with $E(B - V) \gtrsim 0.2$ –1.0.
6. The warm/hot dust components inferred from WISE observations ($\lambda_{\text{rest}} \sim 3$ –20 μm) of local LRDs and the stacked rest-frame MIR excess ($\lambda_{\text{rest}} = 3 \mu\text{m}$) reported for high-redshift LRDs are consistent with hot/warm dust (~ 300 –1000 K) near central engines of LRDs. We note that MIR-emitting dust need not be identical to the material responsible for broad-line attenuation. Together, the line-ratio and MIR constraints are consistent with dense, optically thick line-forming gas surrounded by, or viewed through, a low-column-density counterpart of the classical AGN torus, which we refer to as a “proto-torus.”

Future JWST/MIRI spectroscopy (e.g., GO-10116, 10445, 11376, 12312, 12396, and future observations) will expand the sample of LRDs with Paschen series coverage, especially at higher redshifts. These data will provide key diagnostics of the physical conditions in the central engines of LRDs, including the non-Case B conditions and the existence of dust. Deeper MIR observations, such as the PRobe for-Infrared Mission for Astrophysics (PRIMA; J. Glenn et al. 2025), will also provide constraints on the dust continuum emission of LRDs, especially from warm/hot dust.

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Facilities: JWST/NIRSpec

Software: Astropy (Astropy Collaboration et al. 2013, 2018, 2022), CLOUDY (C. M. Gunasekera et al. 2023), emcee (D. Foreman-Mackey et al. 2013), LMFIT

(M. Newville et al. 2025), Matplotlib (J. D. Hunter 2007), NumPy (C. R. Harris et al. 2020), pandas (W. McKin-

ney 2010) PyNeb (V. Luridiana et al. 2015), SciPy (P. Virtanen et al. 2020),

APPENDIX

A. CLOUDY MODEL GRID RESULTS

We show the CLOUDY modeling results obtained from “total” emission line intensity outputs in the $\Phi(\text{H})-n_{\text{H}}$ plane for $\text{H}\alpha/\text{H}\beta$, $\text{Pa}\alpha/\text{Pa}\beta$, and $\text{Pa}\beta/\text{Pa}\gamma$ in Figure A1, Figure A2, and Figure A3, respectively.

B. SENSITIVITY TO GEOMETRY AND DIRECTIONAL LINE OUTPUT

The fiducial calculations adopt the total line intensity from open plane-parallel slabs. To test this choice, we compare the total (I_{tot} ; usual CLOUDY output) and the outward-only (I_{out}) plane-parallel outputs with the total emission from the closed spherical models (CLOUDY command `sphere`). For the plane-parallel models, we calculate the shielded-face emission as $I_{\text{out}} = I_{\text{tot}} - I_{\text{in}}$, where I_{in} leaves the illuminated face toward the ionizing source. Figures B1, B2, and B3 show the resulting hydrogen-line ratios of $\text{H}\alpha/\text{H}\beta$, $\text{Pa}\alpha/\text{Pa}\beta$, and $\text{Pa}\beta/\text{Pa}\gamma$, respectively. We show the values at $\log U = -1.48$ for reference. The outward-only models provide the most extreme values, reaching $\text{H}\alpha/\text{H}\beta > 100$ near $\log(n_{\text{H}}/\text{cm}^{-3}) \sim 8$ (see also Z. Yan et al. 2026). Thus, the Balmer decrement alone might not exclude a dust-free configuration dominated by shielded-face “outward” emission.

We nevertheless adopt the total plane-parallel emission as the fiducial reference. The LRD broad lines are expected to arise from gas distributed around the central engine rather than from clouds viewed exclusively from its shielded face. In several optically thick models, the inward component accounts for a substantial fraction of the intrinsic line emission. Selecting only the outward component might therefore discard a large fraction of the line-emitting gas in an angle-integrated description. Moreover, total-emission models with a large covering factor reproduce the observed $L_{\text{H}\alpha, \text{broad}}-L_{\text{bol}}$ scaling relation (H. Yanagisawa et al. 2026a). Retaining only one directional component would reduce the predicted $\text{H}\alpha$ luminosity.

In the closed spherical calculations, most of the total hydrogen-line intensity is assigned to the inward component in CLOUDY. In this geometry, however, inward emission is included in the closed-shell calculation rather than being discarded as in the outward-only slab limit. The total spherical and total plane-parallel models also show broadly similar regions of the $\text{H}\alpha/\text{H}\beta$ – $\text{Pa}\beta/\text{Pa}\gamma$

and $\text{Pa}\alpha/\text{Pa}\beta$ – $\text{Pa}\beta/\text{Pa}\gamma$ planes as shown by blue dashed lines in Figure B4.

