RETRIEVAL OF ATMOSPHERIC PROPERTIES FOR HABITABLE PLANETS

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Introduction: Several potentially habitable super-Earths in or very close to the habitable zone of their central star have been found already. The next step would be to search such potentially habitable worlds for indications of the presence of life, so-called biomarkers. Such biomarkers are atmospheric spectral signatures of, e.g., ozone or water. Dedicated exoplanet space mission concepts have been proposed to ESA or NASA with the ultimate aim to characterize the atmospheres of exoplanets (e.g., Darwin, EChO). The main challenge is to retrieve information about the atmospheric parameters from the noisy data. Such retrieval studies could provide valuable clues to instrument design. Therefore, we present a study of the possible retrieval of atmospheric and planetary parameters for hypothetical habitable terrestrial planets from IR emission spectra around secondary eclipse. We illustrate the difficulties of atmospheric retrieval for habitable planets and quantitatively investigate the potential of planned or near-future space instrumentation to characterize habitable planets.

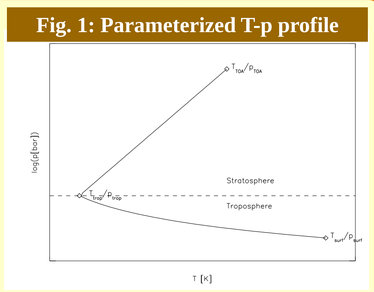
Conclusions:

- **Surface conditions can be characterized relatively well (to within ~10K and a few bars at 3σ) with S/Ns between 10 and 30.**
- **Detection of O_3 remains marginal. H_2O content is not well constrained with current mission designs. Upon increasing the S/N by about a factor of 2−5 compared to current mission designs, the CO_2 content could be characterized to within two orders of magnitude.**
- **The temperature structure could not be retrieved.**
- **Single-visit emission spectroscopy alone is most likely not capable of characterizing the atmospheres of potentially habitable planets. Emission spectroscopy must be combined with transmission spectroscopy, phase curves or photometry in the visible spectral range.**

Forward model

- **Atmospheric model:** 8 parameters (mass, O_3, H_2O, CO_2, T_{surf} , T_{TOA}, p_{surf}, p_{trop}). H_2O controlled by T-dependent vapor pressure, CO_2, O_3 are isoprofiles, troposphere convective (H_2O condensation), N_2 as background gas
- **Radiative transfer model:** line-by-line code [2], H_2O, N_2 and CO_2 continua, Hitran 2008 data
- **Observational model:** target at 10pc, 1hr integration time, 10m² detector, constant Gaussian noise, correction factor to reach arbitrary S/N

Fig. 1: Parameterized T-p profile



Inverse model

- Automated nonlinear least squares solver (Levenberg-Marquardt): Gradient-based algorithm to locate global χ^2 minimum
- p values and reduced χ^2_{red} for fit quality: Assess false-alarm probability of resulting best-fit parameters
- χ^2 maps of parameter space: uncertainties from distance to χ^2_{min} to illustrate degeneracies.

Model scenarios:

We use modern Earth as an example for an inhabited planet. For simulated observations, we use specifications for the proposed EChO mission [3] as well as suggested Darwin science aims [4,5] in terms of spectral resolution and S/N. Fig. 2 shows the parametrized (values in Table 1) temperature and water profiles (black) compared to modern Earth (red). Fig. 3 shows the modeled spectra with EChO and Darwin specifications (spectral range 5-20μm).

Table 1: Target parameters

T_{TOA} [K]	270
T_{surf} [K]	290
p_{trop} [bar]	0.3
p_{dry} [bar]	1.0
humidity	0.5
CO_2 vmr	3.55×10^{-4}
O_3 vmr	10^{-7}
m_P [$M_\oplus$]	1.0

Fig. 2: Model and modern Earth profiles

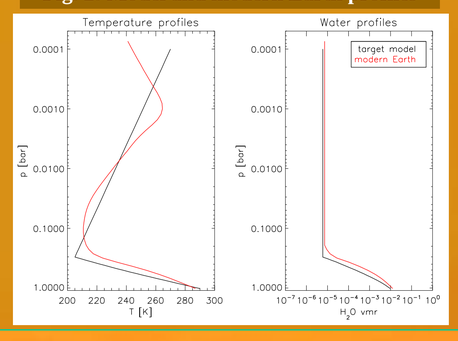


Fig. 3: Example model spectra

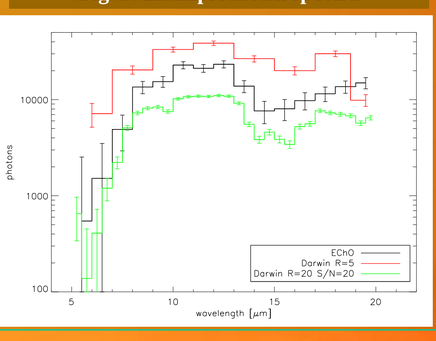


Fig. 4: T_{surf}-p_{surf} χ^2 maps for EChO (R=10, S/N=5)

