

The ESO SupJup Survey

X. A carbon isotope contrast in the young ROXs 12 system

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ABSTRACT

Context. Emerging research suggests that elemental and isotopic ratios of exoplanet and brown dwarf atmospheres may serve as potential tracers of their formation pathways. The ESO SupJup Survey aims to shed light on this hypothesis, with a focus on the $^{12}\text{CO}/^{13}\text{CO}$ ratio, by investigating the atmospheric composition of substellar companions and isolated brown dwarfs.

Aims. In this work, we aim to characterize the atmospheres and determine the ratios of $^{12}\text{CO}/^{13}\text{CO}$ of the Rho Ophiuchus X-ray source (ROXs) 12 system (~ 6 Myr), consisting of an M0 host with an L0 companion, as part of the ESO SupJup survey. This system provides a great opportunity to directly compare the atmospheric compositions of the host star and its companion.

Methods. Using high-resolution CRIRES+ K band spectra of these objects, we perform atmospheric retrieval analyses to derive their atmospheric properties, including the $^{12}\text{CO}/^{13}\text{CO}$ ratio. Our retrieval framework is built on the radiative transfer code `petitRADTRANS`, with which we generate model spectra based on equilibrium chemistry tables computed with `FastChem`, coupled with the nested sampling algorithm `PyMultiNest`.

Results. We report the presence of H_2O , ^{12}CO , ^{13}CO , and HF in both the star and companion, with a tentative detection of H_2^{18}O in ROXs 12B. The $^{12}\text{CO}/^{13}\text{CO}$ ratios of the two objects show a measurable, though not strongly significant, difference, namely 77_{-7}^{+10} and 55_{-7}^{+10} for ROXs 12A and B. Both are consistent with the local present interstellar medium. We measure a C/O ratio of 0.54 ± 0.01 and obtain a lower limit of $\text{H}_2^{16}\text{O}/\text{H}_2^{18}\text{O} \gtrsim 300$ for ROXs 12B, while the C/O ratio of the star is not reliably constrained due to the absence of atomic oxygen lines in the K band. The companion also appears to exhibit a more isothermal temperature structure than expected from models. Furthermore, we retrieve moderate veiling in the host star of $r_k = 0.17_{-0.03}^{+0.02}$.

Conclusions. Systems such as ROXs 12, in which both star and planet can be chemically and isotopically characterized, are crucial for constraining potential formation mechanisms of massive, wide-orbit super-Jupiters. The differing $^{12}\text{CO}/^{13}\text{CO}$ ratios in the ROXs 12 system highlight the need for a broader sample to assess the frequency of isotopic variations and whether they may be linked to formation history.

Key words. techniques: spectroscopic – stars: atmospheres – brown dwarfs

1. Introduction

Directly imaged substellar companions, which range from planets to brown dwarfs at distances of up to hundreds of AU, provide very favorable conditions for atmospheric studies. Although the sample size of these objects is currently rather small, the number of discoveries has been steadily increasing in the last decade (e.g., Deacon et al. 2016; Kuzuhara et al. 2022). Of these widely separated companions, planetary-mass objects have been argued to form in the disk via core accretion closer to the star and eventually become scattered to larger separations (Boss 2006). However, the formation mechanisms of more massive substellar companions, such as giant exoplanets and companion brown dwarfs, are less clear (Bergin et al. 2024). They may also form through cloud collapse and fragmentation

(Boss 2001; Bate 2009), or instabilities in massive protoplanetary disks (Boss 1997; Kratter & Lodato 2016). In this regard, investigating atmospheric tracers is crucial for understanding and possibly distinguishing between these different formation processes.

The composition, climate, and chemical and physical processes of exoplanets and brown dwarfs are encoded within their atmospheric spectra. Since the chemical composition of solids and gases is expected to depend on their birth environment, the chemical constituents of these objects could reveal their formation and evolutionary pathways (Turrini et al. 2021; Pacetti et al. 2022). Formation tracers include elemental ratios such as C/O (e.g., Öberg et al. 2011) and isotope ratios such as D/H and $^{12}\text{C}/^{13}\text{C}$ (e.g., Morley et al. 2019; Mollière & Snellen 2019). For example, objects that formed via gravitational collapse are thought to retain the $^{12}\text{C}/^{13}\text{C}$ ratio of their parent cloud (Öberg & Bergin 2021), which is expected for isolated brown dwarfs

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and stars (Bate et al. 2002). Conversely, objects that formed by core accretion are believed to inherit the $^{12}\text{C}/^{13}\text{C}$ ratio of local disk solids, which can vary throughout the disk due to isotope fractionation processes (Visser et al. 2009; Yoshida et al. 2022).

To disentangle the formation pathways of super-Jupiters, substellar companions, and isolated brown dwarfs, the atmospheric properties of a large sample of these objects are analyzed as part of the ESO SupJup survey (Program ID: 1110.C-4264, PI: Snellen, de Regt et al. 2024). High-resolution K band and some J band spectra of 19 isolated objects, 19 lower-mass companions, and 11 hosts were obtained with the upgraded CRYogenic high-resolution InfraRed Echelle Spectrograph (CRIRES+) on the Very Large Telescope (VLT) at the Paranal Observatory in Chile (e.g., Kaeufl et al. 2004; Follert et al. 2014; Dorn et al. 2014). This work is part of the ongoing analysis of the data obtained throughout the survey, with the aim of characterizing the Rho Ophiuchus X-ray source (ROXs) 12 system, which consists of a stellar host and a substellar companion.

The star ROXs 12 was first discovered by Montmerle et al. (1983) during a study of the ρ Ophiuchus star-forming region. Bouvier & Appenzeller (1992) determined that it is a very young M0 star, with its position in the Hertzsprung-Russell diagram indicating a subsolar mass and an age of a few Myr. While conducting a stellar multiplicity survey, Ratzka et al. (2005) identified a widely separated candidate companion for ROXs 12. This companion, denoted ROXs 12B, was finally confirmed years later by Kraus et al. (2014), located at a separation of $1.7''$ from its host star. ROXs 12A appears to host a passive disk with no signs of accretion, and ROXs 12B likewise shows no evidence for active accretion, as indicated by the absence of Pa β emission (Bowler et al. 2017). This is consistent with the non-detection of submillimeter continuum emission at 0.88 mm at the location of the companion (Wu et al. 2020), which rules out the presence of a massive dust disk. Furthermore, the spectrum of ROXs 12B exhibits indications of low surface gravity (Bowler et al. 2017), such as shallower KI doublets and reduced FeH absorption (Allers & Liu 2013). Using high-resolution spectroscopy from the Keck Planet Imager and Characterizer, Xuan et al. (2024a) find values of $\text{C}/\text{O} = 0.54 \pm 0.05$, a $0.5^{+0.4}_{-0.2} \times$ solar metallicity ($[\text{C}/\text{H}] = -0.30^{+0.26}_{-0.22}$, assuming a clear atmosphere), and $^{12}\text{CO}/^{13}\text{CO} \sim 100$ for ROXs 12B, though the detection significance for the latter is below 3σ . For ROXs 12A, Swastik et al. (2021) report a metallicity of $[\text{Fe}/\text{H}] = 0.14 \pm 0.01$. The main properties of ROXs 12A and B are summarized in Table 1.

In this work, the atmospheres of the stellar host and brown dwarf companion in the ROXs 12 system are analyzed. We apply an atmospheric retrieval framework to their observed high-resolution spectra to infer their atmospheric properties. The observational setup and spectral extraction are outlined in Section 2. Section 3 describes our applied retrieval framework, which encompasses atmospheric modeling and application of a nested sampling tool. In Sections 4 and 5, we report and discuss our findings, concluding our work in Section 6.

2. Observations

We obtained high-resolution K band spectra of the ROXs 12 system on March 5, 2023, with the CRIRES+ instrument on the VLT. A slit width of $0.4''$ was used, with both ROXs 12A and ROXs 12B being observed simultaneously. The observations were carried out in the K2166 wavelength setting, covering the wavelength range of 1.92 to 2.48 μm . The total exposure time of 3 h 40 min was split into 22 exposures of 600 s each, utilizing an ABBA nodding sequence with a $4.5''$ nod throw along

Table 1. Properties of the ROXs 12 system from the literature.

Parameter	ROXs 12A	ROXs 12B
Spectral type	M0 ^(a)	L0 ^(a)
Mass	$0.65^{+0.05}_{-0.09} M_{\odot}$ ^(a)	$17.5 \pm 1.5 M_{\text{Jup}}^{\text{(a)}}$
Semi-major axis (AU)	–	$210 \pm 20^{\text{(b)}}$
Separation ($''$)	–	$1.7^{\text{(b)}}$
Distance (pc)	$138.6 \pm 0.3^{\text{(c)}}$	
RA, Dec (ICRS, J2000)	$16:26:28.0397, -25:26:47.7175^{\text{(c)}}$	
Radial velocity (km/s)	$-5.8 \pm 1.9^{\text{(d)}}$	–
Rotational velocity (km/s)	$7.21 \pm 0.07^{\text{(d)}}$	$3.6^{+1.2}_{-1.6}^{\text{(e)}}$
Age (Myr)	$6^{+4}_{-2}^{\text{(a)}}$	
K_s (mag)	$9.10 \pm 0.03^{\text{(a)}}$	$14.14 \pm 0.03^{\text{(a)}}$
[Fe/H]	$0.14 \pm 0.01^{\text{(f)}}$	$-0.30^{+0.26}_{-0.22}^{\text{(e)}}$
Effective temperature [K]	$3850^{+100}_{-70}^{\text{(b)}}$	$2500 \pm 140^{\text{(e)}}$

Notes. ^(a)Bowler et al. (2017), ^(b)Kraus et al. (2014), ^(c)Gaia Collaboration (2020), ^(d)Bowler et al. (2023), ^(e)Xuan et al. (2024a), ^(f)Swastik et al. (2021).

