Exoplanet Research at the University of Oxford

Patrick Irwin

Oxford Astro/AOPP

Who's who

- Astrophysics
  - Transit modelling and Stellar Variability – **Suzanne Aigrain**
    - Hannu Parviainen, Ben Pope, Ed Gillen, Ruth Angus, Vinesh Rajpaul
  - Planet formation modelling – **Caroline Terquem**
  - Telescope Instrumentation – **Niranjan Thatte**
    - Matthias Tecza, Fraser Clarke

- Atmospheric, Oceanic and Planetary Physics
  - Radiative Transfer and Retrievals – **Patrick Irwin**
    - Exoplanet atmospheric characterisation (transit spectroscopy) and clouds – Jo Barstow, Leigh Fletcher
    - Brown dwarf atmospheric characterisation – Ryan Garland, Jo Barstow
  - Instrumentation – **Neil Bowles, Simon Calcutt**
    - EChO, Ariel
  - GCM modelling – **Peter Read**

Stars & Planets @ Oxford

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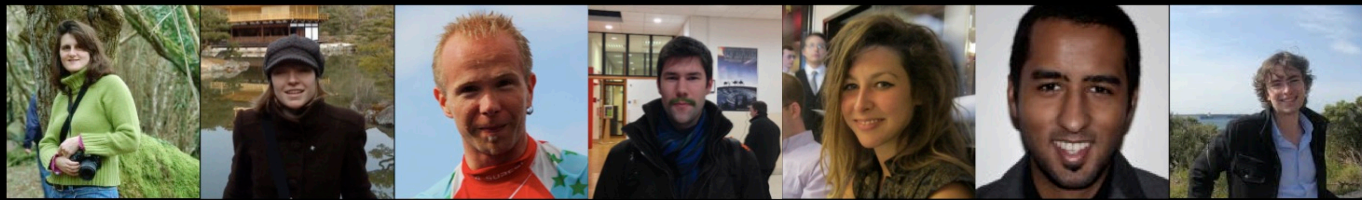
research into exoplanets and their host stars at the University of Oxford



Suzanne Aigrain Hannu Parviainen Ruth Angus Ben Pope

Jo Barstow Ed Gillen Vinesh Rajpaul

Current research areas include

- Space-based transit searches: CoRoT, Kepler, K2, TESS, PLATO
- Stellar variability and rotation using transit search data
- Atmospheric characterisation of transiting planets: HST, JWST,
- Bayesian data analysis, Gaussian processes
- Modelling and mitigating stellar activity in radial velocity data
- Young eclipsing binaries and planets in clusters and star forming regions
- Direct imaging using the Kernel phase method
- Future large space-based telescopes

Some recent highlights

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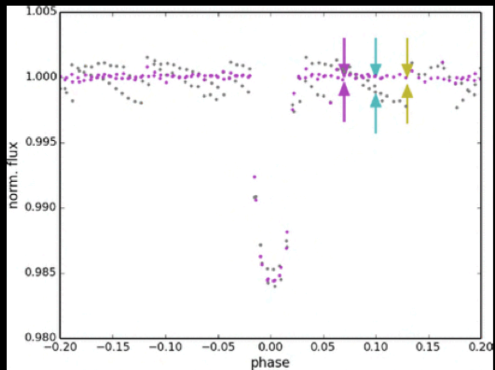
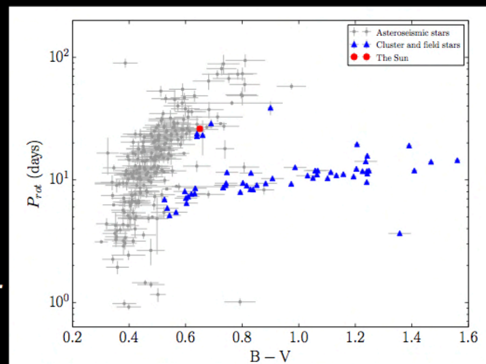
Evans et al. (2013)
The Deep Blue Color of HD 189733b: Albedo Measurements with Hubble Space Telescope/Space Telescope Imaging Spectrograph at Visible Wavelengths



Aigrain et al. (2015)
Precise time-series photometry for the K2 mission

Angus et al. (2015)
Calibrating Gyrochronology using Kepler Asteroseismic targets



Some things to look forward to

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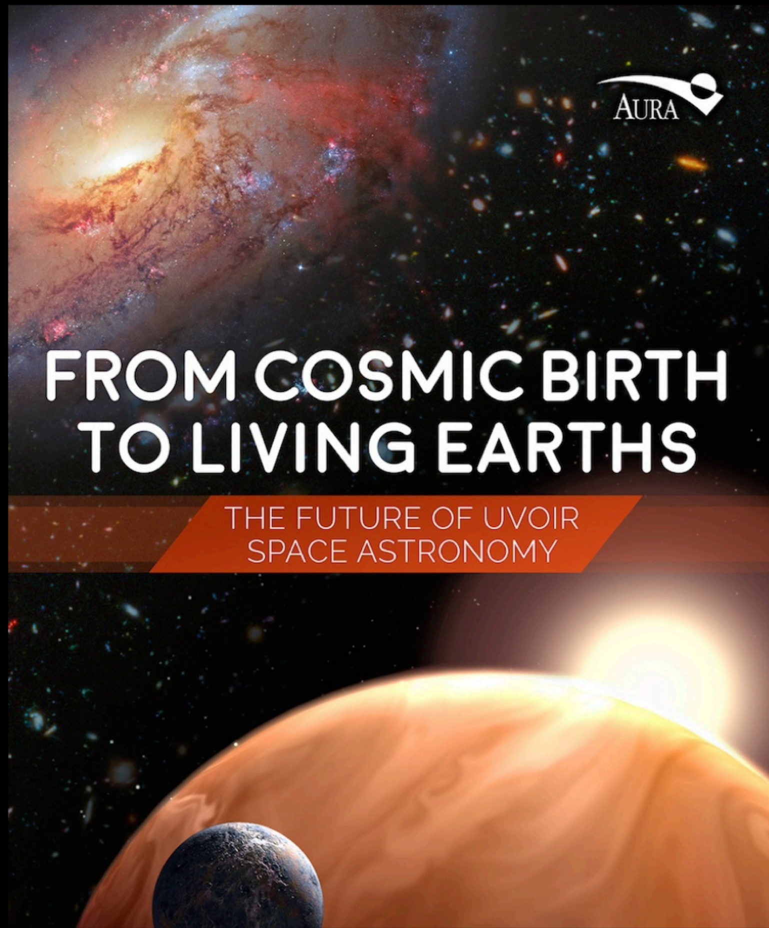
Statistics and Exoplanets
Focus Meeting 8
IAU General Assembly, Honolulu
3-5 August 2015
www.exostats.org

SOC chairs:
S. Aigrain, E. Feigelson

Report of AURA “Beyond JWST committee”
Chairs: S. Seager, J. Dalcanton
To be published shortly

“We believe humans have reached a unique point in history where it is possible to construct a revolutionary space-based observatory capable of directly finding habitable planets showing signs of life.”

