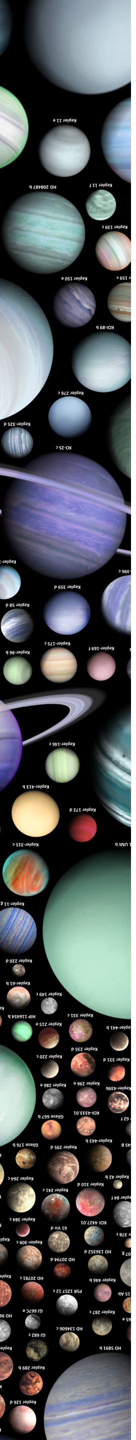
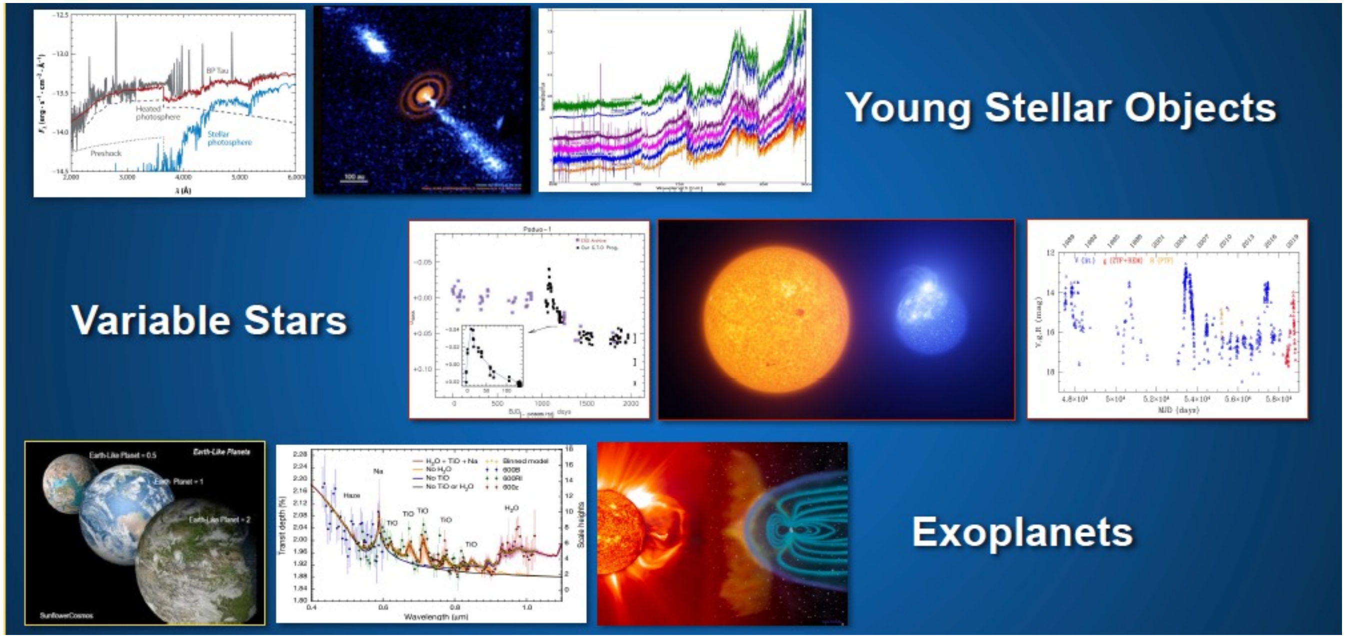
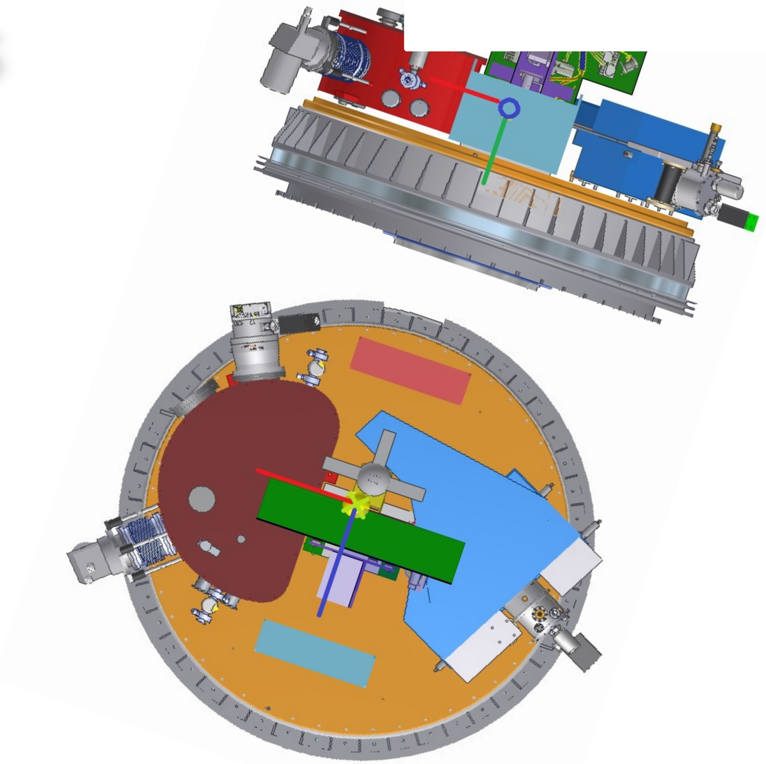
SOXS Consortium Science Meeting
Naples, 25 - 27 June 2024

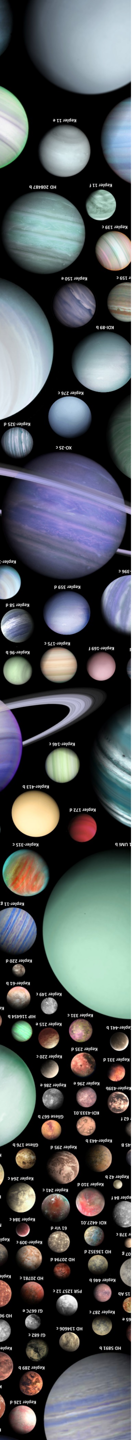


WG2 - Stellar variability, Exoplanets & Young Stellar Objects





WG Leader: Isabella Pagano, INAF–OA Catania
WG Deputy: Juan Alcalà, INAF–OA Capodimonte



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ISTITUTO NAZIONALE DI ASTROFISICA
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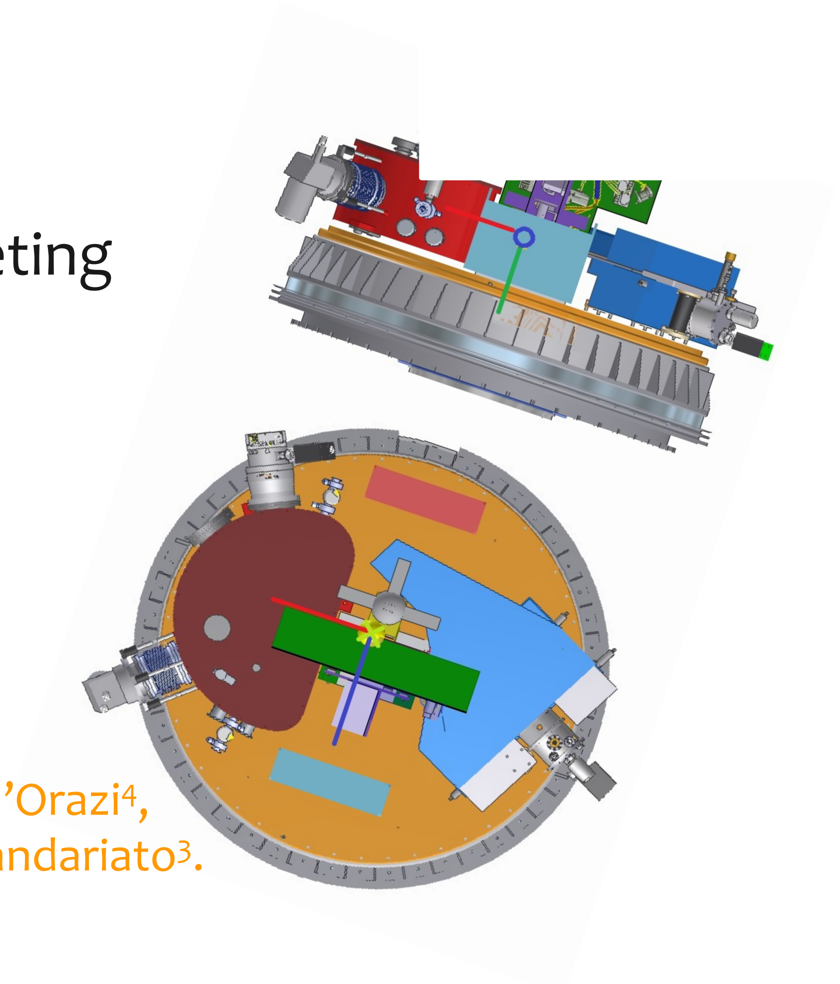


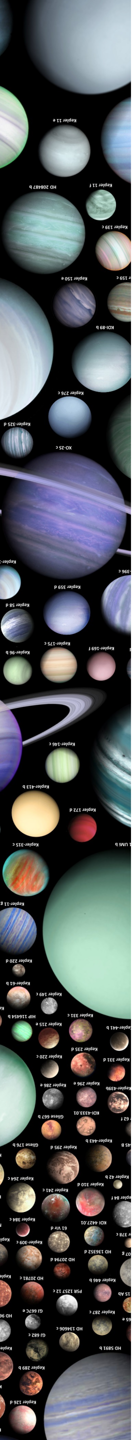
WG2: Exoplanets

Team:

J. Alcalà[1], F. Borsa[2], G. Bruno[3], R. Claudi[4], E. Covino[1], S. Desidera[4], V. D'Orazi[4], A.F. Lanza[3], G. Leto[3], M. Montalto[3]; V. Nascimbeni[4], I. Pagano[3], G. Scandariato[3].

