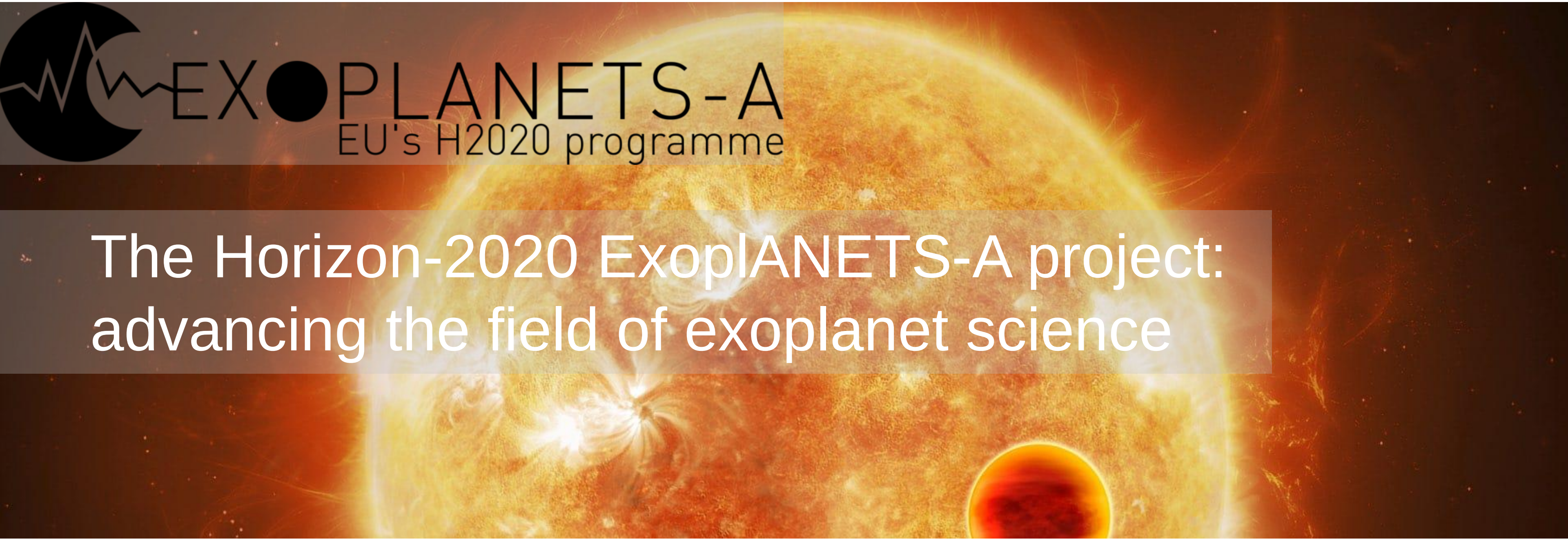

The Horizon-2020 ExoplANETS-A project: advancing the field of exoplanet science

Fred Lahuis, Jeroen Bouwman, Pierre-Olivier Lagage (PI),
Marine Martin-Lagarde, Michiel Min, Ingo Waldman
and more

ExoplANETS-A: CEA Saclay, Paris, France; CAB-INTA, Madrid, Spain; MPIA, Heidelberg, Germany; University College London, U.K.; University of Leicester, U.K.; SRON, Utrecht, NL; Universität Wien, Austria

SRON

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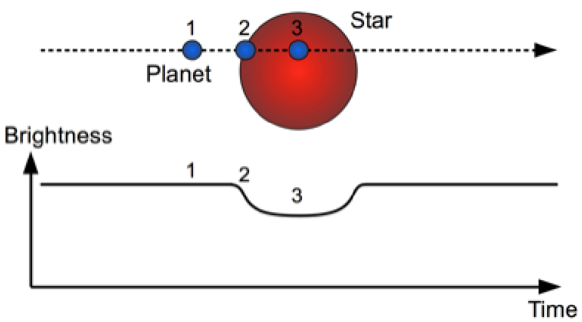
Netherlands Institute for Space Research