Finally, the outward-only models producing the largest Balmer decrements do not simultaneously reproduce the observed Balmer and Paschen ratios at the same model parameters. In particular, the $\text{Pa}\beta/\text{Pa}\gamma$ ratio of J1022+0841 remains outside the dust-free model range and requires additional attenuation ($E(B-V) \sim 1$ in Figure 9). We therefore treat the outward-only calculations as a directional upper envelope and the total plane-parallel calculations as the fiducial global-emission reference. The inference of additional dust attenuation from the joint Balmer and Paschen ratios would not be consequently driven solely by the adopted geometry or directional output.

C. SDSS HIGH BALMER DECREMENT AGN CANDIDATES

We find 167 SDSS AGNs at $z < 0.35$ that satisfy broad $\text{H}\alpha/\text{H}\beta > 13$, $\text{S/N}(\text{broad H}\alpha) > 3$, and $\text{S/N}(\text{broad H}\beta) > 3$ in the catalog of H.-Y. Liu et al. (2019) (see also the gray points of Figures 3 and 4). We refer to these objects as extreme-decrement AGN candidates. To provide a qualitative comparison with LRDs, we compile the Galaxy Evolution Explorer (GALEX; D. C. Martin et al. 2005), SDSS, Two Micron All Sky Survey (2MASS; M. F. Skrutskie et al. 2006), and WISE photometry listed by H.-Y. Liu et al. (2019), inspect WISE multi-epoch photometry, and visually examine the SDSS spectra. Figure C1 shows representative examples of the SED and SDSS spectra. The candidate sample shows various features, including V-shaped SEDs with weak WISE emission like LRDs (top panel of Figure C1), V-shaped SEDs with stronger MIR emission than that of “The Egg” (middle panel of Figure C1), and sources without a V-shaped SED (bottom panel of Figure C1).

Some parts of objects show compact and V-shaped SEDs qualitatively similar to those of LRDs. Weak WISE emission relative to the optical continuum looks consistent with a weak warm/hot-dust component compared with dusty galaxies such as dust-obscured galaxies (DOGs), or ALMA dust continuum sources (e.g., T. Kiyota et al. 2026). Interestingly, we find that a large number of sources among the extreme-decrement AGN