External Co-I: G. Micela[5], R. Spinelli[5]

1) INAF-OA Capodimonte; 2) INAF-OA Brera; 3) INAF- OA Catania; 4) INAF-OA Padova; 5) INAF-OA Palermo



Exoplanet contest

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- **Thousands of exoplanets discovered over the past decade**
  - Including discoveries of potentially habitable planets around nearby low-mass stars.
  - Huge diversity of planets and planetary systems
  - Efforts going on to reckon theories for formation and evolution with observables
- **The field is rapidly progressing**
  - detailed spectroscopic observations to characterize the atmospheres of these planets.
- Various surveys from space and the ground are detecting and are expected to detect numerous more exoplanets orbiting nearby stars
  - **Transiting exo-planets** are good targets for atmospheric characterization, habitability, biomarkers.

SOXS and Exoplanets

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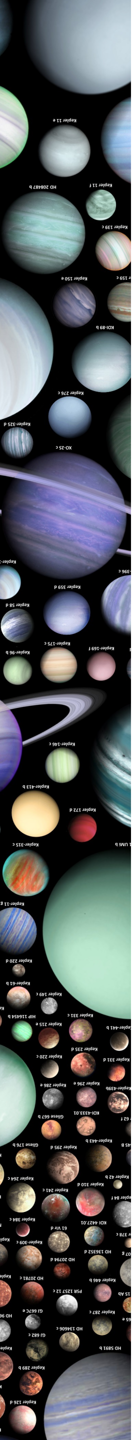

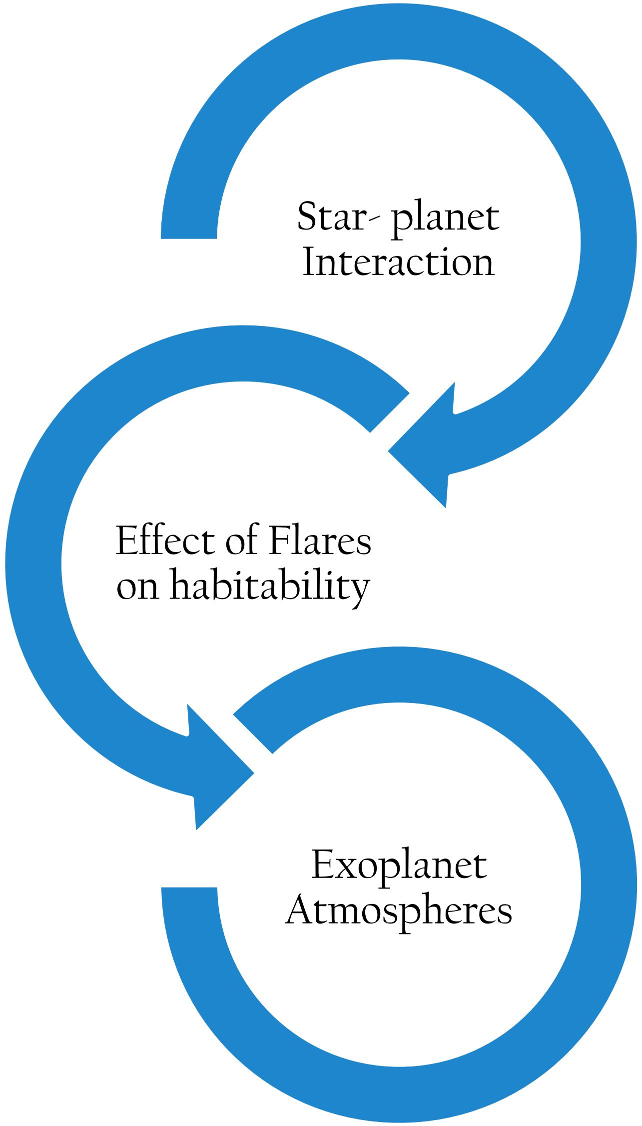

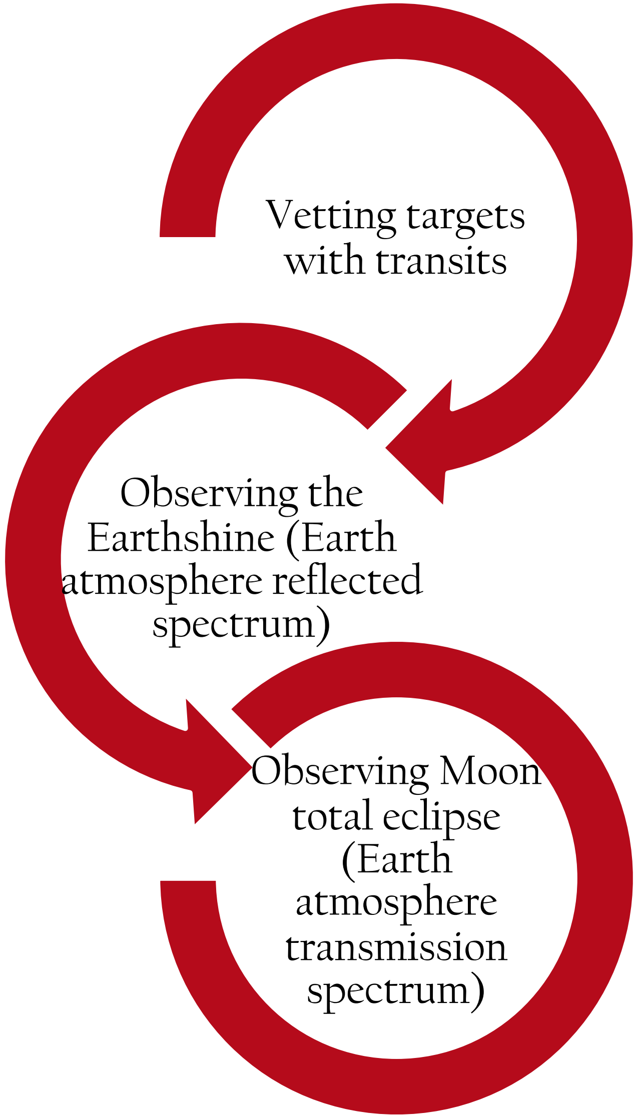

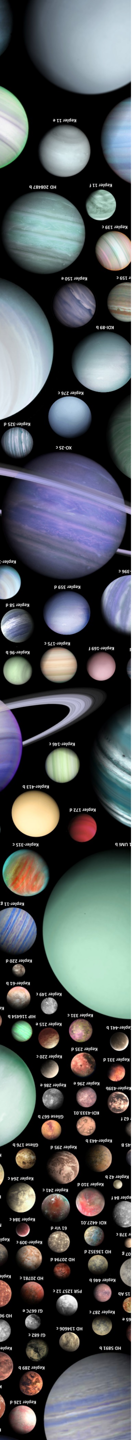

Star Planet Interaction (SPI)

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Gravitational interaction

⇒ Planet deformation, internal heating, orbit circularization, spin axis alignment

MHD Interactions

⇒ Magnetic activity phenomena, accretion and transfer of angular momentum

Wind-magnetosphere SPI

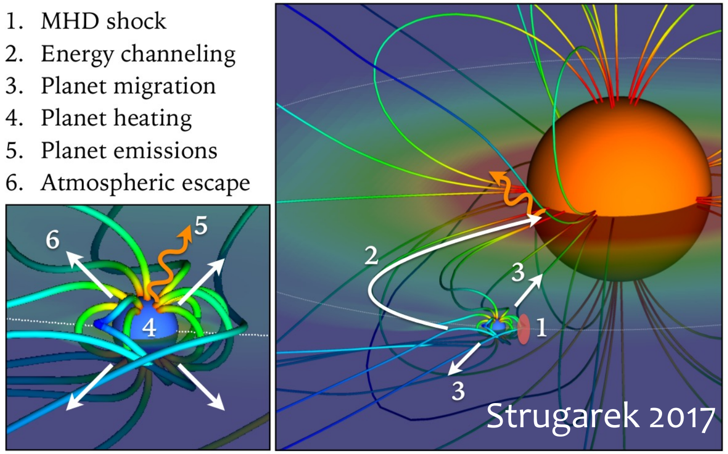
⇒ Magnetic storms and space-weather effects

⇒ Outflows/inflows

Irradiation

⇒ Ionosphere generation, Chemical process, heating and evaporation of planetary atmospheres

Interaction with the host star drives atmospheric escape in close-in exoplanets and shapes the morphology of the escaped material (cf. A. Oklopčić)



SPI model predictions

- Magnetic SPI expected within one day from periastron
- Energy release predicted in the range $10^{27} – 10^{28}$ erg/s (Lanza 2013)
- Expected increase of Lx by a factor 2–10

SPI observations

- Increased chromospheric emission, at periastron, e.g. Ca II H & K line core, coherent with brightening in X-rays (e.g., Maggio et al. 2015)

