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CHARACTERIZATION OF EXOPLANETARY ATMOSPHERES WITH VLT-SPHERE

B. Charnay[1], M. Bonnefoy[2], A. Boccaletti[1], G. Chauvin [2,3], S. Lacour[1], M. Nowak[1] and VLT-SPHERE Consortium

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1 Introduction

Around 4000 exoplanets have been confirmed during the last 20 years and thousands of other planets should be discovered during the next decade by the Gaia,TESS, CHEOPS and PLATO missions. The analysis of exoplanetary atmospheres provides clues on their formation and evolution, allowing to understand their diversity and ultimately to place the Solar System in context with respect to all other known planetary systems. There are currently two main ways to analyse the atmosphere of an exoplanet. First in the case of very short periods taking advantage of the transit depth modulation in time and wavelength, and second for young massive ($\sim$10 Mjup) giant planets at large orbital separations (10-100 au) using high contrast direct imaging. In this context, the SPHERE (Spectro Polarimetric High contrast Exoplanet REsearch) instrument installed at the VLT (Beuzit et al. 2008, 2019) is a new generation high-contrast imaging instrument dedicated to the detection and spectroscopy of young giant exoplanets. First light was obtained in May 2014 and the instrument is on operation since February 2015. In section 2, we briefly described some characteristics of physics and chemistry of young giant planets. In section 3, we present the SPHERE instrument and results obtained during 5 years of operation. In section 4, we detail perspectives for the futur SPHERE upgrade its complementarity with GRAVITY.

2 Physics and chemistry of young giant planets

Planets are believed to originate from disks of gas and dust which surround young stars. Two main theoretical frameworks are proposed for planet formation. In the Core Accretion model (CA), solids made of the aggregation of dust and ice settle in the mid-plane of the disk to form solid cores which can attract the surrounding gas from the disk and create a giant planet. The Gravitational Instability (GI) considers instead that part of the disk can fragment and collapse to form a giant planet. The reality may be more complex, with potentially both mechanisms occuring in parallel. The thermal evolution of planets may be impacted by the formation mechanism, leading to differences for the luminosity and radius of young giant planets. Moreover, the atmospheric composition (i.e. metallicity and C/O) of planets formed by CA is expected to be different from the host star, depending on the mass of the core relative to the envelope, where the planet formed in the disk and how it interacted with it (Öberg et al. 2011). Probing the luminosity, radius and atmospheric composition of exoplanets therefore allows to test formation mechanisms.

Brown dwarfs are very useful to understand of the atmospheres of young giants. We expect that the physics and chemistry are very similar, the main difference being the mass so the gravity. The surface gravity of known young giant planets is typically one to two order of magnitude as low as that of field brown dwarfs. A key feature of the photometry of field brown dwarfs is the L-T transition. L dwarfs which are CO dominated appear

[1] LESIA, Observatoire de Paris, Université Paris Sciences et Lettres, CNRS, Université Paris Diderot, 5 Place Jules Janssen, 92190 Meudon, France
[2] IPAG, Grenoble, France
[3] Unidad Mixta Internacional Franco-Chilena de Astronomía, CNRS/INSU UMI 3386 and Departamento de Astronomía, Universidad de Chile, Casilla 36-D, Santiago, Chile

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redder than T dwarfs which are CH4 dominated (see Fig. 1). The favored explanation for the L-T transition is linked to silicate and iron clouds. These clouds form in the photosphere of L dwarfs, blocking spectral windows and making these object red. However for colder objects as T dwarfs, they form below the photosphere and do not impact the emission spectra and colors. Young giant planets appear close to field brown dwarfs in color-magnitude diagram, but redder and the L-T transition seem to occur at a lower effective temperature (see Fig. 1). That could be due to the lower gravity making cloud optically thicker and delaying the L-T transition (Charnay et al. 2018). Photmetric observations are too limited to constrained the atmospheric properties of directly imaged planets. Spectra obtained by high contrast imaging instruments are required to make progresses.

