The carbon isotope ratio of the GQ Lup system

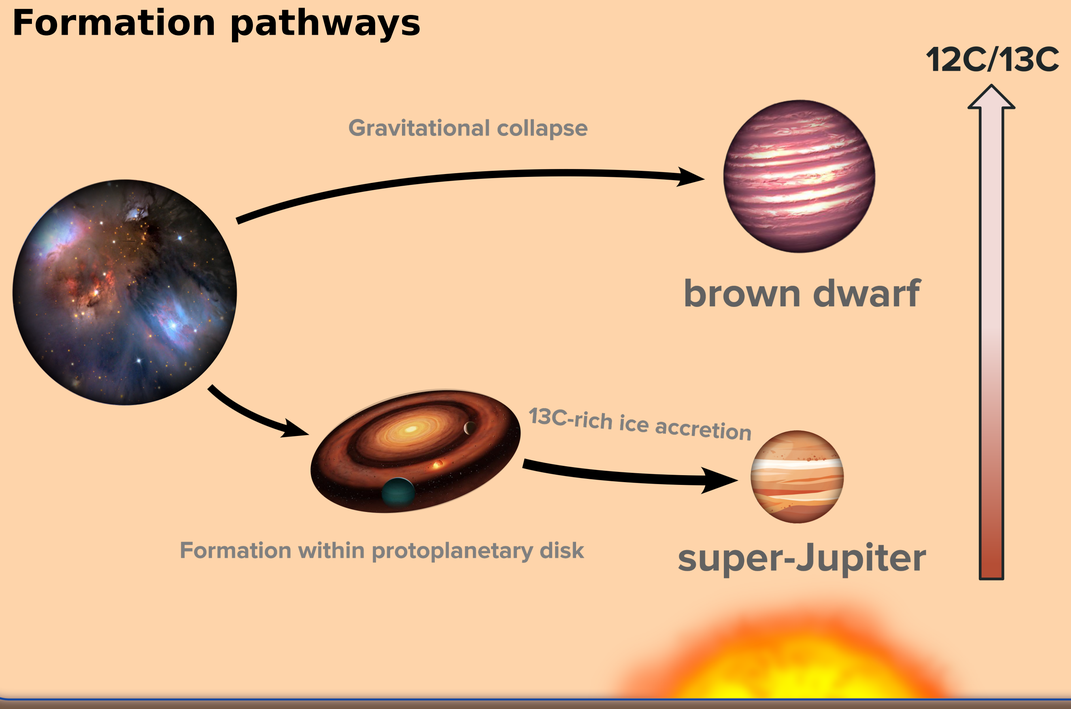
Unraveling formation pathways of super-Jupiters

Darío González Picos, Ignas Snellen, Sam de Regt, et al.
Leiden Observatory, Netherlands
picos@strw.leidenuniv.nl

Abstract

We characterise the atmosphere of a super-Jupiter in the GQ Lup system with the upgraded CRIRES+ instrument as part of the ESO SupJup survey [1]. We measure the composition, temperature profile and carbon isotope ratio of GQ Lup B through atmospheric retrievals. Additionally, we constrain the isotope ratio of the host star with a grid of PHOENIX spectra and a a veiling model.

Formation pathways

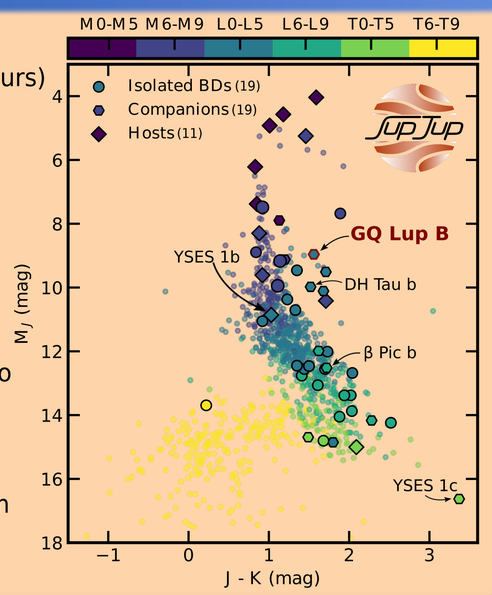


ESO SupJup survey

The ESO SupJup survey is a large programme (~100 hours) with VLT/CRIRES+ aimed at assessing the role of **isotope ratios as tracers of formation pathways** of super-Jupiters and free-floating brown dwarfs.