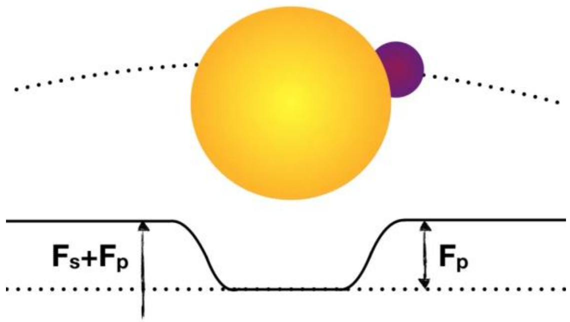
Netherlands Organisation for Scientific Research (NWO)

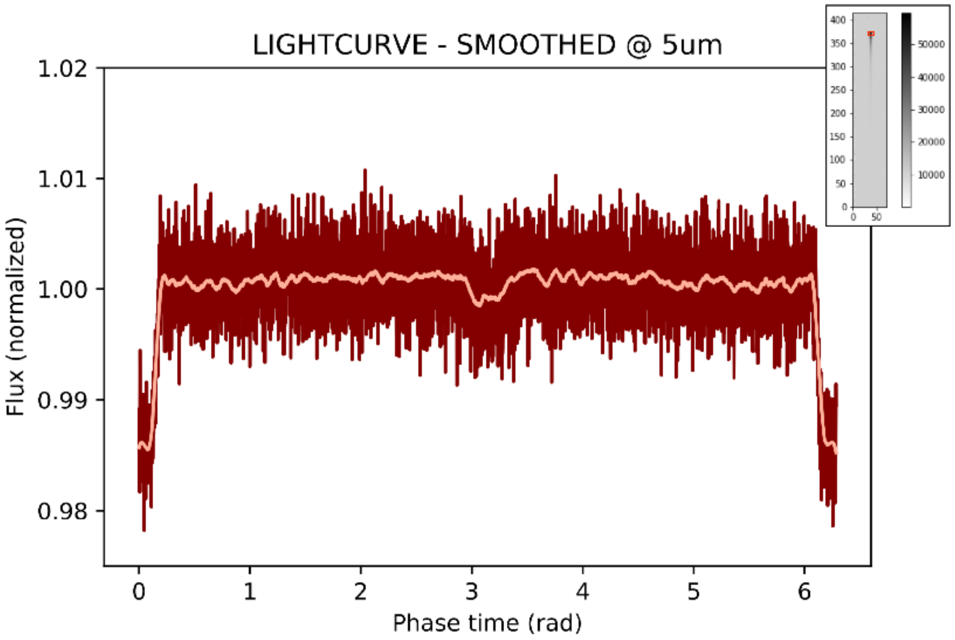
Project objectives

- To establish new knowledge on the atmosphere of exoplanets by exploiting archived space data (HST, Spitzer, Kepler)
  - Develop novel data reduction methods
    - Produce a homogeneous set of exoplanet spectra from HST and Spitzer archives
  - Improve ‘classical’ atmosphere parameter retrieval approaches
    - simultaneously deal with transmission and emission observations
    - combining data reduction and retrieval models
  - Use the novel data reduction and retrieval tools to prepare the analysis of JWST observations
    - In particular conducted in the framework of the JWST Early Release Science program
- To establish new insight on the influence of the star on the planet atmosphere
- To disseminate knowledge, which consists of our WP science products, public outreach and educational resources

Exoplanet observations







Simulated JWST ERS phase-curve observation of WASP43-b with the MIRI-LRS instrument.
Martin-Lagarde (2019)

