Ground-based high-resolution transit spectroscopy with CARMENES

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CARMENES for Exoplanet Atmospheres

In recent years a new generation of highly-stabilized high-resolution spectrographs with a broad wavelength coverage have started regular operations. One of them is CARMENES (Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Échelle Spectrographs), mounted at the Calar-Alto Observatory 3.5m telescope.

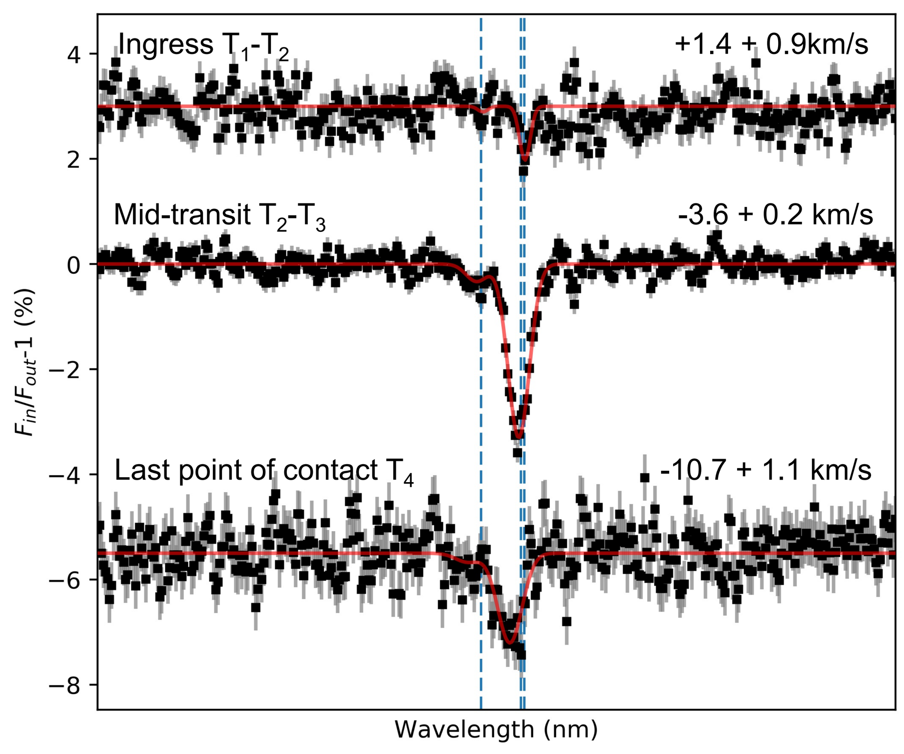
CARMENES was initially designed to detect exoplanets via the radial velocity method but has proven itself as an excellent tool for the study of atmospheres of warm and hot giant planets in the wavelength range between 520 - 1710 nm. This range covers the planetary absorption lines of sodium, potassium, titanium oxide, iron, calcium and hydrogen lines in the optical channel and water, and helium lines in the near infrared channel.

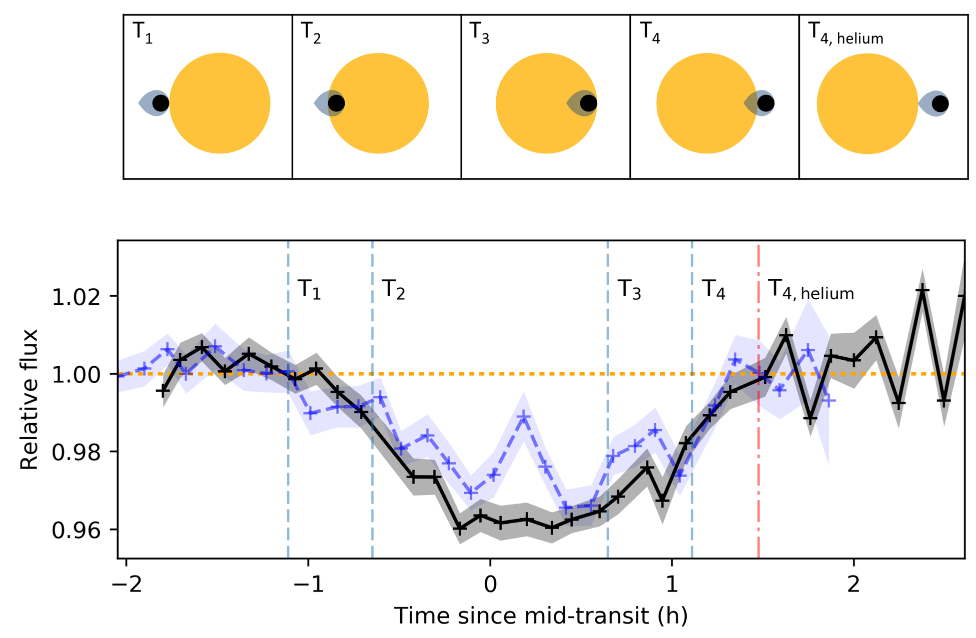
What can we learn from resolving (helium) absorption lines spectrally and over time?

