Planet-forming Regions at the Highest Spectral and Spatial Resolution with VLT–CRIRES

Klaus M. Pontoppidan[1]
Ewine van Dishoeck[2,3]
Geoffrey A. Blake[4]
Rachel Smith[5]
Joanna Brown[6,3]
Gregory J. Herczeg[3]
Jeanette Bast[2]
Avi Mandell[7]
Alain Smette[8]
Wing-Fai Thi[9,10]
Edward D. Young[5]
Mark R. Morris[5]
William Dent[9]
Hans Ulrich Käufl[8]

[1] Space Telescope Science Institute, Baltimore, USA
[2] Leiden University, the Netherlands
[3] Max Planck Institute for Extraterrestrial Physics, Garching, Germany
[4] California Institute of Technology, Pasadena, USA
[5] University of California at Los Angeles, USA
[6] Harvard-Smithsonian Center for Astrophysics, Cambridge, USA
[7] NASA Goddard Space Flight Center, Greenbelt, USA
[8] ESO
[9] University of Edinburgh, Scotland, United Kingdom
[10] University of Grenoble, France

The inner regions (< 10 AU) of discs surrounding young pre-main sequence stars are thought to be places of active planet formation. The disc surfaces are traced by molecular emission lines in the infrared. We have carried out a spectroscopic 3–5 μm survey at the highest spectral resolution (as high as $R = 100\,000$) using CRIRES on the VLT, and have used the data to map the dynamics and chemistry of molecular gas, with the aims of constraining disc evolution and learning more about the process of planet formation. In this paper, we provide a brief overview of our CRIRES observing campaign and discuss the results obtained.

The era of exoplanetary science, starting with the first radial velocity detection of a planet orbiting a star other than our own Sun more than 15 years ago, is certain to be remembered as a truly remarkable time in the history of astronomy. We now know that planetary systems are common in our Galactic neighbourhood, and that many of them are very different indeed from the Solar System: some giant planets orbit very close to their parent stars — the so-called hot Jupiters, while others orbit at larger distances from their parent stars. As planet detection methods become increasingly refined, the hunt for true Earth analogues is in full swing, and few doubt that it is only a matter of time before we discover the first terrestrial (rocky) planets orbiting their stars at distances suitable for life as we know it.

Yet, we are far from having a comprehensive understanding of the formation of planets and planetary systems. In parallel with the emergence of exoplanetary science, the field of circumstellar discs around young stars has come into full swing. While discs have long been predicted to be the inevitable outcome of the collapse of a rotating cloud, firm proof of their existence came only in the mid-1990s with the Hubble Space Telescope optical images of proplyds in Orion and the detection of gas in Keplerian rotation at millimetre wavelengths. Surveys have shown that many young stars retain gas-rich circumstellar discs with enough material to form a planetary system for a few million years after the formation of the star.

However, the connection between discs, exoplanetary systems and the formation of planets is not at all understood yet. Much of the observed structure of exoplanetary systems is thought to be the result of the protoplanets interacting with their parent disc. This is particularly true for the hot Jupiters, which are thought to migrate from a birthplace at disc radii of several astronomical units (AU) to a fraction of an AU, by way of angular momentum exchange with a gas-rich disc. The idea that circumstellar discs are actively forming planetary systems, at least up to the point of making gas giants, is so strong that these discs are often labelled as being protoplanetary, in spite of the fact that, as of now, no unambiguous protoplanet within a circumstellar disc has ever been seen.

It can be argued that the lack of understanding of planet formation and the paucity of detected protoplanets relative to mature planetary systems primarily results from a deficiency in observational capabilities, rather than insufficient theoretical tools or ideas, which currently are quite advanced and in dire need of constraints. It is clear that planets do form, protoplanetary discs must contain planetesimals and planetary embryos, and gas giants must accrete most of their mass during the gas-rich phase of the disc. In a nutshell, the problem is one of spatial resolution. The nearest protoplanetary discs are located at distances in excess of 100 pc, with a few exceptions, meaning that protoplanets are expected to exist on angular scales of 10–100 milliarcseconds — or less. The aim of our ESO large programme was to characterise the physical and chemical conditions as well as the kinematics of these planet-forming zones of discs.