S. Aigrain committee member

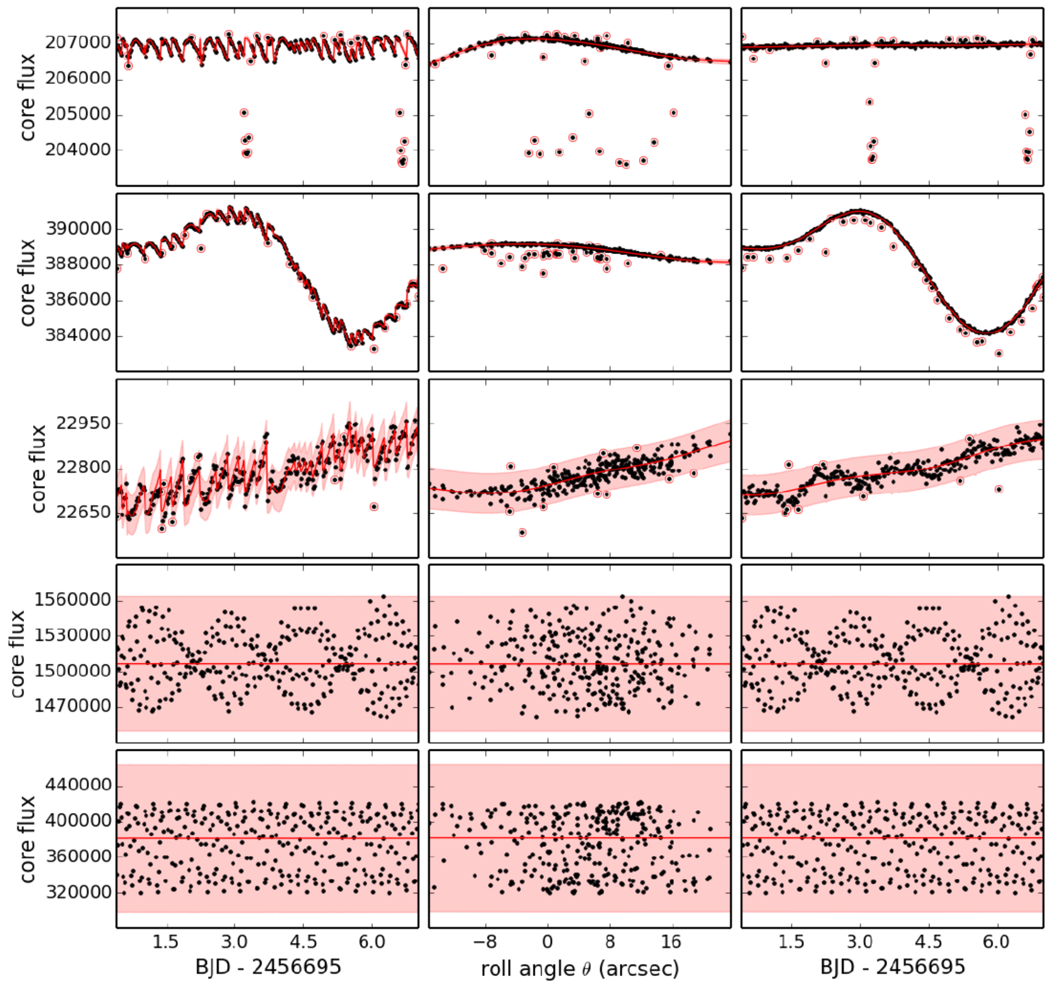


Kepler – 2 at Oxford

- Group:
  - Oxford: Suzanne Aigrain, Steve Roberts, Hannu Parviainen, Ed Gillen, Benjamin Pope
  - Cambridge: Simon Hodgkin, Mike Irwin, Jonathan Irwin, Jim Lewis
- *Kepler*-2 is the two-wheel successor to the *Kepler* mission
- Consists of a sequence of ~ 80 day ecliptic plane campaigns
- Poor pointing stability requires careful correction of systematics in the photometry
- Exciting cluster science - ecliptic pointings take in Pleiades, Hyades, M35, ρ Oph and more!

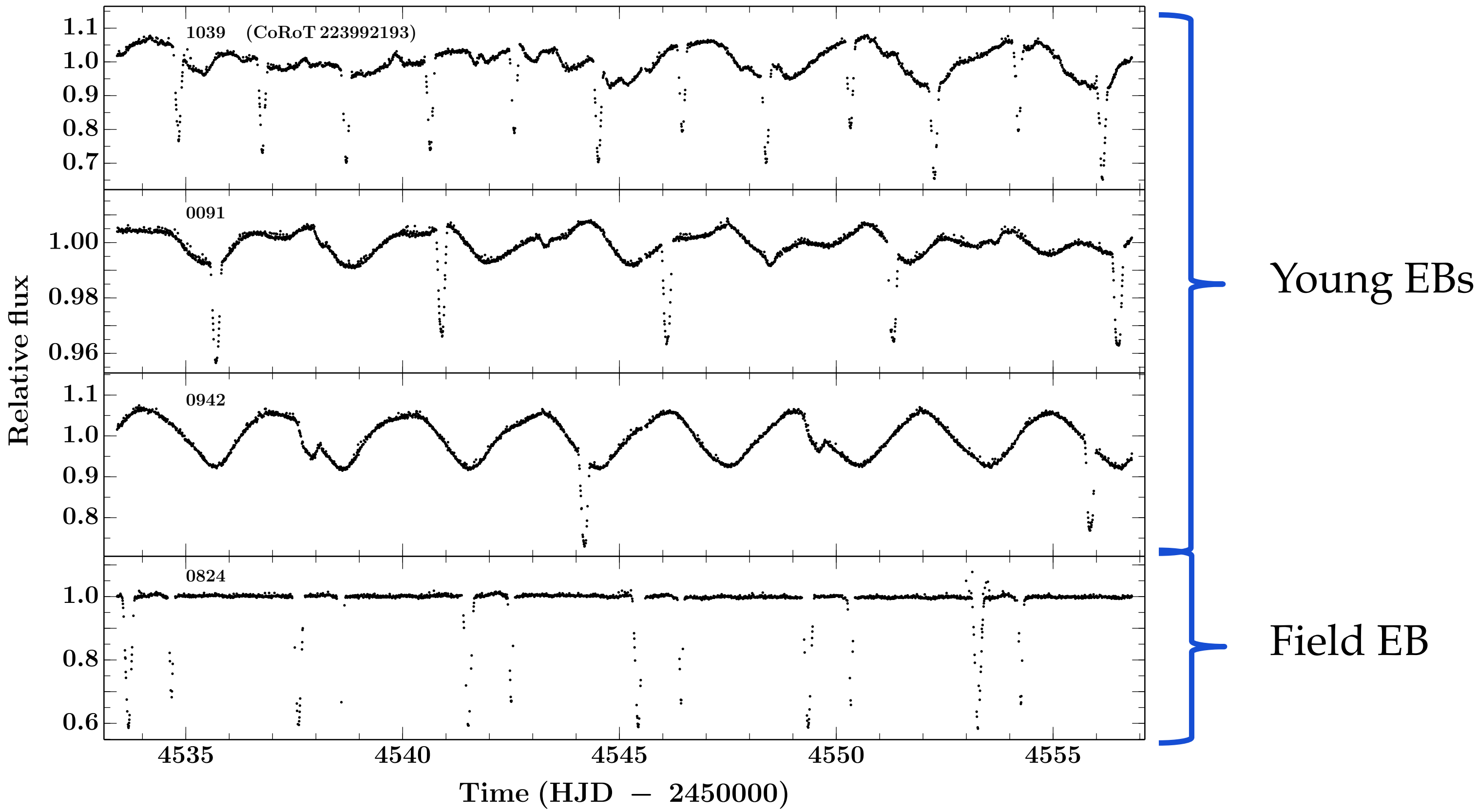
Kepler – 2 Lightcurves

› Left to right:
- Raw light curve
- Roll angle – dependent Gaussian Process fit
- New light curve with roll angle-related systematics subtracted
- Note at the bottom: large amplitude signals from stellar variability distinguished from pointing jitter and unaffected by calibration



Young eclipsing binaries in NGC 2264 (~3 Myr)

- Team: **Oxford** (Ed Gillen & Suzanne Aigrain)
  + Caltech, UFMG Brazil, **Cambridge**, **Keele**, Grenoble, Geneva, ESA etc…
- CoRoT Observations. Excellent photometry – similar to K2.