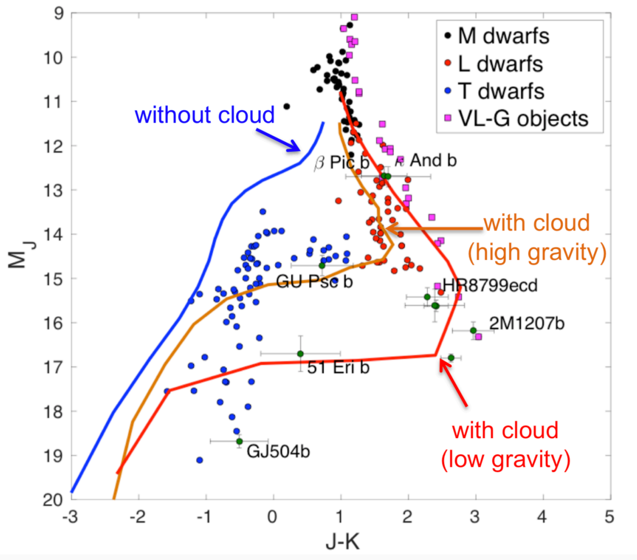

Fig. 1. Color–magnitude diagram of M, L, and T dwarfs with J - K colors plotted against the absolute J magnitude (MKO). M dwarfs are plotted as black dots, L dwarfs as red dots, T dwarfs as blue dots, low-gravity brown dwarfs as purple squares, and directly imaged substellar companions as green dots. The blue line was computed with spectra from Exo-REM assuming no clouds, log(g)=5, with Teff evolving from 400 to 2000 K. The orange (red) line was computed with silicate and iron clouds and log(g)=5 (4). Figure adapted from Charnay et al. (2018).

3 Five years of observations with VLT-SPHERE

3.1 Instrument SPHERE and SHINE program

Four last generation high-contrast instruments are currently operating: SPHERE at VLT, GPI on Gemini South, SCExAO on Subaru and MagAO on the Giant Magellan Telescope. Among them, SPHERE (Beuzit et al. 2008, 2019) can reach constrast lower than 10^{-5} by combining extrem adaptative optics with coronography (apodized-Lyot or four-quadrant coronograph). The instrument has three science subsystems:
- the infrared dual-band imager and spectrograph (IRDIS) in YJHK
- an integral field spectrograph (IFS) in Y-J with a spectral resolution R=30-50
- an imaging polarimeter (ZIMPOL).

IRDIS and IFS can be used simultaneously enabling angular differential and/or spectral imaging technics to improve the contrast. The SPHERE consortium Guaranteed Time Observations consists of 260 observing nights over 5 years. The SpHere INfrared survey survey for Exoplanets (SHINE) is the main program of the SPHERE GTO and includes 200 observing nights to conduct a large near-infrared survey of 400-600 young, nearby stars. The science goals are to characterize known planetary systems (architecture, orbit, stability, luminosity, atmosphere), to search for new planetary ones, ultimately to determine the occurrence and orbital and mass function properties of the wide-orbit, giant planet population as a function of the stellar host mass and age.

3.2 Results for the characterization of exoplanetary atmospheres

SHINE observing program led to the discovery of two new exoplanets:
- HIP 65426b (Chauvin et al. 2017), a massive (6-12 Mjup) and warm (Teff$\sim$1600 K) giant planet orbiting at a wide distance of a young star ($\sim$14 Myr). It spectral type correspond to a mid-L dwarf, intermediate between β Pictoris b and HR8799bcde. This object is quite red and its spectral fitting requires thick clouds (see Fig. 2).
- PDS 70 b (Keppler et al. 2018; Müller et al. 2018), a protoplanet discovered in the cavity of a transition disk around PDS 70 ($\sim$5 Myr, see Fig. 3). Atmospheric models have difficulties to reproduce the red spectrum of this very young object which must be surrounded by thick clouds. They predict an unphysically large radius (1.4-3.7 Rjup). The high luminosity of this young object might be due to on-going accretion and/or emission from a circumplanetary disk. A luminosity peak in Hα at the position of PDS 70 b has been detected with MagAO (Wagner et al. 2018), suggesting hydrogen accretion at a rate of $\sim 10^{-8}$ Mjup/yrs. Observations with VLT-SINFONI also suggests the possible presence of a circumplanetary disk (Christiaens et al. 2019). PDS 70 is an outstanding system for testing theories of planetary formation and planet-disk interaction.

