ARIEL

The Atmospheric Remote-sensing Infrared Exoplanet Large-survey

Giovanna Tinetti & ARIEL team
The exoplanet revolution

~ 2000 planets in our Galaxy with little resemblance with Solar System siblings
Exoplanet diversity: where does it come from?

Howard et al., 2013
Tens of thousands of planets....

- GAIA
- K2
- TESS
- Cheops
- PLATO
- WASP
- HAT-NET
- NGTS
- MEarth
- Espresso
- HARPS
A host of questions...

- What are they made of?
- Why are they so exotic?
- How did they form?
- How will they evolve?
- What’s the weather like there?
- Are they Habitable?

To answer, we need to observe the atmospheres.
Exo-atmospheres with current telescopes

and many more…
Issues with current atmospheric data

- We are dealing with low SNR & R observations
- Data are sparse, not enough wavelength coverage
- Broad wavelength coverage is not simultaneous
- Absolute calibration at the level of $10^{-4}$ is not guaranteed!
- Instrument systematics are difficult to disentangle from the signal
- Stellar activity is the largest source of astrophysical noise
- We need observations on a population of objects to draw conclusions
Stars are well behaved: HR diagram

The breakthrough to understanding stars, was the coherent analysis of a LARGE sample.
ARIEL
ATMOSPHERIC REMOTE-SENSING INFRARED EXOPLANET LARGE-SURVEY

ESA-M4 mission candidate (launch 2026)

Selected for Phase A study (3 mission candidates)

1m class telescope in space (L2)

Highly stable over a few hours, high visibility of sky

Spectral range: 0.5-8 micron

~500 Exoplanet atmospheres

Pathways to habitable planets – 2015
Key questions

1. What are (exo)planets made of?
2. How did they form?
3. How do they evolve?

Ingredients:
- ~ 500 (exo)planets
  E.g. ~ 320 Gas giants, ~ 100 Neptunes, ~ 80 Super-Earths & sub-Neptunes
- They transit, they are hotter than ~ 500K, their star is brighter than K=9-9.5

ARIEL recipe

Probe their atmospheric chemistry & dynamics through VIS+IR transit spectroscopy
ARIEL will focus on planets hotter than 500K

- Large sample of atmospheres (~ 500), super-earths, Neptunes, Giants
- Hot exoplanets are a natural laboratory for chemistry and formation studies
- Atmosphere is the window into the planetary bulk composition
- We will have hundreds of hot transiting planets to select from
1. What are exoplanets made of?

- **Equilibrium Temperature**

- Planet Mass

- **H$_2$+He**
  - runaway H/He accretion
  - $H_2$O runaway greenhouse
  - hydrodynamic escape limit

- **H/He accretion/escape limit**

- **CO$_2$/co (can depend on weathering)**
  - N$_2$
  - H$_2$O (liq/vap equ)

- **N$_2$+CO/CH$_4$**
  - N$_2$ collapse
  - CO$_2$ collapse

- **Silicate atmosphere**
  - $H_2$O (steam)
  - Abiotic O$_2$

- **Tenuous atmosphere**
  - Collapse
  - Impact escape limit

Forget & Leconte, 2013
1. **What are exoplanets made of?**

The atmospheric composition and thermal properties help constraining the interior composition.
2. How do planets form?

ARIEL as a time-machine: measure relative elemental composition

Turrini et al., 2014
Probing elemental composition (O, C, N, S) in Sun’s giant planets

In the 4 Solar System giant planets, the most common heavy element, **oxygen**, cannot be measured directly by spectroscopy. Its main molecular carrier, **water**, condenses in the atmosphere and is removed from the observable region.
Probing elemental composition (O, C, N, S..) in hot, gaseous exoplanets

We can probe elemental composition for hot gaseous planets.

Water never condenses at $T_{eq} > 500$ K.

Most of the other main reservoirs of oxygen, carbon, and nitrogen (e.g. CO, CH$_4$, CO$_2$, NH$_3$, N$_2$) condense at even lower temperatures.
3. How do planets evolve?

Is temperature & equ. chemistry the driver of their evolution? Measure trace gases + clouds

High atmospheric temperatures limit the effects of condensation and sinking of the volatile species

Lodders et al., 2006
3. How do planets evolve?

