Strong Accretion and Mass Loss Near the Substellar Limit

F. COMERÓN, ESO, Garching, Germany
M. FERNÁNDEZ, Instituto de Astrofísica de Andalucía, Granada, Spain

Accretion and outflows of mass are among the most distinctive phenomena associated to star formation. Their observational manifestations cover a broad range of appearances and wavelengths, from the large X-ray emitting bubbles caused by stellar winds moving at several thousands of kilometres per second, to the cold dust shells around low-mass stars detected by their millimetre-wave emission. Even stars with only a few tenths of the mass of the Sun display in their earliest stages spectacular signatures of interaction with the circumstellar environment, such as the strong emission lines seen in T Tauri stars or the fast-moving jets that produce Herbig-Haro objects.

Can strong accretion and mass loss take place even at substellar masses? Young brown dwarfs are currently known to share many characteristics with the more massive T Tauri stars. The similarities include mid-infrared emission, revealed by ISOCAM (e.g. Comerón et al. 1998, Persi et al. 2000) from warm dust in circumstellar disks or envelopes that provide large *reservoirs* of mass for accretion. The spectra of very young brown dwarfs often display

Figure 1: A B, V,R_C image of the field around LS-RCrA1 obtained with the Wide Field Imager at the ESO-MPG 2.2-m telescope. LS-RCrA 1 is the faint object at the centre and marked with an arrow. The bright nebulosity at the upper left corner contains the T Tauri stars R and T CrA. The comma-shaped nebula to the bottom right of that nebula is the Herbig-Haro object HH 100, and the red compact nebula at the bottom centre of the image is HH 101. The bright star near the centre of the image, to the left and below LS-RCrA1, is V709 CrA. The field is approximately 10′ × 10′ in size.

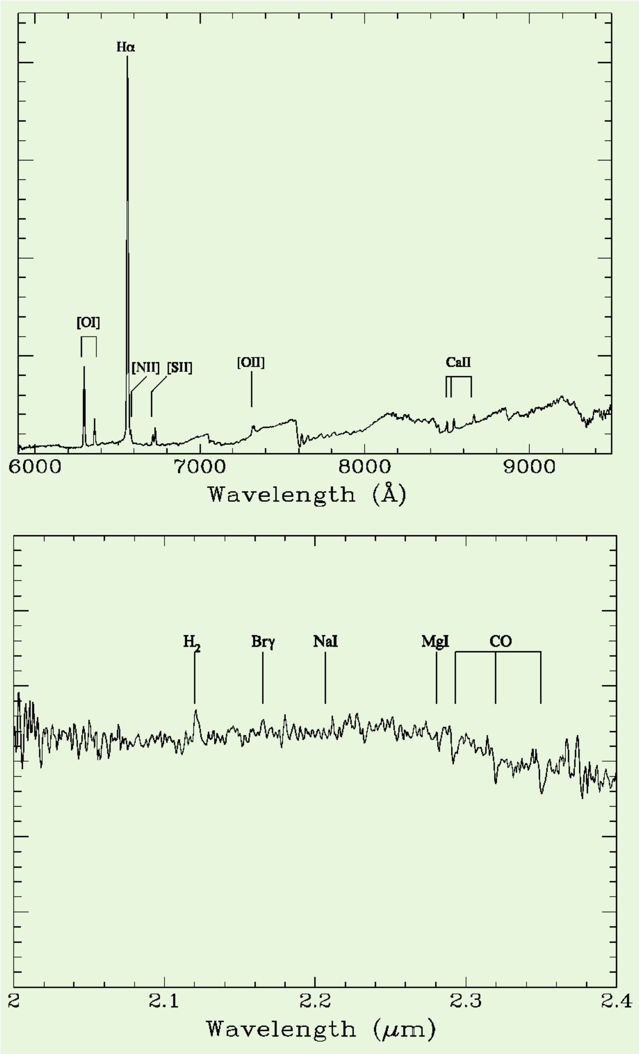

Figure 2: Visible (top) and near-infrared (bottom) spectra of LS-RCrA 1, obtained respectively with FORS2 and ISAAC in March 2000. The most prominent emission lines are marked in the visible spectrum. In the infrared spectrum we mark the position of the detected lines due to H_2 and CO, as well as the expected positions of some atomic features that should be detectable in this region for a normal M6 star.

Hα emission that is commonly associated to accretion, as confirmed from high-resolution spectroscopy (Muzerolle et al. 2000). Like T Tauri stars, young brown dwarfs also have been found to possess X-ray emission (Neuhäuser & Comerón 1998; Comerón, Neuhäuser, and Kaas 1998) caused by the magnetic fields that play a fundamental role in regulating the flow of mass from the accretion disk onto the surface (Hartmann 1998). In view of these similarities, one may wonder if the spectral signposts of intense accretion sometimes displayed by classical T Tauri stars, and very often found to be correlated with strong mass loss, may also be found near the substellar limit or even below.