- Strong synergies with *Kepler*/K2
  - Oxford group searching for Planets and EBs in young open clusters
- See talk by Ed Gillen tomorrow morning

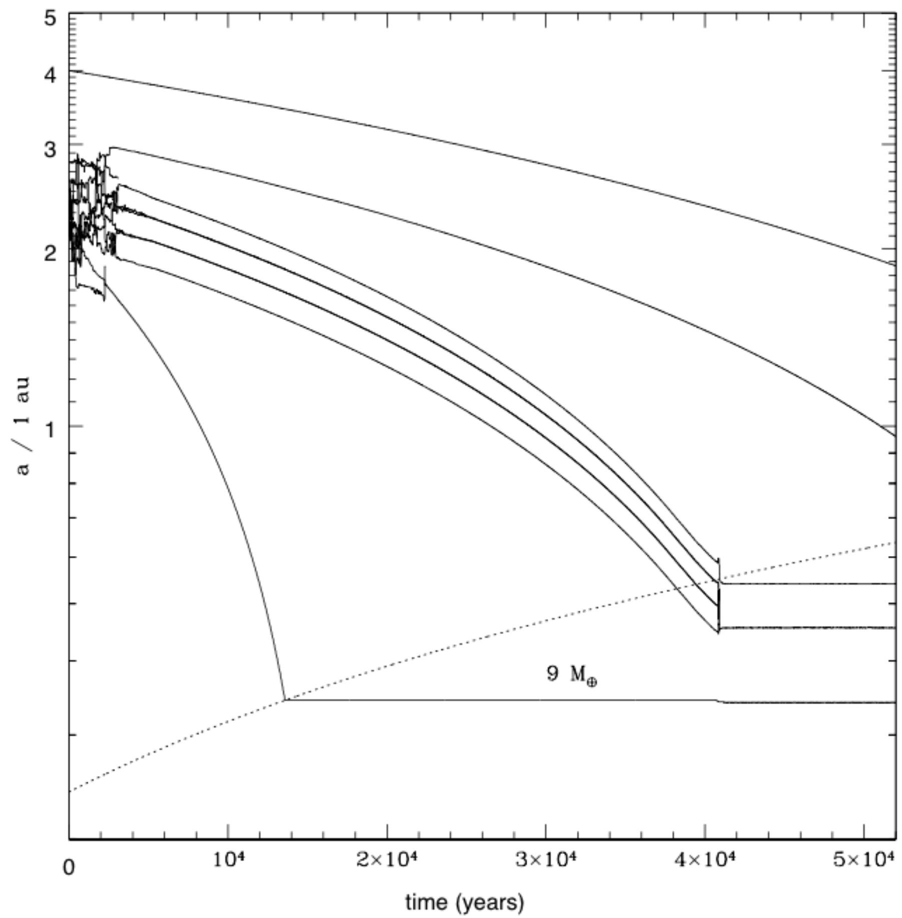
Gillen et al. 2014, A&A, 562, 50

Planet formation

Caroline Terquem

- N body simulations of cores migrating in a disc and interacting with each other:
  - growth of cores and terrestrial planets
  - formation of mean motion resonances

- Critical core mass required for the accretion of massive gaseous envelope



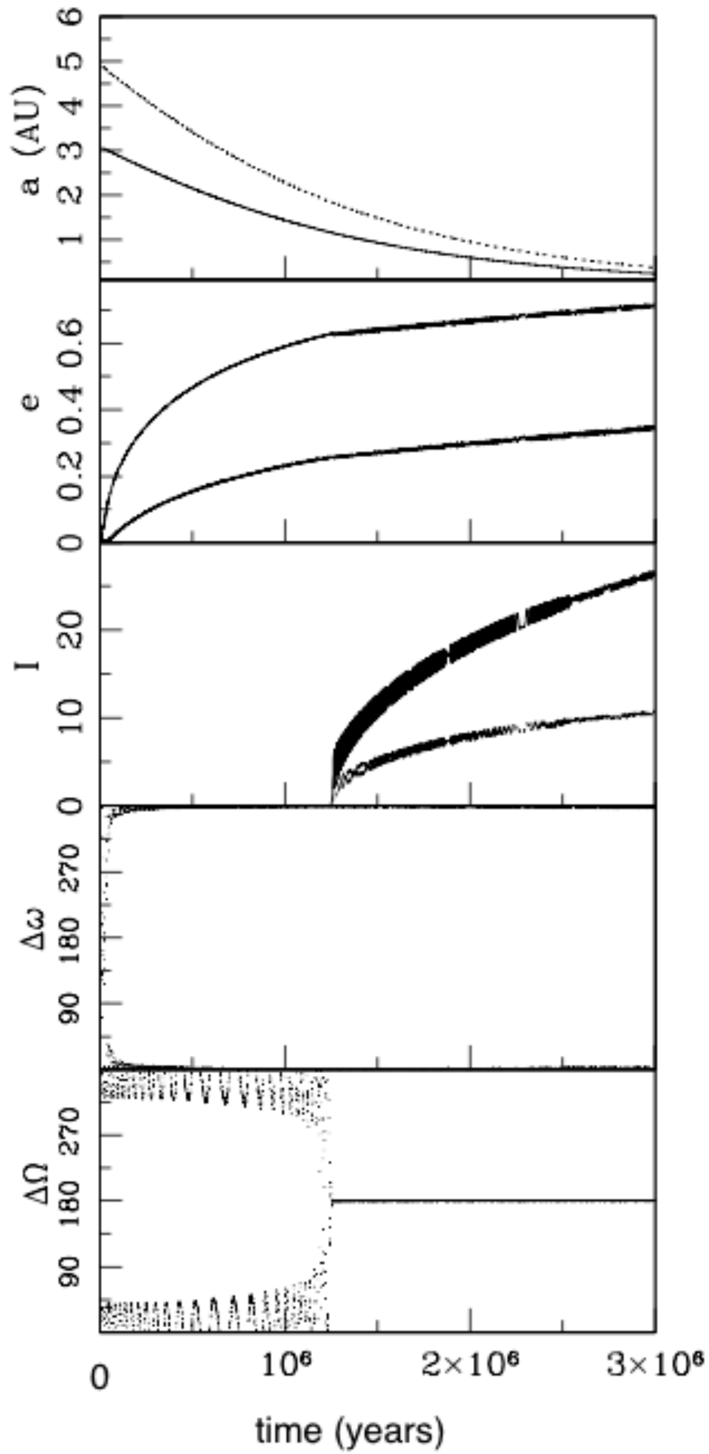
Formation of the Kepler-10 system
Terquem 2014