Is non-equilibrium chemistry the driver of their evolution? Measure trace gases.
3. How do planets evolve?

Does atmospheric dynamics play a key role in their evolution? Measure thermal structure

Cho et al., 2008
Transit & eclipse spectroscopy

Aiming at $\sim 10^{-4}$ stellar flux at multiple wavelengths through stable instrument, external calibration & postprocessing analysis
Phase curves & eclipse mapping @ multiple $\lambda$

\[ \frac{\Delta F_j}{\Delta A_j} = \frac{\Delta I_j'}{\Delta t_j'} \]

\[ \Delta F_1 \]

\[ \Delta I_1 = \frac{\Delta F_1}{\Delta A_1} \]

Majeau et al., 2014
Spectra as function of orbital phase

Katari et al, 2015
Spectral region

Visible

- Albedo, clouds,
- Atoms, a few molecules,
- Escape processes, stellar activity

Infrared

- Thermal properties
- Key molecules

photometry bands (VIS+NIR) + spectroscopy 2-8 micron
Planetary energy balance

![Graph showing the energy balance of different planets with their respective wavelengths and temperatures.](image)

- HAT-P-7 b ($T_p = 2166$ K)
- CoRoT-1 b ($T_p = 1850$ K)
- HD209458 b ($T_p = 1408$ K)
- HD189733 b ($T_p = 1168$ K)
- GJ 1214 ($T_p = 545$ K)
- GJ 1214 ($a = 0.3$, $T_p = 512$ K)

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Key molecules absorbing in IR

H$_2$O  CO$_2$  CH$_4$  CO  H$_3^+$  HCN  NH$_3$  SO$_2$  SiO  TiO  VO  C$_2$H$_2$  C$_2$H$_4$  C$_2$H$_6$  PH$_3$
Correcting stellar activity

Danielski, Micela et al., in prep.; Micela, 2014; Scandariato et al., 2014; Herrero et al., 2014; Ballerini et al., 2012
Very hot-Jupiter – ARIEL spectrum

WASP 76b
very hot Jupiter @ 2200 K
1 eclipse
Very hot-Jupiter – ARIEL spectrum

WASP 76b
very hot Jupiter @ 2200 K

(R_p/R_*)^2 \times 10^{-2}

Waldmann & Pascale
Hot-Jupiter – ARIEL spectrum

WASP 54b
hot Jupiter @ 1800 K

Waldmann & Pascale
Hot-Jupiter – ARIEL spectrum

WASP 54b
hot Jupiter @ 1800 K

Waldmann & Pascale
Warm Neptune – ARIEL spectrum

(Wavelength ($\mu$m))

(HAT-P 11b)

(warm Neptune @ 800K)

(Waldmann & Pascale)
Hot super-Earth – ARIEL spectrum

55 Cnc e
hot-SuperEarth

Waldmann & Pascale

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NEMESIS & Tau-Rex retrieval models

Blind tests with 2 very different spectral retrieval models

Barstow et al., 2012, 2014; Waldmann et al., 2014, 2015
Comparison with JWST-NIRSPEC

http://www.cosmos.esa.int/web/jwst/exoplanets
Optimal targets for ARIEL

Courtesy of TESS team
Optimal targets for ARIEL

PLATO expected numbers of planets

Courtesy of PLATO team
Spacecraft design & Payload module

Telescope (~1 meter class), passively cooled to <80K, diffraction limit at ~3 \( \mu m \)

ESA CDF
Payload design

consortium of 12 EU countries: UK, FR, IT, DE, NL, BE, SP, PL, AU, DK, IR, PT

FGS system (redundant) which doubles as a VIS-NIR photometer

Single IR spectrometer module with dual optical chains on single detector
Conclusions

• Thousands of exoplanets discovered and more to come.

• We now need to understand how do planets form & evolve

• The way forward is to study the atmospheric chemistry of exoplanets

• We need to study a large population of objects to draw conclusions

• Ariel would deliver transformational science:
  - Large survey of planetary atmospheres (~ 500)
    Hundreds of hot & warm planets spectroscopically observed
    Tens of molecules hunted; cloud & thermal structure sounded

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