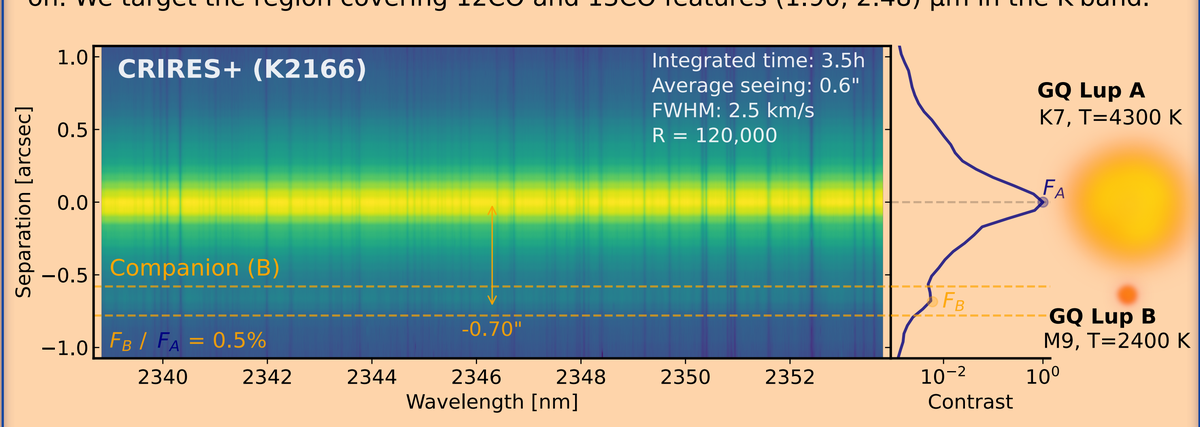
Super-Jupiters are widely-separated, self-luminous, gas giants straddling the boundary between planets and brown dwarfs, with masses ~ 5 - 30 M_{jup}.

- Formation within a **protoplanetary disk** may lead to distinct chemical and isotopic compositions due to the **accretion** of gas and solids [2].
- **Gravitational collapse or disk fragmentation** results in objects that **inherit the composition** from the molecular cloud.



Observations with CRIRES+

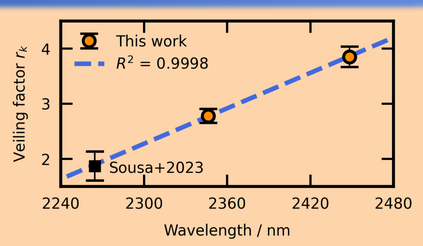
We observed the GQ Lup system with the narrow slit mode of CRIRES+ and adaptive optics on. We target the region covering 12CO and 13CO features (1.90, 2.48) μm in the K-band.

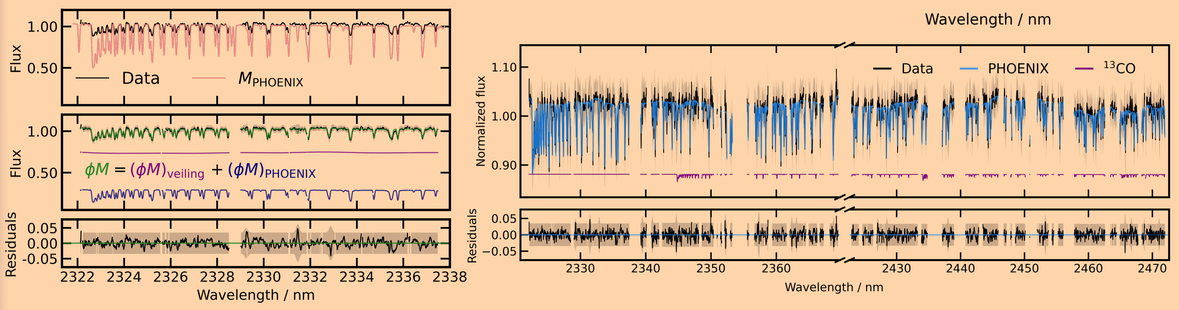


Starlight at the position of the planet dominates over GQ Lup B's signal by a factor of ~ 3