At the high-resolution of CARMENES (approx. ~80000) the cores of individual lines in the planet atmosphere can be resolved and their position can be determined precisely, allowing us to draw conclusions about the wind speed of the absorbing gas.

Resolved over the phase of the transit, e.g. at ingress and egress, we can determine velocities at the planet terminator and probe for effects such as global circulation patterns.

On the right we show an example for the helium triplet lines at 1083 nm in warm Saturn-mass planet WASP-69b. Helium in particular probes the upper atmosphere and potential atmospheric escape. However, other lines originating from deeper in atmosphere can be probed in a similar manner.

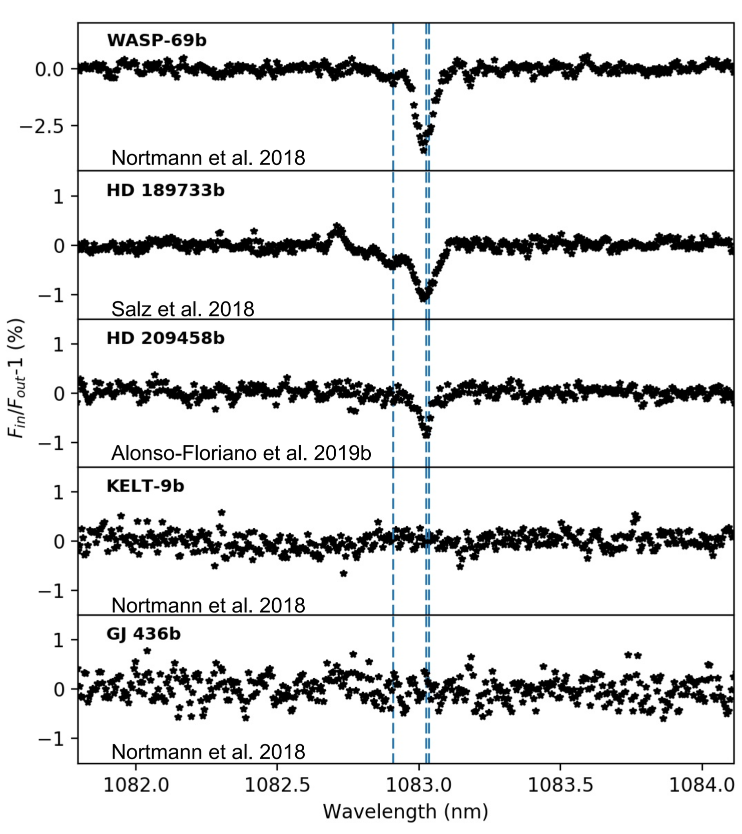


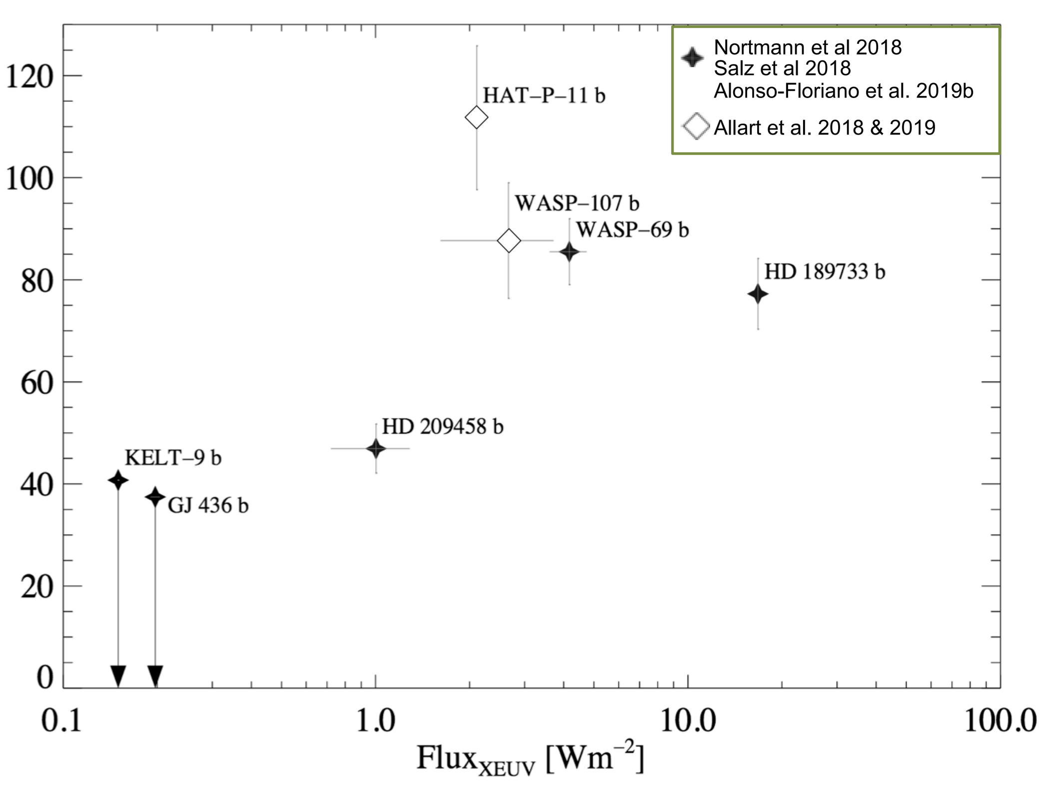


Left: The shape of an absorption line, i.e. depth, width, and symmetry as well as its Doppler shifted position can give us insights into the dynamics of the gas. For the Saturn-mass planet WASP-69b we find that the helium absorption lines at 1083 nm are blue-shifted during mid-transit, corresponding to a net velocity of 3.6 km/s towards the observer. Investigating the feature in time, we find that there is no blue-shift during ingress but that it is larger during egress at a net velocity of -11 km/s.

Right: We further find that absorption is still present after the last contact of the planet transit (T_4). The light curves for both nights of observation for this target show the post transit absorption to last up to 22±3 min after the egress.

From a small sample towards comparative science





Left: We detect the features in the Saturn-mass planet WAP-69b, and the hot Jupiters HD189733b and HD209458b and derive upper limits for the ultra-hot Jupiter KELT-9b and the Neptune-size planet GJ436b (Nortmann et al. 2018, Salz et al. 2018, Alonso-Floriano et al. 2019).

