Highlights of Spanish Astrophysics IV

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Proceedings of the Seventh Scientific Meeting of the Spanish Astronomical Society (SEA), held in Barcelona, Spain, September 12-15, 2006

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The book cover's background image shows the projected primordial gas distribution on a scale of 500/h Mpc width. The filamentary structure is because baryons accurately trace the underling dark matter distribution. This image was obtained from the largest cosmological gasdynamical simulation done up to now, known as 'MareNostrum Universe'. It consists of 2 billion particles distributed in a cubic box of 500/h Mpc on a side, half of them representing the dark matter and the other half representing the baryons. The image shows the gas density in one of the cube's projections. The simulation was made with the Mare Nostrum supercomputer at the Barcelona Supercomputer Center (BSC). (courtesy of G. Yepes, UAM)

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Preface

The Seventh Scientific Meeting of the Spanish Astronomical Society (Sociedad Española de Astronomía, SEA) was held at the Universitat de Barcelona in Catalonia from September 12–15, 2006. The event brought together 301 participants, who presented 161 contributed talks and 120 posters, the greatest number up to now. The fact that most exciting items of current astronomical research were addressed in the meeting proofs the good health of the SEA, a consolidated organization founded 15 years ago in Barcelona. Two plenary sessions of the meeting were devoted to the approved entrance of Spain as a full member of the European Southern Observatory (ESO) and to the imminent first light of the largest telescope in the world, the Gran Telescopio de Canarias (GTC), milestones that will certainly lead the Spanish Astronomy in the near future. During the meeting, the SEA made public the Fourth Prize to the Best Spanish PhD Thesis in Astronomy and Astrophysics for the period 2004–2005 ex aequo to Dr. Andrés Asensio Ramos and Dr. Patricia Sánchez Blázquez. The excellent PhD thesis of all applicants confirms the high-level scientific career of young Spanish astronomers. Several specialists were invited to review central aspects in the different domains of astrophysics. We want to thank here all of them for their superb contributions. The effort of the Scientific Organizing Committee was crucial for the achievement of the scientific success of the meeting.

The Society is indebted to the Universitat de Barcelona for hosting the meeting in its historical building; its pleasant and relaxing atmosphere sheltered and protected us against an intense Mediterranean storm. The Local Organizing Committee took care of all the logistic details to ensure a nice stay to all the participants. The meeting was possible thanks to the financial support of several research centers, universities, governmental institutions, and private Spanish companies, these latest sharing with the astronomers the responsibility of achieving a great technological challenge in both, space and ground-based instrumentation.

The proceedings of the Third, Fourth, and Fifth Scientific Meetings of the SEA were published in the series “Highlights of Spanish Astrophysics”.

Contributions to the Sixth SEA meeting, held in Granada in 2004 as a Joint European and National Astronomy Meeting, were published in the series JENAM Astrophysics Reviews. With this volume we return to the series "Highlights of Spanish Astrophysics", with the hope of providing, now and in the future, a good compilation of the state of the art Spanish Astronomy to the international community. Invited talks are all collected in this book whereas contributed talks and posters presented at the meeting are published in the attached CD.

Barcelona, January 2007

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Session I

Spain in ESO

Youth, Accretion, and Mass Loss at the End of the Main Sequence

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Summary. The characterization of the properties of very low mass stars and substellar objects in star forming regions is an important research topic at ESO telescopes, and it has been pursued through the use of a wide variety of instruments and observing techniques. In this paper we focus on a project developed over the past few years devoted to the study of a particular group of very low-mass, low-luminosity objects in a number of nearby star forming regions that display strong indicators of accretion and mass loss. In this context, we also refer to related research carried out by other teams using ESO telescopes. Although the results amassed thus far do not allow us to unambiguously determine the nature of the objects exhibiting these characteristics, it appears that the examples studied until now span a wide range with regard to the relative importance of the accretion and mass loss signatures, the way in which the latter takes place, and possible also our vantage point with respect to them. This stresses the complexity of the earliest stages of stellar and substellar evolution, particularly regarding the comparison of evolutionary models that do not include mass accretion with the observational characteristics of real objects whose physical parameters are usually derived by using such models.