Probing gas in the inner disc

Gas-rich discs are not flat, but flare in such a way that the disc surface is exposed to direct energetic stellar radiation. This gives rise to a warm layer of gas, extending from the inner edge of the disc out to at least tens of AU. Lines tracing the temperatures and densities prevalent within 10 AU are therefore found at infrared (IR) wavelengths (3–40 μm). The topmost layer is atomic, as harsh ultraviolet radiation dissociates molecules faster than they can form. Deeper in the disc, as densities rise and as the gas becomes shielded from the stellar radiation, molecules begin to dominate the gas. Even deeper, temperatures drop rapidly, and many molecular species freeze out, thus becoming invisible at IR wavelengths, due to a combination of high opacities and low excitation conditions. The intermediate, so-called warm molecular layer, on the other hand, gives rise to a veritable forest of molecular emission lines. The most prevalent species is CO, but other carbon-bearing molecules such as CO_2, C_2H_2 and HCN, and oxygen-dominated molecules, H_2O and OH, can be detected as well.

The fundamental rovibrational band of CO centred in the atmospheric *M*-band window at 4.5–5.2 µm turns out to be the best spatio-kinematic tracer available to the high spatial and spectral resolution of large aperture ground-based telescopes. CO has the highest feature-to-continuum ratio of all species observed and produces a simple spectrum with a regular series of lines originating from levels with a wide range of energies, up to several thousand Kelvin. Moreover, lines of CO isotopologues lie in the same wavelength range, so that both temperature and optical depth can be determined. All of these lines (typically a few dozen) can be observed simultaneously in just a few spectral settings, allowing accurate relative calibration. This ease of observing is in contrast with millimetre lines of CO and its isotopologues, which often require different receivers (and even different telescopes) to observe a wide range of excitation conditions. Figure 1 shows an example of different types of CO, H_2O and OH IR emission from T Tauri stars. Warm gas (typically > 400 K) is seen in emission, whereas colder gas is detected in absorption against the continuum or line emission.

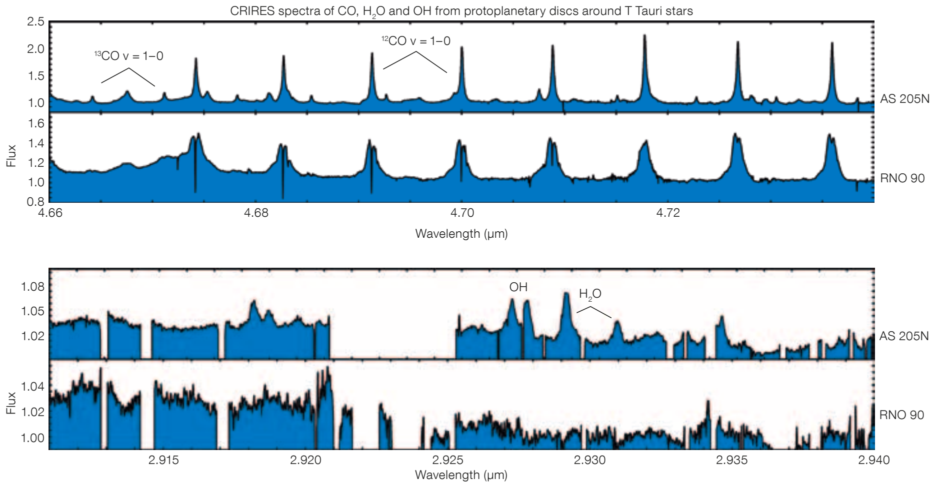


Figure 1. Examples of two types of molecular spectra seen in classical T Tauri stars. The highly accreting star AS 205N (K7) shows single-peaked CO line profiles indicative of a disc wind, along with strong rovibrational water and OH lines at shorter wavelengths tracing hot gas (Bast et al., 2011; Pontoppidan et al., 2011). RNO 90 (G5) shows classical double-peaked emission line profiles from a disc in Keplerian rotation, and much weaker or absent line emission from hot water and OH. Note that numerous patches of the water spectra around 3 µm are missing due to strong absorption from telluric water vapour.