GQ Lup A spectrum and model

GQ Lup A is a young (2-5 Myr), active T Tauri star with a circumstellar disk. Its photospheric lines exhibit veiling due to an additional emission source [3].
We fit the excess continuum as a component of the linear model, with a fitted amplitude for each order.





Atmospheric Retrieval

Composition
12CO, H2O, **13CO**, HF
Ca, Na, Ti

Temperature Profile
Temperature gradients
Fit pressure of PT knots
Radiative-convective eq.

Surface gravity
Spin
Radial velocity

Telluric model
Fit airmass of Molecit model

Emission Spectrum
petitRADTRANS [4]

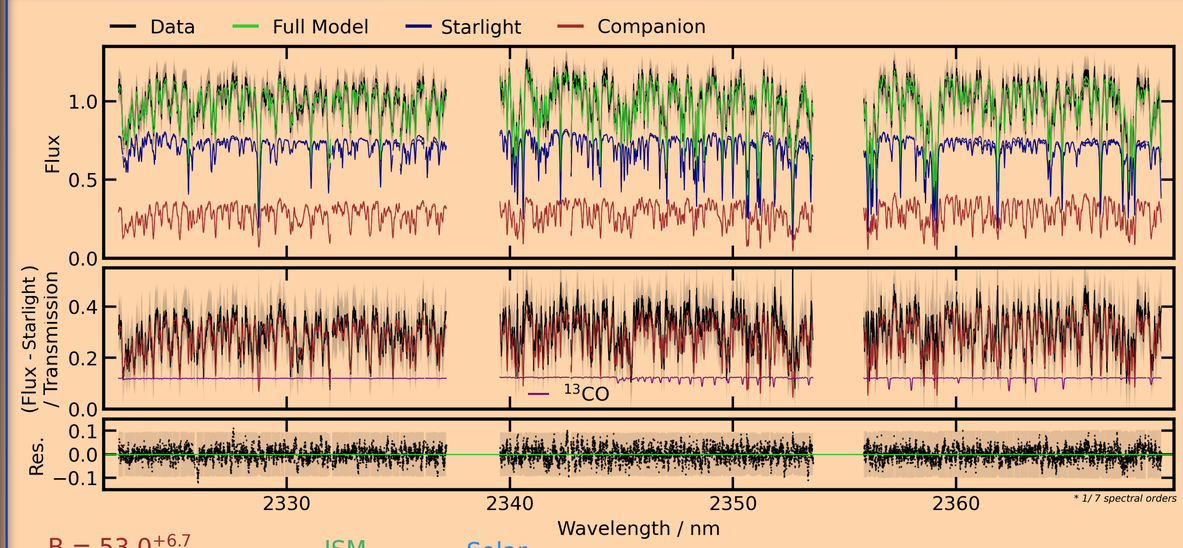
Starlight
Shifted and scaled versions of on-axis spectrum.

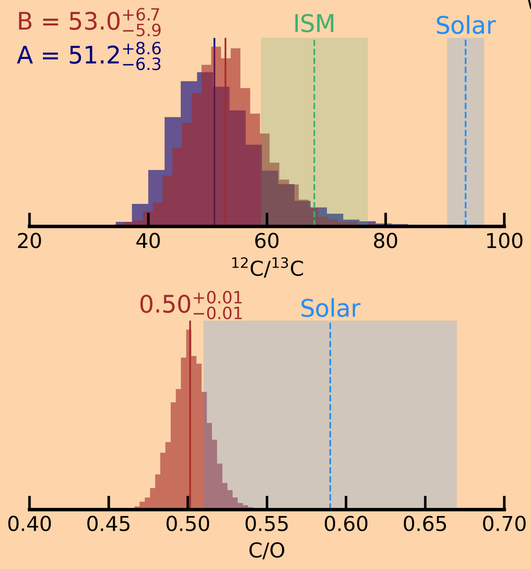
$$\mathbf{d} = \phi\mathbf{M} + \mathbf{n} = \underbrace{\phi_0\mathbf{M}_0}_{\text{companion}} + \underbrace{\phi_{1..i}\mathbf{M}_{1..i}}_{\text{starlight}} + \mathbf{n}$$