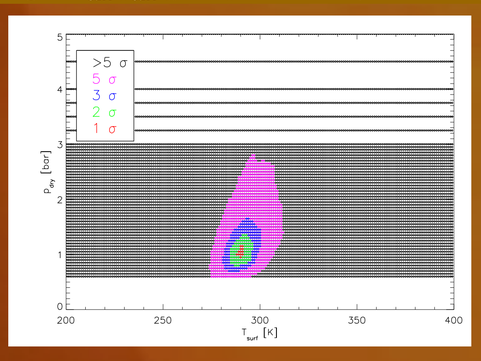


Fig. 5: CO_2-H_2O χ^2 maps for EChO (R=10, S/N=5)

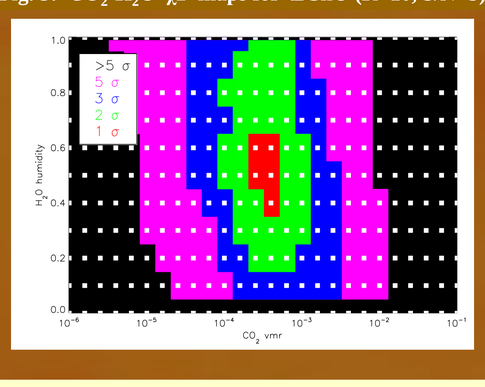


Fig. 6: CO_2-O_3 χ^2 maps for EChO (R=10, S/N=5)

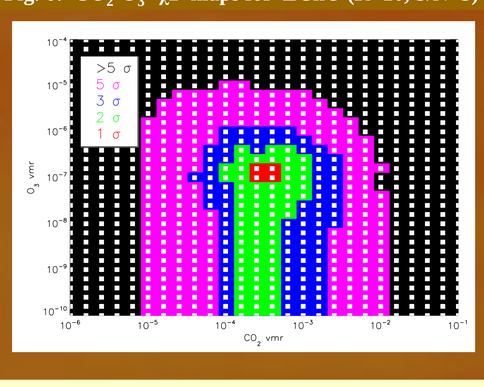
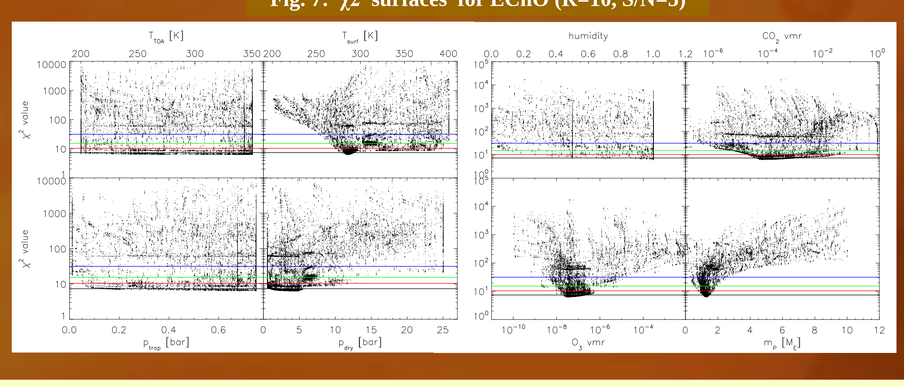


Fig. 7: χ^2 surfaces for EChO (R=10, S/N=5)



Results (EChO specifications):

Figs. 4-6 show the maps of χ^2 for surface conditions (4) and atmospheric composition (5,6) when keeping all other parameters fixed. Although surface conditions indicating possible habitability were found with relatively high confidence, atmospheric composition could not be characterized. H_2O and O_3 are only marginally detected at less than 2σ. The CO_2 content is only weakly constrained within a few orders of magnitude. Fig. 7 shows the χ^2 surfaces for all fit parameters as calculated by the least-square solver when simultaneously fitting all 8 parameters. Atmospheric composition and surface conditions are only weakly constrained. No constraints on temperature structure could be inferred.