A CRIRES large programme

The CO rovibrational band was the main target of an ESO large programme (179.C-0151) carried out with the Very Large Telescope CRyogenic high-resolution InfraRed Echelle Spectrograph (CRIRES) over the course of about 30 nights during the period 2007–2009. Significant additional time was allocated to survey water and OH lines at around 3 µm, as well as exploratory forays to search for H_3^+, HCN, CH_4 and NH_3.

The final dataset[1] includes high quality spectra of about 100 young, mostly low-mass, stars, spanning a range of evolutionary stages, from sources still surrounded by a natal envelope, to discs in the process of clearing out their inner regions, the final stage at which inner disc molecular gas can be observed. In total, nearly 600 individual spectral settings were observed. The targets were selected from nearby star-forming clouds, including Ophiuchus, Lupus, Chamaeleon, Corona Australis, Taurus, Serpens and Orion. The main selection criterion was the IR brightness of the sources, typically $F_{4.7\,\mu m}$ > 0.5 Jy to generate a relatively uniform sample of spectra with high signal-to-noise ratios.

Until the completion of the European Extremely Large Telescope (E-ELT), CRIRES offers, to our knowledge, the highest combined spatial and spectral resolution available for molecular line imaging. The typical adaptive optics (AO)-assisted imaging resolution at 3–5 µm is 0.1–0.2 arcseconds and the resolving power is of order R = 95 000. The aim of the large CRIRES programme was to fully exploit these unique capabilities to explore the dynamics and chemistry of warm molecular gas as an ingredient for planet formation. Central questions identified at the beginning of the programme included: What is the timescale for the dissipation of (molecular) gas in protoplanetary discs? What is the distribution of the molecular gas, as compared to the dust, in the terrestrial planet-forming zones of discs? Are radial motions present in discs and, if so, what drives them? Are inner discs turbulent, and can this turbulence be measured and quantified? Is there a relation between embedded discs and those surrounding T Tauri stars? What is the temperature structure of inner envelopes and discs? What is the extent of hot chemistry producing water and organic molecules of astrobiological interest?

Pushing beyond the diffraction limit

Since 0.1 arcseconds still corresponds to at least ~ 10 AU at the distance of our sources, a significant fraction of the survey was dedicated to the development of a spectro-astrometric mode for CRIRES that can provide even higher spatial resolution (Pontoppidan et al., 2008; 2011). Infrared spectro-astrometry is a pioneering capability of CRIRES that exploits the combination of AO-assisted imaging, stable optics and high spectral resolution to image lines at sub-milliarcsecond resolution, several orders of magnitude below the formal diffraction limit. Spectro-astrometry works by measuring the centroid offset of a spectrum as a function of wavelength (or line velocity), essentially generating position–velocity diagrams. There is no fundamental limit to how accurately astrometric offsets can be measured, but in practice the accuracy achieved with CRIRES is 0.1–0.5 milliarcseconds (a fraction of an AU!) for the 4.7 µm CO band for typical protoplanetary discs around solar-mass stars, es-sentially limited by photon statistics. We developed, in collaboration with ESO staff, an observing template that ensures optimal stability of the instrument. This accuracy resolves the molecular line emission in nearly all nearby protoplanetary discs. This spectro-astrometry template has been available for use by the general ESO community since Period 81.

To summarise the results of the spectro-astrometric campaign; some discs are, as expected, dominated by emission from gas in Keplerian motions around the central star, having line profiles and astrometric position–velocity spectra that can be modelled simultaneously by simple Keplerian models. Moreover, the basic geometries (size, position angle and inclination) of the discs can be determined with much less ambiguity than is possible from pure continuum imaging and interferometry. We found that CO emission from Keplerian discs obeys a size-luminosity relation, such that more luminous stars have larger line-emitting regions: the size of the CO emitting region is found to be proportional to the square root of the stellar luminosity (see Figure 2). This result is similar to that found for the near-IR continuum (Monnier et al., 2005), except that CO is found to emit at larger radii corresponding to theoretical equilibrium dust temperatures of about 350 K (the gas excitation temperature is actually significantly higher, 1000 K, demonstrating that it is not in thermal equilibrium).

