

TBD LBD: The nature of ‘little blue dots’

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ABSTRACT

Previous *Sirocco* radiative-transfer models of gas-cocooned AGN predicted lower-column counterparts to little red dots (LRDs): compact, **X-ray-weak sources with bluer continuum slopes** and **Balmer jumps rather than Balmer breaks**. The recently identified population of little blue dots (LBDs) closely resembles this predicted phase. Here we explore these lower-column-density cocoons in which nebular recombination emission remains visible while strong Balmer-continuum absorption is avoided. We find that a sequence of increasing column density connects more classical AGN spectra, Balmer-jump LBD-like spectra at $N_{\text{H}} \sim \text{few} \times 10^{24} \text{ cm}^{-2}$, and Balmer-break LRD-like spectra at higher columns. In this sequence, electron scattering produces exponential line wings and suppresses X-ray emission before strong Balmer absorption features, characteristic of higher column densities, appear. We therefore propose that LBDs are lower-column analogues of LRDs within a common gas-cocooned AGN sequence. This interpretation predicts that Balmer-jump emission, X-ray weakness, permitted lines with exponential wings, He II $\lambda 4686$ emission, smaller H α FWHM values and equivalent widths than in LRDs, and weak or absent absorption features are characteristic of LBDs. We compare to three example LBD spectra and identify Balmer-jump signatures in them.

1. Introduction

An early phase of supermassive black hole (SMBH) growth buried in translucent and dense gas has been invoked to explain the *JWST* population of ‘little red dots’ (LRDs, Matthee et al. 2024). Notable signatures of the gas include continuum and line absorption from hydrogen gas in $n = 2$ (Setton et al. 2025; Inayoshi & Maiolino 2025; de Graaff et al. 2025b; Naidu et al. 2025; Torralba et al. 2026), deviations from ‘Case B’ line ratios (Nikopoulos et al. 2025; D’Eugenio et al. 2025; Torralba et al. 2025) and exponential wings indicative of an electron-scattering cocoon (Rusakov et al. 2026; Chang et al. 2026; Kokorev et al. 2025; Sneppen et al. 2026b; Matthee et al. 2026) that could be responsible for partially suppressing X-ray emission due to the Compton-thick gas (Maiolino et al. 2025; Comastri et al. 2026; Tortosa et al. 2026; Sneppen et al. 2026c). Self-consistent radiative transfer modelling of LRDs (Sneppen et al. 2026b) predicts a complementary population of lower-column cocooned AGN, which should be characterised by exponential line profiles and Balmer continuum emission (i.e. a Balmer jump as opposed to a break).

A high-redshift AGN population recently dubbed ‘little blue dots’ (LBDs, Brazzini et al. 2026) is distinguished by their blue rest-frame UV–optical continua, but, similar to LRDs, LBDs display compact morphologies, non-detection of X-rays, weak hot dust emission and exponential-shaped broad lines (Rusakov et al. 2026; Brazzini et al. 2026; Scholtz et al. 2026). This phenomenological overlap suggests that LBDs may represent a more weakly dust-reddened view of the same accretion phase due to orientation (Madau & Maiolino 2026), or they may be the lower-column cocooned AGN predicted by radiative transfer modelling of ionised gas cocoons (Sneppen et al. 2026b,a). A key distinction between the two hypothesised gas-cocoon regimes is the visibility of the Balmer jump emission. In the higher column density *Sirocco* models, with $N_{\text{H}} \sim 10^{25} \text{ cm}^{-2}$, strong nebular emission signatures are produced, including large H α equivalent

widths and a Paschen jump, but the associated Balmer jump is partly hidden by absorption in a partially neutral layer at larger radial distances (Sneppen et al. 2026a). This absorption in an outer layer produces the Balmer-continuum inflection and line absorption characteristic of LRDs. By contrast, the blue continua of LBDs suggest a more direct view of the Balmer-jump region, in which nebular recombination emission remains visible and without strong imprinted neutral absorption.

Here we investigate the lower-column, Balmer-jump phase of cocooned AGN and examine whether it can account for the emerging LBD population, focusing on their predicted continua, exponential broad-line wings, X-ray weakness, and connection to LRDs.