Table 2. Setup and conditions during the observation of the ROXs 12 system.

Observation date	2023-03-05
Wavelength setting	K2166
Slit width ($''$)	0.4
Exposure time	3 h 40 min
Seeing ($''$)	0.8 ± 0.07
Airmass	1.7–1.0
Integrated water vapor (mm)	7.99 ± 0.21
Resolution	60 000

the slit. No adaptive optics were used due to high humidity, with the integrated water vapor being 7.99 ± 0.21 mm on average during our observations. The observing conditions were relatively stable, with an average seeing of $0.8 \pm 0.07''$, although the air mass changed considerably from 1.7 at the beginning to 1.0 at the end of the observations. Table 2 lists the main parameters of our observing setup and conditions. To help remove the atmospheric features of Earth from our data, the telluric standard star *i* Sco was observed immediately before ROXs 12, at an air mass of roughly 1.9–1.8.

The observations were reduced using *excaliburr*¹ (Zhang et al. 2024), a Python package for reducing CRIRES+ spectroscopy implementing methods from Holmberg & Madhusudhan (2022) and *pycrires* (Stolker & Landman 2023). The pipeline includes flat-fielding the exposures to account for pixel-to-pixel variations, tracing the spectral orders as well as their curvature, extracting the blaze function, and removing the sky background through nodding pair subtraction. We used the wavelength solution of the standard star as our initial wavelength grid for the data. To obtain the spectra, we applied the optimal extraction methodology from Horne (1986) using a Gaussian spatial profile. The extraction ranges were chosen to obtain a favorable balance between the S/N and contrast. We find that using a narrower extraction range for the companion is essential to avoid contamination from the star. Modest changes in the extraction apertures do not significantly

¹ <https://github.com/yapenzhang/excaliburr>

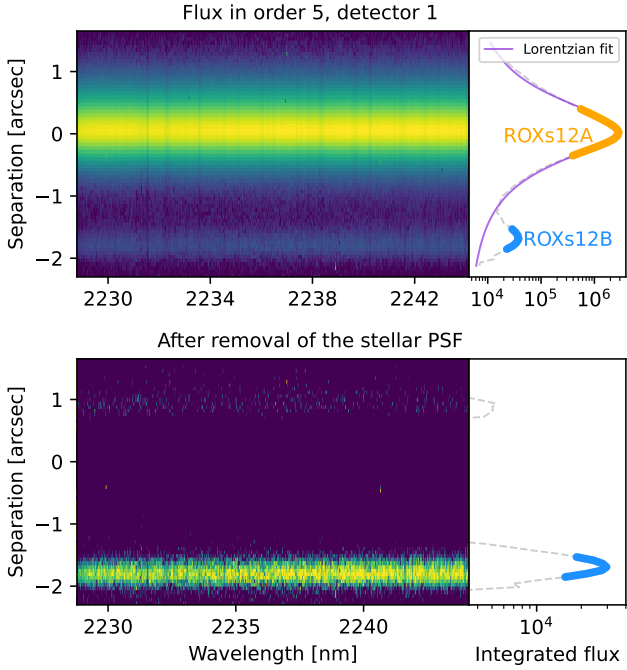


Fig. 1. Calibrated observational data of order 5, detector 1, nodding position A. The x -axis on the left panels shows the wavelength in nanometers, while the separation from the star in arcseconds is shown on the y -axis. The bright signal in the center is the star ROXs 12A. Its companion ROXs 12B is seen as the faint source at -1.7 arcsec. The integrated flux as a function of the separation is shown in the right panels, where the extraction range of the star and companion are highlighted. The Lorentzian fit to the stellar PSF is shown in purple, which is used to remove the starlight, as shown in the bottom panel.

affect the spectral shape or line depths, as the companion signal is dominated by the central pixels of the point spread function (PSF), while the wings contribute little additional information but increase noise and potential contamination. We set a half-aperture of 5 pixels for ROXs 12A and 3 pixels for ROXs 12B, corresponding to $0.295''$ and $0.177''$ on the sky.

The top left panel of Figure 1 shows a section of the calibrated observations of the ROXs 12 system. The bright central signal is from the host star, while the fainter signal below is from the companion. Telluric absorption features can be seen as vertical lines. To remove the starlight for the extraction of the companion, we found that a Lorentzian fit was best able to reproduce the stellar PSF at the position of the companion. We fit a Lorentzian profile to the host star’s integrated flux in each order-detector pair, which we use to scale and subtract the stellar spectrum accordingly. The integrated flux in the top right panel of Figure 1 highlights the extraction range (central index with the half-aperture extent) of the star and companion in their corresponding colors, along with the Lorentzian fit to the stellar PSF. In the bottom panel, we show the flux after removal of the stellar PSF.

The extracted spectra have a median per-pixel S/N of approximately 13 for the companion star and 112 for the host star at 2345 nm. We refined the wavelength solution using the wavelength optimization routine from `excalibuhr`, which adjusts the wavelength solution through a quadratic polynomial correction, obtained by maximizing the cross-correlation functions between the data and a telluric template. Only minor corrections up to ± 0.003 nm, corresponding to 0.4 pixels, were required, which is well below one resolution element. Before combining the spectra

extracted from the individual nodding positions, we divided each order-detector pair by the corresponding blaze function extracted with `excalibuhr`. Furthermore, we identified $\lesssim 100$ problematic pixels by taking the difference between the two nodding positions, which reveals outliers that occur only in one nodding position, such as cosmic rays. As the detector edges tend to be more problematic, we also masked the first and last 10 pixels of each detector. We then combined the spectra of the two nodding positions by interpolating the flux of nodding position B onto the wavelength grid of nodding position A and subsequently adding them.

To fit the telluric features of Earth’s atmospheric transmission, we applied the software `Molecfit` (Smette et al. 2015) to the observations of the standard star, which generates a synthetic telluric model based on the atmospheric conditions. Dividing our data by this model yields the final telluric-corrected spectra. Due to the significant changes in air mass during our observations, tellurics are particularly challenging to accurately correct for. Before applying the model, we scaled its air mass to match the science data. After testing several scaling factors, we find that the correction performs best when adopting an air mass slightly higher than the mean of the observations (1.4 rather than 1.22). The high humidity further enhances the strength of the telluric absorption, making certain wavelength regions especially difficult to correct. Therefore, we masked pixels containing the deepest tellurics, where the flux is below 60% of the normalized continuum, as well as the region of 30 pixels around them. As a result, the entire bluest order is masked out. The instrumental throughput is recovered by dividing the blackbody spectrum of the standard star ι Sco, namely $T_{\text{eff}} = 15\,000$ K (Royer et al. 2024), to remove the continuum of the standard star from the telluric model.

The spectral data consists of seven spectral orders, each of which covers three detectors with 2048 pixels each. As the line profiles of the standard star were fit with a Gaussian, the resolving power \mathcal{R} can be estimated through the full width at half maximum (FWHM). According to the telluric line fits, the spectral data exhibit a spectral resolution of $\mathcal{R} = 60\,000$, which surpasses the nominal resolution of CRILES+ in the wide slit mode at $\mathcal{R} = 50\,000$, due to good seeing conditions.

3. Retrieval framework

For the analysis of the extracted spectra, we applied the atmospheric retrieval framework described in our previous study (Grasser et al. 2025). Using the radiative transfer code `petitRADTRANS` (pRT; Version 2.7; Mollière et al. 2019), we generated model spectra based on the object’s properties, which we retrieved as free parameters. We utilized the nested sampling tool `PyMultiNest` (Buchner et al. 2014), a Python wrapper of the Bayesian inference algorithm `MultiNest` (Feroz et al. 2009, 2019), to iteratively sample the parameter space. A few notable changes were made to the framework used in Grasser et al. (2025). For one, we continuum-normalized the data as well as the generated model spectra. We also placed Gaussian priors on the surface gravity and include veiling effects.

We list the free parameters in Table 3, including their descriptions, prior ranges, and retrieved values for ROXs 12A and B. Following `MultiNest` recommendations, we used importance nested sampling (INS) mode with a sampling efficiency of 5% (Feroz et al. 2019). The retrievals were run with 500 live points until an evidence tolerance of 0.1 was reached.

Table 3. Free parameters, prior ranges, and retrieval results for ROXs 12A and ROXs 12B.