Dynamic of planetary systems

Caroline Terquem

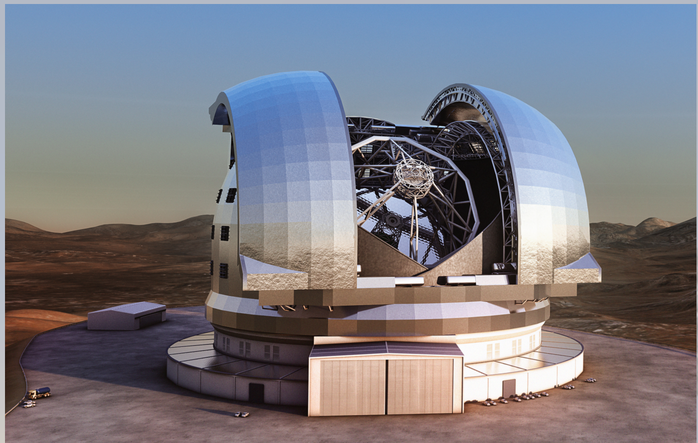
- Interaction between a planet on an inclined orbit and a disc: Kozai oscillations driven by the gravitational potential of the disc

- Interaction between 2 planets in resonance migrating in a disc: pumping of their inclination through an inclination-type resonance (with Jean Teyssandier, now at DAMTP)



Inclination-type resonance for a pair of planets in 2:1 mean motion resonance Teyssandier & Terquem 2014

HARMONI – THE FIRST LIGHT INTEGRAL FIELD SPECTROGRAPH FOR THE E-ELT



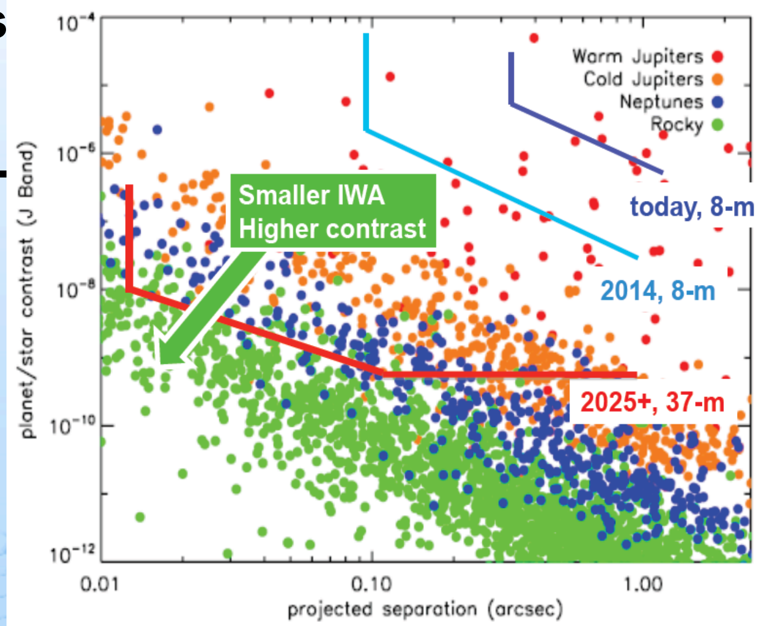
First light instrument, led from Oxford
[PI: N. Thatte,
Instr. Sci: M. Tecza,
Sys. Engg: F. Clarke]
and UKATC
[Proj. Manager: I. Bryson,
Sys. Engg: H. Schnetler]

- High contrast capability for direct detection of exo-planets being studied in detail until 2017 (many error sources that might potentially limit contrast achievable).
- Goal is follow-up spectroscopy of every SPHERE/GPI detected planet, capitalising on large collecting area of E-ELT and small inner working angle
- Provide moderate resolution (R~3500) spectroscopy across 0.8 to 2.45 μm, coupled with SCAO using deformable M4 and fast tip-tilt M5 of E-ELT

Science & Technology Facilities Council UK Astronomy Technology Centre · Instituto de Astrofísica de Canarias · CRA Lyon · University of Oxford · CSIC · RAL Space · IPAG · ONERA The French Aerospace Lab · ESO · LAM Laboratoire d'Astrophysique de Marseille

Exo-planets with ELT-PCS

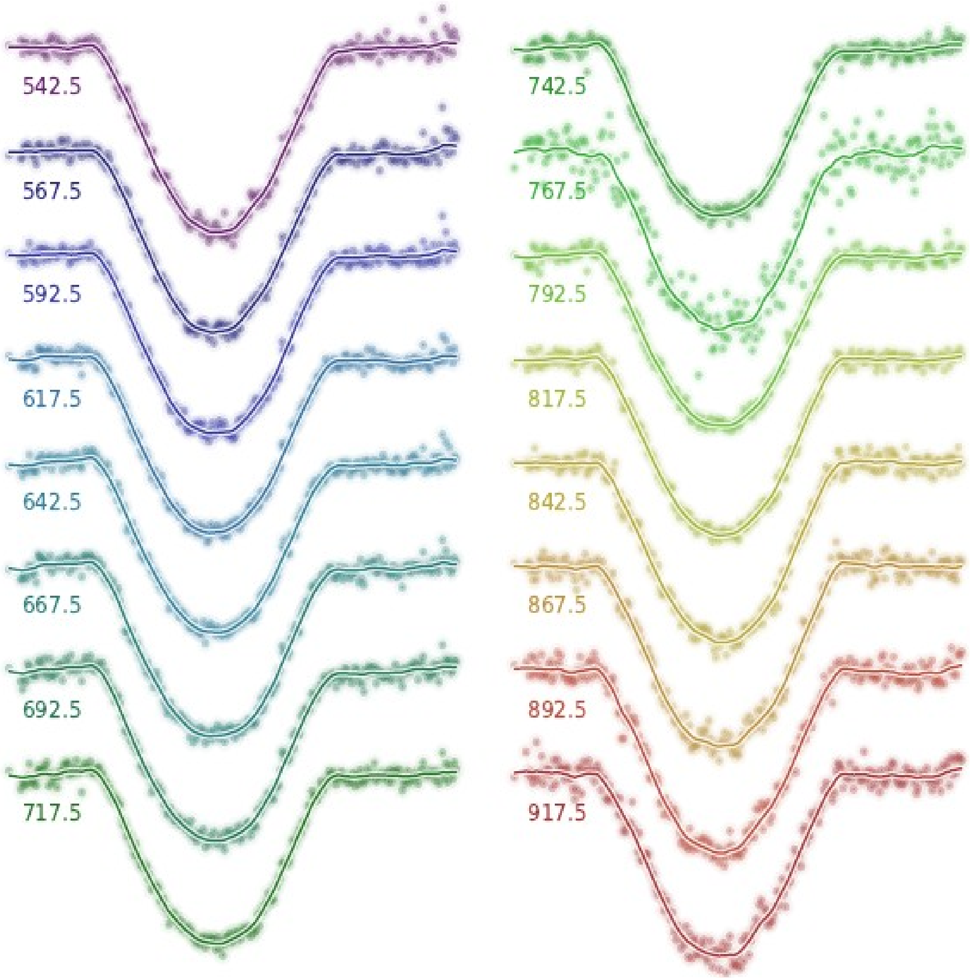
- **Discovery and characterisation of exo-planets is one of the main drivers to build the E-ELT**
- **ELT-PCS is dedicated Direct Imaging Spectro-graph** to characterise large samples (hundreds) of exo-planets (niche lower inner working angle)