In addition to these two new planets, SPHERE obtained photometry and spectra for a dozen of already known exoplanets and brown dwarfs companions, including HR8799 bcde (Zurlo et al. 2016; Bonnefoy et al. 2016), β Pictoris b (Lagrange et al. 2019), GJ504b (Bonnefoy et al. 2018), 51 Eri b (Samland et al. 2017) and HD206893b (Delorme et al. 2017). A common feature of young exoplanets is that they appear redder and have weaker water spectral features than field brown dwarfs, likely due to the presence of thicker clouds.

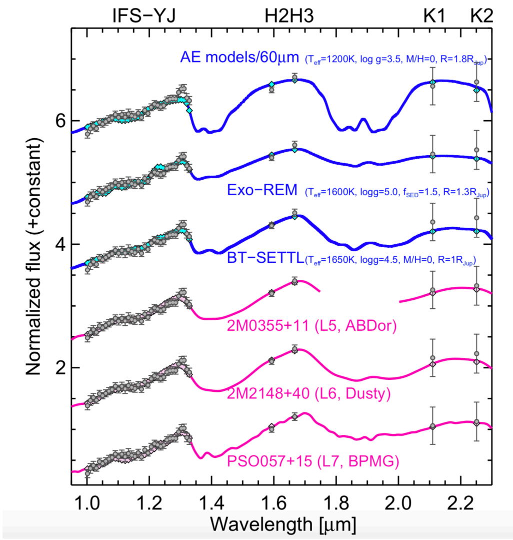

Fig. 2. SPHERE near-infrared spectrum of HIP 65426 b compared with (i) the best-fit empirical spectra in pink, and (ii) the best-fit model atmosphere from the Exo-REM, PHOENIX BT-Settl-2014 and thick AE cloud atmospheric models in blue. Figure from (Chauvin et al. 2017).

4 Perspectives

4.1 Complementarity with GRAVITY/VLTI

GRAVITY consortium recently achieved the first detection of an exoplanet (HR8799e) by optical interferometry using VLTI (GRAVITY Collaboration et al. 2019a). They obtained very accurate astrometry (0.1 mas precision) and a spectrum in K band at R=500, a resolution typically 10 times higher than GPI and SPHERE. This spectrum revealed the presence of thick clouds and CO in the atmosphere of HR8799e. GRAVITY observations were also performed for β Pictoris b (GRAVITY Collaboration et al. 2019b) providing a high quality K spectrum, showing several CO features (see Fig 4). Atmospheric retrieval from these data suggests a substellar C/O value, favoring a formation by core accretion. GRAVITY clearly is a powerful instrument for atmospheric characterization in K band. It is very complementary to SPHERE which covers YJH for spectroscopy, and which is less time-consuming and more efficient for exoplanet detection.

