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Star-disk interaction in young stars with E-ELT/HIRES

A preview from X-Shooter spectra

S. Antoniucci

Istituto Nazionale di Astrofisica – Osservatorio Astronomico di Roma, Via Frascati 33, I-00078 Monte Porzio Catone, Italy, e-mail: simone.antoniucci@oa-roma.inaf.it

Abstract. High-resolution multi-band spectra are a fundamental tool to investigate the inner regions of young stellar objects (YSOs) and thus probe the processes that involve interaction between star and disk, like the accretion and ejection of matter. Recent works with VLT/X-Shooter have shown the potential of wide-band simultaneous spectroscopic observations to provide a full characterization of both the stellar and accretion properties of YSOs. X-Shooter results give us an exciting preview of what E-ELT and HIRES will achieve with a much more increased spatial/spectral resolution and sensitivity. Exploiting HIRES high-resolution coupled with spatially-resolved information at the diffraction limit of the E-ELT will reveal the dynamics, chemistry, and physical conditions of the innermost regions of the disks, thus providing unprecedented constraints on the physics of the accretion, on the jet-launching mechanism and on the planetary formation. A few scientific cases for which HIRES is expected to provide breakthrough results are presented.

Key words. Stars: formation – Protoplanetary disks – Accretion, accretion disks – Instrumentation: spectrographs – Stars: jets

1. Introduction

Circumstellar disks play a central role in the star formation process, as they first mediate accretion onto the central star, triggering energetic collimated jets, and later on represent a reservoir of material out of which planetary systems form. Observations have provided multiple pieces of evidence that the evolution of a young stellar object (YSO) and its disk are tightly coupled, but many aspects of the star-disk interplay remain poorly understood to date, such as the structure of the magnetic field and the protostellar jet launching mechanism. Morevoer, understanding the structure and evolution of the inner disk is critical for the outcome of planet formation, especially for planets in the habitable zone. These regions of interest remain mostly spectrally and spatially unresolved with the current or near-future space facilities and AO-systems working on 8-10m telescopes. Indeed, one needs to probe spatial scales of about 10 mas (i.e. down to Earth-orbit scales in the nearby star-forming regions) and velocity fields of a few km/s. Recent works based on VLT/X-Shooter spectra have shown the potential of medium-spectral-resolution wide-band simul-

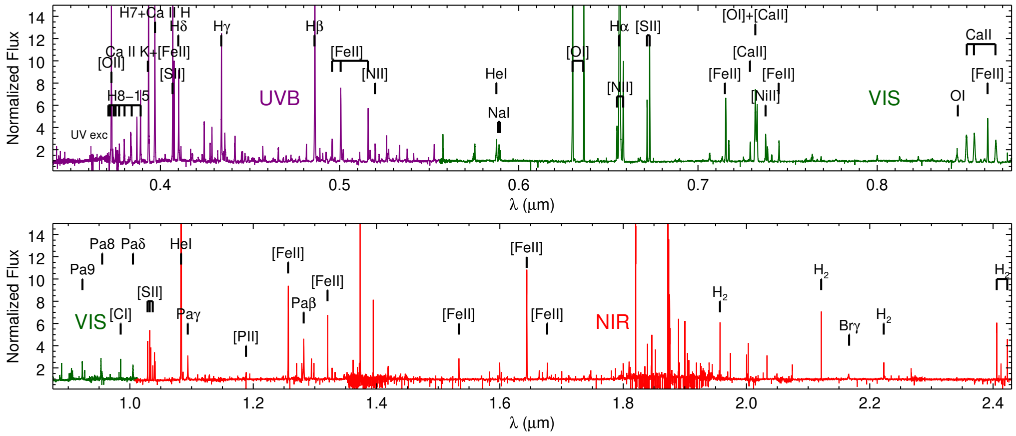

Fig. 1. X-Shooter spectrum of the pre-main sequence object Sz102 (Antoniucci et al., in prep.). The main emission features detected, which trace different structures of the source (see text), are indicated.

taneous spectroscopy to probe the processes that take place in the innermost regions of YSOs. Thanks to its characteristics, X-Shooter provides us with an exciting preview of the results that we expect to obtain through E-ELT and HIRES with a much more increased spatial/spectral resolution and sensitivity.