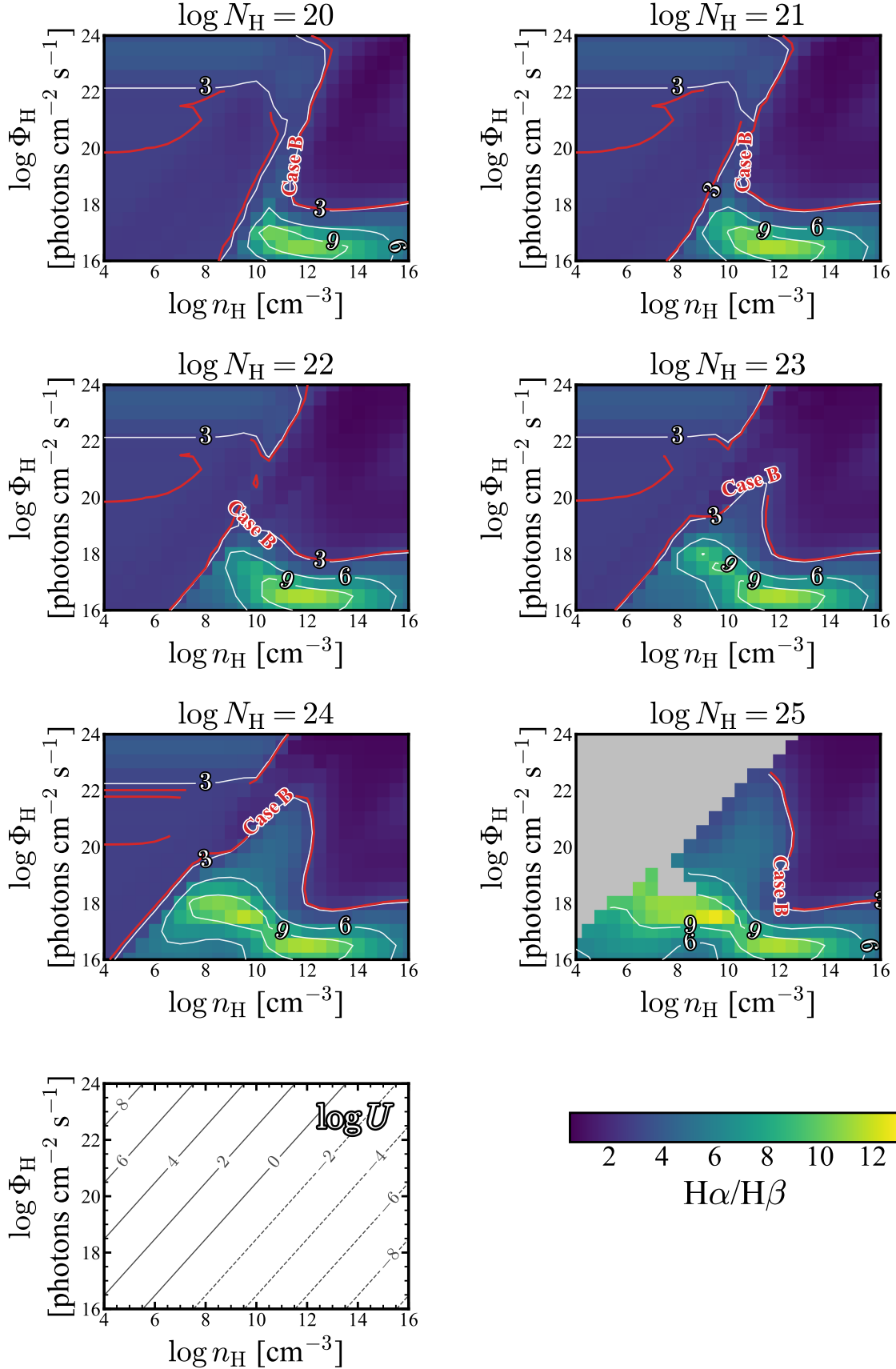


Figure A1. The model grids of the $\Phi(\text{H})$ – n_{H} plane for the $\text{H}\alpha/\text{H}\beta$ (see also K. T. Korista & M. R. Goad 2004; A. Schnorr-Müller et al. 2016). The color shows the $\text{H}\alpha/\text{H}\beta$ ratio obtained from the CLOUDY modeling. The white contours show $\text{H}\alpha/\text{H}\beta$ ratios of 3, 6, and 9. The red contours show the Case B intrinsic value ($= 2.87$). Each panel represents the different column density ($\log(N_{\text{H}}/\text{cm}^{-2}) = 20$ –25). The gray region is where the CLOUDY calculation fails to complete due to nonphysical conditions. The bottom left panel shows the corresponding ionization parameter $\log U$ for each $\log \Phi(\text{H})$ and $\log n_{\text{H}}$.