Parameter	Description	Prior range		Retrieval results	
		ROXs 12A	ROXs 12B	ROXs 12A	ROXs 12B
v_{rad} (km/s)	Radial velocity	$\mathcal{U}(-20,20)$		$-5.46^{+0.03}_{-0.03}$	$-5.28^{+0.02}_{-0.02}$
$v \sin i$ (km/s)	Projected rotational velocity	$\mathcal{U}(0,40)$		$8.37^{+0.05}_{-0.05}$	$2.14^{+0.21}_{-0.16}$
$\log g$ (cm/s ²)	Surface gravity	$\mathcal{G}(4.1,0.2)$	$\mathcal{G}(4.0,0.2)$	$4.45^{+0.04}_{-0.04}$	$4.03^{+0.04}_{-0.04}$
ϵ_{limb}	Limb-darkening coefficient	$\mathcal{U}(0.2,1)$		$0.63^{+0.05}_{-0.05}$	$0.60^{+0.21}_{-0.25}$
C/O	Carbon-to-oxygen ratio	$\mathcal{U}(0.1,1)$		$0.87^{+0.01}_{-0.01}$	$0.54^{+0.01}_{-0.01}$
[Fe/H]	Metallicity	$\mathcal{U}(-1,1)$		$-0.06^{+0.02}_{-0.03}$	$-0.53^{+0.03}_{-0.03}$
$\log ^{12}\text{CO}/^{13}\text{CO}$	\log_{10} ratio of ¹² CO to ¹³ CO	$\mathcal{U}(1,6)$		$1.89^{+0.06}_{-0.05}$	$1.74^{+0.08}_{-0.07}$
$\log \text{H}_2^{16}\text{O}/\text{H}_2^{18}\text{O}$	\log_{10} ratio of H ₂ ¹⁶ O to H ₂ ¹⁸ O	$\mathcal{U}(1,6)$		$4.34^{+0.90}_{-1.08}$	$2.53^{+1.17}_{-0.33}$
T_0 (K)	Temperature at $P_0 = 10^2$ bar	$\mathcal{U}(1\text{e}3,3\text{e}4)$	$\mathcal{U}(1\text{e}3,1\text{e}4)$	$27797.57^{+1064.09}_{-1282.16}$	$3445.75^{+160.55}_{-140.52}$
∇T_0	Gradient at $P_0 = 10^2$ bar	$\mathcal{U}(0,0.4)$		$0.30^{+0.03}_{-0.03}$	$0.03^{+0.03}_{-0.02}$
∇T_1	Gradient at $P_1 = 10^0$ bar	$\mathcal{U}(0,0.4)$		$0.33^{+0.01}_{-0.01}$	$0.11^{+0.01}_{-0.01}$
∇T_2	Gradient at $P_2 = 10^{-2}$ bar	$\mathcal{U}(0,0.4)$		$0.00^{+0.01}_{-0.01}$	$0.06^{+0.01}_{-0.01}$
∇T_3	Gradient at $P_3 = 10^{-4}$ bar	$\mathcal{U}(0,0.4)$		$0.36^{+0.02}_{-0.02}$	$0.02^{+0.01}_{-0.01}$
∇T_4	Gradient at $P_4 = 10^{-6}$ bar	$\mathcal{U}(0,0.4)$		$0.15^{+0.10}_{-0.08}$	$0.26^{+0.07}_{-0.09}$
$r_k(\lambda_{\text{mid}})$	Veiling at 2166 nm	$\mathcal{U}(0,2)$		$0.17^{+0.02}_{-0.03}$	$0.02^{+0.01}_{-0.01}$
T_{disk} (K)	Disk temperature	$\mathcal{U}(300,1500)$		$915.77^{+97.46}_{-81.78}$	$548.81^{+114.11}_{-96.87}$
$\log \kappa_{\text{cl},0}$ (cm ² /g)	Opacity at cloud base	–	$\mathcal{U}(-10,3)$	–	$-5.76^{+2.24}_{-1.93}$
$\log P_{\text{cl},0}$ (bar)	Cloud base pressure	–	$\mathcal{U}(-6,3)$	–	$-0.68^{+1.71}_{-2.07}$
f_{sed}	Cloud decay power	–	$\mathcal{U}(0,20)$	–	$11.89^{+3.99}_{-4.92}$
$\log a$	GP amplitude	$\mathcal{U}(-1,1)$		$0.95^{+0.01}_{-0.01}$	$0.17^{+0.01}_{-0.01}$
$\log l$ (nm)	GP length-scale	$\mathcal{U}(-3,0)$		$-1.52^{+0.01}_{-0.01}$	$-2.01^{+0.01}_{-0.01}$

Notes. The three columns on the left show the parameter notation, description, and prior ranges. \mathcal{U} represents a uniform prior within the given range, whereas \mathcal{G} stands for a Gaussian prior with the given mean and standard deviation. The retrieval results for ROXs 12A and ROXs 12B, including their 1- σ credible interval, are shown in the two columns on the right.

3.1. Model spectra

The model spectra for our retrievals are generated with pRT according to the atmospheric properties which we retrieve as free parameters. In the sections below, we describe our modeling setup, following the methodology in Grasser et al. (2025).

3.1.1. Chemistry

Collision-induced absorption from H₂–H₂ and H₂–He, as well as Rayleigh scattering of H₂ and He (Dalgarno & Williams 1962; Chan & Dalgarno 1965; Borysow et al. 1988) are considered continuum opacities in our models. We use the HITEMP line lists for ¹²CO and ¹³CO (Li et al. 2015), the ExoMol line lists for H₂O (POKAZATEL; Polyansky et al. 2018), H₂¹⁸O (Polyansky et al. 2017), and HF (Li et al. 2013; Coxon & Hajigeorgiou 2015; Somogyi et al. 2021). These species are included in the retrievals of both objects. For the host star, we additionally include OH and CN (Wang et al. 2020; Tennyson et al. 2020), as well as the atomic species Na (Allard et al. 2019), H, Ca, Ti, Si, Sc, and Fe (Castelli & Kurucz 2003). The H-opacity is included as implemented in pRT following Gray (2008).

To minimize the number of free parameters, we assume thermo-chemical equilibrium, which is especially advantageous given the large number of species included in the stellar model. We retrieve the C/O ratio, metallicity, and base-10 logarithm of the isotope ratios ¹²CO/¹³CO and H₂¹⁶O/H₂¹⁸O as free parameters. We pre-compute a table of equilibrium abundances using FastChem Cond (Kitzmann et al. 2024) where the most extensive reaction networks and condensation are employed. The table is constructed in four dimensions: temperature, pressure, metallicity, and C/O (see Table 4). During the retrieval, linear interpolations are performed to obtain the volume mixing ratios (VMRs) for the model atmospheres.

3.1.2. Thermal profile and clouds

We parameterize the pressure-temperature (P – T) profile of the atmosphere through temperature gradients, following Zhang et al. (2023). The atmospheric layers are defined along a log₁₀-uniform grid between 10²–10^{–6} bar, with 50 layers in total. The temperature at the bottom of the atmosphere (T_0 , at a pressure of $P_0 = 10^2$ bar), as well as the temperature gradients ∇T_i at the

Table 4. Dimensions and steps of the chemical equilibrium table calculated with FastChem Cond (Kitzmann et al. 2024).

T (K)	150, 200, 250, ..., 6000
P (bar)	$10^{-5.0}, 10^{-4.9}, 10^{-4.8}, \dots, 10^{+3.0}$
[Fe/H]	-1.0, -0.9, -0.8, ..., +1.0
C/O	0.10, 0.20, 0.30, ..., 1.00

pressure $\log_{10}(P) = [-6, -4, -2, 0, 2]$ bar, are retrieved as free parameters. The gradients at the remaining atmospheric layers are quadratically interpolated from the five retrieved gradients. We calculate the temperature T at the pressure point P using the temperature gradient ∇T_i at each atmospheric layer i , where i increases with altitude

$$T_i = T_{i-1} \cdot \left(\frac{P_i}{P_{i-1}} \right)^{\nabla T_i} \quad \text{where} \quad \nabla T_i = \frac{d \ln T_i}{d \ln P_i}. \quad (1)$$

With an effective temperature of approximately 2500 K, ROXs 12B is expected to host clouds composed primarily of refractory Al- and Ti-bearing condensates, such as grossite (CaAl_4O_7), hibonite (CaAl_2O_9), corundum (Al_2O_3), and calcium titanate ($\text{Ca}_3\text{Ti}_2\text{O}_7$) (Wakeford et al. 2017). To ensure unbiased atmospheric retrieval, we adopt a simple gray cloud treatment similar to that of Mollière et al. (2020). The cloud opacity $\kappa_{\text{cl}}(P)$ is set to $\kappa_{\text{cl},0}$ at the cloud base $P_{\text{cl},0}$, decays above the base with a power-law defined by f_{sed} , and is zero below the base, defined by

$$\kappa_{\text{cl}}(P) = \begin{cases} \kappa_{\text{cl},0} \left(\frac{P}{P_{\text{base}}} \right)^{f_{\text{sed}}} & P < P_{\text{base}} \\ 0 & P \geq P_{\text{base}}. \end{cases} \quad (2)$$

3.1.3. Surface gravity

Bowler et al. (2017) determine a radius of $1.14 \pm 0.07 R_{\odot}$ and mass of $0.65^{+0.05}_{-0.09} M_{\odot}$ for ROXs 12A, implying a surface gravity of $\log g \sim 4.1$, which agrees with predictions by evolutionary tracks, considering the system's age of ~ 6 Myr (Baraffe et al. 2015). Similarly, the mass of ROXs 12B ($17.5 \pm 1.5 M_{\text{Jup}}$), Bowler et al. (2017) would imply a $\log g \sim 4.0$ when interpolating from evolutionary models Baraffe et al. (2015); Phillips et al. (2020). To ensure physical solutions and minimize degeneracies associated with surface gravity, we adopt a Gaussian prior on $\log g$ centered on 4.1 and 4.0 for A and B, with a standard deviation of 0.2 dex, similar to the prior derived by Xuan et al. (2024a) for ROXs 12B. These priors are justified considering that K band spectra lack gravity sensitive features (Zhang et al. 2021b), and the limited wavelength coverage can bias the retrieved $\log g$ and other global parameters (Burningham et al. 2021).