SOXS challenge for SPI studies

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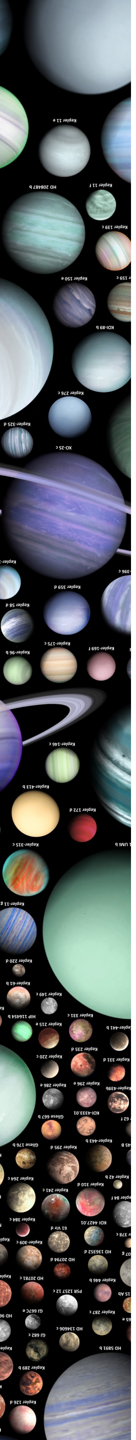
- SPIs have been observationally difficult so far
  - ⇒ Opt/UV/X-ray monitoring programs of selected objects require coordinating ground-based Opt/NIR spectrographs and UV/X-ray space-borne instrumentation
- Search focused where we do expect major effects
  - ⇒ Hot Jupiters around young/active stars, especially those in highly eccentric orbits
  - ⇒ Search for phase-related variability of chromospheric lines
- Observation strategy
  - Option A
  - ⇒ Time-critical observations (periastron passages) of selected stars, relatively bright (V 8–10)
  - ⇒ Sequences of 10–30 m exposures at specific orbital phases, and about 10 epochs per object
  - Option B
  - ⇒ React to alerts… TBD

Overall request for the GTO: under definition

SOXS & exo-atmospheres

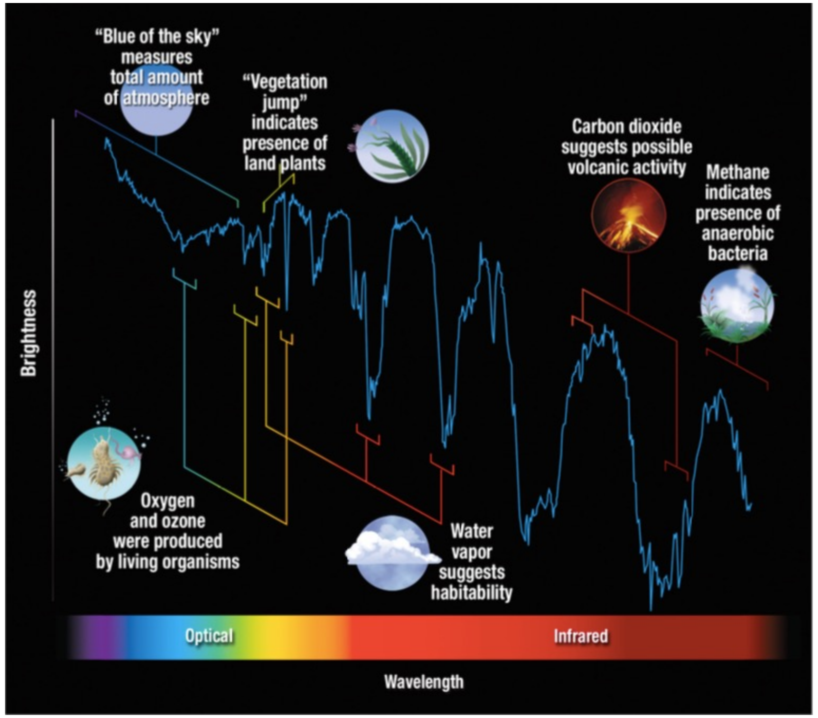


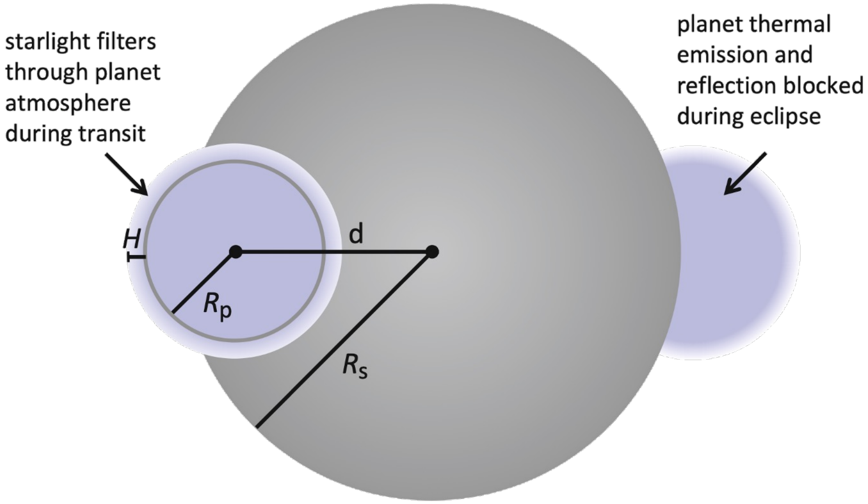
What exo-atmospheres tell us

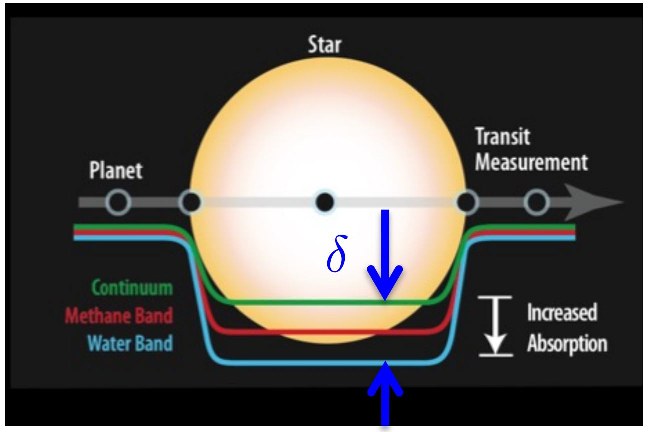
- Elemental abundances of exoplanetary atmospheres place important constraints on exoplanetary formation and migration histories.
- Recent studies reveal **a rich diversity of chemical compositions** and atmospheric processes hitherto unseen in the Solar System.

How to study exo-atmospheres

- Transmission and emission spectroscopy of transiting planets







Exo-atmospheres with SOXS-VIS&NIS

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Transmission spectroscopy of Hot Jupiter-type planets (HJs).

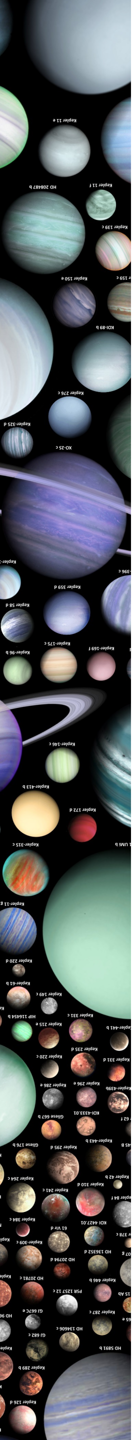
1) **Alkali metals**: NaI doublet at 589 nm and KI line at 770 nm. These lines mainly probe the thermosphere of the planet (huge cross section) and can be exploited as tracers of escape processes (Sing+ 2016)

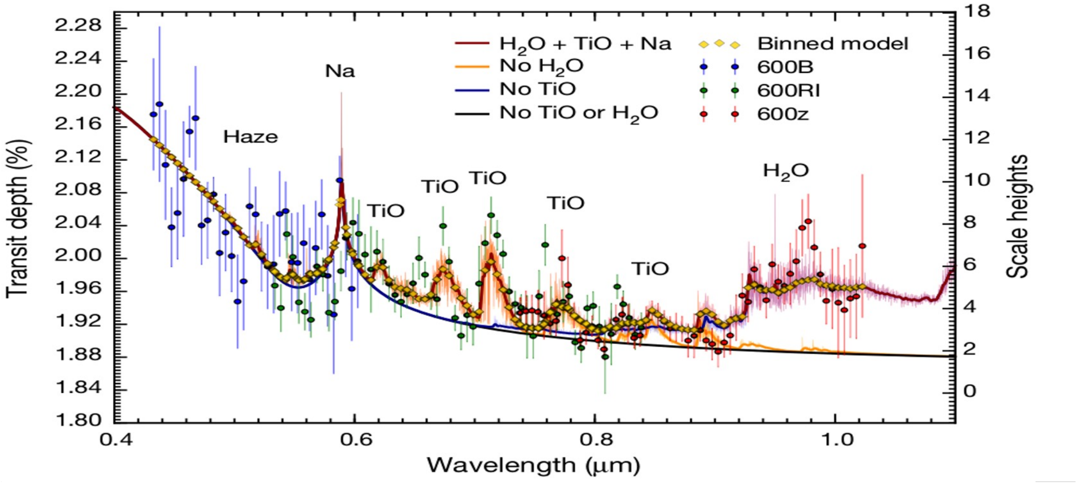
2) **Balmer series**, esp. H-α at 636 nm: hydrogen can be present as a tail in the evaporating planet (Cauley+ 2017)