A particularly exciting result generated by the spectro-astrometry is that many transitional discs, in which the small grains have been cleared out to several tens of AU, still harbour significant amounts of warm molecular gas inside these gaps or holes. This is a strong indication that, if the clearing is due to dynamical interaction with a companion, this object is less massive than a few Jupiters. Alternatively, the dust may not have been cleared and lost, but rather has grown to form an inner swarm of unseen planetesimals. Either way, the observation of warm molecular gas very close to the protostar seems to be directly related to the process of planet formation. Furthermore, the survival of CO in the absence of small dust grains may indicate that molecular self-shielding is operating to ensure the survival of the observed CO molecules against the ultraviolet radiation field from the central star.

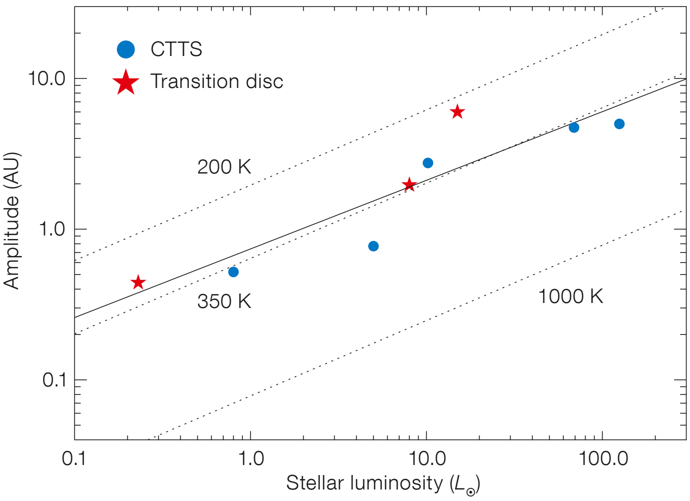


Figure 2. The size–luminosity relation, as measured with CRIRES spectro-astrometry, for discs showing CO emission from gas in Keplerian motion. Adapted from Pontoppidan et al. (2011).

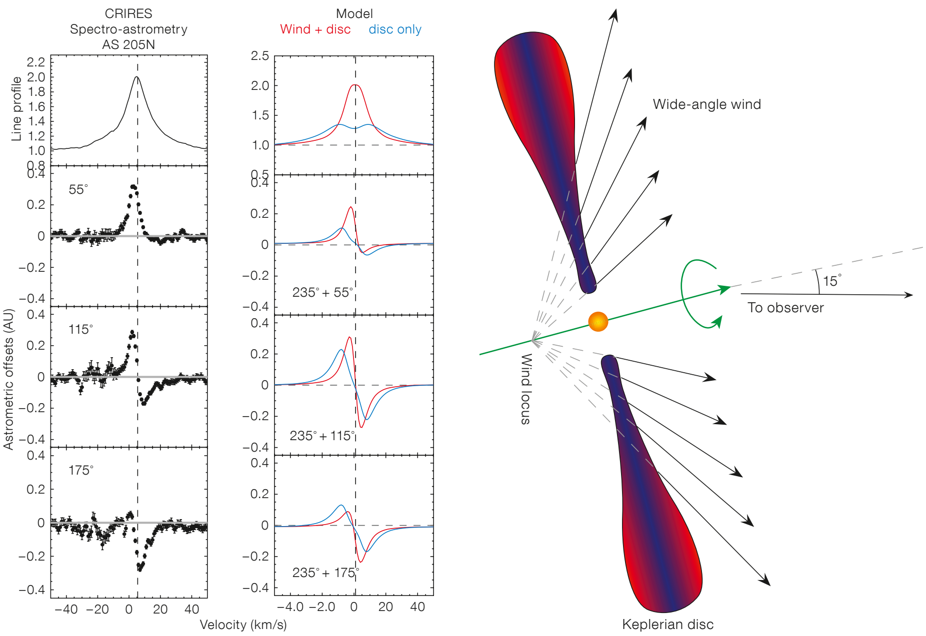


Figure 3. Example of the spectro-astrometry for a wind-dominated disc. The left panels show CRIRES data of the classical T Tauri star AS 205N with the regular line flux spectrum at the top and spectro-astrometry at three different slit position angles. The middle panels show radiative transfer models with (red curves) and without (blue curves) a wind component. The illustration to the right sketches the wind geometry that is consistent with the data. Adapted from Pontoppidan et al. (2011).