3.1.4. Veiling

Due to the youth of the system, a circum(sub)stellar disk may be present, which reduces the depth of its photospheric absorption lines. We include veiling in the retrievals for both objects to test whether it can be constrained. Following Sullivan et al. (2019); Zhang et al. (2024), the observed veiled spectrum F' is expressed as an additive continuum excess

$$F'(\lambda) = \frac{F(\lambda) + r_k(\lambda)F_0}{1 + r_k(\lambda)}, \quad (3)$$

where F is the intrinsic stellar spectrum and F_0 is the median flux level of F . We parameterize the veiling coefficient r_k through a physically motivated approach, using the Planck function $B(\lambda, T_{\text{disk}})$ to model the wavelength dependence (Antonucci et al. 2017; Alcalá et al. 2021)

$$r_k(\lambda) = r_k(\lambda_{\text{mid}}) \frac{B(\lambda, T_{\text{disk}})}{B(\lambda_{\text{mid}}, T_{\text{disk}})}. \quad (4)$$

The temperature T_{disk} sets the wavelength dependence of the veiling through the blackbody flux $B(\lambda, T_{\text{disk}})$, whereas $r_k(\lambda_{\text{mid}})$ specifies the veiling at the median of our wavelength range, namely $\lambda_{\text{mid}} = 2166$ nm, as our midpoint for normalization.

3.1.5. Broadening and normalization

After generating the model spectrum, the fastRotBroad function from PyAstronomy² (Gray 2008; Czesla et al. 2019) is applied to broaden it according to the projected rotational velocity $v \sin i$ and the limb-darkening coefficient ϵ_{limb} . The model spectra are down-convolved to the same resolution as the data.

We continuum-normalize the data and the model spectra, as we noticed a slope in the residuals between the data and a preliminary best-fit model of ROXs 12A. We suspect that this may be caused either by a residual instrumental slope not reflected in the blaze function extracted by excalibuhr or potential extinction effects. To ensure that we treat the data and model in the same way, we found that the most robust method was to use Fourier filtering as implemented in np.fft³ to reconstruct the continuum from the lowest frequencies (using frequencies below 1/150 of the array length, i.e., 13 pixels for each order-detector pair of 2048 pixels). We found that smaller cutoffs began to distort line wings, whereas larger cutoffs did not sufficiently remove residual slopes. The Fourier filtering procedure is applied identically to both the data and the model spectra. After masking the same pixels in the model as in the data, both spectra are divided by their respective continua prior to log-likelihood evaluation.

3.2. Log-likelihood

The likelihood of the models is determined following the methodology in Ruffio et al. (2019). For each order-detector pair, the log-likelihood is calculated as

$$\ln \mathcal{L} = -\frac{1}{2} (\ln(|\Sigma|) + \ln(\mathbf{m}^T \Sigma^{-1} \mathbf{m})) + (N_d - N_{\phi} + \alpha - 1) \cdot \ln \underbrace{(\mathbf{R}^T \Sigma^{-1} \mathbf{R})}_{\chi_0^2}, \quad (5)$$

where \mathbf{R} refers to the residuals between the data and the model spectrum, and Σ represents the covariance matrix, consisting of the flux uncertainties and the potential correlation between pixels. N_d is the number of valid data points. Following Ruffio et al. (2019), we set the normalization term $\alpha = 2$ and the number of linear parameters $N_{\phi} = 1$. The log-likelihood values of each order-detector are subsequently summed to obtain the total log-likelihood of the model. Following the methodology described in de Regt et al. (2024), we also include an uncertainty-scaling parameter to account for potential over- or underestimation of the flux uncertainties.

² <https://github.com/sczesla/PyAstronomy>

³ <https://numpy.org/doc/stable/reference/routines.fft.html>

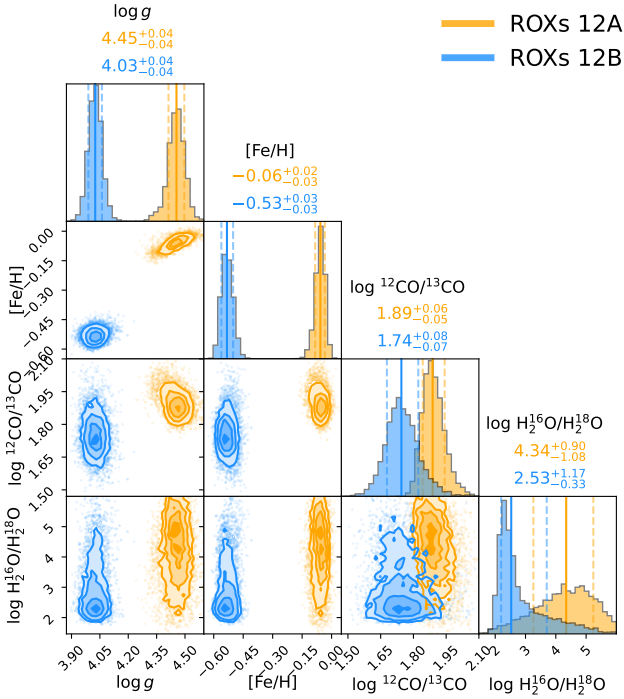


Fig. 2. Posterior distributions of $\log g$, $[\text{Fe}/\text{H}]$, $^{12}\text{CO}/^{13}\text{CO}$, and $\text{H}_2^{16}\text{O}/\text{H}_2^{18}\text{O}$ ratio for ROXs 12A (yellow) and B (blue).

To account for correlated noise, we use the methodology described in [de Regt et al. \(2024\)](#), based on [Kawahara et al. \(2022\)](#), in which the off-diagonal elements of the covariance matrix are determined through Gaussian processes (GP). For this, we introduce two additional free parameters to model a Gaussian with the amplitude a , which scales the uncertainty, and a length-scale ℓ , which sets the contribution of off-diagonal elements. We refer to [de Regt et al. \(2024\)](#); [Grasser et al. \(2025\)](#) for more details.

3.3. Test on injected spectrum

To assess the robustness of our spectral extraction and subsequent retrieval, we generate a pRT test spectrum with selected properties similar to the retrieved values of ROXs 12B. Specifically, we set a solar metallicity, $\text{C}/\text{O}=0.55$, $\log g=4$, $\log_{10}(^{12}\text{CO}/^{13}\text{CO})=1.7$, and $\log_{10}(\text{H}_2^{16}\text{O}/\text{H}_2^{18}\text{O})=2.5$, and a Sonora Bobcat P - T profile of $T_{\text{eff}}=2200$ K. We also include modest veiling at $r_k(\lambda_{\text{mid}})=0.2$ with a disk temperature of $T_{\text{disk}}=1000$ K. We then inject this spectrum on the other side of the stellar PSF at -1.7 arcsec (see [Fig. B.1](#)) and extract it using the same procedure as for the real companion spectrum. The retrieval is performed on this test spectrum with an identical setup to that used for ROXs 12B.

4. Results

[Table 3](#) lists the parameter values retrieved for ROXs 12A and B, with the posterior distributions of the key parameters shown in [Fig. 2](#). We present a section of the data and the best-fit model spectra within a CO-dominated spectral order of ROXs 12A and B in [Figure 3](#). The lower S/N of ROXs 12B can be clearly recognized in the larger residuals in the bottom panel. Overall, the fit reproduces the observed spectra well, with no noticeable residual slopes or systematic features. The full model spectra can be

found in [Appendix A](#). We also show a summary of the results for the injected test spectrum in [Fig. B.2](#).

We note that some of the small parameter uncertainties may be overly optimistic, as narrow posteriors are a well-known limitation of MultiNest retrievals. In particular, when running MultiNest on constant efficiency mode, the sampler tends to focus on the high-likelihood core of the posterior and can underexplore the tails, leading to underestimated uncertainties rather than a fully representative posterior distribution. Higher-dimensional or noisy data may be especially susceptible, as well as parameters affected by degeneracies, weak constraints, or multimodal posterior structure (e.g., [Buchner 2016](#); [Lemos et al. 2023](#); [Dittmann 2024](#)).

4.1. Thermal profiles

We present the retrieved P - T profiles for both objects of the ROXs 12 system in [Fig. 4](#). For ROXs 12A, the profile retrieved closely follows the SPHINX model corresponding to $T_{\text{eff}}=4000$ K, $\log g=4.25$, $[\text{Fe}/\text{H}]=0.0$, and $\text{C}/\text{O}=0.5$ ([Iyer et al. 2023](#)) in the photospheric layers probed by our data. However, our P - T profile deviates from the SPHINX model at lower atmospheric pressures, since our data are not sensitive to those pressure regions.

The profile retrieved for ROXs 12B is slightly cooler than $T_{\text{eff}}=2500 \pm 140$ found by [Xuan et al. \(2024a\)](#), both of which are markedly cooler than $T_{\text{eff}}=3100^{+400}_{-500}$ K reported by [Bowler et al. \(2017\)](#). Our P - T profile visually aligns more closely with Sonora Bobcat models ([Marley et al. 2021](#)) with $T_{\text{eff}} \approx 2200$ K. However, the effective temperature inferred from broadband spectroscopy does not necessarily correspond to the local photospheric temperature at the wavelengths probed, and the [Bowler et al. \(2017\)](#) T_{eff} estimate carries substantial uncertainties. Furthermore, [Bowler et al. \(2017\)](#) themselves claim that their derived T_{eff} is unusually high for an L0 dwarf and quote $T_{\text{eff}} \approx 2260 \pm 60$ K for ROXs 12B when instead using the T_{eff} -spectral type relation from [Filippazzo et al. \(2015\)](#), which agrees with our retrieved photospheric temperature.