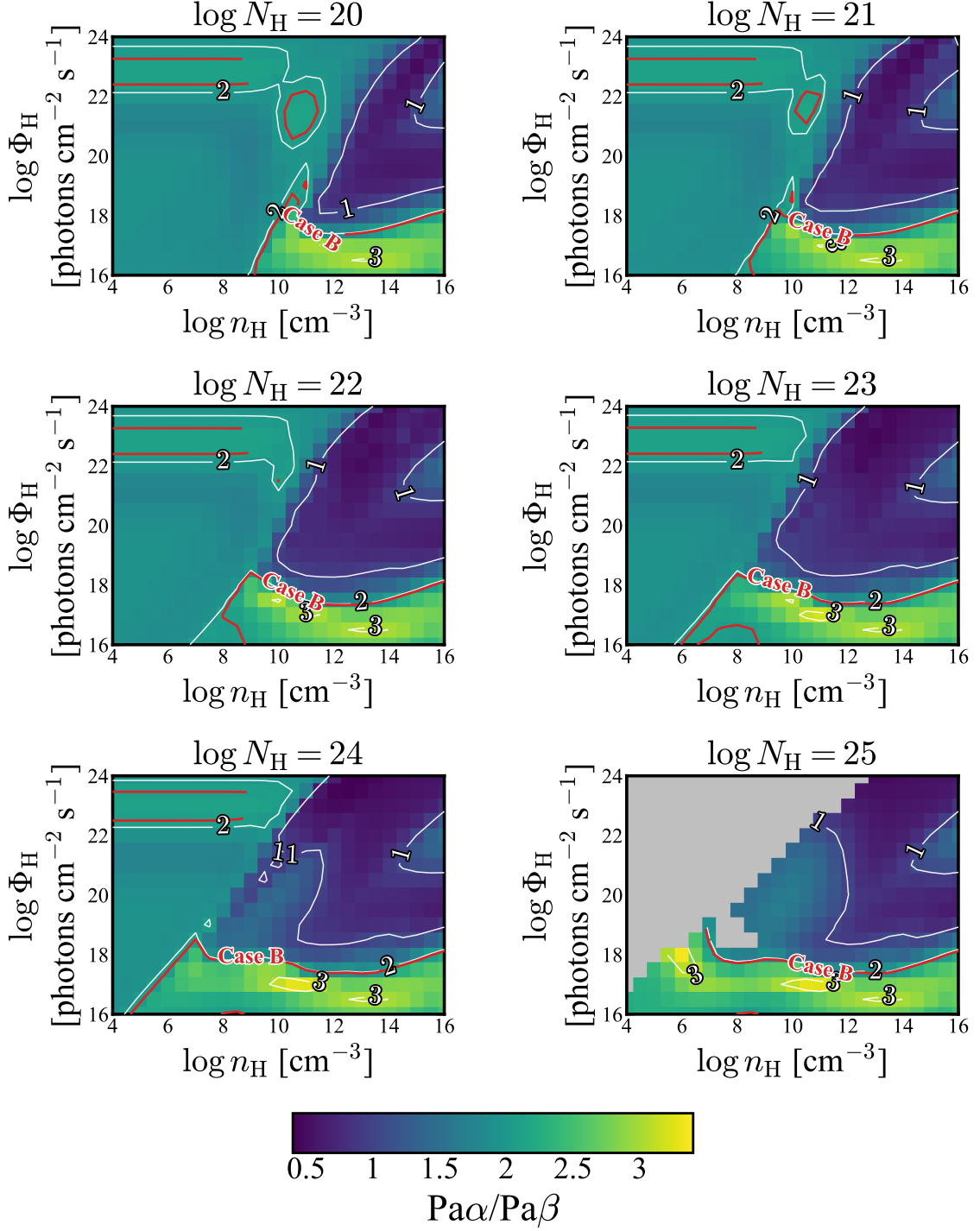


Figure A2. Same as in Figure A1, but for $\text{Pa}\alpha/\text{Pa}\beta$.