Molecular disc winds

While some discs follow convention and display clear signatures of Keplerian motions, most of our observed sample does not match a simple Keplerian velocity field. In fact, one of the surprises of our survey is the large diversity in observed line profiles (Brown et al., 2011). One class of sources — the so-called single-peaked sources — shows indications of radial motions of the gas (Bast et al., 2011). Specifically, they show low velocity gas (< 3 km/s offset from the stellar velocity) at less than a few AU from the central star, as measured directly with spectro-astrometry (see Figure 3 and Pontoppidan et al., 2011). This signature can be modelled as outflowing gas with an azimuthal velocity vector (rotation) that is slowed significantly relative to Keplerian rotation due to conservation of angular momentum.

Thus a key finding of the spectro-astrometric survey is that slow molecular disc winds are prevalent in the inner few AU of classical T Tauri stars. Because the winds are so slow, it is not certain that the gas is able to escape the disc, and may even fall back onto the disc at larger radii; if so, these winds may serve as efficient re-distributors of disc material. The implied mass flow rates of the winds are of order 10^{-8}–10^{-9} $M_{\odot}$/yr, corresponding to the entire inner disc being cycled through the wind over the disc lifetime (Pontoppidan et al., 2011). It is tempting to speculate that if the wind is able to carry dust grains with it, it may be able to contribute to the annealed (crystalline) dust found in the outer disc and in comets, the origin of which is a longstanding, and much debated, problem. Similar ideas were discussed in the 1990s in the context of fast magnetic winds (Shu et al., 1994). However, this type of wind appears to be very different than that observed by CRIRES.

Exo-cosmochemistry

The absorption components seen in many CO spectra, both toward embedded protostars as well as some T Tauri stars, allow an investigation of isotope ratios with unprecedented precision. A central objective of this subprogramme was to search for rare isotopologues of CO, in particular $C^{17}O$ and $C^{18}O$, and obtain accurate measurements of their relative ratios. Why is this particularly interesting? The field of cosmochemistry deals, in part, with high precision measurements of the composition of early Solar System material, specifically primitive meteorites, to infer conditions of the Solar Nebula at the time of planet formation. Ratios of elemental isotopes provide important clues not only to the timing of formation of the meteorites, but also of the chemical and radiative environment of the material. For instance, the oxygen in meteorites is found to be heavy (^{18}O- and ^{17}O-rich with respect to ^{16}O) with a re-lative, mass-independent ratio that indicates the action of a photon-induced process rather than thermal chemistry. A leading hypothesis to explain this non-terrestrial oxygen isotopic relationship is CO self-shielding, i.e. that the Solar System oxygen was once part of gas that was exposed to strong ultraviolet radiation, likely generated by either the central protostar or hot stars in the vicinity of the Solar Nebula (e.g., Clayton, 2002). The effect arises because the light isotopologue $C^{16}O$ is much more abundant than the heavier isotopologues $C^{17}O$ and $C^{18}O$ and therefore self-shields against photo-dissociation at much lower column densities.