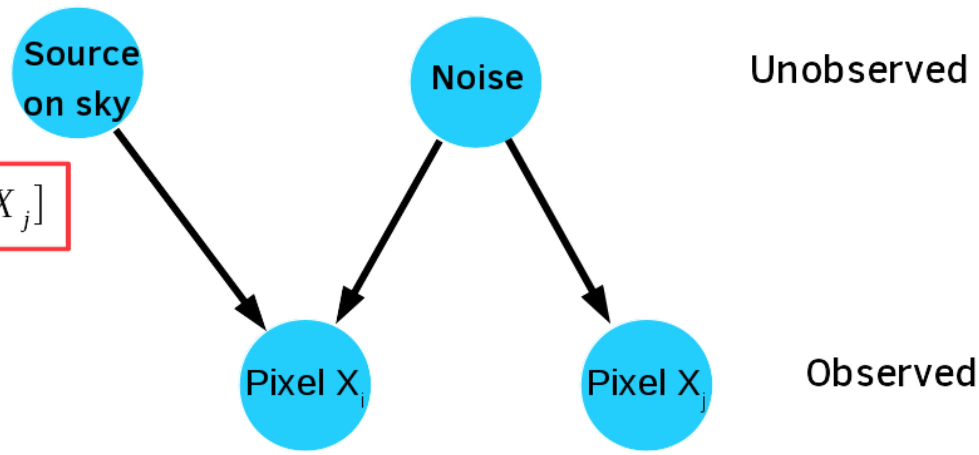
Data reduction

- Data reduction of transiting exoplanet observations is notoriously difficult
  - Weak planet signal
  - Correlated noise and instrument systematics dominate
- Requires
  - High precision calibration
  - Detailed modeling of the instruments
  - modeling of the noise using methods like principle component analysis or Gaussian processes
  - (Simultaneous) observations of many reference stars
- Limitations
  - Assumption made in calibration / modeling
  - Variation in systematics from observation to observation
  - Most data are single object spectroscopic time-series observations
  - No simultaneous reference stars

Causal pixel model

- “data driven” analysis method
- Pioneered by Schoelkopf et al. (2016)
  - Applied to e.g. Kepler multi-object photometry
- For ExoplANETS-A we adopted this to work for single object spectroscopic time-series observations
  - !! calibrate the data at any given wavelength by constructing a regression model using the data at all other wavelengths
- Consistent and efficient

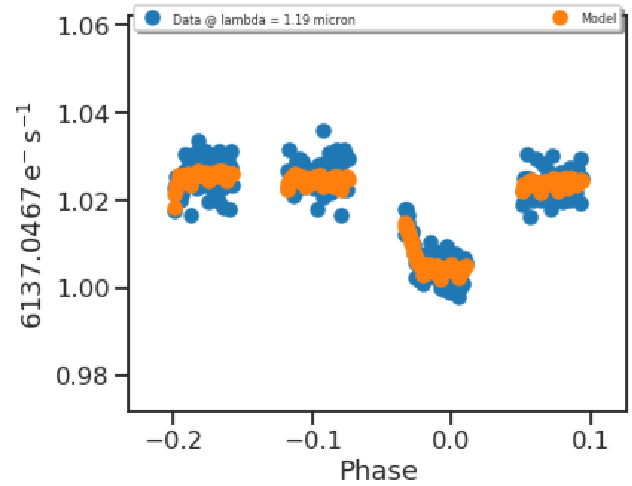
$$\hat{I} = X_i - E[X_i | X_j]$$

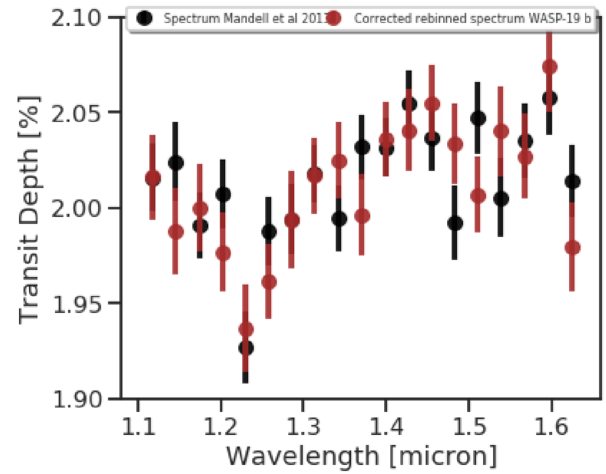


ExoplANETS-A implementation

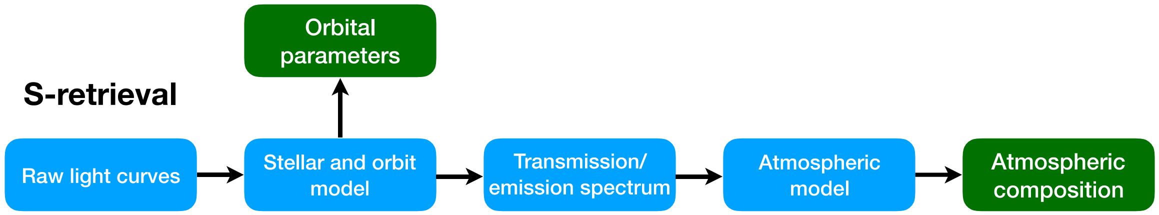
- Works for Spitzer and HST observations
  - Slit and slitless observations
  - High S/N and low S/N
  - Different types of systematics
- Validated against published results
- Validated with Spitzer observation with a chance observation of a star in one of the IRS PU fields