Here we present our observations of a very late-type faint member of the R Coronae Australis star-forming cloud that displays an unusually rich emission-line spectrum, similar to that of more massive counterparts, in which both accretion and outflow signatures coexist. This is the latest-type object for which such an intense emission-line spectrum has been observed so far. The late-type spectrum and the faintness of the underlying object suggest that it is near or below the borderline separating stars from brown dwarfs, showing that such spectacular spectral signatures can be present even at masses of a few per cent of a solar mass. The details of this work are described in extent in a separate paper (Fernández & Comerón 2001).

Observations

The special characteristics of the object that we present here, hereafter referred to as LS-RCrA 1 (where LS stands for La Silla) were first revealed in a slitless spectroscopy survey of the core of the R Coronae Australis star-forming region, carried out with DFOSC at the 1.5-m Danish telescope at La Silla in April 1999. The slitless spectroscopy frames showed only a dot at the expected position of Hα for an otherwise inconspicuous object of $R_C \simeq 19.5$, with a continuum too faint to be seen in those observations. Near-infrared *JHK* photometry was obtained with SOFI at the NTT in February 2000. Further spectroscopic observations were carried out at the VLT, both with FORS2 in the visible and ISAAC in the K band, in March 2000. Finally, short exposures in $BVR_C\ I_C$ were obtained with the WFI at the 2.2-m telescope in August, to check for possible photometric variability. A colour composite of a part of the WFI image is shown in Figure 1, centred on LS-RCrA 1 (see also http://www.eso.org/outreach/press-rel/pr-2000/phot-25-00.html).

Figure 2 shows both the FORS2 and ISAAC spectra of LS-RCrA1. The most outstanding feature in the visible is the abundance of strong emission lines, dominated by Hα with an equivalent width of approximately 330 Å. Forbidden lines due to [OI], [OII], [NII], and [SII] are also clearly identified, as well as the Ca II triplet near 8550 Å. The appearance and intensity of these emission lines is not unprecedented, and the line ratios are similar to those of Krautter's star (Th 28; Graham and Heyer 1988), a G8-K2 star that powers a string of Herbig-Haro objects. However, the underlying spectrum of LS-RCrA1 is much later than that of Th 28 and other T Tauri stars with strong emission, and can be reliably classified as M6-M7. At the age of the R Coronae Australis, such a late spectral type implies a mass below 0.1 solar masses, and probably substellar.

The ISAAC *K*-band spectrum also presented in Figure 2 is remarkably featureless. At the resolution and signal-to-noise of these observations, a late M-type spectrum should display atomic features in that region due to Na I, Ca I, Mg I, as well as prominent CO bandheads starting at 2.29 μm. Only the latter are clearly identified in the spectrum on LS-RCrA 1, but with equivalent widths of less than half the typical value for its spectral type. Finally, the H_2 line at 2.12 μm is clearly seen in emission.

A final surprise from our observations of LS-RCrA1 comes from its faintness. The measured brightness from our WFI images is $B = 23.1$, $V = 21.3$, $R_C = 19.8$, $I_C = 18.0$, and from our SOFI images J = 15.3, H = 14.5, K = 13.9. Since its moderately blue colours imply a slight extinction at most and the R Coronae Australis clouds are only 150 ± 20 pc away, this places LS-RCrA1 among the intrinsically faintest members known of a star-forming region.

Interpretation

The numerous forbidden emission lines in the spectrum of LS-RCrA 1 strongly resemble those seen in low-mass stars undergoing strong mass loss, such as those powering Herbig-Haro objects (e.g. Reipurth et al. 1986). On the other hand, the large strength of the Hα line as compared to [SII] suggests that most of the Hα emission is actually due to accretion, rather than to mass loss. The similar equivalent widths of the Ca II lines near 8500 Å, together with the absence of forbidden-line emission of [CaII], also hint that CaII emission arises from a dense, optically thick region. It seems therefore that LS-RCrA 1 is simultaneously undergoing strong accretion and mass loss, just like its higher-mass T Tauri counterparts that lie at the origin of Herbig-Haro flows.