2. X-Shooter YSO observations

X-Shooter, the new-generation echelle spectrograph of the VLT, provides simultaneous 0.3-2.5 μm medium-resolution spectra of the targets, which allows us to detect a large number of features that probe both the star and the structures in the innermost regions (see Fig.1): the UV and IR excess give information on the accretion rate (e.g. Alcalá et al. 2014), HI & other permitted lines (e.g. OI, HeI, CaI, CaII, NaI) probe the gas in accretion flows and winds (Antoniucci et al., in prep.), forbidden lines (e.g. [FeII], [OI], [SII]]) trace the shocks within winds/jets (e.g. Giannini et al. 2015, Whelan et al. 2014), molecular lines (H_2, CO, H_2O, OH) are a tracer of molecular jets and gas in the disk, photosperic absorptions and the spectral shape provide the spectral type of the star and an estimate of the extinction (e.g. Alcalá et al. 2014). Hence, X-Shooter offers the opportunity to fully characterize the stellar and accretion properties of the targets, which permits to analyze the mass accretion rate evolution and its connection with other stellar parameters in large samples of pre-main sequence objects, mostly composed of Classical T Tauri Stars (CTTSs). The JEDI project[1] (Alcalá et al. 2015) has been particularly active on this topic in the last few years, by carrying out a significant effort to perform observations of several star-forming regions (Cha, Lup, ρ Oph, σ Ori, CrA) (e.g. Antoniucci et al 2013, Alcalá et al. 2014, Manara et al., in prep.). The current activity with X-Shooter is a crucial preparatory work in view of HIRES, not only to set the scientific background about star-disk interaction in YSOs in which HIRES will operate, but also for the development of analysis techniques and tools for the future processing of HIRES data.

3. Star-disk interaction with HIRES

E-ELT HIRES spectroscopy at high spectral resolution ($\mathcal{R}$ = 50 000–100 000) and high sensitivity in the full 0.38-2.5 μm spectral range will make it possible to extend the type of investigation performed so far with X-Shooter

[1] The JEDI (JEts and Disks @ Inaf) group is composed by INAF researchers working in the field of protoplanetary disks and jets in young stars. `http://www.oa-roma.inaf.it/irgroup/JEDI/JEDI/Home.html`

on stellar and accretion properties of YSOs to large samples of brown dwarfs, to farther star-forming regions (LMC/SMC) with fairly different metallicities, and to more embedded (younger) sources. Moreover, by coupling the high spectral resolution with spatially-resolved information (possibly with an IFU mode) at the diffraction limit of the E-ELT, HIRES will reveal the dynamics, chemistry and physical conditions of the innermost regions of the YSOs, thus providing unprecedented constraints on the interaction between star and disk, on the jet-launching mechanisms and on the environment where planetary formation takes place. A brief description of a few scientific cases for which HIRES is expected to provide breakthrough results is presented in the following sections.

3.1. Inner disk regions

Optical/IR observations of the warm/hot molecular (e.g. H_2, H_2O, OH, CO lines in the K band) and atomic (e.g. the [OI] 630 nm line) gas are crucial to probe the physics and kinematics of the inner disk and associated slow winds, providing information on the efficiency of processes such as photo-dissociation and photo-evaporation (e.g. Rigliaco et al. 2013). A spectral resolution R>50 000 is needed to resolve the line profiles (< 15 km/s), to infer size, geometry and dynamics of the emitting region and to detect for example the weak and narrow H_2O lines against the telluric contribution (Najita et al. 2009). With such measurements, HIRES will be able to trace the evolution of both the structure and chemical content of the inner disk, which has heavy repercussions on the formation of planets in the habitable zone.