Right: The depth of the feature varies between planets; we calculate the equivalent height of the helium envelope δ_{Rp} after normalizing it by the atmospheric scale height of the lower atmosphere H_{eq}, also including measurements by other groups (Allart et al. 2018, 2019). We show δ_{Rp}/H_{eq} vs. the XEUV flux < 50.4nm received by each planet (Figure adapted from Alonso-Floriano et al. 2019) .

References: Nortmann et al. 2018, Science, 362, 1388; Salz et al. 2018, A&A, 620, 97; Alonso-Floriano et al. 2019, A&A, 629, 110; Allart et al. 2018, Science, 362, 1384; Allart et al 2019, A&A, 623,58

We have probed five planets for absorption of the helium triplet (see Figures on the left). Furthermore, we investigated the XEUV spectra of all systems. The small but growing sample hints at a correlation between the strength of the He I absorption with the stellar X-ray and extreme UV flux received by the planet. Increasing the size of our sample to cover a wide range of received XUV flux and other planet parameters such as planet density and comparing results to theoretical predictions will help to unveil formation processes of this line in atmospheres of exoplanets and possibly help to understand planet evaporation.

Synergy with ARIEL

The results obtained with CARMENES highlight that ground-based high-resolution observations of exoplanet atmosphere lines can contribute valuable complementary information to the measurements that will be obtained by ARIEL at lower resolution and which in turn will provide robust measurements of the continuum absorption.

High-resolution observations will be obtained for a subsample of the ARIEL targets from current medium-sized and future large and extremely large facilities and will provide further insights into the nature of specific benchmark objects.

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