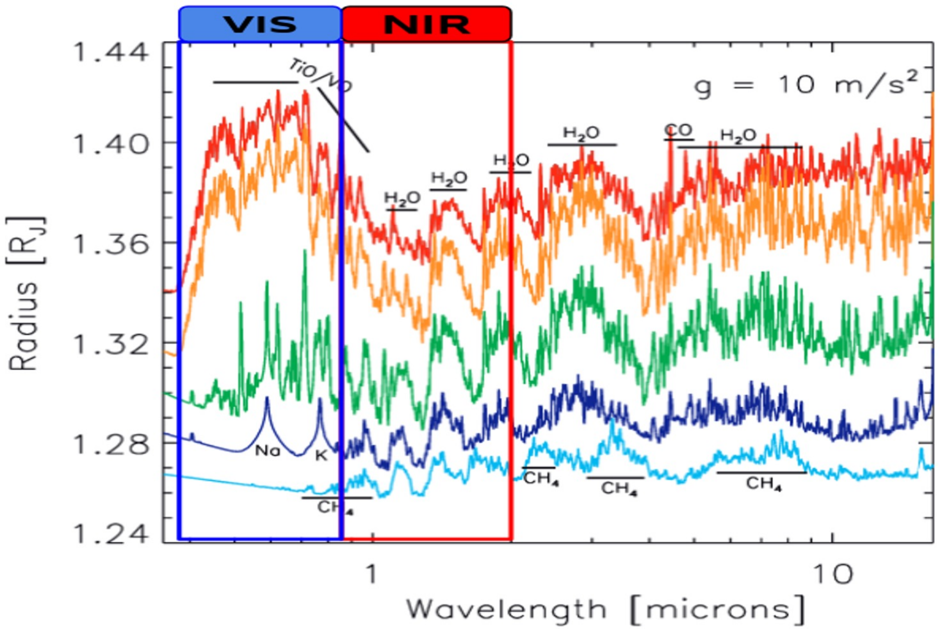
3) **Titanium Oxide (TiO) bands** in the 500-700 nm: thought to be the main optical absorber for very Hot Jupiters (>2000 K), hence fundamental to the thermal equilibrium of the planet (Sedaghati+ 2017)

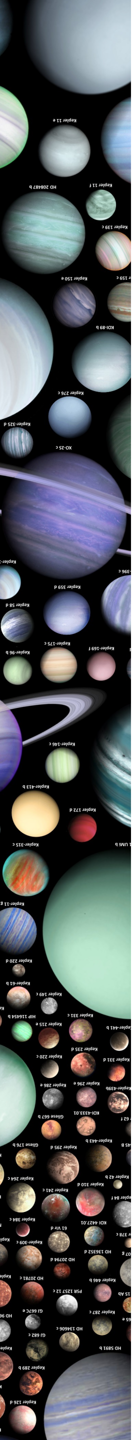
4) **Other less investigated species**, such as MgI at 510 nm and other metals (Astudillo+ 2013, Cauley+ 2018)

5) **The metastable He absorption line at a wavelength of 1083.3 nm** is a diagnostic to probe the escaping atmospheres of exoplanets (Seager + 2000 and Okplopčić & Hirata, 2018).









Spectrophotometry of transits

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Exoplanetary low-resolution transmission spectrum

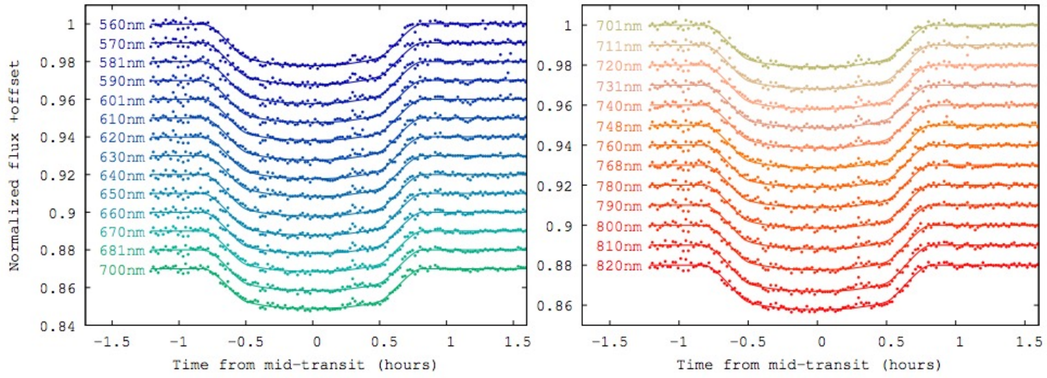
Planetary radius vs. wavelength, adapting “bandwidth” depending on S/N

VIS

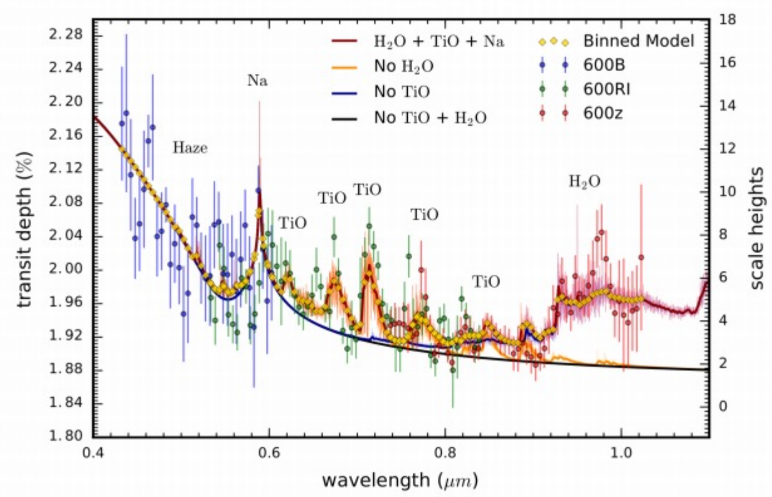
Clouds, hazes, particle size, Na, K, TiO, activity, temperature…

NIR

H2O, CO, CH4, He…



Pilot Study?