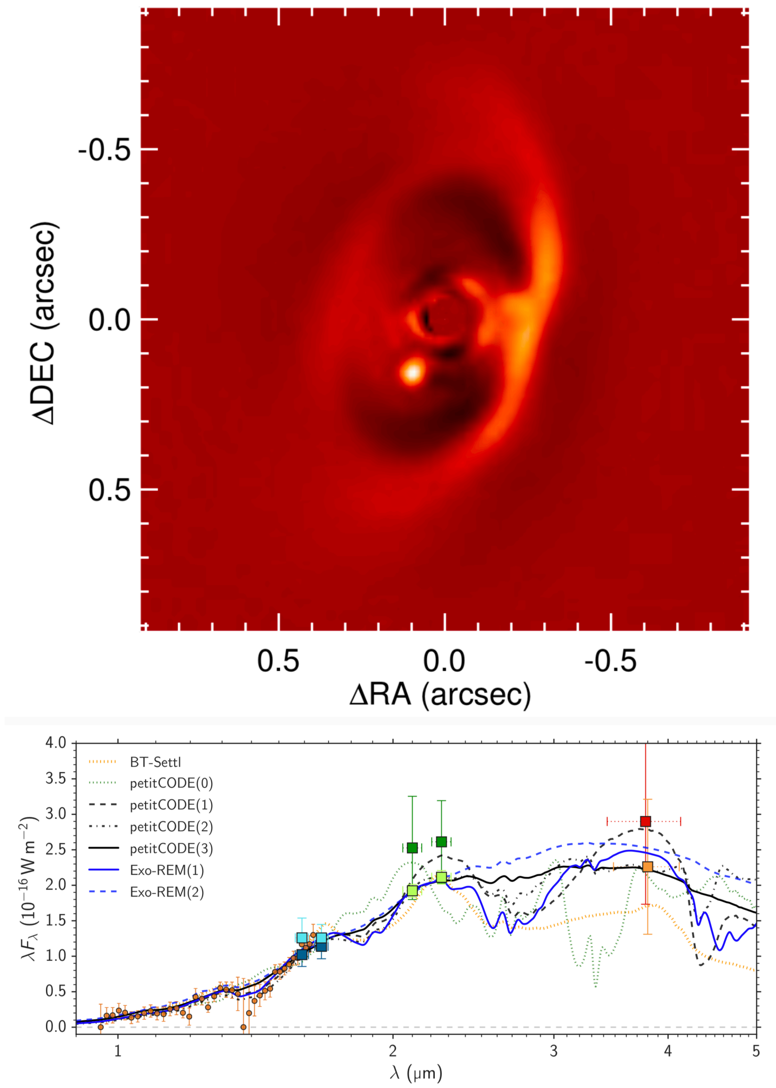

Fig. 3. Top panel: IRDIS combined K1K2 image of PDS 70 showing the planet inside the gap of the disk around PDS 70. Bottom panel: spectral energy distribution of PDS 70 b as a function of wavelength constructed from IFS spectra (orange points), IRDIS (light/dark blue and green), NaCo (red), and NICI (orange). Plotted are best model fits. Figures from (Müller et al. 2018).

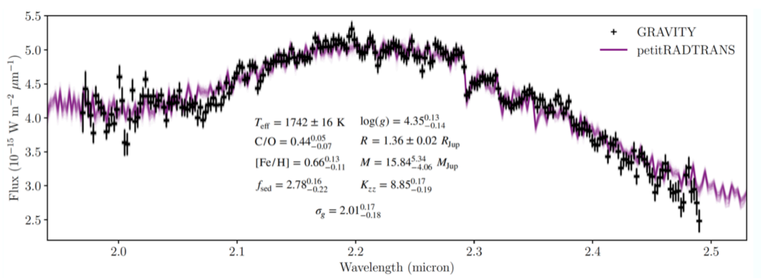

Fig. 4. K spectrum of β Pictoris b from GRAVITY data compared with the best-fit spectrum from PetitRADTRANS. Figure from (GRAVITY Collaboration et al. 2019b).

4.2 SPHERE upgrades

Upgrades of SPHERE (named SPHERE+) are considered in order to decrease the inner working angle and to look at fainter objects. There is also the possibility to add a new medium resolution spectrometer, which would increase the detection and characterization capabilities. Finally, the project HiRISE (PI: A. Vigan) aims at coupling SPHERE to CRIRES+ (both on UT3). This would allow to combine high constrast imaging and high-resolution spectroscopy to characterize exoplanetary atmospheres.

5 Conclusion

The instrument SPHERE has been in operation since five years, leading to more than 80 refereed publications young giant planets, disks and solar system bodies. It detected two new exoplanets, including PDS 70 b, which is a unique case to test models of planetary formation and planet-disk interactions. A catalogue of atmospheric spectra of young giant planets has now been collected from SPHERE and other high-constrast instruments. These observations allow to cover the equivalent of the L-T sequence of brown dwarfs. A key feature for most of young giant exoplanets is the presence of quite thick clouds. Clouds also constitute a major issue for the characterization of transiting exoplanets, limiting our ability to measure molecular abundances. Two main strategies are favored to probe cloudy atmospheres with futures instruments: either by looking at longer wavelengths where clouds are optically thinner (this will be the case with JWST and ARIEL) or by doing medium/high resolution spectroscopy to separate molecular lines. This last option will be done for direct imaging by SPHERE+ and the ELTs.

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