2. Methods

We model cocooned AGN using the Sobolev Monte Carlo code *Sirocco* (Long & Knigge 2002; Matthews et al. 2025), which follows photon propagation through multi-dimensional, optically thick flows and includes electron scattering, Sobolev line transfer, and bound-free processes. For a specified gas density and velocity structure, *Sirocco* self-consistently computes the radiation field and ionisation state, enabling predictions of continuum shapes, line profiles, line ratios and luminosities, and their correlations across the spectral energy distribution (SED) from X-rays through the near-infrared (Sneppen et al. 2026a,b,c).

The models considered here are cocoons with hydrogen column densities of $N_{\text{H}} \sim \text{few} \times 10^{24} \text{ cm}^{-2}$, sub-solar metallicity, $Z = 0.1 Z_{\odot}$, spatial scales $R \sim 10^{16}\text{--}10^{17} \text{ cm}$, characteristic velocities of $v \sim \text{few} \times 100 \text{ km s}^{-1}$, illuminated by a central blackbody source following the models in Sneppen et al. (2026b). Fig. 1 shows a spherical density-sequence (i.e. $N_{\text{H}} = (1\text{--}15) \times 10^{24} \text{ cm}^{-2}$, and irradiated with $T_{\text{BB}} = 30\,000 \text{ K}$), where an individual spectrum is further detailed in Fig. 2 with $N_{\text{H}} = 5 \times 10^{24} \text{ cm}^{-2}$. In Fig. 3, we employ a 2-dimensional model with a similar column density and inflows/outflows from Sneppen et al.

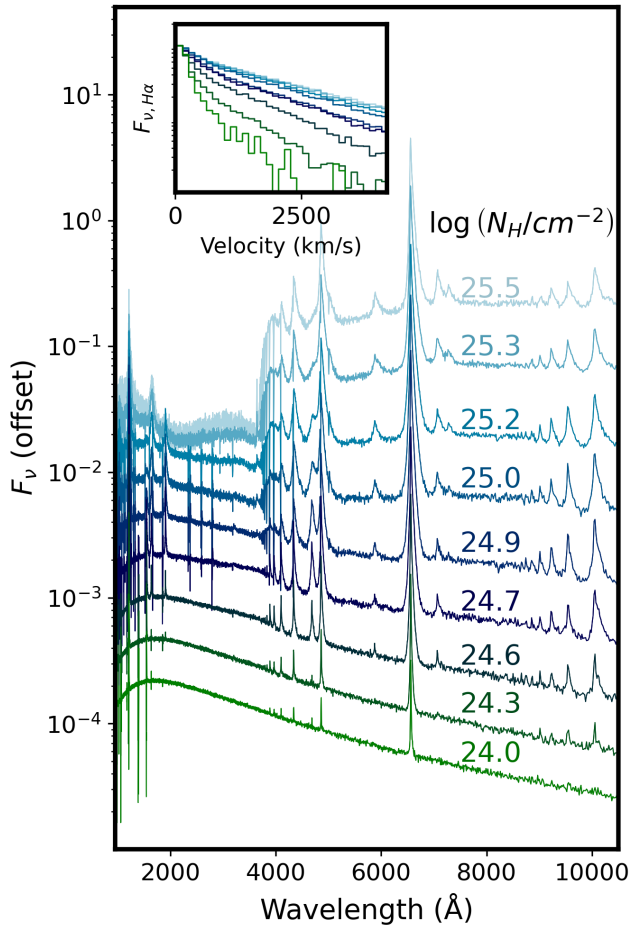


Fig. 1. Sirocco model sequence in column density, varying only N_H . Spectra are vertically offset for clarity. At low columns, $N_H \lesssim 10^{24} \text{ cm}^{-2}$, the emergent spectrum remains close to the assumed incident SED. At intermediate columns, $N_H \sim 10^{24.5} \text{ cm}^{-2}$, nebular Balmer-continuum emission produces LBD-like Balmer jumps. At higher columns, $N_H \sim 10^{25} \text{ cm}^{-2}$, neutral absorption produces LRD-like Balmer breaks. The inset shows the corresponding $H\alpha$ profiles, demonstrating that exponential electron-scattering wings arise across both the LBD-like and LRD-like column regimes, and grow wider with increasing column density in this regime.