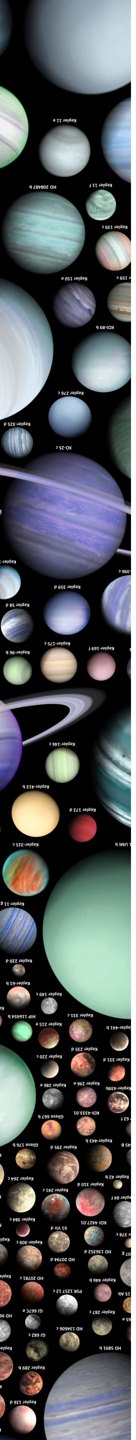
e.g., Sedaghati+17, Nature, 549, 238

Challenges

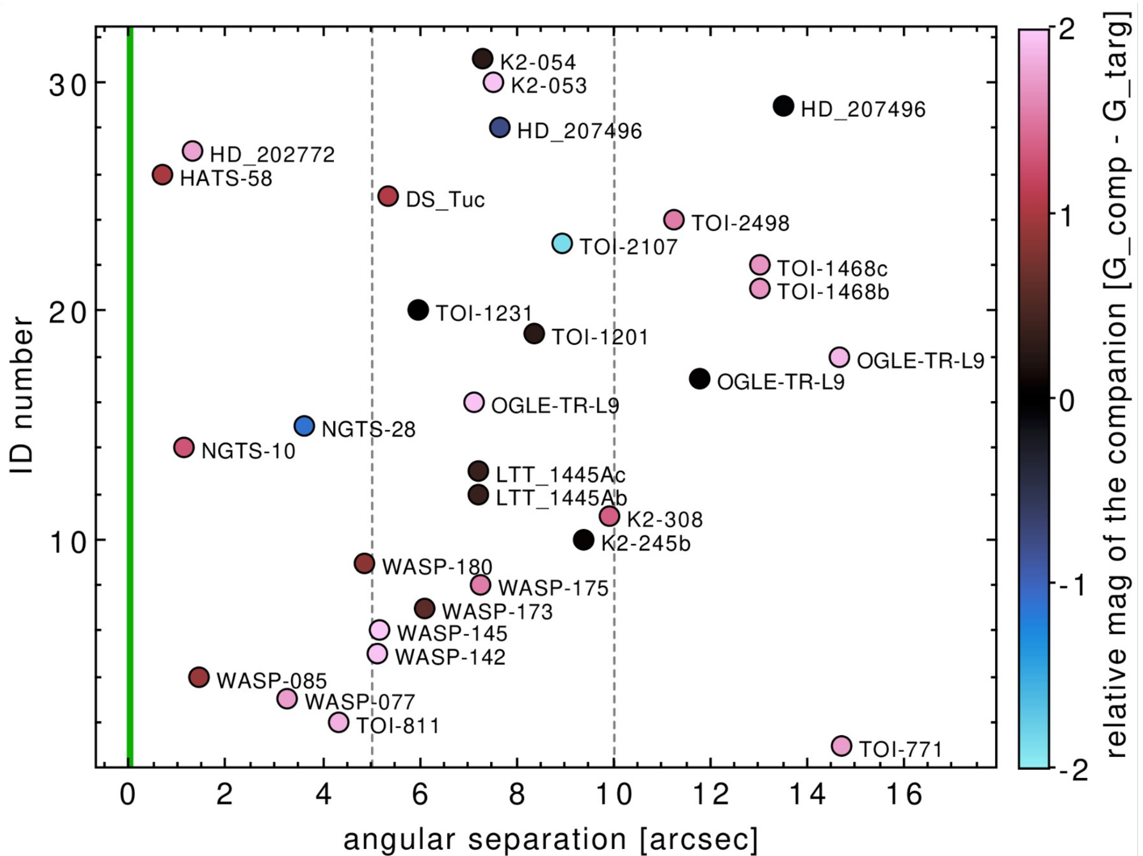
Telluric lines

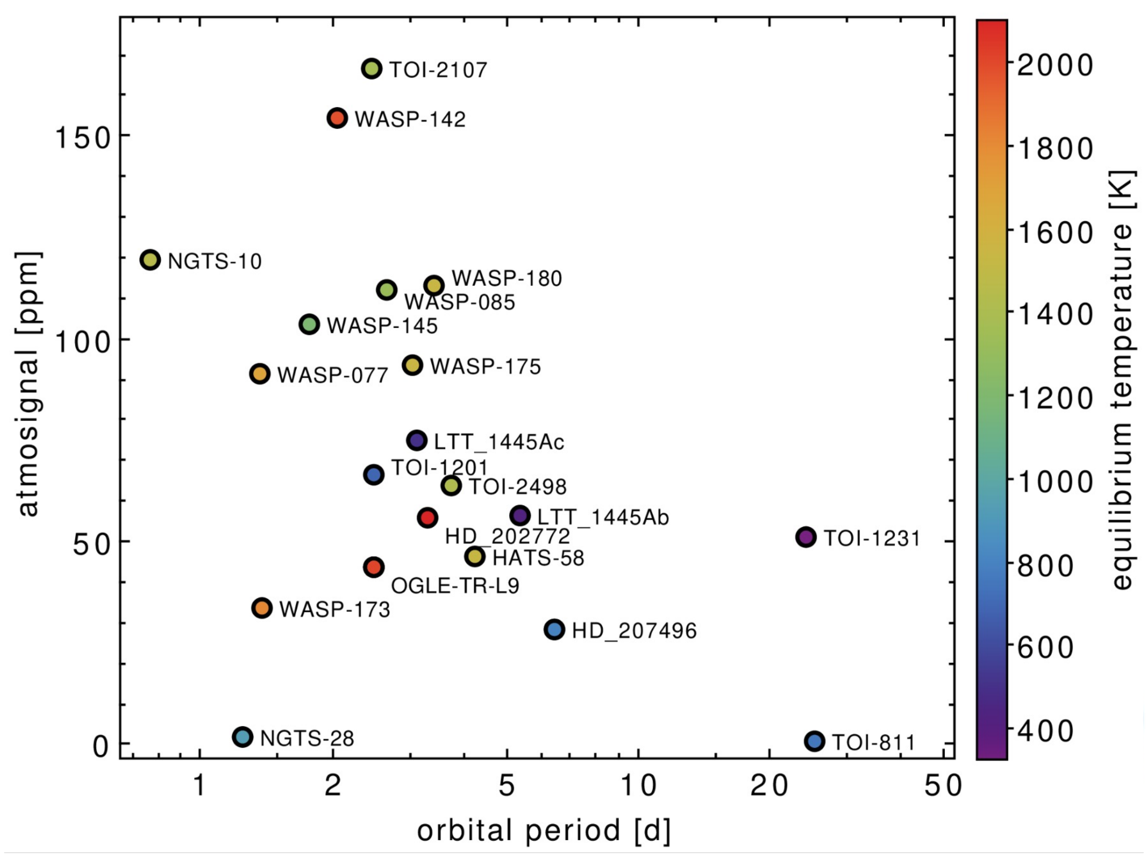
Limited to targets with a closeby similar reference star (need for both target+reference centered in the slit)

Finding suitable pairs with a transiting planet



Confirmed transiting planets (TEPCAT), visible from La Silla (DEC<+20°), reasonably bright (*V*<15), with at least one companion at <15″ in Gaia DR3 and with a |Δ mag| > 2 (in the Gaia *G* band). **31 entries**, but TOI-1231 is a matching error and LTT 1445A is repeated (2-planet system) -> **29 planetary systems.** *Separations <5″ could be difficult to deblend, separations >10″ could lead to unacceptable slit losses (the slit is ~12″ long)*





The best-positioned pairs after some vetting...

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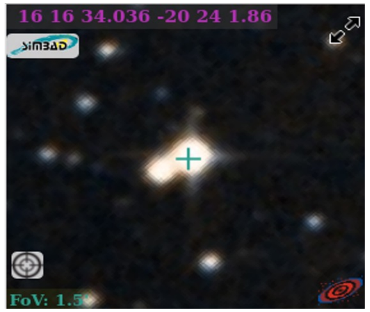
TOI-2107 🎯

TOI-1201

DS Tuc ⚠️

K2-54

K2-53

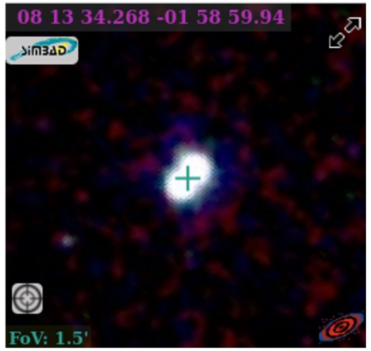


WASP-142 🎯 ⚠️

K2-245 ⚠️

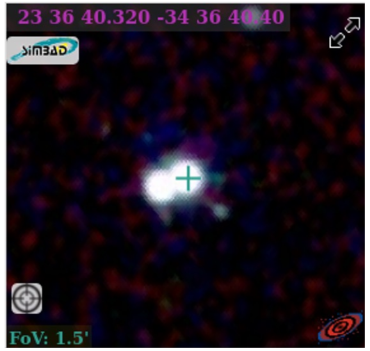
K2-308 ⚠️

WASP-180 🎯 ⚠️

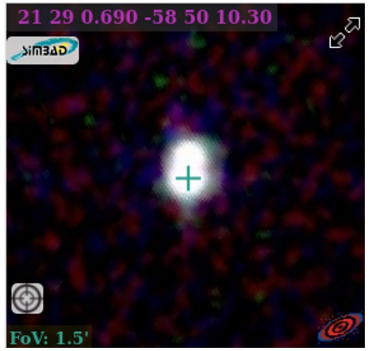


WASP-175 🎯

WASP-173



WASP-145 🎯 ⚠️



🎯 also a favorable signal in transmission; ⚠️ at or close the inner limit ~5", or the outer limit ~10"

Transit windows from La Silla, 2025

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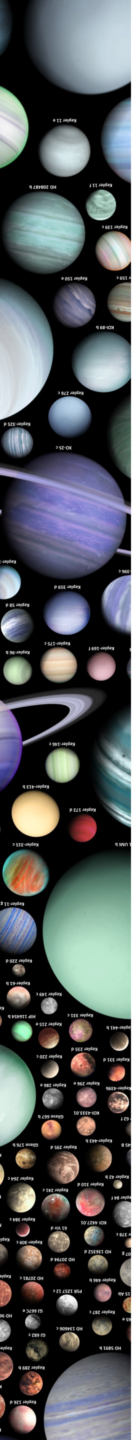
- Reasonable "good transits": at least full transit and 1h+1h off-transit at *h*>20° and no strong twilight; very bright nights filtered out
  - From about 3 to 7 hr per transit
- 66 transits visible in 2025 for eight planets: **WASP-145** (24), **WASP-173** (16), TOI-2107 (7), WASP-175 (7), WASP-142 (6), DS Tuc (3), K2-308 (2), WASP-180 (1).
- High density from July to September

NAME	EVE	HMIN	HSUNMAX
WASP-142	2025-01-20	50.31	-13.24
WASP-180	2025-01-22	40.55	-24.55
WASP-175	2025-02-01	38.4	-30.31
WASP-175	2025-02-04	59.59	-14.51
WASP-142	2025-02-22	45.8	-16.12
WASP-142	2025-02-24	52.31	-31.4
WASP-142	2025-02-26	34.07	-33.98
WASP-175	2025-03-19	50.66	-43.97
WASP-175	2025-03-22	29.22	-29.26
WASP-142	2025-03-31	53.79	-11.04
WASP-142	2025-04-02	35.5	-28.1
TOI-2107	2025-04-11	27.56	-20.68
WASP-175	2025-05-01	41.09	-28.91
WASP-175	2025-05-04	20.07	-49.84
TOI-2107	2025-05-08	40.96	-24.21
WASP-145	2025-05-10	32.1	-31.37
WASP-145	2025-05-26	25.46	-57.82
WASP-145	2025-06-02	43.03	-34.68
TOI-2107	2025-06-04	51.29	-27.14
WASP-145	2025-06-18	36.41	-60.61
WASP-173	2025-06-22	20.1	-34.64
WASP-145	2025-06-25	52.96	-37.16
TOI-2107	2025-07-01	38.39	-28.63
WASP-145	2025-07-02	46.97	-14.12
WASP-145	2025-07-04	29.78	-52.15
WASP-173	2025-07-17	27.44	-47.78
WASP-145	2025-07-18	52.69	-37.93
WASP-145	2025-07-20	23.36	-26.27
WASP-145	2025-07-25	36.03	-13.84
WASP-145	2025-07-27	40.98	-49.49
TOI-2107	2025-07-28	24.61	-27.3
WASP-173	2025-07-28	61.	-18.03
DS_Tuc	2025-07-30	32.24	-46.92
TOI-2107	2025-08-02	38.93	-55.09
WASP-145	2025-08-03	56.29	-60.84