The *K*-band spectrum presented also shows some characteristics commonly found among very young objects enshrouded by circumstellar material, such as H_2 emission and the absence of any detectable absorption features apart from much weakened CO bandheads. The lack of absorption lines is commonly interpreted as due to strong veiling of the photospheric spectrum by emission from warm circumstellar dust, that contributes most of the flux at 2 µm and beyond, and is usually correlated with the appearance of H_2 emission (Greene & Lada 1996). In that respect, the *K*-band spectrum of LSRCrA 1 is “Class I-like”, following the widely-used classification of young stellar objects (e.g. Shu, Adams, and Lizano 1987). However, the shape of the continuum at 2 µm is remarkably flat in that region, while the infrared *JHK* colours show no appreciable sign of the circumstellar excess emission that would be needed to dilute the photospheric features beyond detectability in our spectra. In other words, dust does not seem to significantly contribute to the flux of LS-RCrA 1 in the 2 micron region, which in that respect is “Class III-like”. Such a coexistence of Class I-like and Class III-like features in the *K*-band spectrum of LS-RCrA 1 is not found among the higher-mass objects that have been studied so far, and leads us to consider other possible explanations to the lack of atomic features and the weakness of the CO bands. An interesting possibility in this respect is that the photospheric spectral features in the 2 µm region may be largely filled by emission produced in the heated infalling material near the surface of the star, without being accompanied by continuum emission (Martin 1996).

What is the mass and age of LS-RCrA 1? Its membership in the R Coronae Australis star-forming region and the vigorous accretion and mass-loss activity, found only at the earliest stages of stellar evolution, both suggest an age of only a few million years. At this age, LS-RCrA 1 should be early in its contraction track and have a relatively large radius, and therefore brightness. However, as mentioned earlier, LS-RCrA 1 is surprisingly faint as compared to objects of similar spectral type in star-forming regions. Figure 3 illustrates this: we have plotted in it the position of LS-RCrA1 in a temperature-luminosity diagram, where these quantities are inferred from its spectral type and available photometry. Also shown for comparison are pre-main sequence evolutionary tracks and isochrones from Baraffe et al. (1998), and the positions of other very low mass stars and brown dwarfs identified in other star-forming regions. The main contribution to the error bars is due to uncertainties in translating spectral types and magnitudes into temperatures and luminosities. Since the position of the other objects plotted in Figure 3 was computed in the same way as that of LS-RCrA1, any systematic errors in the estimate of temperature and luminosity of the latter should move both LS-RCrA 1 and the other sources in the same direction and by a similar

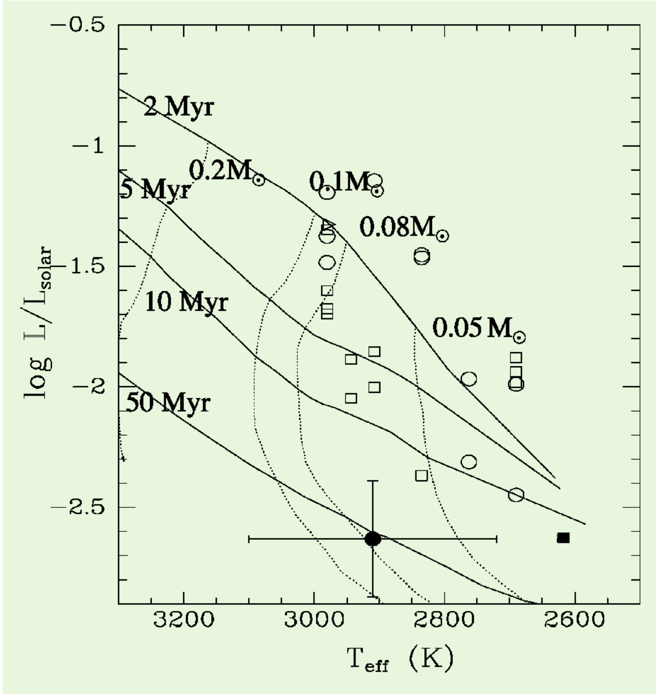

Figure 3: Position of LS-RCrA 1 (filled circle with error bars) in a temperature-luminosity diagram, with theoretical isochrones and evolutionary tracks from Baraffe et al. (1998) plotted for comparison. Also shown are the positions of other late-type objects in star-forming regions, whose spectral types and infrared photometry are taken from the literature and transformed into temperature and luminosity using the same method as for LS-RCrA 1 (see Fernández and Comerón 2001 for details on the transformation). The other sources are from Chamaeleon I (open circles; Comerón, Neuhäuser, and Kaas 2000) and IC 348 (open squares; Luhman 1999). Also plotted are V410 X-ray 3 (open triangle; Luhman 2000) and Oph 162349.8-242601 (filled square; Luhman, Liebert, and Rieke 1997). As explained in the text, the error bars come primarily from the uncertainty in the transformation from spectral type and photometry to temperature and luminosity, and affect in a similar way the positions of all the sources. Therefore, although the precise luminosity and temperature of LS-RCrA1 are uncertain by the amount given by the error bars, the offset relative to the other sources plotted is a well established feature.

amount. Therefore, although the temperature and luminosity of LS-RCrA 1 are determined with only a rather limited accuracy, its large offset with respect to other known late-type young objects is well established.