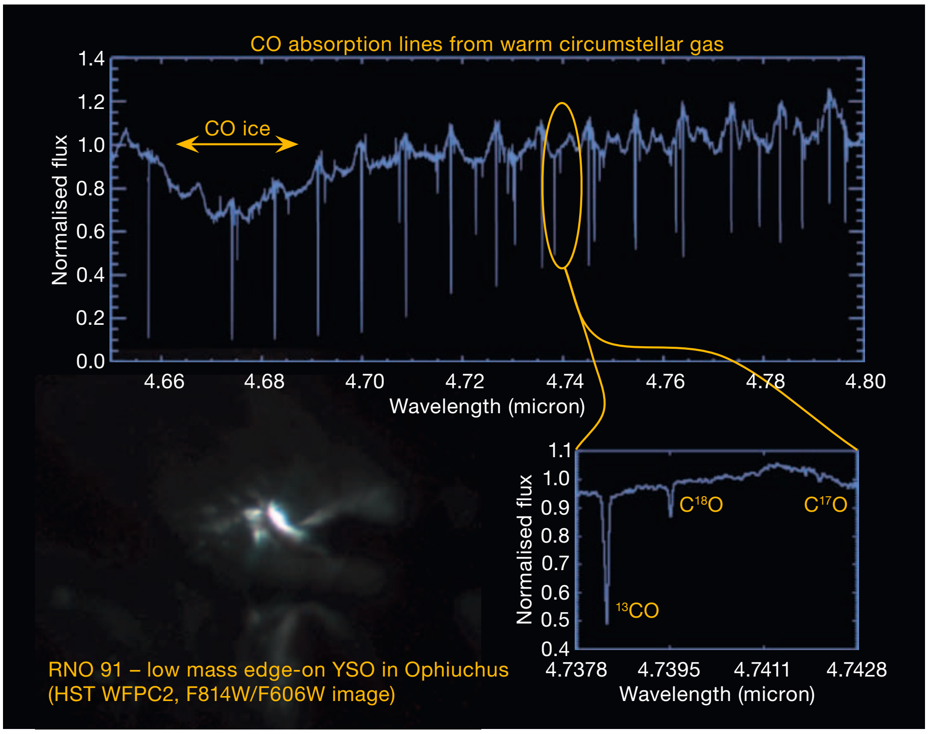
Due to its high spectral resolving power, CRIRES is, in principle, capable of measuring column densities of the four main CO isotopologues ($^{12}C^{16}O$, $^{13}C^{16}O$, $^{12}C^{18}O$ and $^{12}C^{17}O$) to high precision in discs, given a favourable geometry in which the gas is seen in absorption. This opens up the exciting possibility for directly comparing protoplanetary disc chemistry, as it is unfolding, with that inferred from 4.6 billion year old rocks from the ancient Solar System. As part of our CRIRES large programme, we have carried out a mini-survey of discs and protostars with CO absorption lines deep enough to allow an accurate measure of isotopologue ratios to a relative precision as high as 5 % (Smith et al., 2009).

The analysis is aided by *K*-band absorption spectra of the ^{12}CO v = 2–0 overtone band at 2.3 μm, which has much smaller oscillator strengths and thus low optical depth. The first results are indeed consistent with isotope selective photo-dissociation in other planetary systems, in support of the model for Solar System oxygen fractionation. Remarkably, the oxygen isotopic data have also been used as evidence for supernova enrichment of the Solar Nebula (Young et al., 2011). Finally, our survey has uncovered anomalously high $^{12}CO/^{13}CO$ ratios in many absorption components in the protostellar sample, the origin of which is still undetermined (Smith et al., 2011; see Figure 4).

Embedded discs

While our understanding of fully formed protoplanetary discs is rapidly improving, in part due to fundamental improvements in the spatial resolution of continuum and line imaging data across the wavelength

Figure 4. CRIRES spectrum of CO absorption lines from the young low-mass star RNO 91. The insert shows detected lines from ^{13}CO, $C^{18}O$ and $C^{17}O$ (adapted from Smith et al., 2011).



range, the formation of the discs during the embedded phase of star formation is still very poorly understood. Because the mid-IR molecular forest may provide a unique tracer of such young discs at scales of a few AU, an important part of our CRIRES programme was to investigate whether molecular emission from embedded discs shares the properties of the emission from T Tauri discs. Even though AO was not possible on these optically weak sources, we were fortunate to have several nights of exceptional natural seeing (down to 0.3 arcseconds at visible wavelengths) which we used to observe these sources. Our results showed that, while complexities such as absorption from cloud material and (episodic) outflowing gas (Thi et al., 2010) interfere with the emission components, embedded discs appear similar to the inner regions of highly accreting T Tauri stars (Herczeg et al., 2011).