WASP-173	2025-08-04	49.13	-38.1
WASP-145	2025-08-12	34.49	-23.45
WASP-145	2025-08-17	24.8	-11.01
WASP-173	2025-08-18	21.59	-35.05
WASP-145	2025-08-19	51.47	-46.58
WASP-173	2025-08-22	52.9	-26.76
WASP-145	2025-08-26	48.56	-56.38
TOI-2107	2025-08-29	24.95	-49.08
WASP-173	2025-08-29	57.29	-45.75
WASP-145	2025-09-11	53.89	-43.03
WASP-173	2025-09-12	29.45	-19.84
WASP-173	2025-09-16	44.59	-32.77
WASP-145	2025-09-18	37.5	-49.46
WASP-173	2025-09-23	58.64	-45.47
DS_Tuc	2025-09-25	42.2	-42.18
WASP-145	2025-09-25	20.01	-25.85
WASP-145	2025-09-27	55.38	-17.58
WASP-173	2025-09-30	51.65	-25.7
WASP-145	2025-10-11	26.	-41.8
WASP-173	2025-10-11	36.12	-36.08
WASP-173	2025-10-18	49.95	-30.09
WASP-145	2025-10-20	49.61	-13.88
WASP-173	2025-10-25	60.4	-10.25
WASP-145	2025-10-27	32.24	-32.99
WASP-173	2025-11-05	27.61	-32.56
WASP-173	2025-11-12	41.16	-14.87
WASP-145	2025-11-19	20.99	-27.54
DS_Tuc	2025-11-21	26.47	-22.6
K2-308	2025-11-29	27.54	-23.34
K2-308	2025-12-16	22.03	-13.1
WASP-175	2025-12-29	27.02	-10.89



Literature search

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LTT1445Ab
No atmo detection con 4 transiti Magellan (6.5m) con MOS, 620-1020nm

TOI-2107b:
only discovery paper, brand new, looks ok ✅

TOI-1201b:
Only discovery paper

DS Tuc:
Ok but huge stellar activity
Transito ESPRESSO (see Benatti+) + transito X-Shooter

K2-54b:
Validated, only discovery

K2-53b:
Discovery+spitzer follow up, transito piccolissimo 🚩

WASP-145b
only discovery paper, looks ok ✅

WASP-142b:
only discovery paper, looks ok ✅
Transito FORS2 🚧

K2-245b:
only validated 🚧

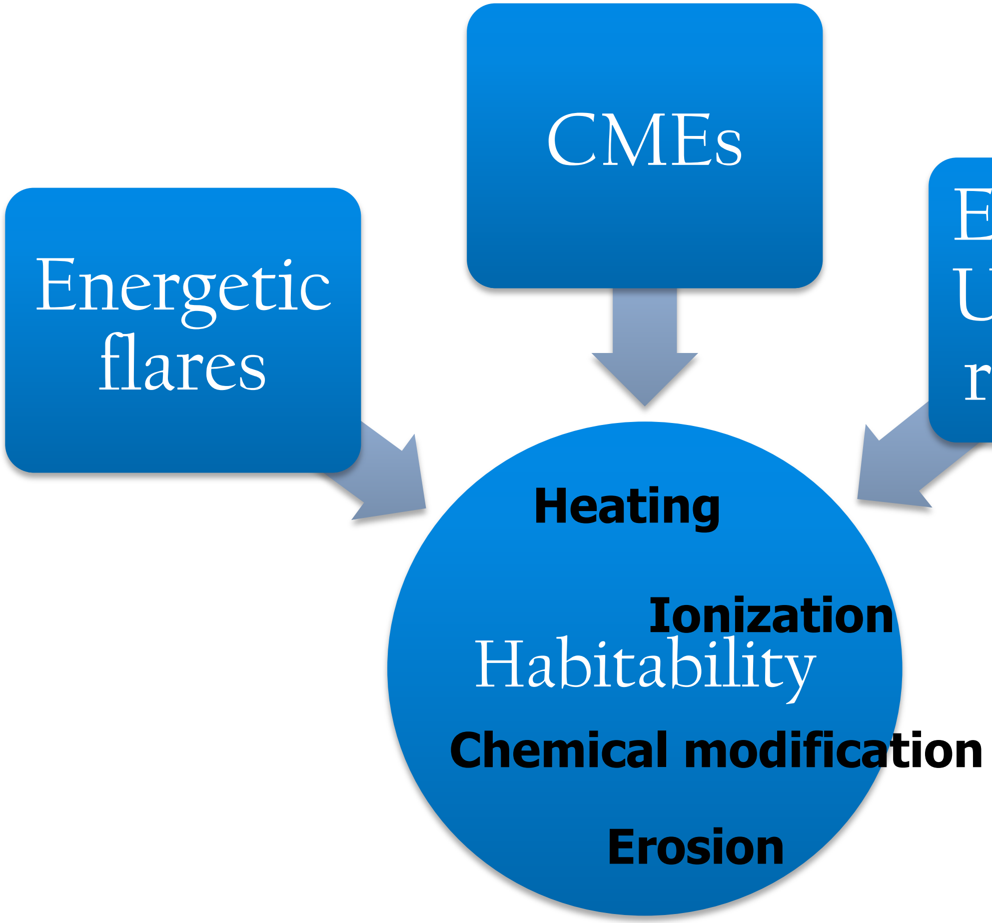
K2-308b:
only discovery paper, v=15, only 2 RVs 🚧

WASP-180b
only discovery paper, looks ok ✅
transito HARPS x RML 🚧

WASP-175b
only discovery paper, looks ok ✅

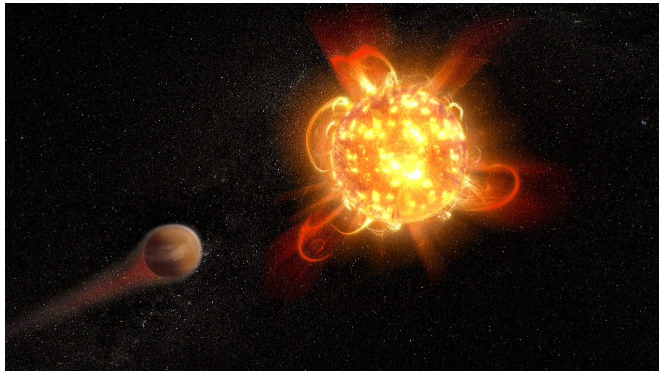
WASP-173Ab a.k.a. **KELT-22Ab:**
only discovery papers, massive
transito HARPS+ESPRESSO x RML 🚧

Planets of dMe stars: flare irradiation of planetary atmospheres

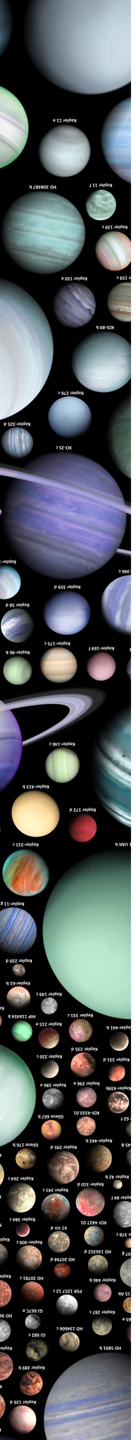


Not suitable for GTO

We aim to apply for GO time (filler program)



- M dwarfs are the main targets to search for rocky, low-mass planets with the potential capability of hosting life (e.g. Dressing & Charbonneau 2013; Sozzetti et al. 2013).



Vetting targets with transits:

SOXS follow-up observations of transiting planetary candidates identified using space-based data (TESS, PLATO)

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- **Space missions searching for transiting planets** produce thousands of planetary candidates which can be observed with low resolution spectrographs to identify false positive candidates. For SOXS we expect spectral performances similar to those of X-SHOOTER (R~10000 with slit width 0.5 arcsec and RV precision of a few km s-1, Gonneau et al. 2020, A&A, 634, 133; Verro et al. 2022, A&A, 660, 34).
  - SOXS is a unique medium resolution (R~4,500) wide wavelength coverage (350-2000 nm) spectrograph on a 4m class telescope. It is optimally suited to follow-up bright sources. Transiting candidates from present and future space missions are focused on bright (V<13) targets.

- For TESS targets lists are already available and observations can be already scheduled
- For PLATO observations will start late 2026 and targets will be available during following years.

- Observations at quadrature times permit to determine the amplitude of the radial velocity signal and therefore to estimate the mass of the transiting body. SOXS spectra can be also used to identify blends, hierarchical triple systems, AND provide an excellent spectral classification of the transiting candidates' hosts.