1 Introduction

There is no doubt that we live in an era of renewed interest in the topic of circumstellar disks, mass loss, and their connection to the origin of stars. The reasons for this are manifold, but they may be grouped under three broad categories: (a) the discovery of ever less and less massive substellar objects, which severely question basic assumptions of some models for the formation of stars and brown dwarfs; (b) the connection between accretion and the formation of planetary systems, and the importance of dynamical interaction with a massive circumstellar disks leading to orbital migration as a determining factors in shaping the main features of the resulting planetary systems; and (c) instrumental breakthroughs in sensitivity, resolution and spectral coverage achieved by unique facilities both on the ground and in space, which have enabled an increasingly direct observation of disks and jets. On the ground, such facilities

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include adaptive optics and coronagraphic instrumentation nowadays available on 8 m class telescopes, sensitive thermal infrared instruments that make it possible to image at the diffraction limit of such large apertures, and high-resolution visible and near-infrared spectroscopy. Future unique facilities such as ALMA are ideally suited for high-resolution imaging of cold dust and molecular line emission around stars and brown dwarfs. At the very large telescope interferometer (VLTI), upcoming improvements in fringe tracking and new instrumentation hold the promise of obtaining milliarcsecond-level spatial resolution even at faint magnitudes. From the space, the Spitzer observatory is living up to the expectations of revolutionizing the field by providing spectral energy distributions and spectroscopy of all but the outermost regions of disks around young objects at stellar and substellar masses, providing unprecedented insights into their structure and mineralogy, and there is no doubt that ESA's Herschel observatory will follow on this path.

1.1 Some contributions at ESO

Since this paper was delivered at the plenary session devoted to the accession of Spain to ESO, it is especially appropriate to outline here some of the major contributions that research groups making use of ESO's facilities have made to the identification and study of the circumstellar environment of low-mass stars. Such an enumeration is necessarily incomplete and subjective, but it hopefully serves the purpose of stressing the important role that state-of-the-art instrumentation at ESO telescopes, most notably at the VLT, has played in the current knowledge in this field. It is also remarkable in the context of the present talk that several of the teams that have carried out this research are led by, or at least include, Spanish astronomers.

- Deep imaging with narrow- and intermediate-band filters carried out with the Wide-Field Imager at the MPI/ESO 2.2 m telescope on La Silla has detected faint, cool members of nearby Southern star-forming regions thanks to the identification of Hα emission, providing statistically significant samples that demonstrate that Hα is still one of the preferred methods for the identification of young stellar objects, even at substellar masses ([1,31–33]).
- Thermal infrared imaging and spectroscopy of young stellar objects, with TIMMI2, ISAAC, and VISIR, have provided information on the large-scale structure of disks around very low-mass stars and massive brown dwarfs, as well as on the composition of their minerals and ices [17, 41, 42, 47, 48, 50, 2, 3, 34].
- High-resolution spectroscopy carried out with Ultraviolet Echelle Spectrograph (UVES) at the very large telescope (VLT) has made possible the detailed analysis of the indicators of accretion and mass loss, as well as the monitoring on short timescales of their variability and rotational modulation. The application of innovative techniques such as spectroastrometry has also provided detailed insights