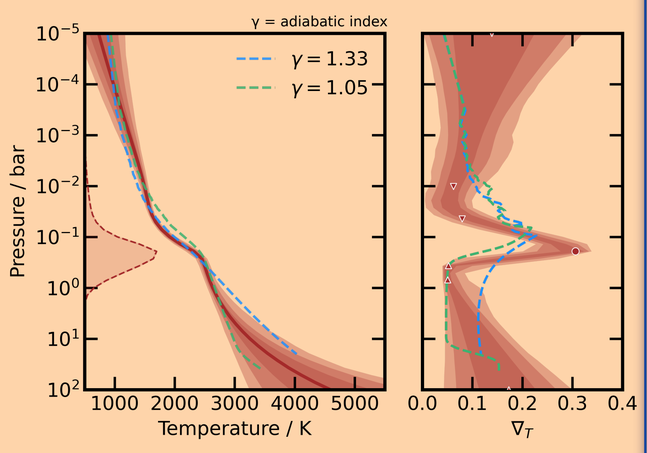
linear model

Least Squares → **Nested Sampling**

Best-Fit Model GQ Lup B







Composition
We retrieve the abundances of the main opacity sources with *free chemistry* and derive elemental and isotope ratios.

Surface gravity
log g = 3.83 ± 0.18

Spin
v sin i = 5.56 ± 0.02 km s^{-1}

Temperature Profile
Best-fit PT profile similar to ATMO models [5]:
T_{eff} ~ 2300 K, log g ~ 4.0.
The reduced temperature gradient in the deep atmosphere may originate from nonadiabatic convection (γ < 1.33) [6].

The low surface gravity and slow spin are consistent with previous measurements of GQ Lup B and other young super-Jupiters and brown dwarfs [7, 8].

Conclusions

- We present a detailed characterization of the atmosphere of GQ Lup B with K-band high-resolution spectroscopy.
- We forward-model the starlight at the position of the companion and the telluric features to robustly derive atmospheric parameters.
- We report the detection of 13CO in the atmosphere of GQ Lup B and its host star.
- The homogeneous carbon isotope of the system suggests that GQ Lup B formed via graviational collapse or disk fragmentation.
- Veiling of photospheric lines affects the spectrum of hosts T Tauri stars and must be included to fit stellar models.

References

[1] de Regt, S. et al. "The ESO SupJup Survey I: Chemical and isotopic characterisation of the late L-dwarf DENIS J0255-4700 with CRIRES+". arXiv:2405.10841 (2024).
[2] Zhang, Y., et al. "The 13CO-rich atmosphere of a young accreting super-Jupiter." Nature 595.7867
[3] Sousa, A. P. et al. "New insights on the near-infrared veiling of young stars using CFHT/SPIRou data". A&A 670, A142 (2023).
[4] Mollière, P., et al. "petitRADTRANS-A Python radiative transfer package for exoplanet characterization and retrieval." A&A 627 (2019): A67.
[5] Phillips, M. W. et al. "A new set of atmosphere and evolution models for cool T–Y brown dwarfs and giant exoplanets". A&A 637, A38 (2020).
[6] Leggett, S. K. & Tremblin, P. "The First Y Dwarf Data from JWST Show that Dynamic and Diabatic Processes Regulate Cold Brown Dwarf Atmospheres". ApJ 959, 86 (2023).
[7] Schwarz, H. et al. "The slow spin of the young substellar companion GQ Lupi b and its orbital configuration". A&A 593, A74 (2016).
[8] Ruffio, J.B. et al. "Deep Exploration of the Planets HR 8799 b, c, and d with Moderate-resolution Spectroscopy". AJ 162, 290 (2021).