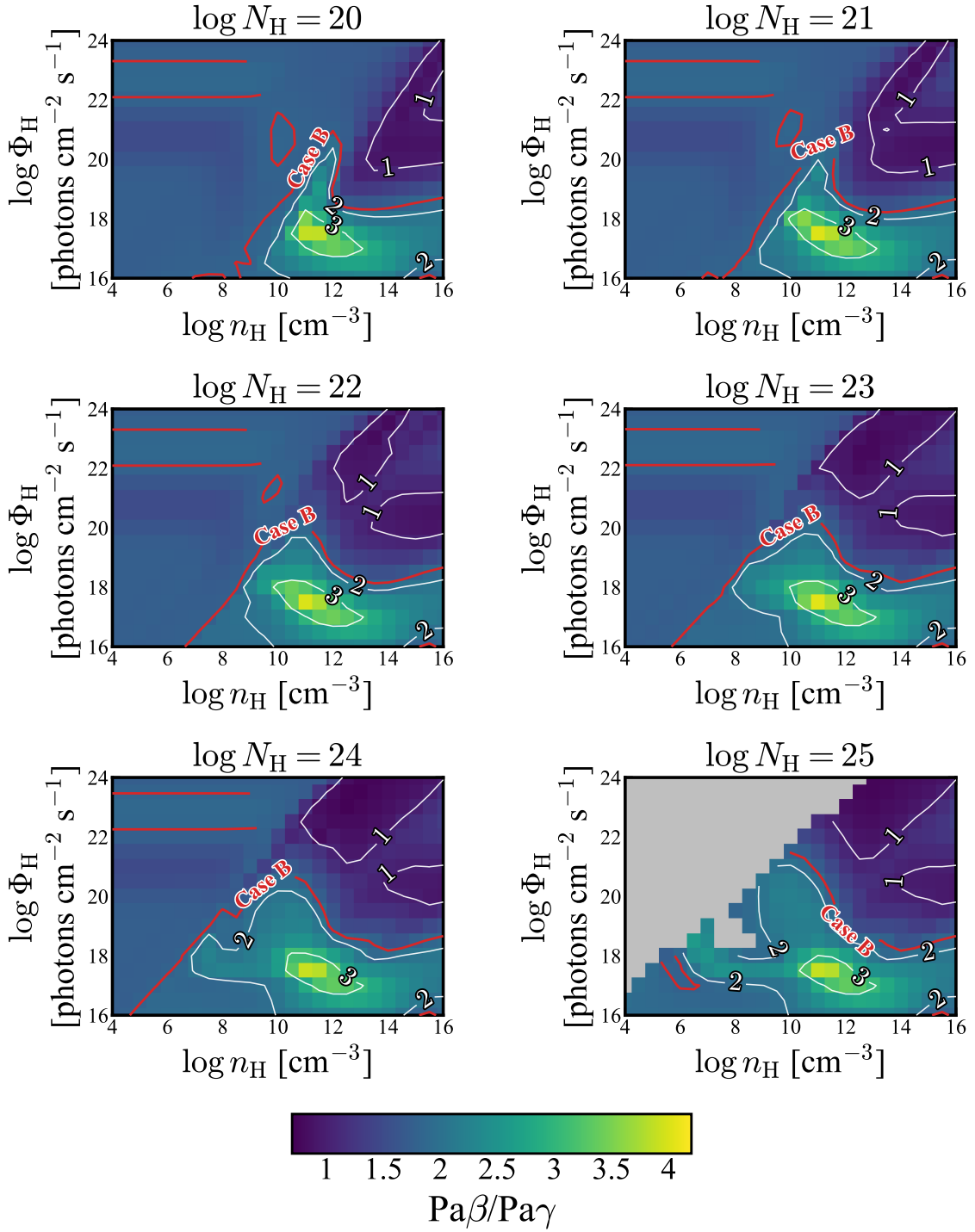


Figure A3. Same as in Figure A1, but for $\text{Pa}\beta/\text{Pa}\gamma$.

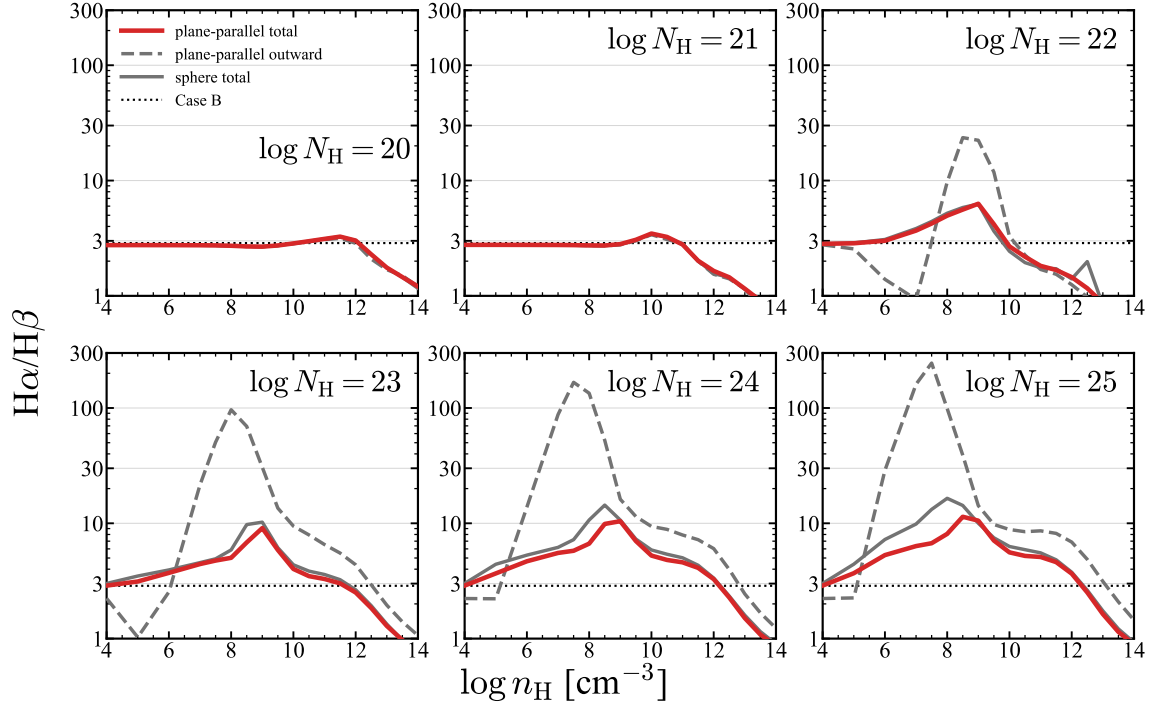


Figure B1. Cloudy predictions for the $H\alpha/H\beta$ line ratio as a function of hydrogen density, $\log n_H$, at $\log U = -1.48$ (the grid value closest to -1.5), metallicity of $Z/Z_\odot = 0.1$. The panels show the hydrogen column density, $\log N_H = 20$ – 25 from upper left to lower right. The red solid curves show the plane-parallel total line ratio, the gray dashed curves show the plane-parallel outward component, computed as total minus inward emission, and the gray solid curves show the spherical-model total line ratio. The black dotted line marks the Case B recombination value, $H\alpha/H\beta = 2.87$.