into the jet launch regions at the scale of a few astronomical units [45, 46, 4, 26, 27, 51, 5, 39, 40, 52].
- Radial velocity monitoring of very low-mass objects in young star forming regions with UVES has investigated whether giant planets, particularly hot Jupiters, already form in the first few million years of their lives. Although no conclusive answer has yet been established, the results demonstrate that it is within the possibilities of current instrumentation [24, 25, 49].
- Characterization of young very low-mass objects and their activity, using low-resolution spectroscopy in the visible and near-infrared with VIMOS, FORS1/2, or ISAAC [7–9, 20, 43, 23].
- Spectroscopic characterization of disks and jets to the infrared, using SOFI and ISAAC, yielding emission-line diagnostics on deeply embedded sources [39, 40, 37, 38].
- Detection and study of sources surrounded by nearly edge-on disks, both with imaging (SOFI, ISAAC) and spectroscopy (UVES). Edge-on disk systems are particularly useful to study the circumstellar environment, as the disk acts as a natural coronagraph of the central source [12, 22].
- Detection of L'-band infrared excesses with ISAAC, making it possible to identify very low-mass members of embedded stellar aggregates and demonstrating that the excess emission due to warm circumstellar dust continues well beyond the substellar limit [30].
- Finally, we should mention the studies carried out by Van Boekel et al. using MIDI at the VLTI, which have provided unprecedented spatial resolution of inner disks around bright stars demostrating the power of mid-infrared interferometry [11].

2 Subluminous Objects Near the End of the Main Sequence

In the rest of this paper we will focus on an intriguing class of young stellar objects that have received detailed attention in recent years due to the combination of apparently peculiar photospheric and circumstellar characteristics. Members of this class have spectra with intense emission lines, both those associated to outflows and to mass loss. The underlying photosphere has a late spectral type, and the $BVRIJH$ colors are similar to those of normal stars, obscured by low to moderate extinction. K-band excess is weak or absent, and the very low luminosities, if taken at face value, place these objects on isochrones indicating ages much older than those expected in star forming regions, or even below the main sequence; see Fig. 1. The accretion rates are estimated to lie in the 10^{-9}–10^{-10} $M_{\odot}yr^{-1}$ range.

Despite these common features, important differences can be noticed among the different objects belonging in this class: on the one hand, the relative intensities of the lines used for accretion and mass-loss diagnostics

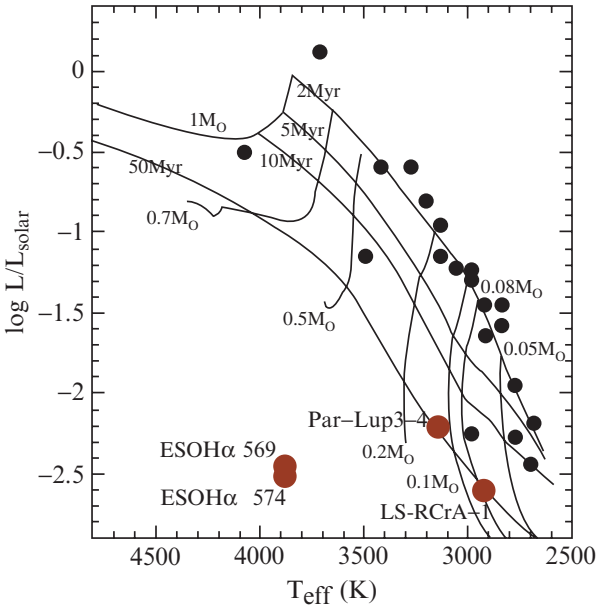

Fig. 1. Temperature-luminosity diagram showing the positions of the four objects discussed in this paper with respect to evolutionary tracks [6] corresponding to typical ages in young aggregates. The small dots correspond to the stellar population at the center of the Chamaeleon I cloud [14], which are well matched by a 2 Myr isochrone. The horizontal locations of ESO-Hα 569 and 574 are only approximate, as their spectral types are poorly determined.

change dramatically from object to object. On the other hand, their morphologies range from being unresolved even when observed at high-spatial resolution, to resolved sources displaying hints of arc second-level structure, to the presence of well-formed jets near the central source. Alhough we discuss in what follows four objects that we have discovered and followed up, earlier studies had already identified examples, such as HH 55, which was interpreted by Graham and Chen as a jet powered by a low-mass, relatively old member of the Lupus 3 cloud [21]. Some of our objects also bear resemblance to 04158+2805, a possible class I source in the Taurus clouds [29]. Other examples can be found in the literature (see [15]).