(2026b). Here we also adopt a narrow-line Seyfert 1 input X-ray spectrum with $k_{\text{bol,X}} = L_{\text{bol}}/(L_{2-10\text{keV}}) = 50$ to examine Compton-thick X-ray suppression using the same Sirocco-based treatment as in Snejpe et al. (2026c). For Fig. 2 and Fig. 3, we convolve the model spectra to the observed spectral resolution and modestly modify the continuum UV-optical slope with reddening of $A_V = 1$ using a Calzetti attenuation prescription (Calzetti et al. 2000) without imposing the very steep far-UV suppression characteristic of the SMC extinction curve. This reddening is somewhat larger than, but of the same order as, that inferred for GS 3073 with $A_V \sim 0.4\text{--}0.5$ (Ji et al. 2024) and is consistent with the generally weak mid-infrared dust emission of the LRD class (Chen et al. 2025). The Fig. 1 sequence in column-density is attained by varying the local density n_H and not by changing the geometrical scale of the cocoon, while Figs. 4–5 illustrate independent variations of both local density and geometrical scale (e.g., n_H and N_H).

These model spectra are typical of this part of the simulation grid, rather than extreme cases. For these gas columns, the gas is moderately optically thick to electron scattering, while the par-

tially neutral absorbing layer remains weak enough that strong Balmer-continuum and Balmer-line absorption are avoided.

3. Results

At column densities lower than those required to model LRDs (see Fig. 1), Sirocco predicts a population of cocooned AGN with nebular emission signatures indicated by a Balmer jump (see Sect. 3.1), X-ray weakness from Compton-thick gas and non-Gaussian exponential wings of electron-scattering (see Sect. 3.2) and blue UV-optical spectra with higher-ionisation lines and without strong absorption signatures (see Sect. 3.3). We address each of these predictions in turn.

3.1. Balmer-jump emission from nebular recombination

Fig. 2 shows that both Sirocco model spectra and selected LBD observations display a continuum offset across the Balmer limit. We highlight this feature by fitting the continuum blueward of the Balmer edge and extrapolating the fit to longer wavelengths. In the right panel of Fig. 2, the spectra show a deficit redward of the edge, consistent with Balmer-jump emission from nebular recombination. The feature is not expected to be abrupt, because broad emission from high-order hydrogen lines smooths the continuum, similar to Paschen jumps in LRDs (Snejpe et al. 2026a). Notably, Fe II pseudo-continuum emission could in principle mimic a similar continuum offset (Ji et al. 2025); however, we find no direct evidence for the other Fe II line emission and the blue continuum often extends smoothly down to 2000 Å. To assess the prominence of the jump, the continuum blueward of H_∞ must be compared with that redward of $H\delta$ or $H\gamma$ (e.g. $F_V(\lambda = 4500 \text{ Å})/F_V(\lambda = 3400 \text{ Å})$). All three LBDs shown in Fig. 2 exhibit this Balmer-limit continuum offset with Nexus 5819 showing the most prominent and significant offset in both wavelength intervals (see Table 1).

3.2. A shared electron-scattering regime: Compton-thick X-ray suppression and exponential line wings

The presence of strong bound-free emission in LBDs and LRDs implies that a substantial ionised gas column exists around the central source. The same gas column both produces broad exponential-shaped line wings and suppresses X-ray emission, see Fig. 3. The fact that all available fitted broad $H\alpha$ lines in LBDs are better modelled with exponential profiles than by multiple Gaussians (e.g. Rusakov et al. 2026; Brazzini et al. 2026), in contrast to the general JWST/X-ray AGN population (e.g. Scholtz et al. 2026), provides strong evidence for an electron-scattering interpretation. This is further substantiated by the X-ray weakness of these objects, since such Compton-thick columns lead to significant X-ray suppression (e.g. see the modest dependence on break strength for low column density models in Fig. A1 of Snejpe et al. 2026c). Here, the left panel in Fig. 3 provides a consistency check: the column density regime that produces broad exponential $H\alpha$ wings also suppresses X-ray emission below current limits at $0.1 Z_\odot$. The dearth of X-ray emission in LBDs is therefore informative in the same sense as the X-ray weakness of LRDs (Maiolino et al. 2025; Comastri et al. 2026; Tortosa et al. 2026).