Compared to the Sonora Bobcat P - T profile ([Marley et al. 2021](#)), we obtain shallower temperature gradients, with cooler temperatures at higher pressures and warmer temperatures at lower pressures than predicted. This behavior, also seen in other L-dwarf retrievals ([Bunningham et al. 2017](#); [Kitzmann et al. 2020](#); [Lueber et al. 2022](#)), could be explained by clouds, although our retrieval is unable to constrain any cloud properties, or possibly chemical instability affecting the adiabatic index ([Tremblin et al. 2015, 2016](#)).

4.2. Chemical composition

As shown in [Fig. 2](#), we obtain a roughly solar metallicity of ROXs 12A at $-0.06^{+0.02}_{-0.03}$, while [Swastik et al. \(2021\)](#) suggest a slightly supersolar metallicity of 0.14 ± 0.01 . The metallicity we find for ROXs 12B at -0.53 ± 0.03 is consistent with $-0.30^{+0.26}_{-0.22}$ reported by [Xuan et al. \(2024a\)](#), who report similarly subsolar values for several other substellar companions. While such low metallicities are unexpected for young systems ([Santos et al. 2008](#)) and may be driven by degeneracies between $\log g$, temperature structure, and cloud properties, several other retrieval studies of substellar companions have also reported subsolar metallicities ([Line et al. 2021](#); [Xuan et al. 2024a](#); [Inglis et al. 2024](#)). However, because these analyzes are subject to similar degeneracies, it remains unclear whether these low values reflect true atmospheric composition.

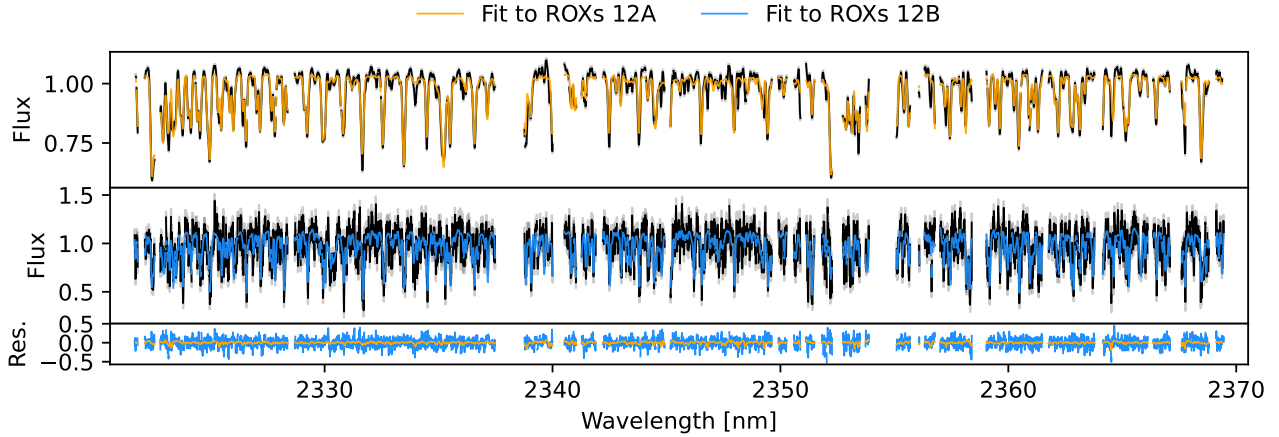


Fig. 3. Best-fit models to ROXs 12A (top) and B (middle), with the residuals (bottom; data minus model), within a CO-dominated spectral order.

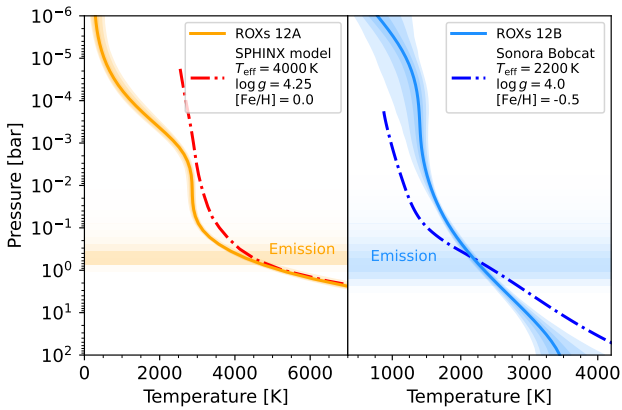


Fig. 4. Retrieved P - T profiles for ROXs 12A (left) and B (right). We compare ROXs 12A to a SPHINX model profile with $T_{\text{eff}}=4000$ K, $\log g=4.25$, $[\text{Fe}/\text{H}]=0.0$, and $\text{C}/\text{O}=0.5$ (Iyer et al. 2023), and ROXs 12B to a Sonora Bobcat model with $T_{\text{eff}}=2200$ K, $\log g=4.0$, $[\text{Fe}/\text{H}]=-0.5$, and solar C/O (Marley et al. 2021).

Interestingly, the retrieval of the injected test spectrum also yields a subsolar metallicity of $-0.29^{+0.04}_{-0.03}$ despite the input being solar (Fig. B.2). Since veiling was included in the model but not recovered by retrieval, this suggests that at low S/N the method struggles to disentangle the effects of metallicity, modest veiling, and clouds on line depths. The small uncertainties place the retrieved metallicity significantly away from the true value, which decreases our confidence in the metallicity retrieved for ROXs 12B. Accurate retrievals of the metallicity may only be possible for objects unaffected by veiling. Consequently, it cannot be ruled out that the subsolar metallicity inferred for ROXs 12B may reflect such parameter degeneracies rather than the true composition. However, recent JWST studies of disks around similar young companions (e.g., Cugno et al. 2024) indicate typical disk temperatures of ≈ 500 K, implying that veiling contributions in the K band are expected to be negligible and primarily affect longer wavelengths. This consideration strengthens the interpretation that the low metallicity may be intrinsic rather than driven by unaccounted for veiling.

Our results indicate a C/O ratio for ROXs 12B of 0.54 ± 0.01 , close to solar (Asplund et al. 2021), and in agreement with Xuan et al. (2024a), who find $\text{C}/\text{O}=0.54 \pm 0.05$. In contrast, we obtain a higher C/O ratio for ROXs 12A around 0.87 ± 0.01 . However, we caution that this value may not represent the true

C/O ratio of the host star. Within the star’s photospheric temperatures, the dissociation of H_2O shifts oxygen into OH and, more significantly, atomic oxygen, which becomes the second-largest oxygen reservoir after ^{12}CO according to our equilibrium chemistry tables, with its abundance increasing markedly toward lower C/O. Although atomic oxygen does not exhibit spectral features in the K band, OH does. However, OH responds only weakly to changes in total oxygen abundance at these temperatures, limiting the sensitivity of our retrieval to the full oxygen budget and making it difficult to obtain a reliable estimate of the true C/O ratio (Asplund & García Pérez 2001).

We retrieve a $^{12}\text{CO}/^{13}\text{CO}$ ratio of 77^{+10}_{-7} and 55^{+10}_{-7} for ROXs 12A and B. Both ratios are consistent with the present-day local interstellar medium (ISM) within the 1σ scatter ($^{12}\text{C}/^{13}\text{C}_{\text{ISM}}=68 \pm 15$, Milam et al. 2005), with the companion’s ratio somewhat lower and the host star’s somewhat higher. Xuan et al. (2024a) report that their $^{12}\text{CO}/^{13}\text{CO}$ posterior peaks near ~ 100 for ROXs 12B, but their detection does not exceed a 3σ significance level. Other young companions (Zhang et al. 2024; Xuan et al. 2024a; González Picos et al. 2025b) and young isolated brown dwarfs (González Picos et al. 2024; de Regt et al. 2026) likewise exhibit $^{12}\text{CO}/^{13}\text{CO}$ ratios consistent with the ISM.

For ROXs 12B, we find a ratio of $\text{H}_2^{16}\text{O}/\text{H}_2^{18}\text{O}=337^{+4682}_{-181}$. The large upper uncertainty is due to the tail of the posterior distribution being in \log_{10} -space, as seen in Fig. 2. The posterior distribution shows a clear peak of $\text{H}_2^{16}\text{O}/\text{H}_2^{18}\text{O}$ at ≈ 300 , suggesting that there may be a slight enrichment of H_2^{18}O compared to the Sun (525 ± 21 ; Lyons et al. 2018) and the ISM (557 ± 30 ; Wilson 1999). However, due to the very large uncertainty towards larger values, the inclusion of H_2^{18}O is not favored at a statistically significant level, therefore this ratio should be interpreted as a lower limit. Other retrievals of isolated brown dwarfs show a wide range of $\text{H}_2^{16}\text{O}/\text{H}_2^{18}\text{O}$ ratios, with some being above the ISM (Grasser et al. 2025), some below (González Picos et al. 2024), and some undetectable (Mulder et al. 2025).

The retrieval of the injected test spectrum recovers the C/O (0.51 ± 0.01 vs. 0.55), $^{12}\text{CO}/^{13}\text{CO}$ ($1.64^{+0.04}_{-0.03}$ vs. 1.7), and $\text{H}_2^{16}\text{O}/\text{H}_2^{18}\text{O}$ ($2.68^{+0.16}_{-0.11}$ vs. 2.5) ratios reasonably well, with only small offsets from the input values (see Fig. B.2). This suggests that these ratios for ROXs 12B are relatively robust and less affected by degeneracies, such as those between metallicity, $\log g$, veiling, clouds, or temperature structure.

