SPIRou, CRIRES+, VISIR, JWST

Perspectives pour l'étude de la structure, chimie et évolution des disques protoplanétaires avec la spectroscopie IR

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Protoplanetary disks

Observational understanding
• What are the gas and dust physical and chemical structures in disks?
• How do these structures evolve with time?

Physics/Chemistry understanding
• What physical/chemical processes are taking place?

Connexion Solar System & Exoplanets
• How these processes can lead to the diversity of planets known?
• How can we capture signatures of planets in the making?
Multiwavelength Observations

CARMONA Andrés Candidature CNRS concours n°17/03

Figure 2: Summary of gas diagnostics in protoplanetary disks.

VLT near-IR spectrograph CRIRES is the tool that we extensively use to study these lines.

- **molecular lines in the mid-IR**: such as $\text{H}_2$ emission at 12 and 17 $\mu$m, $\text{H}_2 \text{O}$, $\text{OH}$, $\text{C}_2$, $\text{H}_2$, $\text{HCN}$ emission at 12 $\mu$m trace warm gas at a few hundred K at $R < 10$ AU. They trace the giant planet forming region of disks.

For the same reasons exposed for the near-IR lines, mid-IR lines require high-spectral resolution in ground-based observations, or high sensitive spectrographs in space telescopes. To study these lines we use for example mid-IR spectrograph VISIR at the VLT, or the spectrograph IRS on-board Spitzer.

- **atomic lines such as the $[\text{Ne II}]$ at 12.8 $\mu$m** trace gas that has been exited by energetic radiation (e.g. X-rays) or shocks. They originate in the surface layers of disks, photoevaporative winds, or jets. Sources displaying this line have been found mostly with IRS/Spitzer, but follow-up ground-based high spectral resolution observation has been needed to unveil their origin.

- **forbidden emission of oxygen and carbon in the far-IR**: such as the $[\text{OI}]$ lines at 63 and 145 $\mu$m, and the $[\text{CII}]$ line at 157 $\mu$m trace the bulk of the gas in the disk within tens of AU and hundred AU. These transitions are only visible from space, for example with the instrument PACS on-board Herschel.

- **molecular lines in the sub-mm** trace the gas in the outer cold parts of the disk. Single dish observations are use to survey for molecules and study the outer disk chemistry. Ground-based sub-mm and mm arrays (e.g. Plateau de Bure, SMA, ALMA, CARMA) provide high spatial resolution to study extent of the disk and spatially resolved chemistry. Single dish and interferometry observations provide high spectral resolution data that is used to constrain disk dynamics and the origin of the emission lines.

**Complementary Instrumentations**

- **near-IR**: $\text{H} \alpha$, $\text{Br} \gamma$
- **mid-IR**: VLT/CRIRES, NIRSPEC/Keck
- **far-IR**: Herschel
- **1 - 5 $\mu$m**: Terrestrial Planets
- **60 - 160 $\mu$m**: Giant Planets
- **8 - 30 $\mu$m**: near-IR
- **400 $\mu$m - mm - cm**: sub-mm & mm
SPIRou @ CFHT

Instrument performances

Main science requirements

- Simultaneous wavelength domain: 0.98 - 2.35 µm (YJHK bands)
- Spectral resolution: 75 000 / RV precision: 1 m/s
- Circular & linear achromatic polarimetry
- S/N~100 (per 2.3 km/s bin) @ H~11.0 in ~1 hr exposure

High-precision Velocimeter and Polarimeter in the near-IR

- CRIRES (VLT) : 0.08 µm coverage, no polarimetry
- Carmenes (Calar Alto) : YJH bands, no polarimetry

Canada France Hawaii Telescope (3.6 m)
Earth-like planets around M-stars

- Habitable zone (HZ)
- Very few HZ super Earths
- 1 m/s
- 1 cm/s
- Sun
- M dwarfs

Mass of Star [Solar Mass] vs. Semi-Major Axis [Astronomical Units (AU)]
SPIRou @ CFHT
investigating star & planet formation

Polarimetrie:
Zeeman Doppler imaging:
Magnetic fields around young M-type stars
hot Jupiters around young Suns
modeling the activity & RV curves of T Tauri stars

V830 Tau
<2 Myr

M = 0.77 M_J; a = 0.057 AU

Perspective
WTTS → Transition Disks

Rotational cycle

Hot Jupiter!
SPIRou at CFHT investigating star & planet formation focussing on class-I, -II (cTTSs) & -III (wTTSs) PMS stars

- Magnetic field of star & disc modifies accretion & outflows
- Impacts internal structure & rotation of stars
- Impacts formation, migration & survival of planets

238 SF2A 2013

Ionized gas in accretion funnel flows:
- HeI 10830 Å, Paβ, Brγ

- Hot gas in the disk surface: ro-vibrational transitions of water at 2.29 μm
- Shocked gas in jets: H₂ 2.12 lines blueshifted >100 km/s

Hot gas and dense gas in the inner disk edge: CO overtone emission at 2.3 μm

Centrifugal outflows:
- H₂ 1-0 S(1)
- [FeII] 1.64 μm, [NI] 1.04 μm, [SI] 1.08 μm, [SII] 1.03 μm, [CI] 0.98 μm emission
- Atomic and ionized gas in jets

Redshifted absorption due to accretion/blueshifted emission due to winds highly variable on a rotation timescale

Atomic winds: blueshifted absorption
- Fischer et al. 2008

Molecular disk winds:
- H₂ emission blueshifted a few km/s

Magnetospheric cavity

Hot gas and dense gas in the inner disk edge: CO overtone emission at 2.3 μm

Hot gas in the disk surface: H₂ 2.12 μm emission at v=0 km/s

Adapted from Camenzind
Validation tests: Jun - Nov 2017

stability 0.3 mK rms (!)