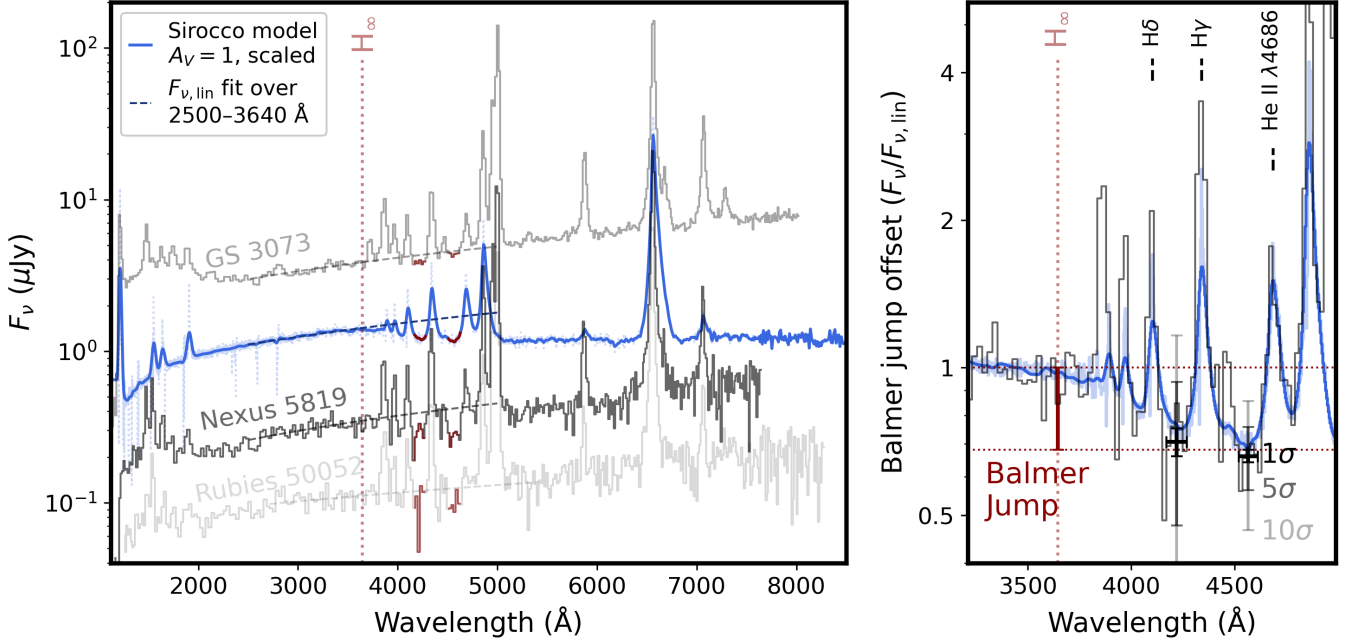


Fig. 2. Comparison of a lower column density Sirocco model spectrum to a set of three LBD spectra: GS 3073, Nexus 5819, and Rubies 50052. Left: UV and optical spectra with strong permitted H and He line emission. Right: zoom-in on the Balmer-limit region, where the same model and observed continua of Nexus 5819 show a Balmer-jump-like deficit redward of the Balmer limit. The spectra are divided by a continuum fit blueward of the Balmer edge, $F_{v,\text{lin}}$, to emphasize the continuum offset across $H_\infty = 3645$ Å. Within the wavelength-windows least affected by line emission in the model-space (highlighted with red), we show the mean observed flux-ratio with 1, 5 and 10σ uncertainty indicated, showing that the observed flux ratios are significantly below unity, as expected for a Balmer-jump offset.