Observation needs: about 3 hrs/target

Observing Earthshine

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Earthashine spectra as template for reflection spectra of exoplanets atmosphere

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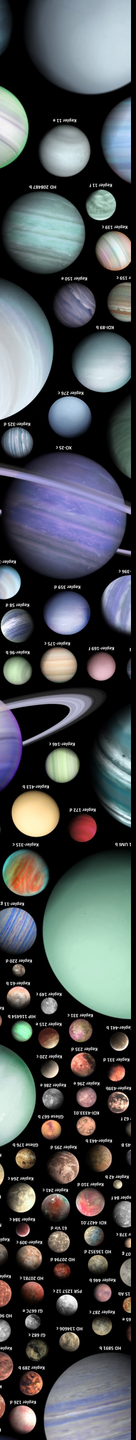

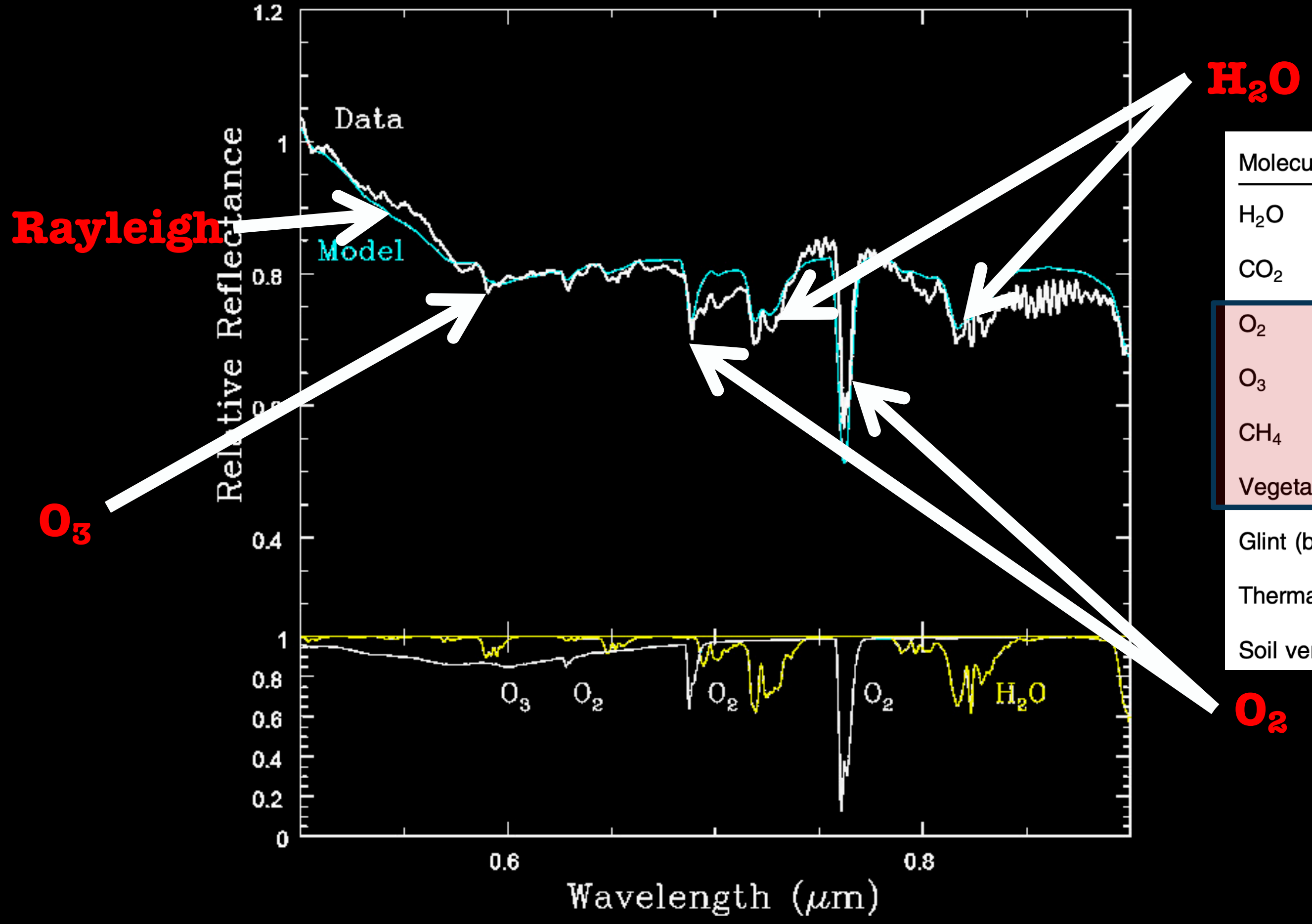

Molecule/feature	Wavelengths (μm)
H_2O	0.65, 0.72, 0.82, 0.94, 1.12, 1.4, 2.7, 6.5 (strong)
CO_2	1.44, 1.59, 4.9, 5.3, 9.5, 10.5
O_2	0.63, 0.69, 0.76 (strong), 1.27 (O_2 dimer), and 6.5 (O_2 dimer)
O_3	0.5 to 0.7, 8.8, 9.5 (strong)
CH_4	1.4, 1.7, 3.4, 7.5
Vegetation red edge	0.7
Glint (best observed at)	0.7 to 0.9, 1.0 to 1.05, 1.3, 3 to 4
Thermal emission	8 to 9, 10.5 to 12
Soil versus water	0.85 (high rotational contrast)

Proposed observing strategy

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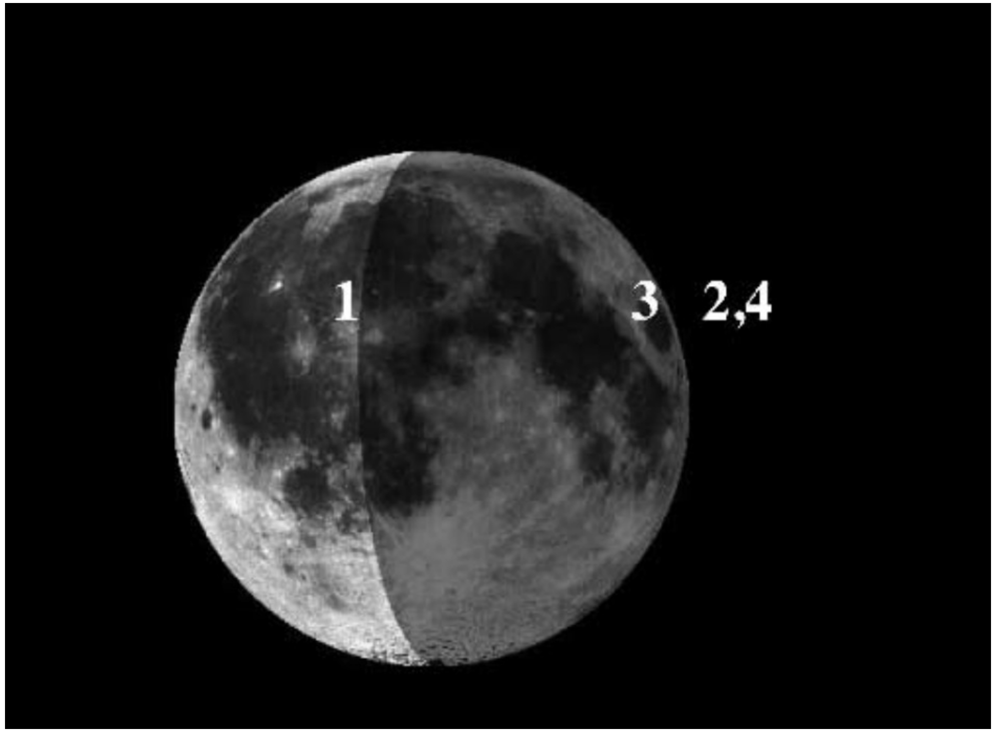
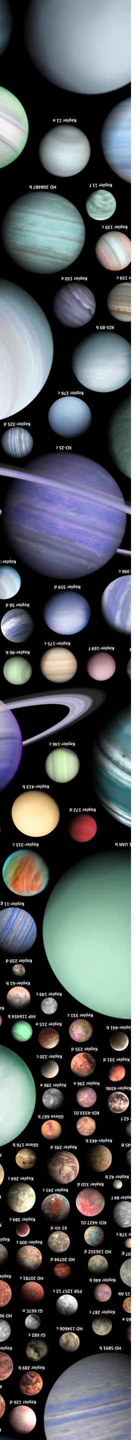


Several positions for the SOXS Slit:

1. the bright limb of the Moon (TBD s exposures, 5–10median- combined),
2. the sky near the dark side of the Moon (TBD s exposure),
3. the dark side of the Moon (TBD s exposure)
4. the sky near the dark side of the Moon (TBD s exposure, averaged with the previous sky observation).

Figure generated by: https://www.fourmilab.ch/earthview/vplanet.html

Turnbull + (2006) describe the several step of data reduction



A plenty of possible observing dates

INAF

- Calendar for ESO La Silla, west longitude (h.m.s) = 4 42 55, latitude (d.m) = -29 15.4 Note that each line lists events of one night, spanning two calendar dates. Rise/set times are given in Chilean time (4 hr W), for 2347 m above surroundings, DAYLIGHT time used, * shows night clocks are reset. Moon coords. and illum. are for local midnight, even if moon is down. Program: John Thorstensen, Dartmouth College.