- **Science objectives for ELT-PCS**
  - Biosignatures of M-star HZ planets
  - Follow-up of self-luminous exo-planets forming beyond the snow-line in star-forming regions
  - Characterisation of nearby irradiated planets, from rocky planets to gas giants
- **R&D roadmap – IFS technology trade-off: *M. Tecza, N. Thatte (Oxford)***
  - Measure contrast limits of image-slicer (Oxford) and lenslet-array (INAF) IFS and compare performance using ESO's XAO test-bench
  - Promote image-slicer IFS to become baseline technology for ELT-PCS in order to secure IFS work package (design and build) for ELT-PCS

Hannu Parviainen

- Time series analysis using modern statistical methods
  - Kepler secondary search and characterisation
  - Transmission spectroscopy using ground-based telescopes
  - Characterisation of Kepler and CoRoT systems based on transit light curves and RVs
  - Transit candidate quality assessment based on multicolour photometry
  - Planet searches from astrometry
- Method & code development
  - PyTransit, PyLDTK



- **Interested in a Python package for automatically generated limb darkening profiles and coefficients for freely defined passbands**?
- Given the stellar parameters with their uncertainties
  - Code downloads the necessary subset of files from the Husser library to a local cache
  - Calculates the limb darkening profiles with uncertainties
  - And estimates the model-specific limb darkening coefficient with uncertainties
  - Or evaluates the likelihood for a limb darkening model directly based on the limb darkening profiles

  - Contact
    hannu.parviainen@astro.ox.ac.uk
    hpparvi@gmail.com

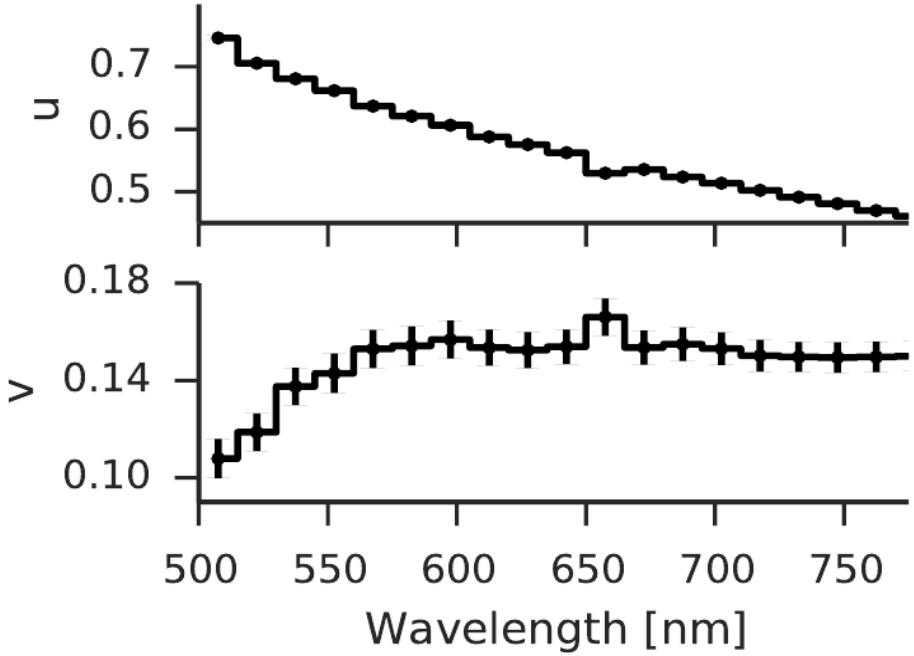
  …Or ask during a break

```
from ldtk import (LDPSetCreator,
                  BoxcarFilter)

filters = [BoxcarFilter('a',450,550),
           BoxcarFilter('b',650,750),
           BoxcarFilter('c',850,950)]

sc = LDPSetCreator(filters,
                   teff=[5400,  100],
                   logg=[4.50, 0.10],
                      z=[0.25, 0.05])

ps = sc.create_profiles()
qc,qe = ps.coeffs_qd()
```

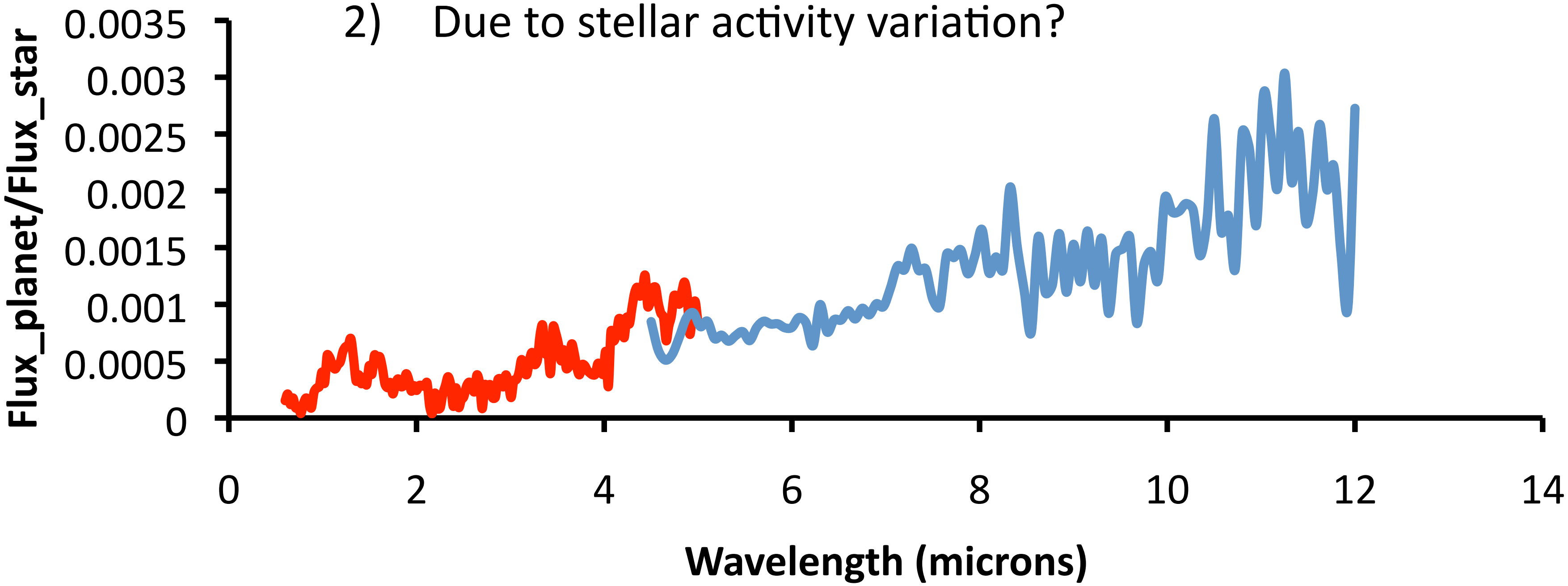


NEMESIS

- **N**on-linear Optimal **E**stimator for **M**ultivariat**E** Spectral Analy**SIS**
- Originally developed for solar system studies, but extended for primary transit, secondary eclipse and direct imaging of exoplanets/brown dwarfs.
- Correlated-k and Line-by-line forward model.
- K-tables currently being updated (Ryan Garland) from ExoMol and other line data.
- Thermal emission and scattering.
- Extended for primary and secondary transit and disc-averaged geometries.