Fig. 8: As Fig.4, but for Darwin (R=5, S/N=10)

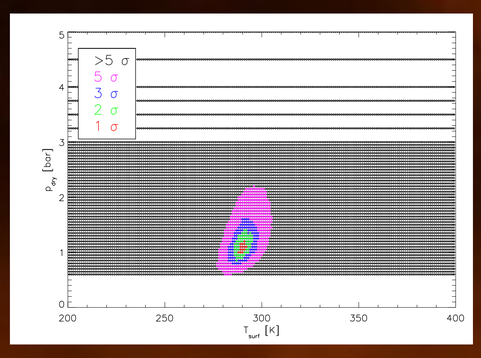


Fig. 9: As Fig.5, but for Darwin (R=5, S/N=10)

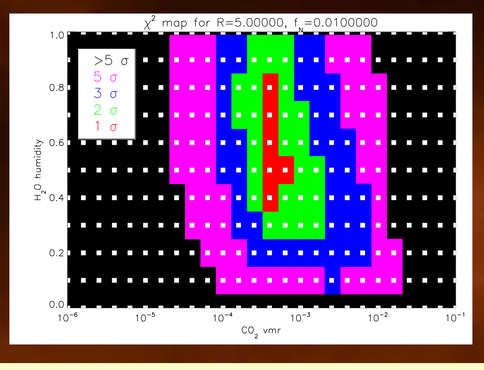


Fig. 10: As Fig.6, but for Darwin (R=5, S/N=10)

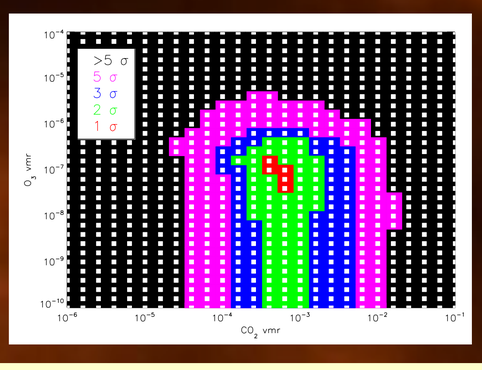
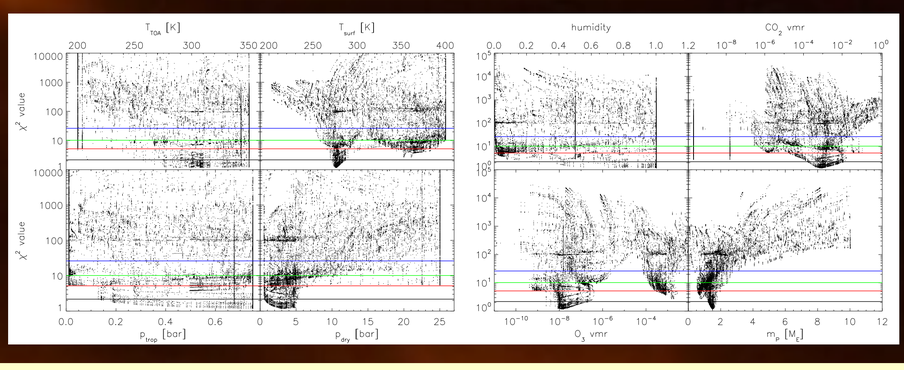


Fig. 11: As Fig.7, but for Darwin (R=5, S/N=10)



Results (Darwin specifications):

Figs. 8-10 show the maps of χ^2 for surface conditions (8,9) and atmospheric composition (10) when keeping all other parameters fixed. Again, surface conditions indicating possible habitability are found with high confidence. As for EChO, atmospheric composition could not be characterized. H_2O and O_3 are only marginally detected at less than 2σ. The CO_2 content is only weakly constrained within orders of magnitude. Fig. 11 shows the χ^2 surfaces for all fit parameters as calculated by the least-square solver when simultaneously fitting all 8 parameters. The existence of local minima and degeneracies is clearly illustrated. Again, no constraints on temperature structure could be inferred.

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References:
(1) v. Paris et al. (2013), A&A 551, A120 (2) Schreier& Böttger (2003), Atmos. Ocean. Optics, 16, 262 (3) Tinetti et al. (2012), Exp. Astronomy, 34, 311 (4) Léger et al. (1996), Icarus, 123, 249 (5) Cockell et al. (2009), Exp. Astronomy, 23, 435