3.2. Winds and jets

Understanding the interplay between the gaseous disks and jets/winds is of great importance because this interaction is expected to strongly affect both disk evolution and planetary formation. The simultaneous access to a large number of forbidden and H_2 lines, from UV to near-IR, provides powerful diagnostic tools to probe the physical parameters (such as T, n, x_e, A_V, and dust depletion) in different excitation layers in the jet beam, as recently demonstrated using X-Shooter observations of a few jet-driving sources (e.g. Bacciotti et al. 2011, Whelan et al. 2014, Giannini et al. 2014). These recent X-Shooter investigations have prompted the development of models for nebular emission line predictions in view of future observations with large telescopes like E-ELT (NEBULIO[2], Giannini et al. 2015, submitted). Since the jet acceleration/collimation occurs within 10-100 AU from the star (70-700 mas at a distance of 150 pc) adaptive optics correction in HIRES will be critical to probe the jet base. This, in conjunction with an IFU capability and an adequate spectral resolution ($\mathcal{R}$ >50000) will allow HIRES to distinguish between the proposed jet-launching scenarios, namely jets coming from the stellar surface, from the magnetosphere/disk interface ("X-winds"), or from a larger region of the disk ("disk winds", e.g. Ferreira et al. 2006), which have different implications for the disk gas dispersal and evolution. IFU observations with $\mathcal{R}$ ~100000 can detect the rotation of the jet structure, which is expected to be of the order of a few km/s (Bacciotti et al. 2002). Probing the jet rotation would put fundamental constraints on the actual efficiency of the jet in removing the angular momentum from the protostellar system.

3.3. Accretion and characterization of embedded protostars

Our knowledge of the formation process for solar-mass stars is mainly based on observations of large populations of CTTSs (~10^6 yr), which still retain a moderate accretion and jet activity. However, in order to trace back the evolution of solar type stars, it is fundamental to understand whether models constructed for T Tauri stars work for less evolved systems that are still embedded in their original infalling envelope and likely derive most of their luminosity from accretion through a massive disk

[2] http://www.oa-roma.inaf.it/irgroup/line_grids/Atomic_line_grids/Home.html

(class I sources, with age $\sim 10^5$ yr). Class I objects are characterized by large extinctions and a strong continuum excess, so that the investigation of their stellar and disk properties is extremely challenging. Up to now, weak photospheric features and emission lines from the inner regions have been detected only in a few class I sources with low/moderate IR excesses, with high-sensitivity observations at high spectral resolution (e.g. Nisini et al. 2005). HIRES observations in the near-IR at $\mathcal{R} \sim 100\,000$ will detect the weak and narrow absorption lines against the strong continuum in large samples of class I sources with different masses and IR excesses, providing a full characterization of these objects and unique constraints on the mass accretion evolution during the first stages of star formation.

3.4. Magnetic fields

Despite its central role for the disk evolution and the accretion/ejection process, measurements of the magnetic field in pre-main sequence objects are very sparse and are currently available for the brightest targets only (e.g. Gregory et al. 2012). This is due to the very high sensitivity and spectral resolution ($\mathcal{R} \sim 100\,000$) required to detect the Zeeman effect in photospheric lines that are sensitive to the magnetic field (e.g. TiI lines in the near-IR). The broad spectral coverage of HIRES will give access to many of such lines as well as to other photospheric features insensitive to the magnetic field that can be used as reference. This kind of measurement would greatly benefit of a spectro-polarimetric mode to separate the Zeeman components with different polarization. HIRES can investigate the magnetic field strength and topology in a large number of sources, which is critical to understand the real impact of the magnetic field diversity on disk and star evolution.

4. Conclusions

Recent results obtained with X-Shooter have shown the potential of wide-band simultaneous spectroscopy at adequate spectral resolution to probe the innermost regions of YSOs and give a preview of what E-ELT/HIRES will be able to achieve with a much more increased spatial/spectral resolution and sensitivity. Scientific topics for which HIRES is expected to provide breakthrough results are for example the dynamics, chemistry, and evolution of the inner disk, the analysis of the formation and structure of jets/winds, the characterization of embedded protostars, and the measurement of the protostellar magnetic fields. Synergy with ALMA will be critical to correlate the processes occurring in the innermost regions with the evolution of the outer disk and the large-scale outflows.

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