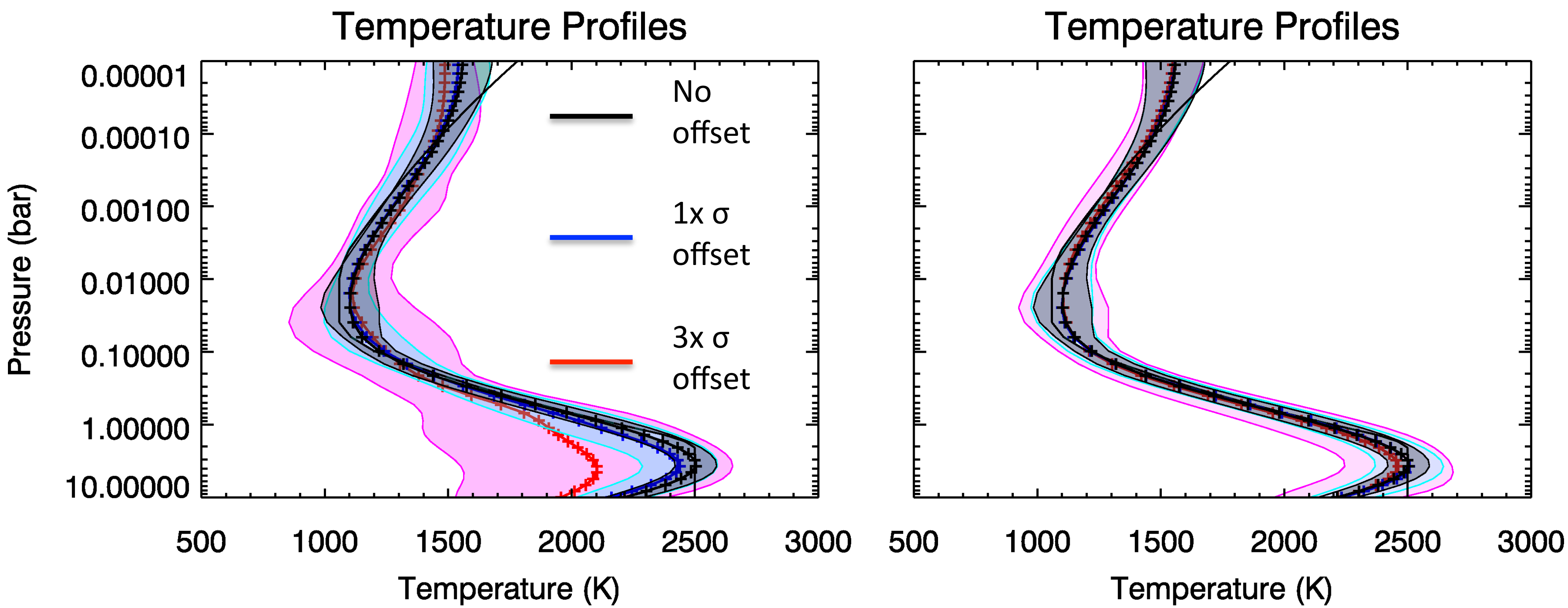
Stitching and systematics with JWST

- Can't observe simultaneously with NIRSpec and MIRI
- Therefore need to observe at least two transits
- What happens if baseline varies between observations:
  1) Due to instrumental effects?
  2) Due to stellar activity variation?



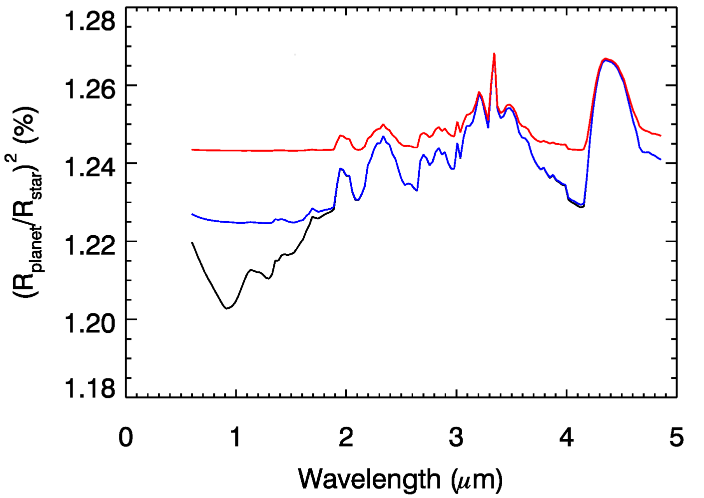
Correcting for offsets with JWST

Wavelength invariant baseline offsets between NIRSpec/MIRI observations of same planet can be easily corrected for