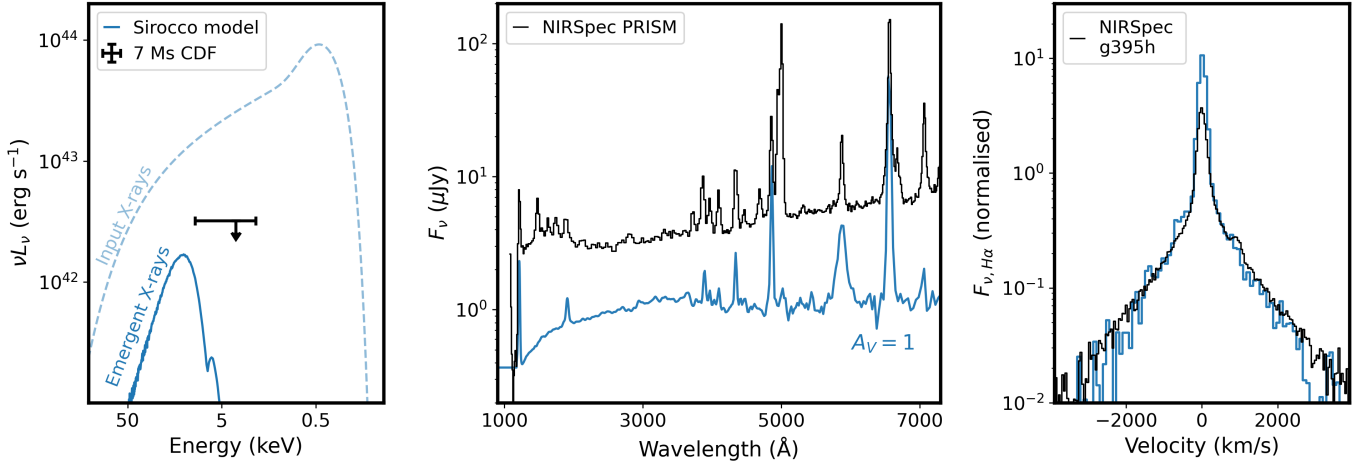


Fig. 3. Panchromatic comparison between a single Sirocco model and GS 3073 observational constraints (Übler et al. 2023). Left: Emergent X-ray spectrum compared with the intrinsic narrow-line Seyfert 1-like input template, assuming $k_{\text{bol,X}} = 50$, and with the 7 Ms Chandra Deep Field constraint (Maiolino et al. 2025). The Compton-thick cocoon suppresses the emergent X-ray luminosity below the observational limit. Centre: rest-frame UV–optical spectra, showing bound-free emission and strong recombination lines. Right: $H\alpha$ profile with broad symmetric exponential wings due to electron-scattering gas. The same electron-scattering column that suppresses the X-ray emission also broadens $H\alpha$.

3.3. Predicted properties of cocoon models displaying Balmer jumps

The lower column density cocoon models with Sirocco allow several observational predictions to be made for objects with Balmer jumps. First, like LRDs, they should have broad lines with exponential wings due to electron scattering. Second, they should have larger core-to-broad line component flux-ratios and smaller broad-component FWHMs compared to LRDs (see Fig. 1, inset panel). Third, strong H and He absorption should be weaker or absent in LBDs. These trends arise because, along the increasing-column sequence, a modest but appreciable electron-

scattering optical depth is reached before the partially neutral absorbing column becomes strong enough to imprint the characteristic LRD-like absorption spectrum. We note that the precise onset column density of absorption signatures depends on the ionisation structure of the cocoon. However, Fig. 4 shows that the emergence of the Balmer jump and the transition to Balmer breaks remain primarily organised by N_H , even when the density normalization and geometrical scale are varied independently. Across the model space we have not found model spectra with simultaneous Balmer jumps and Balmer-line absorption, suggesting such observational configurations should be rare.

Table 1. Continuum-normalised Balmer-jump offset measurements.

Object	Window (Å)	$\langle F_{\nu}/F_{\nu,\text{lin}} \rangle$	Significance (σ)
Nexus 5819	4180–4280	0.750 ± 0.027	9.1
Nexus 5819	4510–4630	0.661 ± 0.019	17.5
Nexus 5819	combined	0.690 ± 0.016	19.5
Rubies 50052	4180–4280	0.844 ± 0.133	1.2
Rubies 50052	4510–4630	0.783 ± 0.037	5.9
Rubies 50052	combined	0.787 ± 0.035	6.0
GS 3073	4180–4280	0.897 ± 0.010	10.3
GS 3073	4510–4630	0.957 ± 0.008	5.6
GS 3073	combined	0.935 ± 0.006	10.7

Notes. The offset significance is calculated as $(1 - \langle F_{\nu}/F_{\nu,\text{lin}} \rangle) / \sigma_{\langle F_{\nu}/F_{\nu,\text{lin}} \rangle}$. For the individual wavelength windows, the uncertainty on the mean is estimated from the scatter of the continuum-normalized flux values divided by $\sqrt{N}$. The combined values are inverse-variance weighted averages of the two windows for each object.

As a consequence of the limited absorption, these predicted Balmer-jump objects should display intrinsically blue spectra, with blue slopes in both the UV and optical. This naturally matches the colour-space suggested for LBDs (see Fig. 5). While dust attenuation can redden both the UV and optical continua, increasing gas column density predominantly reddens the optical spectrum.