It has been suggested (e.g. [10]) that the characteristics of these objects may be readily explained by edge-on disks blocking the light from a central source with the normal luminosity corresponding to the age of the aggregate to which it belongs. The blocking would account for the abnormally low luminosity, whereas the apparently normal colors would be a consequence of the photosphere of the object being seen mainly in scattered light. In turn, the prominence of the emission lines would be explained by the fact that they are produced at some distance from the central object, in regions directly

visible. This may indeed explain some of these objects but, as we will see in the discussion on individual examples that follows, features observed in some of them may be difficult to account for in this scenario.

2.1 ESO-Hα 574: a low-luminosity object with a jet

ESO-Hα 574 is a faint source in the periphery of the Chamaeleon I North cloud discovered by B. Reipurth in objective prism plates thanks to its Hα emission [16]. Its spectral type is poorly determined, probably due to veiling of the photosphere by emission produced by accretion.

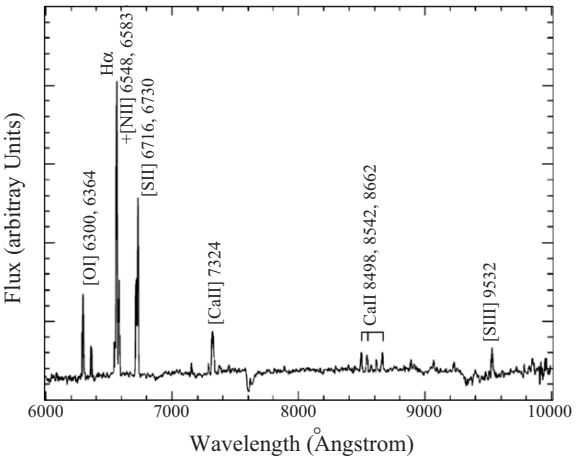

Fig. 2. Spectrum of the central source of ESO-Hα 574, showing its rich emission-line spectrum. The most prominent lines are marked. The underlying continuum is virtually featureless except for telluric absorption bands, possibly due to strong veiling.

The emission-line spectrum is rich in forbidden lines (Fig. 2), implying that mass-loss signatures are dominant over those commonly attributed to accretion. Indeed, HeI emission is not detected and the intensity of the CaII triplet is very modest. Given the intensity of the emission lines, it is not surprising that deep narrow-band imaging in the [SII] filter [13] clearly shows a jet stemming from the central source (Fig. 3). The bipolar jet is rather short, extending for only $\sim 3,000$ AUs of projected distance from end to end. Assuming that the emission-line spectrum at the position of the central source is similar to that along the jet, the derived physical parameters are similar to those of typical T Tauri jets. The central object is marginally resolved in near-infrared images, being elongated in a direction roughly perpendicular to the jet axis. The knotty structure of the northeastern jet suggests variability in the jet ejection parameters on timescales perhaps as short as 1 decade.

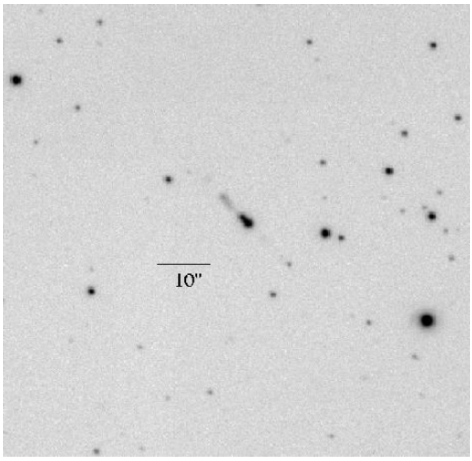

Fig. 3. Narrow-band image of ESO-Hα 574 obtained using FORS1 with a [SII] filter, clearly showing its the bipolar jet, HH 872.

The resolved structure and its elongation, and the prominence of forbidden lines, lead us to consider ESO-Hα 574 as the object most likely to be an edge-on disk, as no characteristics known thus far conflict with this interpretation.