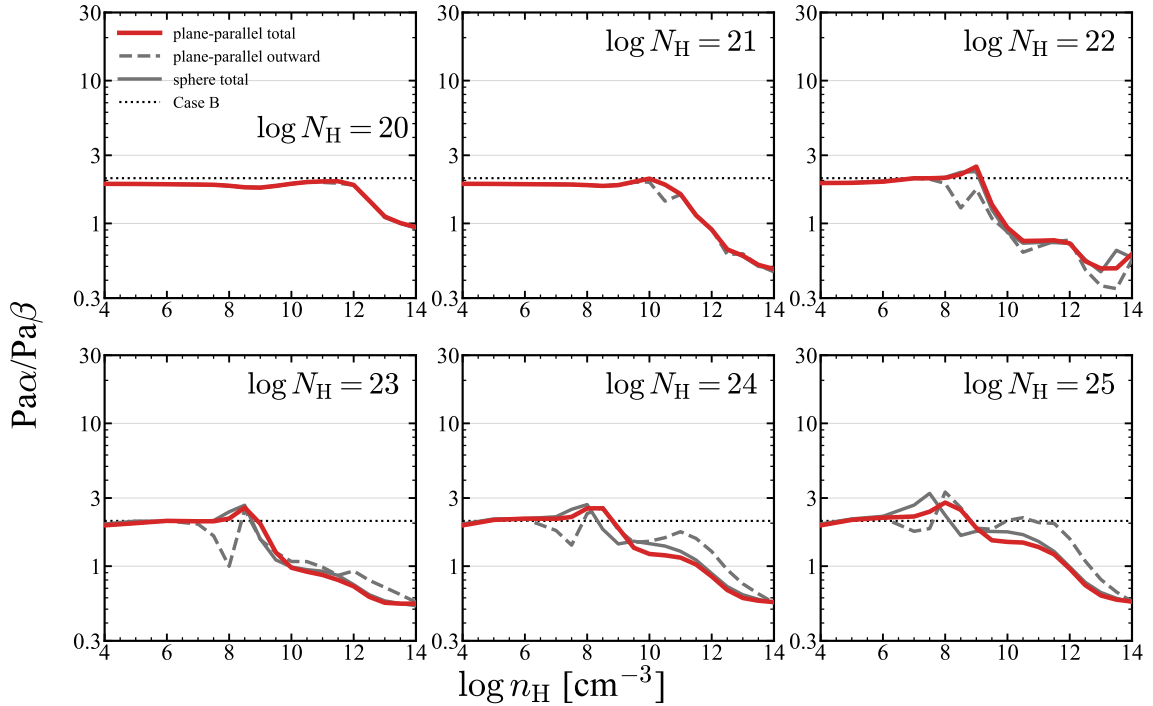


Figure B2. Same as in Figure B1, but for $Pa\alpha/Pa\beta$.