The Sirocco models allow additional LBD predictions to be made, which are more parameter-dependent than those indicated above. Because lower column density cocoons transmit more of the intrinsic optical continuum, $H\alpha$ is less tightly coupled to the underlying continuum and its equivalent width is reduced relative to more nebular-dominated LRD-like models (e.g., Fig. 1). If the parts of the gas experiencing a harder ionising field are no longer obscured, higher-ionisation lines in the UV and optical could become visible. For instance, $\text{He II } \lambda 4686/H\beta$ increases as we move from LRD columns to LBD columns in Fig. 1. Indeed, such high-ionisation emission lines have, for instance, been reported in GS 3073 (e.g. Übler et al. 2023; Ji et al. 2024) and their detection/limits are likely informative (e.g., Lambrides et al. 2026; Ando et al. 2026). The model spectra also predict broad $\text{Ly}\alpha$ emission from the cocoon itself (e.g. Figs. 1–3), a feature also expected in the higher column density Sirocco cocoon models (Sneppen et al. 2026b) and in observations of LRDs (Ji et al. 2026a,b; Tang et al. 2026). However, given the Sobolev approximation assumed in Sirocco and without a dedicated $\text{Ly}\alpha$ radiative-transfer code, we do not attempt to quantify the emergent line shape here.

4. Discussion

In Sneppen et al. (2026b), we showed that a range of column densities in AGN cocoons predicts a sequence in Balmer continuum emission/absorption, while the various outflows and inflows observed in individual objects could be explained with viewing-angle effects. A different orientation-based interpretation has recently been proposed by Madau & Maiolino (2026), in which LRDs are the dust-reddened, high-inclination counterparts of intrinsically blue compact broad-line AGN, or LBDs, powered by super-Eddington accretion. In their model, a geometrically thick accretion flow produces an anisotropic, blue ionising continuum, with self-shadowing suppressing the blue continuum along equatorial sightlines. Both interpretations connect LBDs and LRDs within one rapidly accreting AGN population.

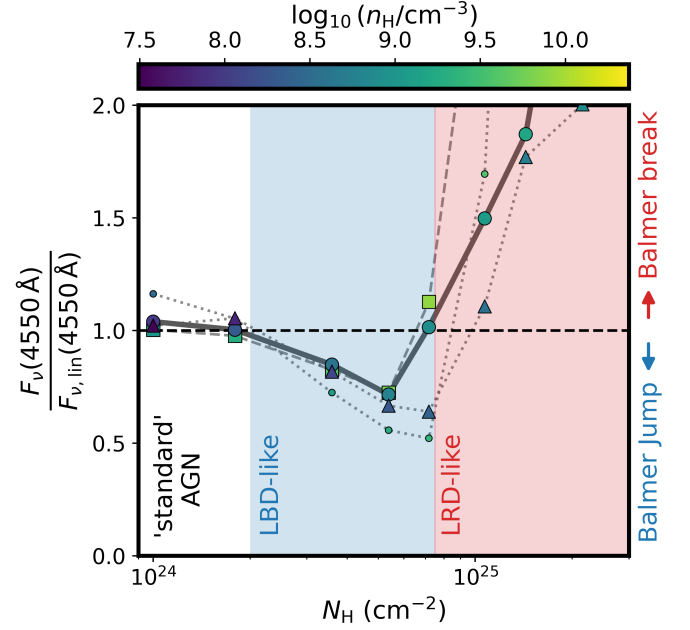


Fig. 4. Balmer break/jump strength versus N_H for various Sirocco density-sequences (solid curve is sequence shown in Fig. 1). Values below unity indicate a Balmer jump, while values above unity indicate a Balmer break. The colorbar highlights the cocoon density, n_H , at the inner boundary. Intermediate columns, $N_H \in (2 - 7) \times 10^{24} \text{ cm}^{-2}$, produce LBD-like Balmer jumps, whereas higher columns can produce LRD-like Balmer breaks.