2.2 LS-RCrA 1

LS-RCrA 1, near the densest part of the R Coronae Australis star forming region, was discovered Hα emitter with 1.5 m Danish telescope on La Silla. Its spectral type was determined shortly thereafter as M6.5 using FORS1 [18]. Its location in the temperature–luminosity diagram corresponds to that of a 50-Myr object. It displays prominent forbidden lines, HeI and CaII triplet emission, and weak H_2 emission in the near-infrared. Colors are similar to those of a normal M6.5 star with light obscuration, with no K band excess, although showing hints of variability. The CO bands longwards of 2.29 μm [18] are significantly less deep than expected for an object of its spectral type.

LS-RCrA 1 has been the subject of many follow-up observations by different groups, making it the most thoroughly studied object thus far in this class. Infrared observations under excellent seeing and adaptive optics imaging have failed to resolve it, placing rather stringent limits on any possible extended structure. Similarly, imaging with narrow-band filters in the visible and the near-infrared did not detect traces of a jet.

Mid-resolution spectroscopy has yielded further constraints on the nature of the emission-line spectrum. Barrado et al. confirmed a temperature close to that estimated from the spectral classification of Fernandez and Comeron but inferred a surface gravity normal for an 8-Myr object, in better agreement with the age expectation for members of R CrA [10, 18]. They also reported single-peaked emission-line profiles,

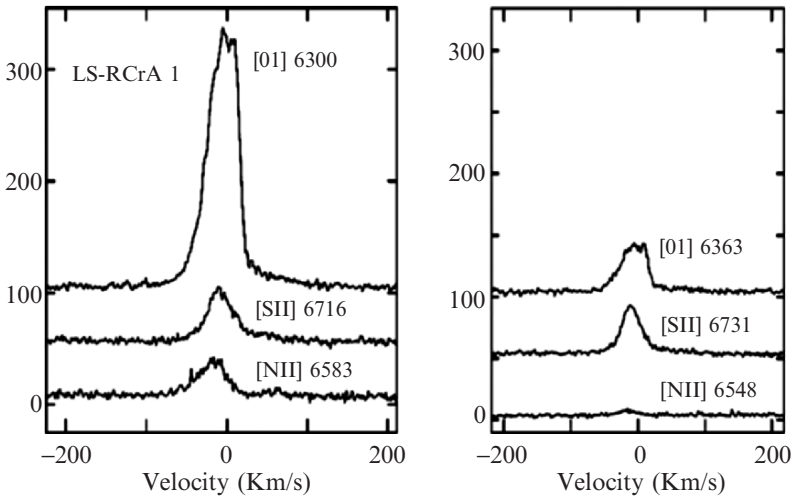

Fig. 4. High-resolution UVES spectroscopy of forbidden lines in the spectrum of LS-RCrA 1. Note the clearly asymmetric profile of the [OI] lines, displaying a wing of blueshifted emission but no corresponding redshifted emission, probably due to the blocking of the red wing by a disk. The [NII] and [SII] lines, originating in regions of lower density and farther away from the central object, do not show such asymmetry, implying that the occultation of the emitting region occurs only in the close vicinity of the central object, where most of the [OI] emission originates.

and concluded that their results supported the interpretation of LS-RCrA 1 being an edge-on disk system. Further arguments in this direction based on variability monitoring have been provided very recently by Scholz and Jayawardhana [44]. Nevertheless, new observations presented by Fernandez and Comerón are difficult to reconcile with that scenario [19]. Their higher-resolution UVES spectra show broad wings of the Hα line with a width exceeding 300 km s^{-1} at 10% intensity, which are thought to arise from the bases of accretion columns near the surface of the object [35] and are missing in the spectra of *bona fide* edge-on systems, where that region is blocked from view [4]. Most importantly, the [OI] lines are clearly asymmetric, with an extended blue wing but with the corresponding red wing missing, as shown in Figure 4. Such a profile is not seen in the [NII] or the [SII] lines, which are much more symmetric. Since the critical density of the [OI] emission is the highest among those species and this is thus the line forming closest to the star, we infer that the receding part of the inner outflow is occulted by a disk, thus excluding an edge-on geometry, whereas other forbidden lines predominantly forming further out are not affected by such blocking. Our UVES observations also show that the wings of the forbidden lines do not reach high velocities, and their profiles are clearly single-peaked, indicating that the outflow probably takes place in the form of a slow, weakly collimated wind, rather than in the form of a jet.