Barstow et al. 2015. MNRAS 448

The effect of clouds

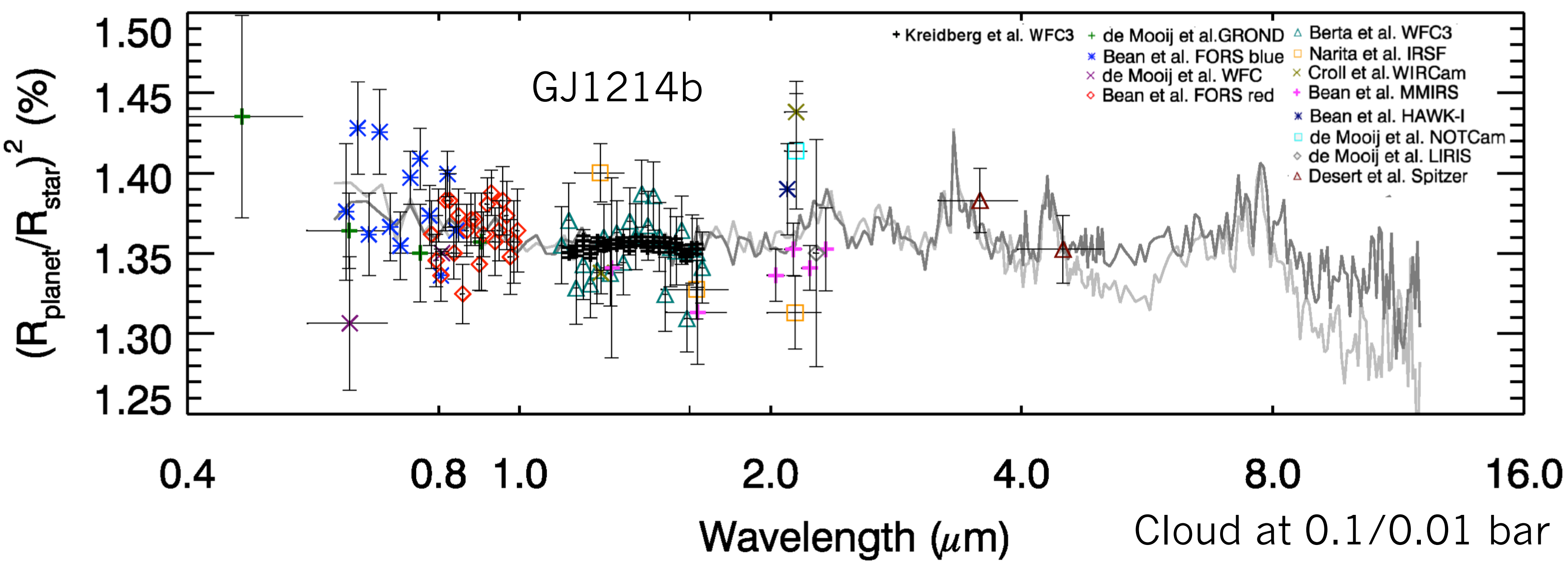


Hot Jupiter primary transit, R=100 at 3 microns

1 mbar cloud

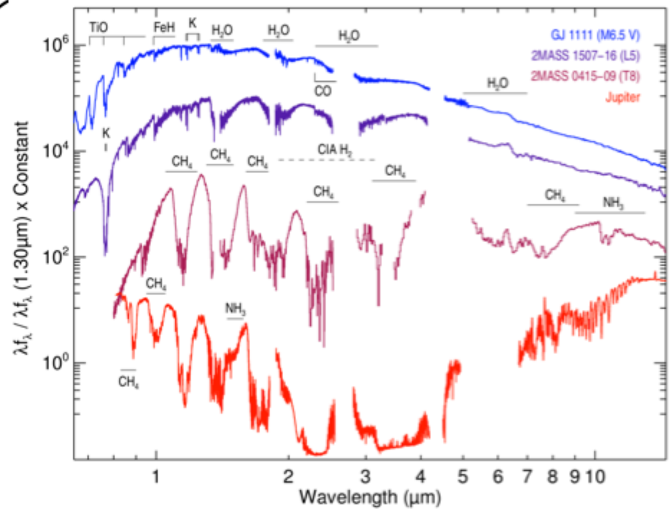
100 mbar cloud

No cloud

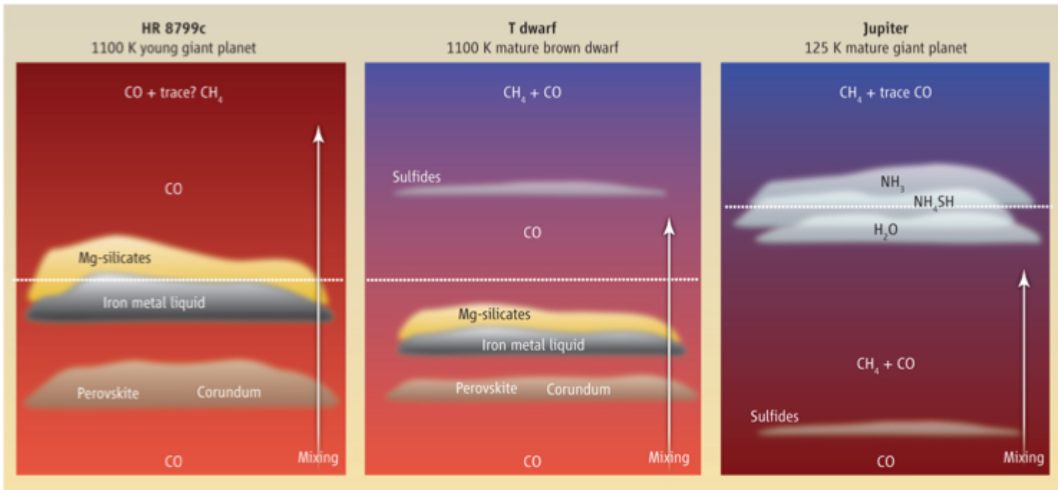


Cloud at 0.1/0.01 bar

Brown dwarfs

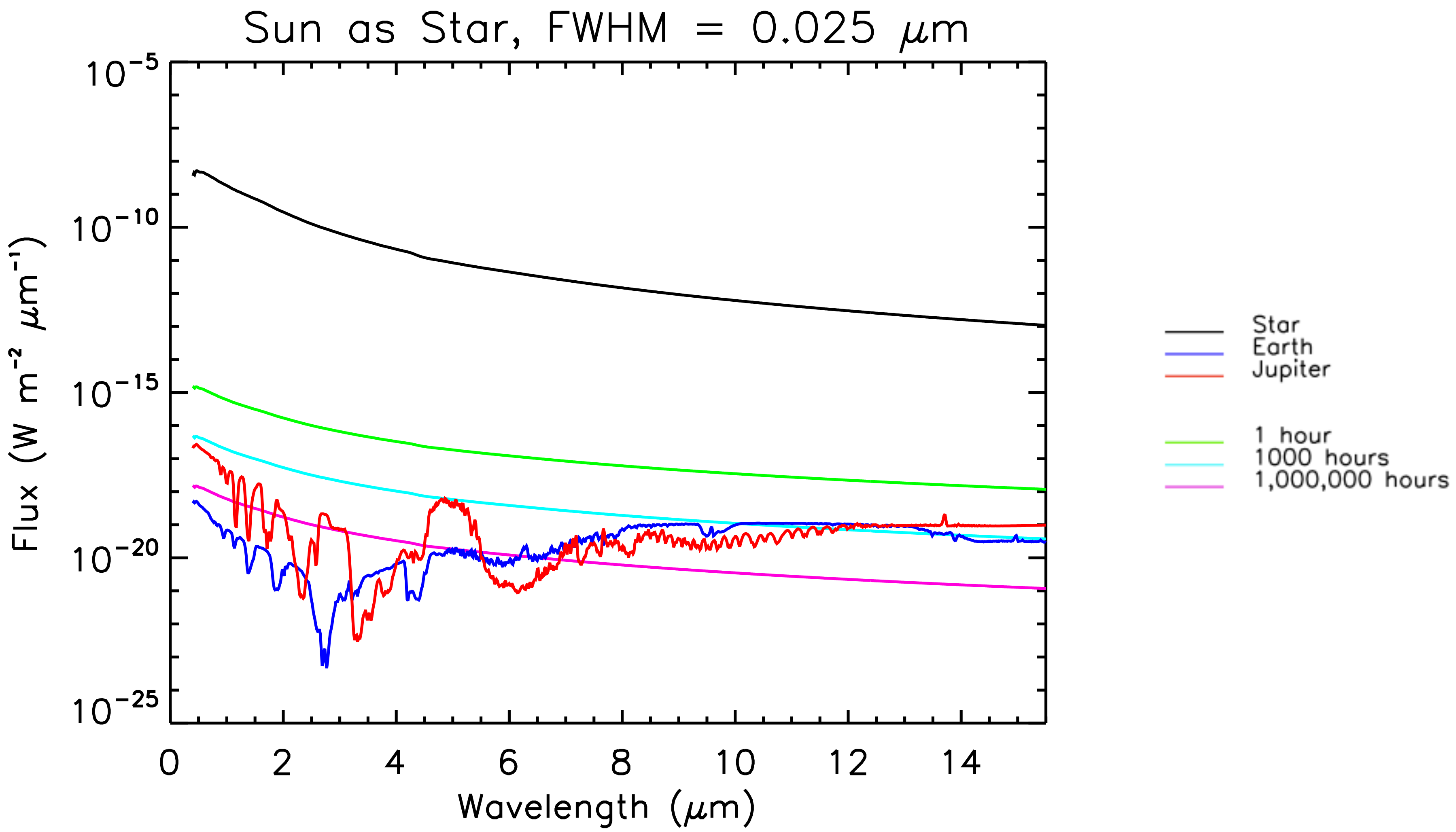


Due to their age-mass-temperature degeneracy, brown dwarfs have their own spectral typing. As they approach T-Dwarfs, they begin to show distinct spectral similarities to Jupiter and gas giant exoplanets.
Left: [1] Below: [2]