  - **Thu Jan 02/Fri Jan 03** 678.6 5 09 04 20 54 22 21 5 14 6 41 3 29 10 24 ..... 23 21 **11** 21 41.8 -16 15
  - **Fri Jan 03/Sat Jan 04** 679.6 5 13 00 20 54 22 21 5 15 6 42 3 33 10 29 ..... 23 55 **19** 22 33.5 -10 26
  - **Sat Jan 04/Sun Jan 05** 680.6 5 16 57 20 54 22 21 5 16 6 42 3 37 10 34 ..... 0 27 **29** 23 23.6 - 4 01
  - **Thu Jan 23/Fri Jan 24** 699.6 6 31 51 20 52 22 14 5 36 6 58 4 45 12 09 2 09 ..... 29 **15** 46.3 -23 40
  - **Fri Jan 24/Sat Jan 25** 700.6 6 35 48 20 51 22 13 5 37 6 59 4 49 12 14 2 53 ..... 20 **16** 39.0 -26 17
  - **Sat Jan 25/Sun Jan 26** 701.6 6 39 44 20 51 22 13 5 39 7 00 4 52 12 19 3 44 17 59 **13** 17 35.0 -27 38
  - **Sat Feb 01/Sun Feb 02** 708.6 7 07 20 20 47 22 07 5 46 7 06 5 14 12 55 ..... 23 00 **16** 0 00.3 1 10
  - **Sun Feb 02/Mon Feb 03** 709.6 7 11 17 20 47 22 06 5 48 7 07 5 17 13 00 ..... 23 32 **25** 0 50.9 7 57
  - **Mon Feb 03/Tue Feb 04** 710.6 7 15 13 20 46 22 05 5 49 7 08 5 20 13 05 ..... 0 06 **36** 1 42.9 14 23

Observation needs: 2 hrs/event; 6 event /year → 12 hr/yr

Earth's transmission spectra from lunar eclipse observations as template for transmission spectra of exoplanets atmosphere

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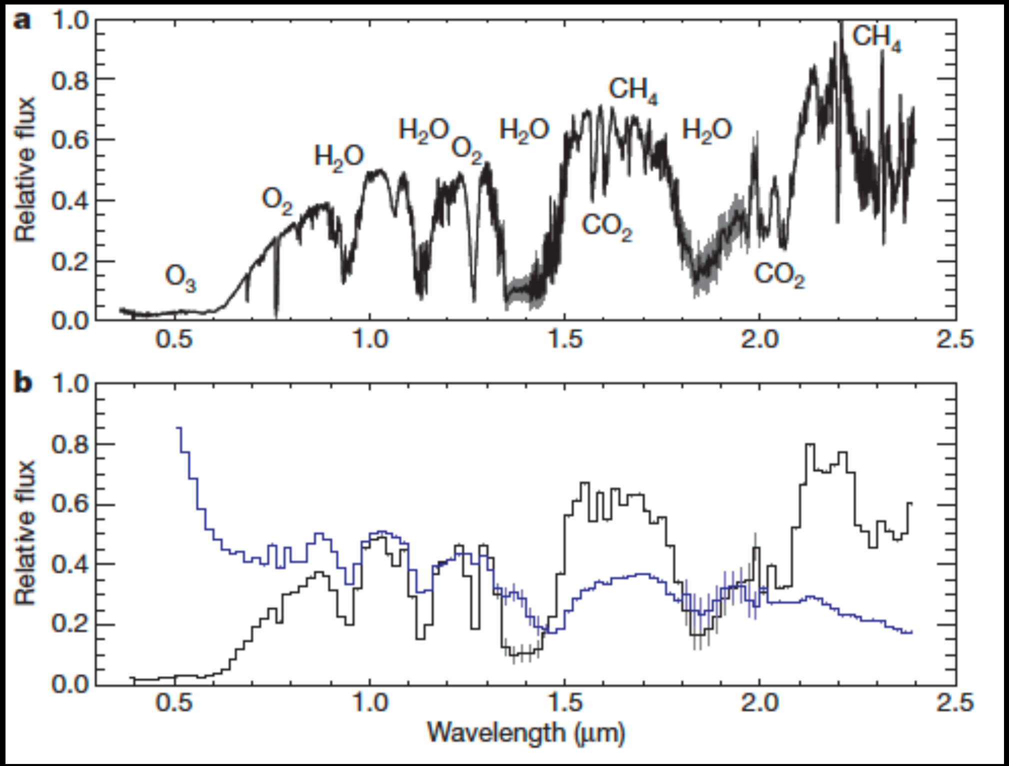
- The reflected sunlight from the lunar surface within the Earth's umbra is entirely dominated by the fraction of sunlight that is transmitted through an atmospheric ring located along the Earth's day–night terminator.
  - Observing the Moon in total eclipse (umbra), we get photons that have been trasmitted through the lower levels of the Earth atmosphere;
  - Observing the Moon during penumbra, we get a spectrum similar to a planetary transit that is dominated by upper atmospheric layers for geometrical reasons (Vidal-Madjar et al. 2010);
  - Observing the Earthshine, we get photons reflected by the Earth atmosphere;



E Pallé *et al.* *Nature* 459, 814-816 (2009)
doi:10.1038/nature08050

Next observable lunar eclipse and interest in making a long-term monitoring

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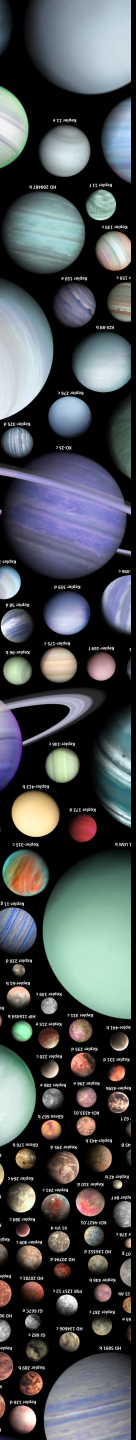
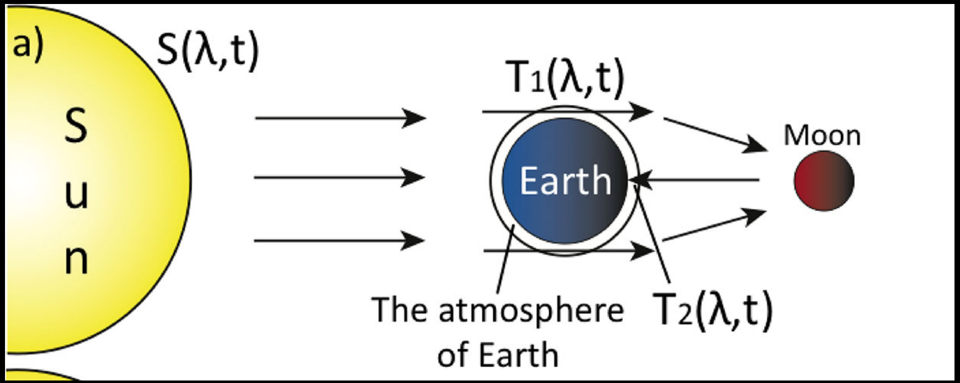


- Next total lunar eclipse observable from La Silla: 14 March 2025; https://www.timeanddate.com/eclipse/in/chile/santiago?iso=20250314

- Danjon (1921) established a relationship between the «darkness» of a total lunar eclipse and the level of solar activity along the 11-year cycle;

- Darker totality are usually observed 1 or 2 years after the solar activity minimum possibly as a consequence of the reduced transparency of the troposphere because of the formation of aerosols due to a lower UV flux from the Sun and an increased flux of galactic cosmic rays; dust and clouds also play a significant role: https://eclipse.gsfc.nasa.gov/OH/Danjon.html

- Volcanos are sources of aerosol forming molecules and dust so it could be interesting to make observations during periods of large volcanic eruptions or close to them (e.g., Komitov & Kaftan 2022).



Geometry of the lunar eclipse
after Kawaguchi et al. 2018, PASJ 70, 84

Observation needs

About 14 hrs in the 1st year before and during the total lunar eclipse of 14 Marc 2025.
From 7 to 14 hr/yr next years to monitor atmospheric variations with solar cycles (there a re a mean of 2 total lunar eclipses/yr).

Bibliographic note

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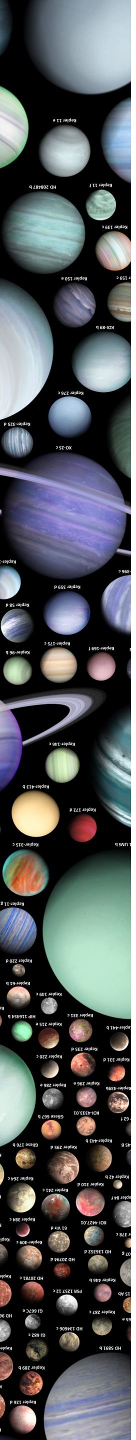
- Pallé et al. (2009) and Vidal-Madjar et al. (2010) provided the methods and the first studies of the Earth spectrum based on lunar eclipses and Earthshine observations;

- Pallé et al. (2009) have a resolution *R* of the order of 1000 and extends to the NIR band, comparable with SOXS;

- On the other hand, Vidal-Madjar et al. (2010) used SOPHIE (*R*=75 000); Arnold et al. (2015) used HARPS and UVES ($R \sim 1.2 \times 10^5$); Yan et al. (2015) used ESPADONS (*R* = 81 000) and studied the CLV effects that are relevant at high resolution and in the blue part of the optical spectrum;

- MacDonald & Cowan (2019) made a MIR spectrum between 2 and 14 microns with resolution up to 100 000 at 5 microns;

- Youngblold et al. (2020) used HST attempting to obtain a UV spectrum between 170 and 320 nm.



SOXS and Exoplanets

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TOPIC OF INTEREST	OBSERVATIONS	TOTAL REQ TIME (5yr)	FEASABILITY	REQ TIME Pilot program
Star-Planet Interaction	ToO	NA	TBD: Difficult to find suitable alerts	
Exo-Planetary Atmospheres	TC	60-160 hr	A pilot program is proposed	7-9 hr
Flare & CMEs	ToO/F	NA	TBD: Difficult to find suitable alerts No GTO? GO proposal as a filler program(?)	
Vetting of targets with transits	TC	60-120 hr	A pilot program is proposed	15 hr
Observing the earthshine	TC	30-60 hr	A pilot program is proposed	4 hr
Observing Lunar total eclipses	TC	40 hr	A pilot program is proposed	7 hr

ToO: Target of Opportunity; TC: Time Critical, Filler