Recent VISIR and Spitzer data have provided the spectral energy distribution of LS-RCrA 1 up to the mid infrared, constraining the distribution of its circumstellar medium. Preliminary results (N. Huélamo, Personal communication, 2007) indicate that no simple disk model can provide a satisfactory fit to the data, but also that the worst fits are obtained with a viewing geometry close to edge-on, seemingly in agreement with the conclusions reached from the spectroscopy.

2.3 Par-Lup3-4

Par-Lup3-4, discovered in a deep Hα slitless spectroscopy survey of the center of the Lupus 3 cloud carried out with FORS1 [15], has a spectrum similar to that of LS-RCrA 1, also with a late spectral-type, M5, and a similar display of emission lines, although in this case the CaII triplet has more prominence. A comparison between the near-infrared photometry by Comerón et al. and that previously obtained by Nakajima et al. shows that the object is clearly variable [15, 36].

There is no evidence for resolved emission at the position of the central source, although no images with the resolution of those available for LS-RCrA 1 exist for Par-Lup3-4. However, narrow-band imaging through in the [SII] and Hα filters, also with FORS1 [19], clearly show an emission knot to the southwest $1''.2$ from the central source, corresponding approximately to 240 AU of projected distance. The knot is accompanied by a much fainter bipolar, well-collimated jet in the northwest–southwest direction. UVES spectroscopy shows a double-peaked profile in the forbidden lines, particularly in [SII], with maxima separated by approximately 40 km s^{-1}. The latter demonstrates that the jet is not aligned with the plane of the sky, contrarily from the expectation if the features of the object were due to a perfectly edge-on disk. Assuming a spatial jet velocity in the range $\sim$100–150 km s^{-1}, typicalof T Tauri stars, the tilt with respect to the plane of the sky is inferred to be between 8° and 12°, relatively close to edge-on. A recent examination of the spectral energy distribution using Spitzer data (F. Ménard, H. Bouy, N. Huélamo, Personal communication, 2007) independently confirms this value, obtaining a good overall fit for a tilt of 8°. Although the precise amount of obscuration caused by such a disk strongly depends on its vertical structure, it appears possible that Par-Lup3-4 may be intermediate between young stellar objects with an unobstructed view to the central object, and edge-on disks completely blocking the line of sight. The clearer line of sight towards the immediate circumstellar environment may help in explaining why Par-Lup3-4 displays broad wings in Hα, like LS-RCrA 1, together with strong CaII triplet lines and a well-visible HeI line. Nevertheless, it remains to be demonstrated that the strong apparent underluminosity of Par-Lup3-4 is consistent with a lightly obscuring disk and its colors, particularly in the light of the fact that such a geometrical explanation is ruled out in the case of the otherwise similar LS-RCrA 1.

2.4 ESO-Hα 569

The last object in the sample that we have studied thus far, ESO-Hα 569, was discovered in the same objective prism survey of the Chamaeleon I cloud that led to the identification of ESO-Hα 574 [16]. The features of both objects are to a first approximation similar: ESO-Hα 569 seems to possess a spectral-type somewhat later than ESO-Hα 574, perhaps early M, although also with a large amount of veiling. The photometry of both objects is also similar, implying comparable amounts of underluminosity. However, when their emission-line spectra are compared, it becomes clear the ESO-Hα 569 and 574 are at opposite ends as far as the relative importance of accretion and outflow signposts are concerned, as seen in Fig. 5. Indeed, ESO-Hα 569 displays the strongest lines of HeI and CaII measured among objects of this class, whereas the forbidden lines formed in jets or winds are by far the weakest when at all measurable. No traces of a well-collimated outflow are noticeable in FORS1 [SII] images of ESO-Hα 569, but faint loop-like emission with low surface brightness towards the southwest can be seen near the detection limit of the available images. Unlike in the case of LS-RCrA 1, the central source of ESO-Hα 569 is clearly resolved in K-band images obtained under moderately good seeing, although the morphology is unclear.