In some cases, embedded protostars also show highly extended CO emission, an example of which is shown in Figure 5, where a continuum-subtracted two-dimensional spectrum of ro-vibrational ^{12}CO is compared to a NACO *K*-band image of the source. The high resolution of CRIRES reveals narrow (~ 3 km/s full width half maximum [FWHM]) line emission extending to more than 2 arcseconds from the source along both outflow cavities. The mechanism forming the extended narrow emission is unclear, but it may be related to combined UV heating and shock interaction between a wind and the outflow cavity surrounding the young star (see Herczeg et al. [2011] for a discussion). The detail seen along a single slit alludes to the potential for line imaging with an integral field unit operating at high spectral resolution in the *M*-band.

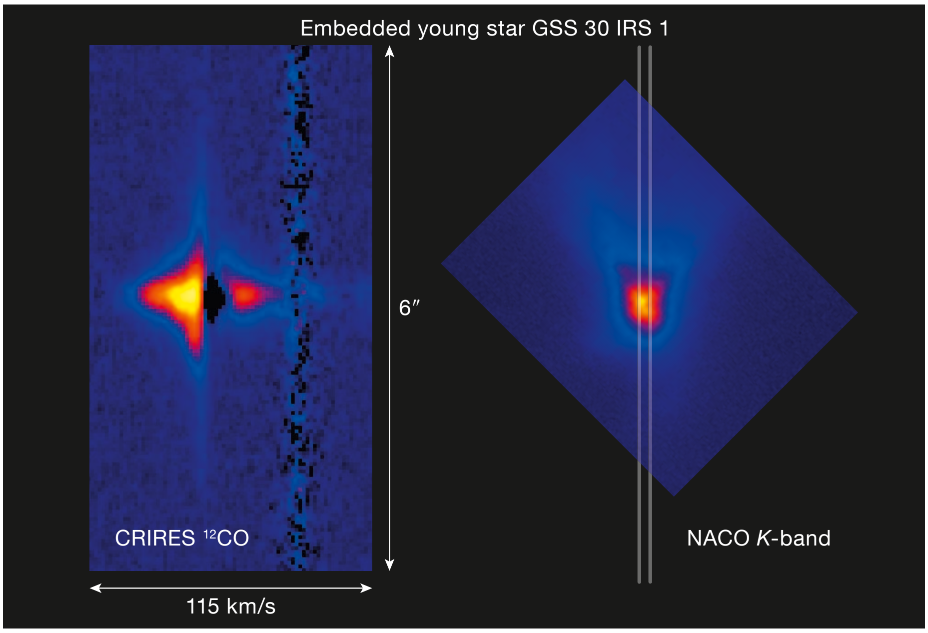


Figure 5. Long-slit spectrum of the ^{12}CO v = 1–0 lines of the embedded young star GSS 30 IRS 1, showing highly extended line emission (from Herczeg et al., 2011). The slit is oriented along the outflow cavity axis, as seen in an archival *K*-band image obtained by NACO (right). The *K*-band image is scaled to correspond to the spatial axis of the CRIRES two-dimensional spectrum.

Outlook

The fundamental outcome of our large programme is a database of high precision *R* ~ 95 000 spectra of molecular gas from many, and perhaps more than half, of the bright protoplanetary discs around T Tauri stars in the southern hemisphere, as well as a significant sample of low-mass protostars. The high quality of the data and the richness of the spectra demonstrate the potential of sub-arcsecond resolution imaging spectroscopy in the mid-IR, in particular for tracing warm molecular gas in circumstellar environments.

The potential of CRIRES is by no means exhausted. The spectro-astrometric mode is a very powerful capability that still has great potential for discovery. For instance, imaging sub-milliarcsecond structure goes beyond protoplanetary discs, and may be applied to other circumstellar (or even stellar) structures and active galactic nuclei. We also foresee significant synergies with the VLTI, as well as potential time-domain investigations. The detail observed even along a single slit (Figures 2 and 3) suggests a high potential for line imaging with an integral field unit operating at high spectral resolution in the *M*-band, such as the E-ELT instrument concept METIS (Brandl et al., 2010). Finally, both CRIRES and METIS will be highly complementary to ALMA, which can observe the dust distribution down to ~ 1 AU but is limited in its imaging of the gas to radii larger than a few AU.

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Links

[1] Reduced spectra are made available for download at: http://www.stsci.edu/~pontoppi/