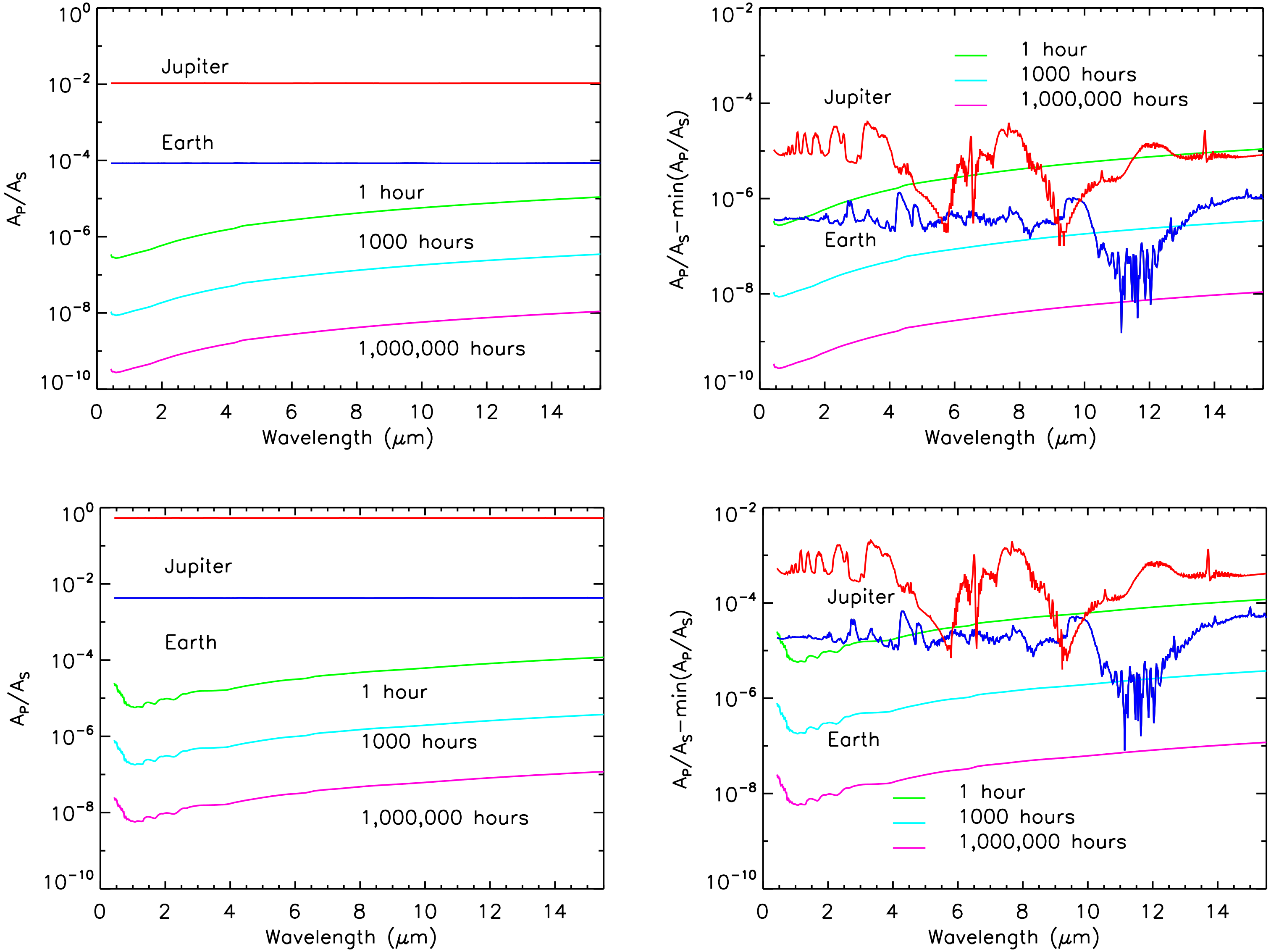
Ryan Garland, Pat Irwin, Suzanne Aigrain, Jo Barstow.

Jupiter and Earth Secondary Eclipse



Photon limited noise: 10m diameter telescope, 0.5 throughput, 0.7 efficiency, 80% duty cycle,10 ly to solar system

Jupiter and Earth Primary Transit



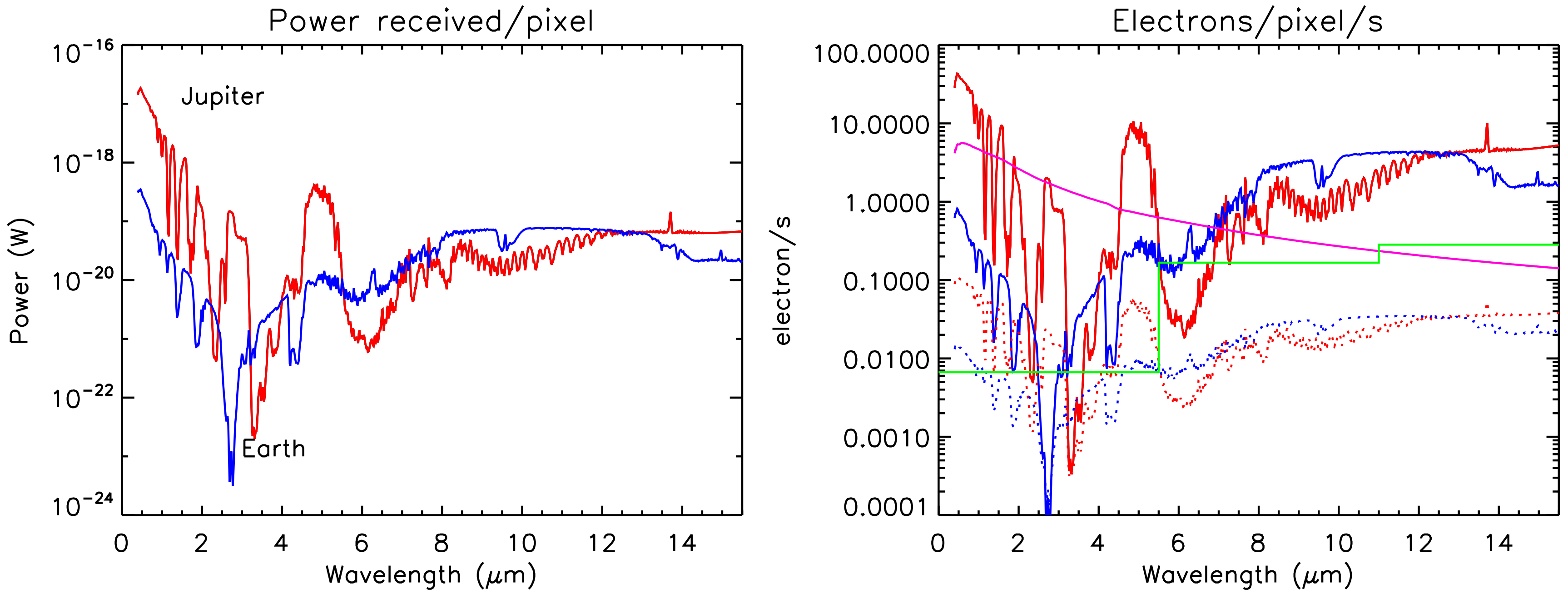
Sun

M-dwarf

Primary transit

- For Earth we found that 1000 h were required to obtain peak SNR of 100. Given that an Earth transit lasts 13 h, this would require observing 77 transits, leading to a total experiment time of 77 years
  - Not feasible.
- For Jupiter, however, we find that the observation of a single transit, lasting 30 h, has peak SNR of 400.
  - Could determine stratospheric temperature and some abundances.
  - Just have to happen to be looking in right place at right time.

Direct Imaging



- Dotted lines are photon limited noise for 1hr integration
- Green line is noise performance of best current detectors (1 hr)
- Pink line is photon noise from Sun arising from incomplete nulling to factor of 10^5.

Irwin et al. 2015. Icarus 242.

That's who we are!

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