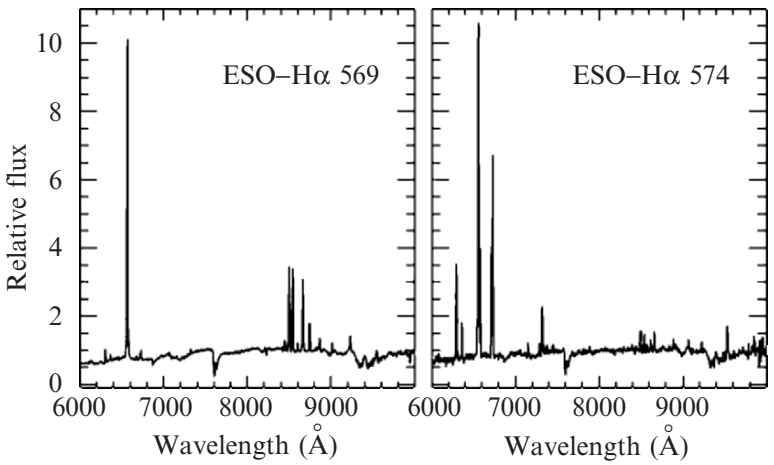

Fig. 5. A comparison between the spectra of ESO-Hα 569, an object dominated by lines commonly associated to accretion, and ESO-Hα 574, dominated by forbidden lines associated to mass loss. Both spectra define the extremes of the class of objects discussed in this paper.

3 Preliminary Conclusions and Intriguing Hypotheses

While the four objects that we have discussed thus far share the essential characteristics of this class regarding apparent underluminosity, strong emission lines, and visible and near-infrared colors, it is somewhat surprising that their morphologies and probably also the inferred viewing geometries display such variety, leading one to wonder whether a single explanation may apply to all the objects under consideration and to others that may be related and that have been studied by other authors. The most immediate explanation for the underluminosity, an edge-on disk, may be the correct one of ESO-Hα 574 given the observations available to date. Partial obscuration by a disk may also apply in the case of Par-Lup3-4, but it seems unlikely in the case of LS-RCrA 1 and probably also ESO-Hα 569 given the evidences already discussed regarding the occultation of the base of the outflow by a non-edge-on disk, the noncoincidence of the jet with the plane of the sky, or the high-velocity wings of the Hα line. We should remark that the discussion presented in this paper corresponds to a work in progress, and that new observations already scheduled for the coming months, particularly high-resolution spectroscopy and imaging, may yield important new clues regarding the nature – or natures – of this class of objects.

Some interesting possibilities can be already considered. If edge-on disks or, more generally, obscuration by the circumstellar environment can be confidently ruled out in at least some cases, the apparent underluminosity would then be a real, intrinsic characteristic of the central object. In previous works we have qualitatively invoked accretion-modified pre-main sequence evolution as a possible explanation for the observed features of these objects if truly intrinsic, based on modeling [28] at higher masses that in principle supported a false aging of accreting objects by increasing their temperature and decreasing their luminosity. However, the rather extreme two objects in Chamaeleon I in terms of underluminosity call into question such explanation, as accretion would then have to account for a decrease in radius to as little as 10% of the value predicted by evolutionary models that do not take accretion into account. A rather exotic, and at this point rather speculative possibility is that the observed objects represent transient periods of intense accretion on much smaller objects, perhaps with masses in the giant planet range, temporarily increasing their temperatures and luminosities. If this were the case, the objects in this class, or at least those for which the low luminosity is not due to accretion, might be among the lowest-mass members of star-forming regions, temporarily rendered visible due to the accretion bursts. It would be interesting in this respect to establish whether these objects have periods of quiescence, during which their spectral characteristics could be much more informative about the true nature of the central source.

Regardless of whether such speculations or rather more mundane explanations should be invoked to account for the observed variety of phenomena in this class of objects, there is no doubt that the substellar boundary is a most