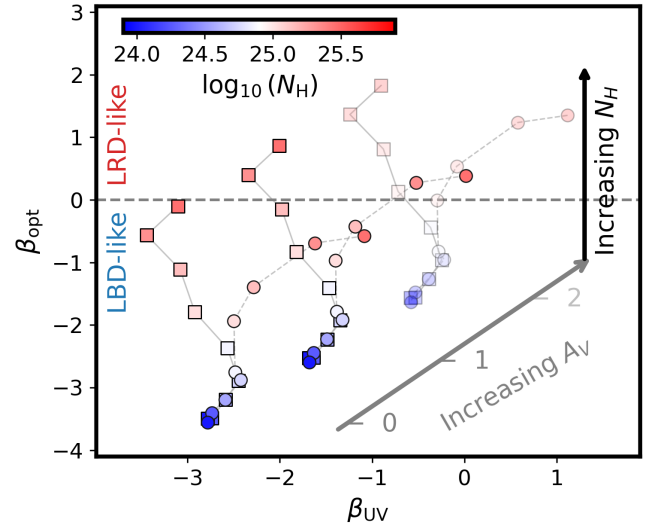


Fig. 5. Sirocco model spectra optical (β_{opt}) versus UV (β_{UV}) continuum slopes. The slopes β_{UV} and β_{opt} are measured using the rest-frame continuum windows in Brazzini et al. (2026) (i.e., 2160–3100 Å for β_{UV} and 5360–6270 Å for β_{opt} , masking Mg II , $\text{He I } \lambda 5876$). Circles and squares show two cocoon density-sequences starting at 10^{16} cm^{-2} and 10^{17} cm^{-2} , respectively. The dividing line highlights regions associated with LBDs and LRDs, where the predicted Balmer jump Sirocco models from Fig. 4 naturally inhabit this LBD color-space.

The distinction is that Madau & Maiolino (2026) attribute the colour sequence primarily to orientation and self-shadowing in a thick accretion flow, whereas here the controlling parameter is the gas column through an electron-scattering cocoon. In our model, lower columns show recombination continua and LBD-like Balmer jumps, whereas higher columns introduce LRD-like Balmer-continuum and line absorption (see Fig. 4). In this pic-

ture, LRDs and LBDs are not separate physical classes, but may instead trace different column densities, perhaps due to evolutionary stage, of dense gas surrounding rapidly growing black holes.

Brazzini et al. (2026) identify GS 3073 as a prototypical LBD and highlight properties shared by LBDs and LRDs, including compact morphologies, X-ray weakness and non-Gaussian broad Balmer-line profiles, which are all properties predicted for lower-column analogues of LRDs as shown here. GS 3073 differs from LRDs in the lack of strong Balmer absorption and in having prominent $\text{He II } \lambda 4686$ emission. This He II emission has a line component broader than $\text{H}\alpha$. In the picture developed here and explored with Sirocco, these differences are naturally associated with lower-column densities through the cocoon (see Fig. 2): the Balmer recombination continuum remains visible, strong neutral absorption is avoided, and He II emission for the more translucent gas can perhaps emerge. These higher-ionisation lines are broader than the hydrogen lines because they arise preferentially in the innermost parts of the cocoon (e.g. Chang et al. 2026). Thus GS 3073 provides a useful test because it exhibits both the LBD phenomenology emphasised by Brazzini et al. (2026) and the Balmer-jump behaviour predicted for the low-column extension of cocooned AGN models.

In this paper we have made a qualitative comparison to LBDs in general using a few well-known LBD spectra to illustrate the point. This is because full Monte Carlo radiative-transfer calculations are computationally expensive, with a Sirocco spectrum requiring of order 10^2 CPU hours, so we have focused here on presenting the general features and predictions of lower column density cocoon models. The natural next step – extracting physical parameters by detailed model inference with LBD spectra, i.e. fitting individual LBD spectra, as well as comparing the population predictions against upcoming and future LBD samples – will be addressed in future work.

5. Conclusions

Sirocco radiative transfer modelling, previously applied to LRDs, predicts a population of lower-column cocooned AGN, which are characterised by i) blue UV-optical colours, ii) compactness, iii) X-ray weakness, iv) exponential broad lines and v) Balmer-jump emission. Their broad permitted hydrogen lines should have narrower FWHM values, smaller equivalent widths, and more emission should escape in the ‘core’ unscattered component relative to LRDs. Unlike their LRD counterparts, they should not be characterised by strong absorption signatures and they can include higher-ionisation lines such as $\text{He II } \lambda 4686$. We suggest that the emerging population of little blue dots may correspond to this lower-column counterpart of LRDs. The LBD spectra highlighted here already show several of these predicted properties, and larger samples will provide a direct test of this interpretation.

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¹ <https://github.com/sirocco-rt/sirocco>

² <https://dawn-cph.github.io/dja>