- Ready to apply to
  - all available Sitzer and HST data
  - JWST simulations

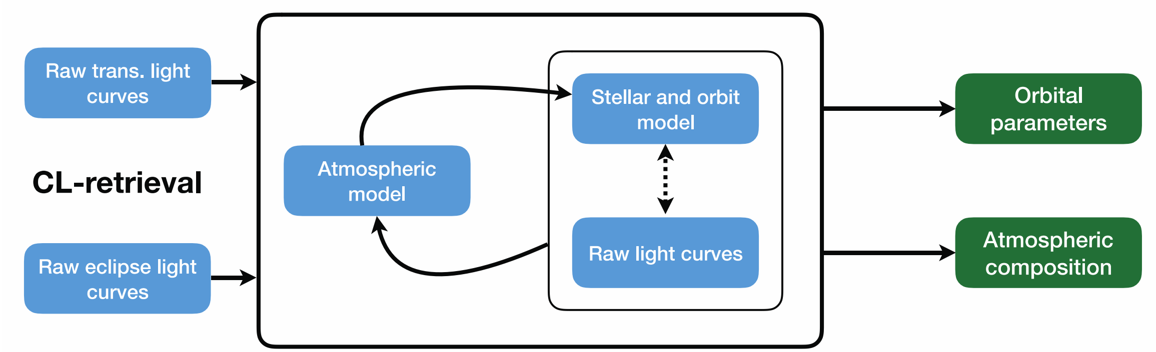




Parameter retreival



- Classic retrieval scheme (Spectral or S-retrieval)
  - Light curves are first converted to spectra.
  - The transmission and eclipse spectra are then fitted independently
- New scheme (Combined Lightcurve or CL-retrieval)
  - The retrieval is performed directly on the raw lightcurves for eclipse and transmission simultaneously.
  - The uncertainties of the spectral extraction are automatically taken into account in the parameter retrieval.



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EXOPLANETS-A
EU's H2020 programme

The Horizon-2020 ExoplANETS-A project: advancing the field of exoplanet science

Fred Lahuis, on behalf of the ExoplANETS-A consortium*

Since the 1990s, astronomers have been detecting planets around stars outside our Solar System: we call them "exoplanets" or "extrasolar planets". In 2019, observations have led to more than 4000 exoplanet candidates with an impressive diversity.

Their distance to the host star and their mass give a first indication of potential habitability. It's time to go a step further and investigate their atmosphere for learning about their molecular composition, searching for biosignature gases and retracing their evolution.

This project aims to provide the community with scientific and educational resources that have been collected and developed by the European Exoplanets-A project: archival data, exoplanet and host star parameters, novel methods and tools for characterizing exoplanet atmospheres, as well online courses, serious games and data visualization.

ExoplANETS-A (**Exopl**anet **A**thmosphere **N**ew **E**mission **T**ransmission **S**pectra **A**nalysis) is organized around six work packages. Here we focus on two of these.

- WP1, Management
- **WP2, Data reduction methods**
- **WP3, Parameter retrieval techniques**
- WP4, Host-star properties
- WP5, Science interpretation
- WP6, Knowledge management

The first year of the project had a strong focus on the development of new techniques and collecting data. The coming year will focus on data reduction, retrieval and science interpretation.
See http://exoplanet-atmosphere.eu/ for more information.