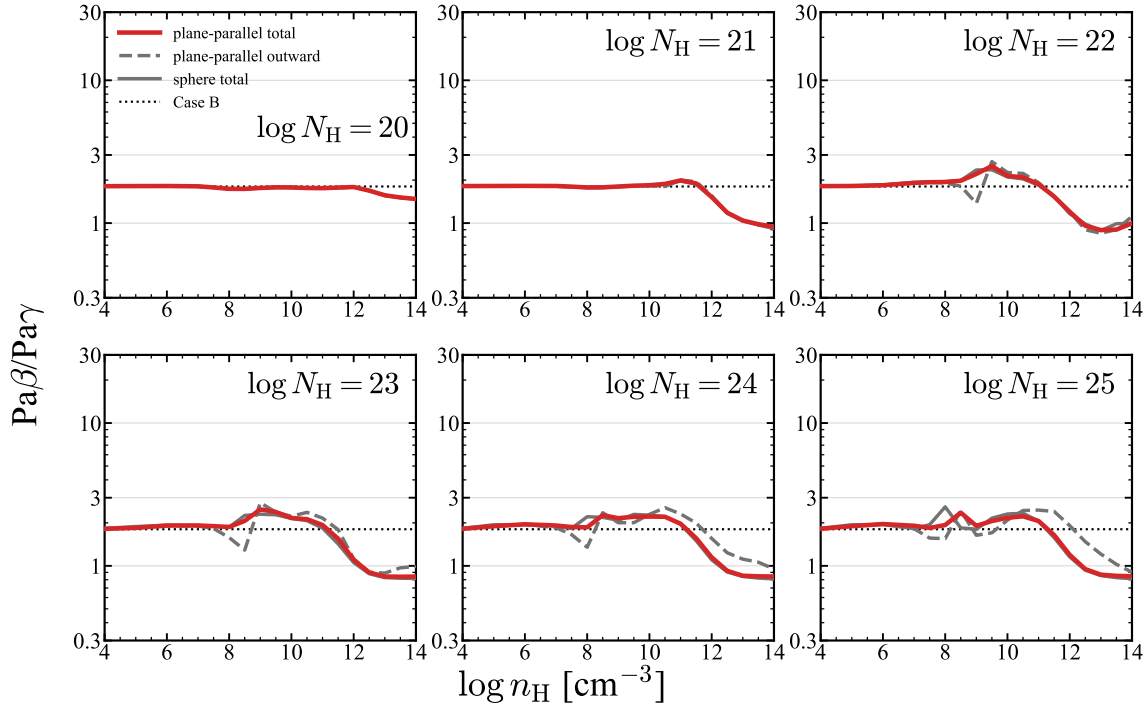


Figure B3. Same as in Figure B1, but for $\text{Pa}\beta/\text{Pa}\gamma$.

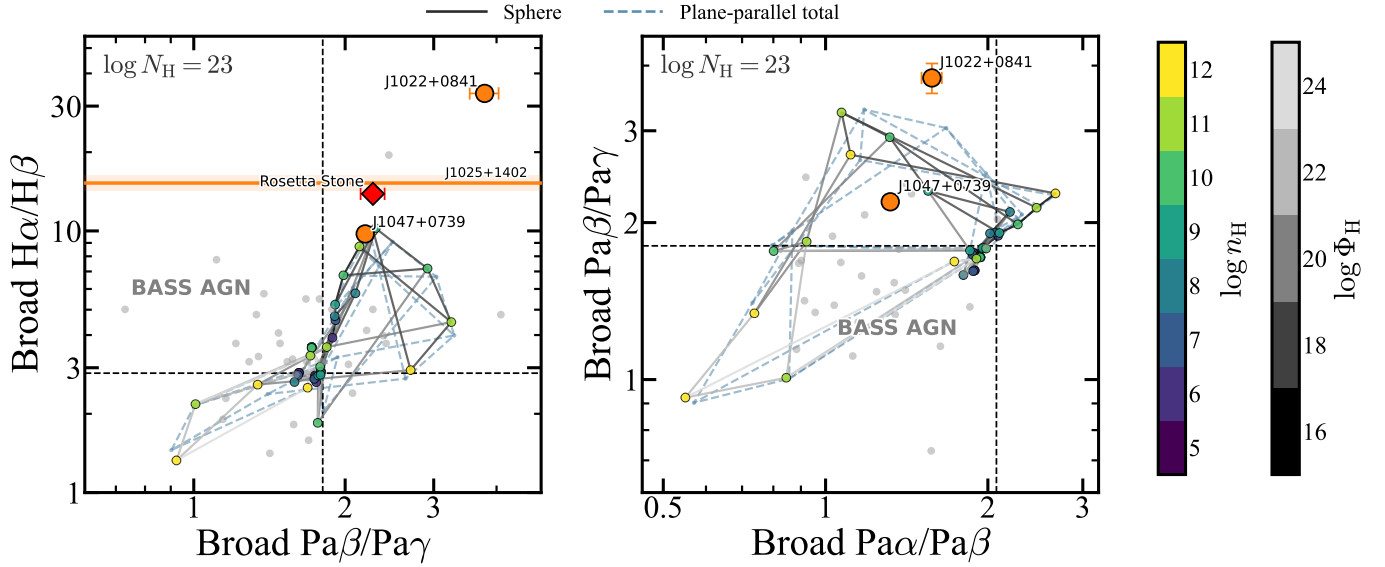


Figure B4. Same as in Figure 5 (left) and Figure 6 (right), but for the model grids of the sphere geometry. For reference, the model grids of the plane-parallel geometry are shown as the blue dashed lines. The other symbols are the same as in Figure 5 and Figure 6.