To further assess the robustness of the detections, we compute the cross-correlation functions (CCFs) for each atmospheric

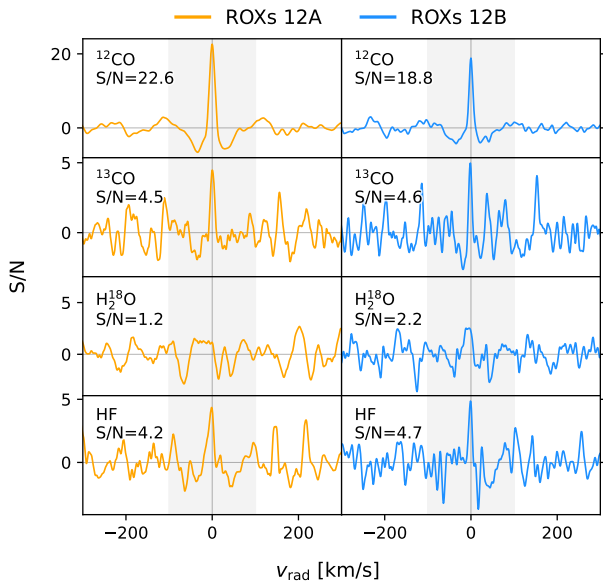


Fig. 5. Cross-correlation functions of selected atmospheric species for ROXs 12A (left, yellow) and B (right, blue).

species. Following Zhang et al. (2021a), we compute the CCF between a template of the selected species, obtained by subtracting the fiducial model without that species from the full fiducial model, and the residuals, defined as the observed spectrum minus the fiducial model without the selected species. Fig. 5 shows the CCFs for ROXs 12A (left) and B (right) of selected atmospheric species. We confirm the presence of ^{13}CO and HF in both objects, while H_2^{18}O only produces a tentative signal in ROXs 12B, as expected from the retrieval posteriors in Fig. 2. This makes our result the first robust constraint of the $^{12}\text{CO}/^{13}\text{CO}$ ratio in ROXs 12B. Interestingly, the detection confidence of ^{13}CO is similar for both objects, despite the S/N of the stellar spectrum being significantly higher. This behavior may result from a combination of effects, including a lower intrinsic ^{13}CO abundance in the star relative to the companion and the presence of modest veiling in the stellar spectrum, which reduces the observed line depths. Similar isotopic detection confidences of the host star and companion have also been found in other studies (e.g., Xuan et al. 2024b; González Picos et al. 2025b).

Due to the low S/N of ROXs 12B, we were only able to include its most prominent absorbers in our retrieval, namely ^{12}CO , ^{13}CO , H_2O , H_2^{18}O , and HF. For ROXs 12A, on the other hand, we retrieve a wide range of species in addition to those retrieved for ROXs 12B, whose presence is confirmed by cross-correlation (see Fig. C.1). At these high temperatures, atomic hydrogen and H- are important constituents of chemical equilibrium. We also retrieved OH and CN, as well as several atomic species, namely Na, Ti, Fe, Ca, Si, and Sc.

Despite our efforts to identify as many species as possible in the spectrum of ROXs 12A, the origin of some features in the spectrum remains unexplained. Mismatches in spectral features and unidentified lines are common issues in M dwarf spectroscopy, often due to the effects of non-local thermodynamic equilibrium in M dwarfs, magnetic fields, and potentially incomplete molecular opacities under these conditions (e.g., Allard & Hauschildt 1995; Rajpurohit et al. 2018; Reggiani et al. 2019; Olander et al. 2021; Cristofari et al. 2022). However, this does not affect our retrieval results for ^{12}CO and ^{13}CO , as the mismatched features occur mainly in the wavelength regions

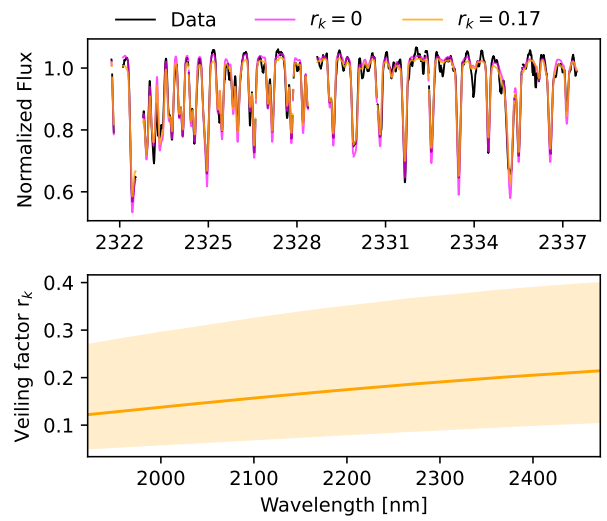


Fig. 6. Top panel: comparison of the best-fit model to ROXs 12A with (yellow) and without (magenta) veiling. Bottom panel: veiling coefficient r_k of ROXs 12A and its $1-\sigma$ uncertainty range throughout the observed wavelength range.

without CO absorption, while CO is the dominant contributor in the last two spectral orders.

4.3. Veiling

We retrieve a veiling coefficient of $r_k = 0.17^{+0.02}_{-0.03}$ at 2166 nm for ROXs 12A. The impact of the veiling is shown in the top panel of Fig. 6, where we compare it to a model without veiling. In the bottom panel, we show the wavelength-dependence of the veiling, which follows a $T \approx 900$ K blackbody. Bowler et al. (2017) also report disk emission for ROXs 12A, with an excess at $22 \mu\text{m}$ with $T \approx 230$ K. However, this likely originates from cooler parts of the outer disk, whereas the veiling we retrieve seems to stem from the hot inner part of the disk. Hot inner-disk dust and gas are known to produce a near-infrared excess in the K band (Muzerolle et al. 2003; Fischer et al. 2011).

The retrieved veiling is modest but clearly non-zero. This is consistent with expectations for ~ 6 Myr systems, where veiling has typically declined relative to younger objects but often remains detectable. Stars with ages similar to ROXs 12A exhibit comparable near-infrared veiling, with somewhat higher values found in more massive stars capable of sustaining larger disks (Sousa et al. 2023). For example, TW Hydra, which has a similar age and spectral type, exhibits $r_k \approx 0.3\text{--}0.4$ at $2.2 \mu\text{m}$ (Sokal et al. 2018).

In contrast, we do not retrieve any veiling for the companion ROXs 12B, with a veiling coefficient of $r_k < 0.03$. This is consistent with the non-detection of a massive accreting disk around ROXs 12B by Bowler et al. (2017) and Wu et al. (2020). The presence of circumsubstellar disks among wide-orbit companions is heterogeneous: while several systems show clear evidence of ongoing accretion or warm inner-disk emission (Bowler et al. 2011; Bailey et al. 2013; Zhou et al. 2014), others exhibit little to no detectable disk signatures (Wu et al. 2017). However, the retrieval of our injected test spectrum also failed to recover the included veiling ($r_k = 0.2$), instead returning a lower metallicity (see Fig. B.2). This demonstrates that modest veiling is challenging to detect at low S/N, so we cannot rule out its presence for ROXs 12B.

4.4. Correlated noise

Our results indicate a negligibly low degree of correlated noise for ROXs 12B, while for ROXs 12A it appears substantially higher. We find a GP amplitude $a = 8.9 \pm 0.06$ and length-scale $\ell = 0.03 \pm 0.01 \text{ nm} \approx 4.4$ pixels for the host star, while $a = 1.5 \pm 0.02$ and $\ell = 0.01 \pm 0.00 \text{ nm} \approx 1.4$ pixels for the companion. The large amplitude and length-scale for ROXs 12A is a direct result of our model being unable to reproduce several spectral features and is therefore not representative of the instrumentally correlated noise. This is further supported by the fact that we find barely any correlated noise for ROXs 12B, whose spectrum was extracted from the same data set.

5. Discussion

Determining an object's formation history is inherently challenging and requires multiple, often ambiguous, chemical and dynamical diagnostics. Objects forming within protoplanetary disks may develop supersolar C/O ratios (>0.59 , Asplund et al. 2021) from accretion outside of the water snowline, as water ice freezes onto dust grains, enriching the C/O of the gas-phase (Öberg et al. 2011; Brewer et al. 2017). In contrast, C/O ratios near the solar value might indicate formation via cloud fragmentation or disk instability, where the composition reflects that of the parent molecular cloud (Boss 2011). Our retrieved C/O ratio of 0.54 ± 0.01 for ROXs 12B, which is close to solar, is consistent with formation through cloud fragmentation or disk instability. However, this diagnostic on its own is not definitive, particularly as we are unable to reliably compare it to its host star. The retrieved C/O ratio of ≈ 0.87 for ROXs 12A may not be robust as it misses the contribution from atomic oxygen, which is expected to be non-negligible at these temperatures. Similar C/O ratios have been found for other directly imaged companions in the SupJup survey, such as 0.59 ± 0.01 for AB Pic b (Gandhi et al. 2025), $C/O = 0.57 \pm 0.01$ for YSES 1 b (Zhang et al. 2024), and 0.50 ± 0.01 for GQ Lup B (González Picos et al. 2025b). Studies of other directly imaged planets also report near-solar C/O ratios, albeit with modest variations between systems (Konopacky et al. 2013; Landman et al. 2024; Xuan et al. 2024a).