Spectral retrieval

In the retrieval scheme now often used, the raw lightcurves are transformed into eclipse and transmission spectra by fitting the orbital elements of the planet. As a next step the retrieval is performed on the obtained spectrum (see Fig 1). The disadvantage of this approach is that the uncertainties on the orbital elements can only be partly accounted for in the final parameter retrieval for the atmospheric composition. In Yip et al. (2018) a new approach is investigated combining the retrieval of orbital and atmospheric parameters. In the ExoplANETS-A project we want to go one step further, combining the eclipse and transmission spectra of an exoplanet (see Fig 2). These spectra probe different layers in the atmosphere and different longitudinal regions. Thus we have to include an inhomogeneous exoplanet atmosphere and define the relations between the different atmospheric regions. We do this using chemical and physical models for the abundances of the molecules and the presence and characteristics of possible cloud layers. Our final aim is to investigate complex, inhomogeneous exoplanet atmospheres and obtain the physical and chemical characteristics in a robust way.

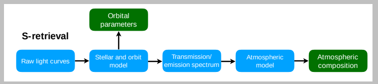


Fig 1. Classic retrieval scheme (Spectral or S-retrieval) where the light curves are first converted to spectra. The transmission and eclipse spectra are fitted independently.

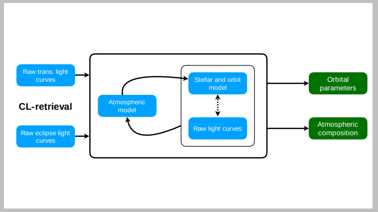


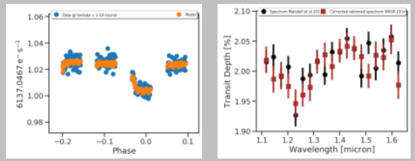
Fig 2. New scheme (combined lightcurve or CL-retrieval) where the retrieval is performed directly on the raw lightcurves for eclipse and transmission simultaneously. The uncertainties of the spectral extraction are automatically taken into account in the parameter retrieval.

Data reduction

Data reduction of transiting exoplanet observations are notoriously difficult. The planet signal is extremely weak while (correlated) noise and (instrument) systematics can be an order of magnitude larger and also may vary from observation to observation.

Within the ExoplANETS-A project we decided, therefore, to pursue a novel "data driven" analysis method based on causal connections within the data as pioneered by Schoelkopf et al. (2016). We adopted this to calibrate single object spectroscopic time-series observations. This is an important step, as future missions like JWST and current instruments on HST generally only provide single object data without simultaneous reference star observations to calibrate the data.

The key step in our implementation is to calibrate the data at any given wavelength by constructing a regression model using the data at all other wavelengths rather than using the data of reference objects.

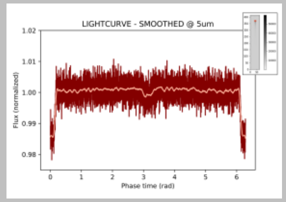


The left panel shows the observed flux-density as a function of orbital phase (blue dots) and the fitted regression model (orange dots) for the HST/WFC3 observations of WASP 19b for a single spectral channel at 1.19 μm. The right panel shows the extracted transmission spectrum of WASP 19b (red squares) compared to published results from Mandell et al. (2013, black circles).

Data simulations

An important project goal was to apply our novel data reduction and retrieval techniques to JWST Early Release Science (ERS) data. However recent JWST launch delays results in ERS data being observed not before late 2021, well after project closure.

To compensate we developed a simulator, ExoNoodle, to generate time-series spectra of star-planet systems. Special attention is taken to calculate precisely ingress and egress. It includes contributions from stellar limb-darkening, day and night emission, planet reflection spectra (Albedo) and planet transmission spectra ($R_p/R_*(\lambda)$). ExoNoodle works in combination with a dedicated instrument simulator.



Simulated JWST ERS phase-curve observation of WASP43-b with the MIRI-LRS instrument. The raw synthetic data at 5 μm is plotted at full cadence with a smoothed curve overplotted for clarity. The insert shows the MIRI-LRS slitless image, with the small box showing the 5 μm bin.

See Martin-Lagarde (2019, EPSC-DPS 13) for more details.

Fred 

*CEA Saclay, Paris, France; CAB-INTA, Madrid, Spain; MPIA, Heidelberg, Germany; University College London, U.K.; University of Leicester, U.K.; SRON, Utrecht, NL; Universität Wien, Austria
Exoplanet Atmosphere New Emission Transmission Spectra Analysis; https://cordis.europa.eu/project/rcn/212911/en
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