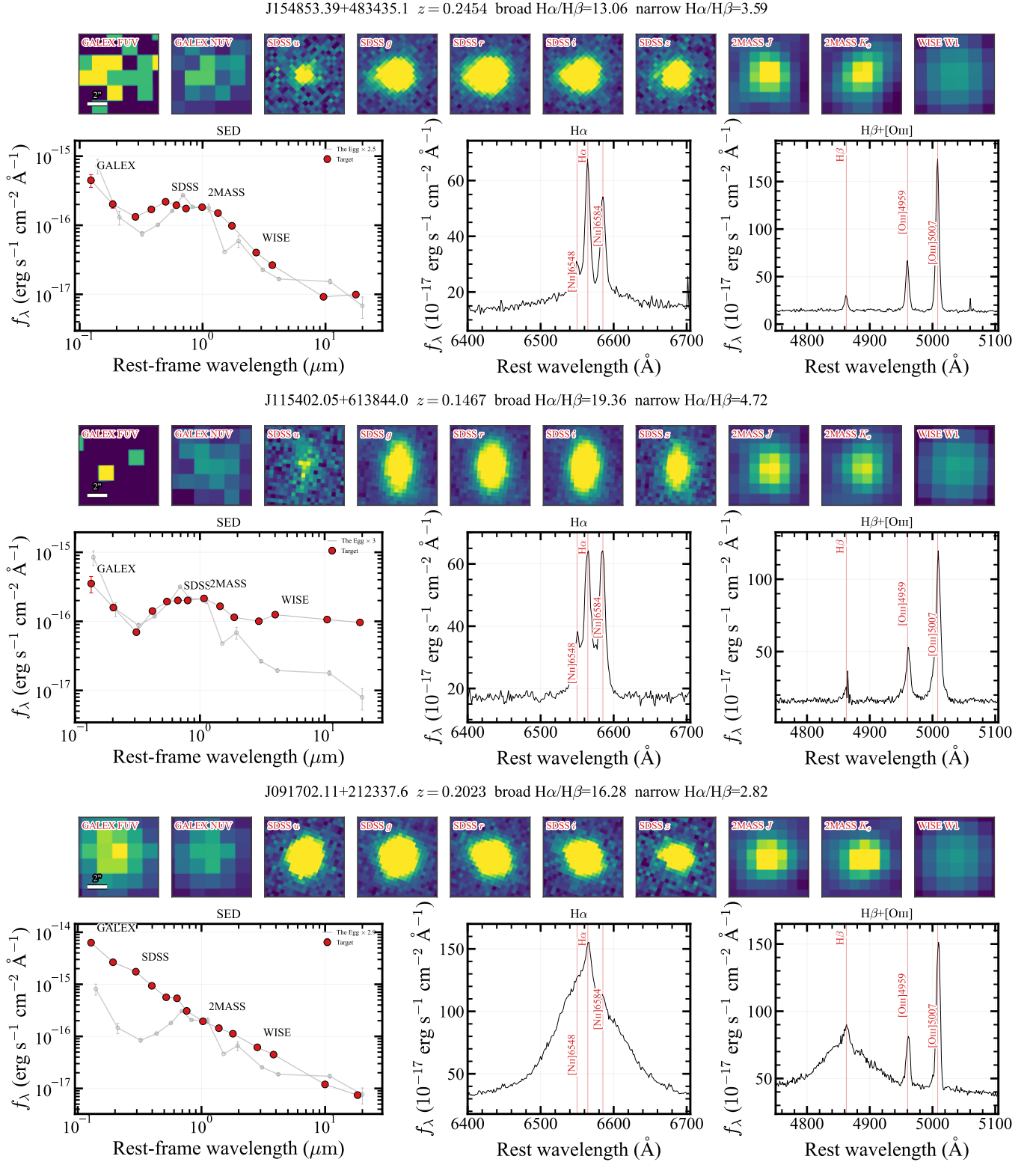


Figure C1. The representative SDSS extreme-decrement AGN candidates. For each object, the top row shows the imaging cutouts from the GALEX, SDSS, 2MASS, and WISE. The lower-left panel shows the SED. The red circles show the target photometry, while the gray symbols and curves show the SED of the local LRD “The Egg” (J1025+1402) scaled by the factor indicated in each panel. The lower middle and right panels show the SDSS spectra around the $H\alpha$ + $[N II]$ and $H\beta$ + $[O III]$ complexes, respectively. The vertical red lines mark the expected wavelengths of the indicated emission lines. The source name, redshift, and the broad and narrow $H\alpha/H\beta$ ratios from H.-Y. Liu et al. (2019) are listed above each panel.

candidates have V-shaped SEDs ($\sim 50/167$), similar to LRDs.

Most of them differ from high-redshift LRDs in some aspects. The SDSS sources often show strong [N II] $\lambda\lambda 6548, 6584$ emission, possibly reflecting different metallicities and/or ionization conditions. They may represent “high-metallicity LRDs” in a late evolutionary stage from the [N II] weak LRDs (see also W. Ding et al. 2026; L. Bao et al. 2026; L. Seyberlich & S. E. I. Bosman 2026, for other objects/samples that have the V-shaped

SEDs in the low-redshift Universe). Many show WISE variability in contrast to local LRDs (e.g., C. J. Burke et al. 2026). In addition, blue UV photometry can be affected by strong emission lines (e.g., A. Noboriguchi et al. 2022, for a DOGs study) and/or strong UV scattered light from AGNs. In any case, these objects would be valuable low-redshift comparison candidates, but establishing a physical or evolutionary connection with LRDs requires a detailed analysis, which we defer to future work.

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