While the C/O ratio has long been suggested as a potential tracer of substellar formation pathways, the hypothesis that $^{12}\text{CO}/^{13}\text{CO}$ might also serve as a formation tracer is fairly recent. The enrichment of ^{13}C in the companion compared to the host star may indicate accretion of ices in the protoplanetary disk during its formation (Zhang et al. 2021a), although the difference in isotopic ratios is only marginally significant within the $1\text{-}\sigma$ uncertainties. Although the isotopic contrast between host and companion should be interpreted with caution as MultiNest may underestimate the uncertainties, this effect should be less pronounced for parameters that are not strongly affected by degeneracies, as supported by our injection-retrieval test. Since the isotopolog ratio is mainly constrained by the relative strengths of line features rather than their absolute depths, it depends less on parameters such as veiling and metallicity that scale the spectrum more globally and is therefore less strongly affected by degeneracies. Objects formed by core accretion are thought to inherit the $^{12}\text{C}/^{13}\text{C}$ ratio of local disk solids, which is expected to vary throughout the disk due to isotope fractionation processes (Visser et al. 2009; Yoshida et al. 2022). This is in contrast to Xuan et al. (2024b) and González Picos et al. (2025b), who find homogeneous isotopic compositions in the HIP 55507 and GQ Lup systems, which may indicate that these systems

were formed instead by gravitational collapse from the same parent cloud.

Interestingly, the possible core-accretion interpretation suggested by ROXs 12B's $^{12}\text{CO}/^{13}\text{CO}$ ratio contrasts with the implications of its C/O ratio and the conclusions of Bowler et al. (2017). They report a misalignment in the orbit of ROXs 12B with the spin axis of ROXs 12A by 49_{-32}^{+20} , which could indicate that it formed from a fragmenting molecular cloud core rather than in the disk of the star. Spin-orbit misalignments between widely-separated substellar companions and their hosts stars appear to be common (Bowler et al. 2023), in contrast to directly imaged planets in more compact systems (Albrecht et al. 2013; Winn et al. 2017). Hydrodynamic simulations also predict spin-orbit misalignments for binary systems that form via cloud fragmentation (Bate 2009; Offner et al. 2016).

Together, these diagnostics paint an ambiguous picture of ROXs 12B's origin. Although both the near-solar C/O ratio and the spin-orbit misalignment favor a formation pathway involving gravitational collapse, the companion's slightly lower $^{12}\text{C}/^{13}\text{C}$ ratio compared to the host can instead be interpreted as pointing toward core accretion. Given these indications, the gravitational collapse scenario currently appears more plausible, but additional observational and modeling efforts will be required to possibly constrain the formation pathway of ROXs 12B and determine other complementary tracers.

However, the $^{12}\text{CO}/^{13}\text{CO}$ ratio appears to be a more robust indicator of a system's age. Galactic chemical evolution models predict a gradual enrichment of the ISM in ^{13}C over time, for instance via nova eruptions (Romano 2022), a trend also seen in observations of nearby M dwarfs (González Picos et al. 2025a). Given the young age of the ROXs 12 system, its $^{12}\text{CO}/^{13}\text{CO}$ ratios are therefore expected to be close to the present ISM values, which we confirm in our analysis. Similar $^{12}\text{CO}/^{13}\text{CO}$ ratios consistent with the ISM have been found in other young companions (Zhang et al. 2024; Xuan et al. 2024a; González Picos et al. 2025b) and young isolated brown dwarfs (González Picos et al. 2024, de Regt et al. 2026).

6. Conclusions

Our retrievals on high-resolution CRIRES+ spectroscopy of the ROXs 12 system reveal detailed insights into the atmospheres of the M0 host star and its L0 brown dwarf companion. We find evidence of ^{13}CO and HF in both objects, as well as H_2^{18}O in the companion. Their $^{12}\text{CO}/^{13}\text{CO}$ ratios of 77_{-7}^{+10} and 55_{-7}^{+10} for ROXs 12A and B are consistent with the ISM, which is expected due to their youth (~ 6 Myr). Furthermore, we obtain a C/O ratio of 0.54 ± 0.01 for ROXs 12B, similar to other substellar companions, as well as a lower limit of $\text{H}_2^{16}\text{O}/\text{H}_2^{18}\text{O} \gtrsim 300$. The P - T profile we retrieve for ROXs 12B exhibits shallower temperature gradients compared to the models, a phenomenon which has been observed in several other substellar companions in the literature. Although the formation mechanism of ROXs 12B remains ambiguous, ongoing and future efforts to measure the elemental and isotopic ratios in substellar companions and isolated brown dwarfs, such as those of the ESO SupJup Survey, will help shed more light on their physical and chemical properties, as well as help assess the potential of the $^{12}\text{CO}/^{13}\text{CO}$ ratio as a tracer of formation history.

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Appendix A: Full best-fit models

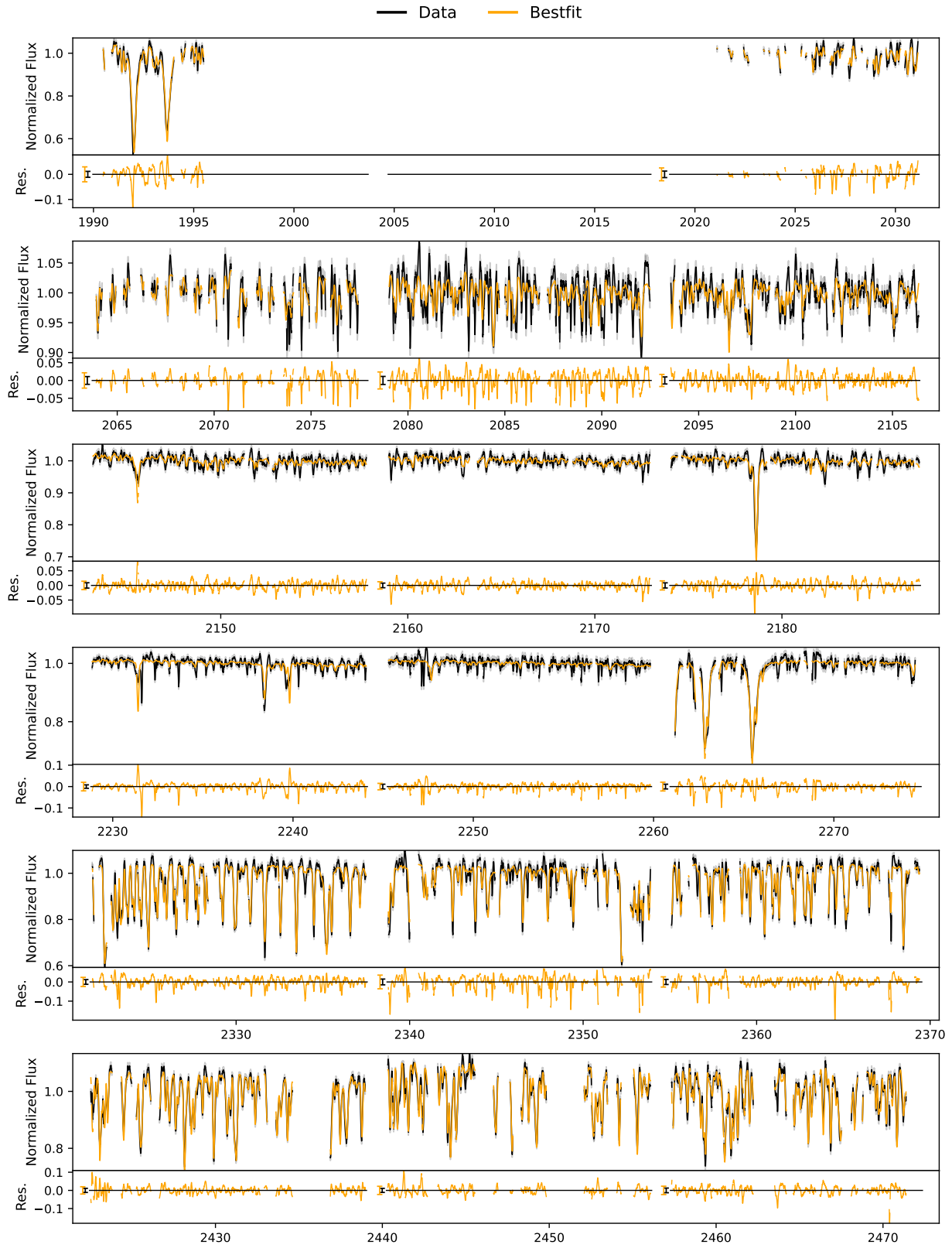


Fig. A.1: Best-fit model for ROXs 12A, with each panel showing a different spectral order. The observed spectrum is shown in black, along with its 1σ uncertainties in gray, and the best-fit model in yellow. In the panel underneath each order, we show the residuals (data minus model), as well as the data uncertainties for each order-detector pair as a black error bar and the standard deviation of the residuals as a yellow error bar.