Spectrograph Temperature

74.8475 K

Andrés CARMONA
Validation tests: Jun - Nov 2017

Radial Velocity stability 0.2 m/s!

SPIRou RV stability with fixed AS

Relative RV drift (science - calibration channel)
Absolute RV drift

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Validation tests: Jun - Nov 2017

Solar Spectrum

SPiRou spectrum vs Solar atlas at 70K resolution & telluric spectrum

R~70000

SPiRou Stokes V solar spectrum

rms 0.02%
Acceptance November 2017

Crates arrived to Hawaii in January

Alignment 01/2018

We installed the H4RG (friday!), commissioning summer!! Beginning of operations in autumn!
CRIRES+ 2019

Near-IR slit high-resolution spectrograph with AO

- 0.9 - 5.3 μm
- R~90 000
- CRIRES 0.08 μm →
  - CRIRES+:
    - Y-band 1 exp.
    - J or H-band: 2 exposures
    - K-band: 3 exposures
- Polarimetry
- AO: 0.2" resolution
  (28 au @ 140pc)
- Sensitivity: $10^{-15}$ erg/s/cm$^2$
Slit observations + AO = Spatial information

$T_{\text{gas}} \gg T_{\text{dust}}$

Carmona et al. 2011
• Water and simple organics in the terrestrial planet region
CO 4.7 micron
best tracer of 300-1500 K gas

- Temperature in the disk surface layer
- Disk evolution tracer!

van der Plas + 2011

HD 97048
HD 100546
Statistically CO 4.7 μm is narrower in TD (few CO gas at R< few au)

Primordial Disk

Transition Disk

Banzatti & Pontoppidan 2015
The line fluxes quoted in the panels are the total integrated line fluxes. In the case of the CO P(10) line the flux is the total flux from the disk. For Fig. 6, the cumulative F values range from 0.0001 to 0.1.

Lower Panels: CO 4.755 m and OI 63.18 m. Similar plots for the CO 3-2 line at 870 m. The black vertical line indicates the position of the planet and the observed accretion rate. The density profile is used in the long-term evolution of the system, and the gap is formed near its Lindblad resonance located at 13 AU.

Profile de surface densité du disque & planète

interaction disque planète

- Initial density
- 10000 yr
- 50000 yr
- 100000 yr
- 200000 yr
- 650000 yr

Tatulli + 2011

Radius (AU)

Σ (g/cm²)
HD 139614 dust disk
a transition disk with a dust gap of 3.5 AU width


A7Ve, d = 140 pc, age: 9 Myr;
accretion rate = $10^{-8}$ $M_\odot$/yr, $L_X = 10^{29}$ erg/s
CRIRES HD 139164

$^{12}\text{CO} \ 1-0 \ P(9)$

$^{13}\text{CO} \ 1-0 \ R(4)$

$^{18}\text{O} \ 1-0 \ R(6)$

Velocity [km s$^{-1}$]

Carmona+ 2017
Gas density drop at R<6 au

$N_{H}(R<6\text{au}) \times 10^{-3} \text{ g/cm}^2$, $\delta_{\text{gas}} = 10^{-2}$

Tracing gas in regions not probed by ALMA

Carmona+ 2017
MID-IR spectroscopy
SPITZER
the inner disk of T Tauri stars has abundant water vapor

abundance $\text{H}_2\text{O} \sim 10^{-4}$ (~CO)
• Abundances are uncertain
• Where is the slab in the disk located?
• What is the contribution of jets?
• Link to other observations
VLT/VISIR 12 micron R~17000 Spectrally resolving the emission

WATER
- Disk emission
- 0.4 to 1 AU
- T = 540 - 600 K
- O/P = 4 (gas chemistry)

[Ne II]
- Disk Winds
- Jet

VISIR up-graded: improved sensitivity ON-GOING LARGE PROGRAM
JWST (R=600-2400)
JWST: Finally detect H$_2$ mid-IR emission from disks?

Carmona et al. 2008

H$_2$ S(0) 28 µm line fluxes: $10^{-17}$ - $10^{-16}$ erg/s/cm$^2$  
$10^{-20}$ - $10^{-19}$ W/m$^2$

JWST: H$_2$ S(0) 28 µm line
Present: r&z thermochemical parametric models

Full multi-wavelength gas + dust radiative transfer modeling (Carmona+ 2014)

Future: 2D/3D hydro + dust + chimie + RT
Perspectives

★ SPIRou:
- Study the magnetic field of M-dwarf disks.
- Search for exoplanets in T Tauri stars (e.g. transition disks).
- Monitoring of the accretion/ejection and hot gas in the disk

★ CRIRES+:
- Gas surface density in transition disks at R< 10au
- Disk temperatures at R<10 au
- Disk winds in primordial disks

★ VISIR:
- Spectrally resolving the water lines detected by Spitzer
- Study of disk dissipation using [NeII] lines

★ JWST:
- Water and simple organic molecules in a large sample of disks
- H$_2$ S(0), S(1) measurement in transition, primordial, and debris disks
Thank you