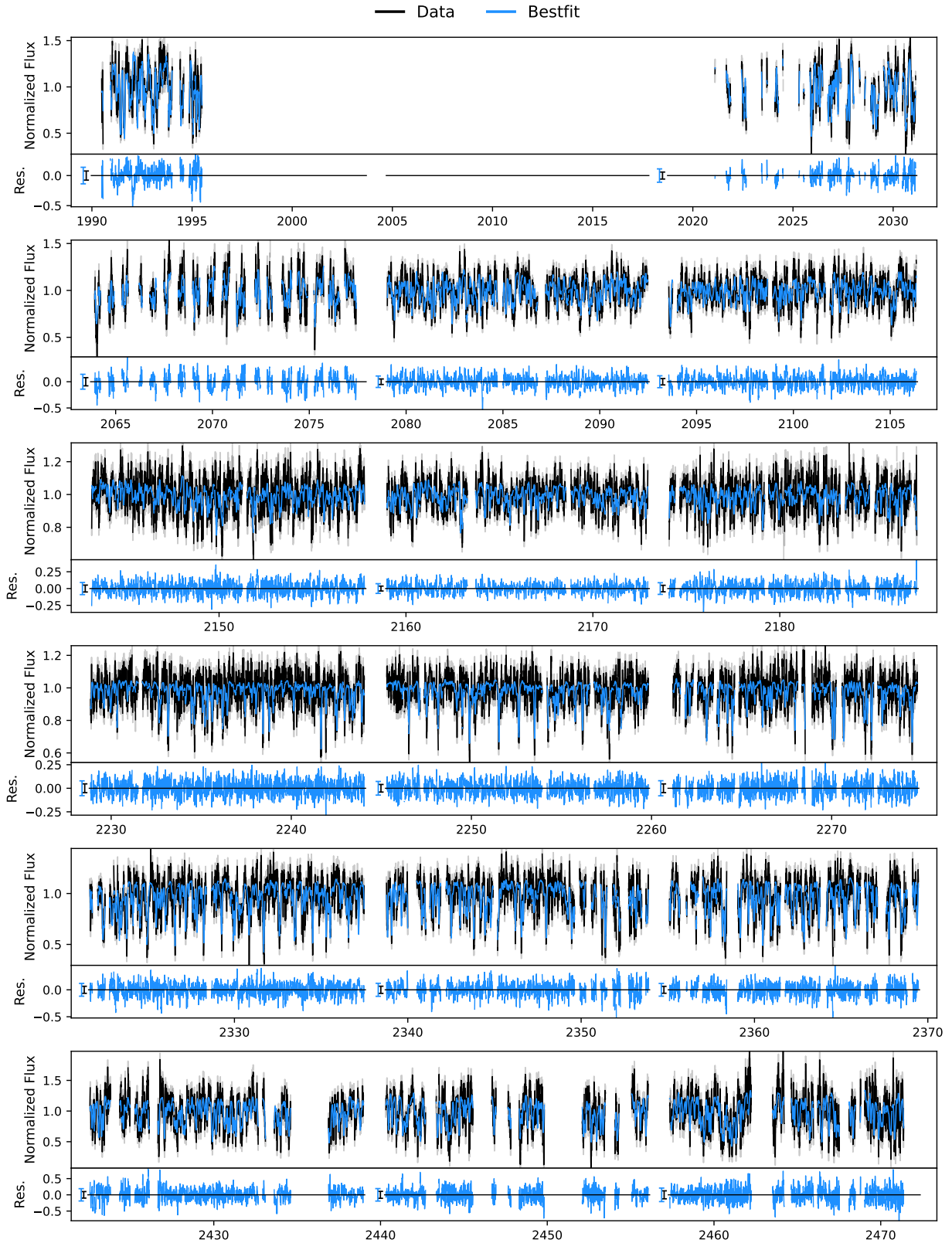


Fig. A.2: Best-fit model for ROXs 12B, with each panel showing a different spectral order. The observed spectrum is shown in blue, along with its 1σ uncertainties in gray, and the best-fit model in blue. In the panel underneath each order, we show the residuals (data minus model), as well as the data uncertainties for each order-detector pair as a black error bar and the standard deviation of the residuals as a blue error bar.

Appendix B: Injected test spectrum

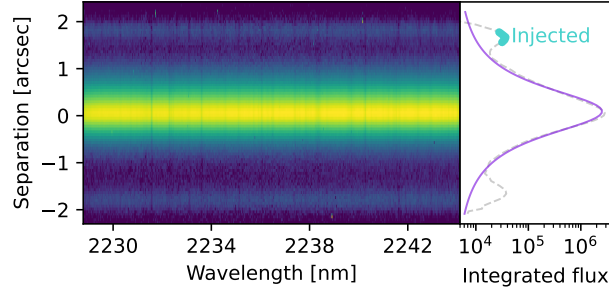


Fig. B.1: Equivalent to Fig. 1, except for the addition of an injected synthetic spectrum on the other side of the stellar PSF at -1.7 arcsec. The spectral extraction follows the same steps as described for the true companion (see Sect. 2).

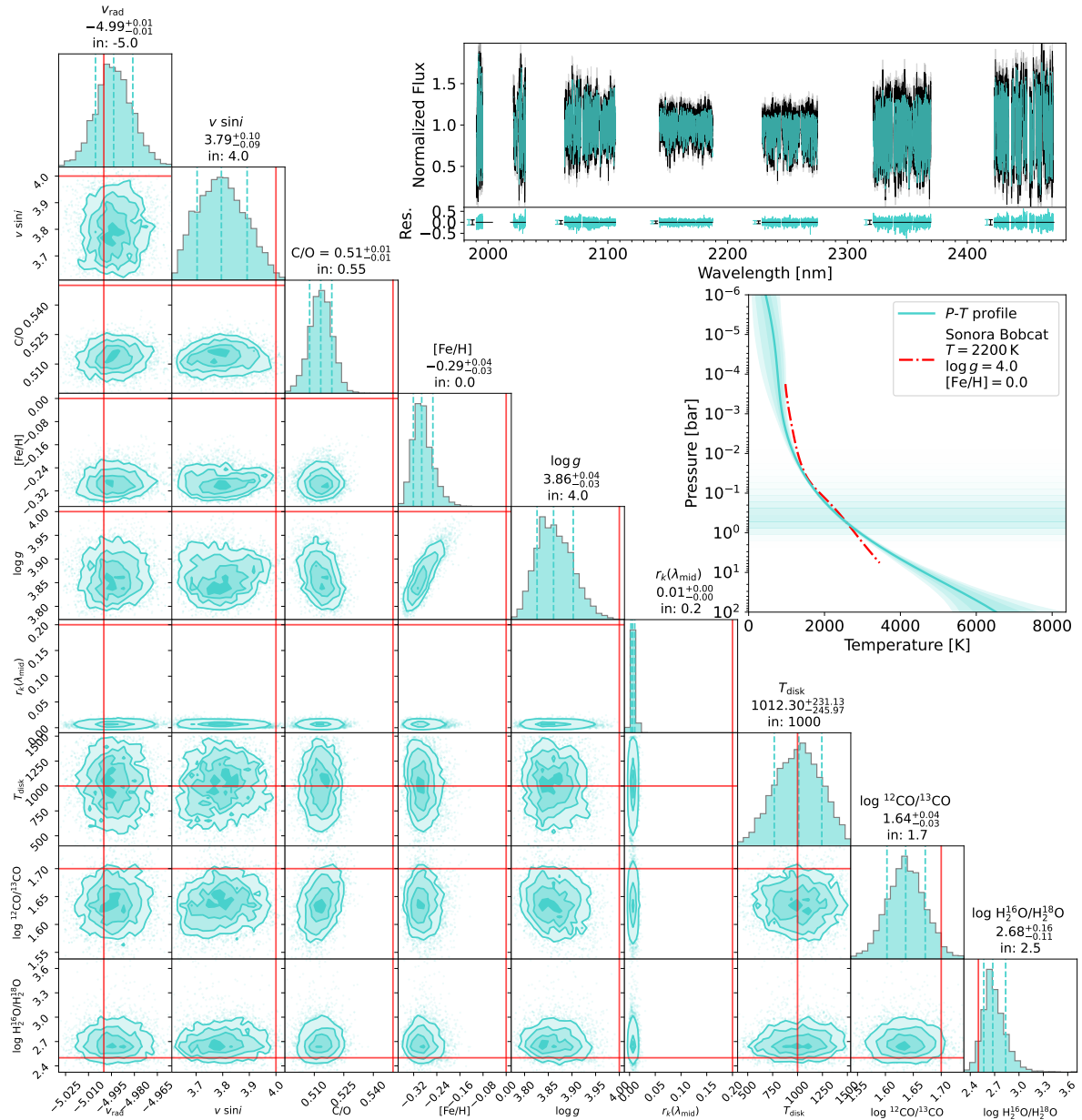


Fig. B.2: Summary of the retrieval results of the injected test spectrum. We show the Sonora Bobcat model P - T profile that was used as an input for generating the spectrum. The red lines in the cornerplot represent the input values.

Appendix C: ROXs 12A cross-correlation functions

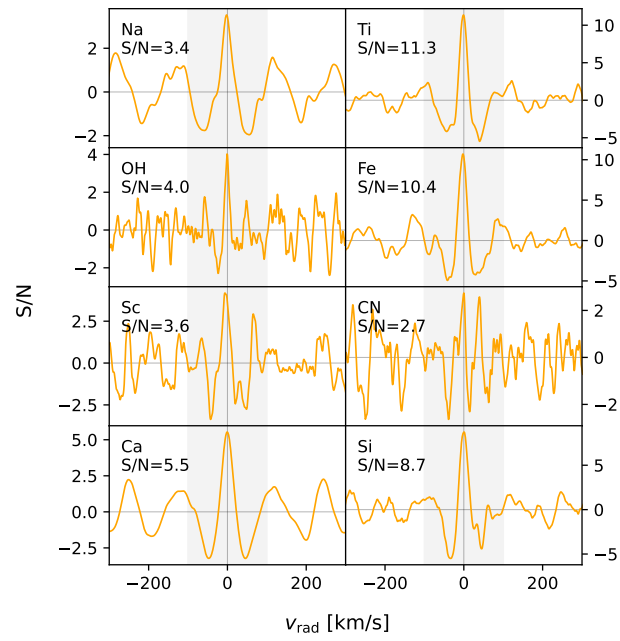


Fig. C.1: Cross-correlation functions of the remaining atmospheric species in ROXs 12A.