If taken at face value, the position of LS-RCrA 1 seems to imply that its age is of the order of several times 10^7 years, about one order of magnitude older than the age inferred from the rest of the members of the R Coronae Australis region (Wilking et al. 1997), and also much older than other stars displaying such strong signs of accretion. The rather implausible age and the offset with respect to other young objects of similar underlying spectral characteristics leads us to look for alternative interpretations to the unexpected position of LS-RCrA 1 in the temperature-luminosity diagram.

The most obvious peculiarity that separates LS-RCrA 1 from the other very low mass objects plotted in Figure 3 is the signs of strong accretion and mass loss on an object of such a low temperature and luminosity, and this may be the reason why LS-RCrA 1 looks so old and so different from those other objects. Modellers of low-mass pre-main sequence evolution in the last decade have stressed the great importance of an appropriate, realistic treatment of the boundary condition represented by the atmosphere for correctly reproducing the evolution of temperature and luminosity as a function of time. The impact of both strong accretion and mass loss on the structure of the atmosphere of LS-RCrA1 may thus be sufficient to invalidate a direct comparison between its observational characteristics and the predictions of theoretical models that do not take those factors into account. Indeed, calculations performed by Hartmann, Cassen, and Kenyon (1997) have found that accretion increases both temperature and luminosity with respect to the predictions of accretionless models that assume the same mass and age of the central object. The net result is to make the object appear hotter, and somewhat older, than an object of equal mass and age but without accretion. The calculations of those authors use only moderate accretion rates on central objects of larger mass than the one presented here, and can therefore not be directly extrapolated to LS-RCrA 1. However, they do suggest that LS-RCrA1 may be actually younger than the 5×10^7 years, and less massive than the ~ 0.08 solar masses, implied by the direct comparison to pre-main-sequence tracks. Since 0.08 solar masses is very close to the borderline separating low-mass stars from brown dwarfs, the possibility that accretion is actually making the spectral type appear *earlier* than it would be without accretion suggests that LS-RCrA 1 may have a mass well below the brown dwarf limit.

In any case, regardless of whether LS-RCrA 1 is stellar or substellar, it is clearly a so far unique object that poses an interesting case study in several respects. It demonstrates that the spectacular emission-line systems found in classical T Tauri stars can be present also at much lower masses, and suggests that intense accretion and mass loss can dramatically alter the spectroscopic and photometric properties of the underlying object. It stresses the need to complement existing models for the early evolution of low-mass objects with significant accretion and mass loss rates. A consequence of this is the intriguing possibility of biases in current studies of the mass and age distributions of young stellar aggregates if a significant fraction of their members undergo accretion and mass loss phases like LSRCrA 1, due to the reliance of such studies on pre-main sequence evolutionary tracks.

Of course, LS-RCrA 1 also suggests a variety of follow-up of observational studies: what information can we obtain from high-resolution spectra of the emission lines? Does the mass loss of LS-RCrA1 cause any visible impact (as yet undetected in our images) in the surrounding interstellar medium, like the Herbig-Haro objects generated by more massive stars? How do the signatures of accretion and mass loss vary with time? What do possible photometric variations tell us about the existence and distribution of dark and hot spots on its surface? Can we trace the *reservoir* of cold circumstellar gas around LS-RCrA 1 through its mid-, far-infrared, and radio emission? How common are objects like LS-RCrA 1 in star-forming regions? Is the rich emission-line spectrum of LS-RCrA1 a rarity among very low mass objects, or does it rather represent a short-lived evolutionary phase? Is the simultaneous appearance of Class I and Class III characteristics a part of the peculiarities of LS-RCrA 1, or is it common among young very low mass stars and brown dwarfs? Are there other signs of activity, such as X-ray emission, associated to LSRCrA 1? Answering these questions and understanding objects like LS-RCrA 1 from a theoretical, quantitative point of view, is essential for placing LS-RCrA 1 in the context of what is already known about the early stages of the lives of stars at different masses, extending such knowledge beyond the substellar edge.

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Star Formation at *z* = 2–4: Going Below the Spectroscopic Limit with FORS1

J. U. FYNBO[1], P. MØLLER[1], B. THOMSEN[2]

[1]*European Southern Observatory, Garching, Germany*
[2]*Institute of Physics and Astronomy, University of Århus, Århus, Denmark*

Introduction

The population of bright galaxies at *z* = 2–4 has been studied intensively using the Lyman-Break technique (Steidel et al. 1996; Cristiani et al. 2000). Currently, redshifts can be determined from absorption features of galaxies selected in this way down to R ≈ 25.5 (e.g. Steidel et al. 2000), which is commonly referred to as the spectroscopic limit. Currently, very little is known about the galaxy population below the spectroscopic limit. This is an unfortunate situation since all the information on the chemical enrichment of young galaxies (Damped Ly-α Absorbers) accessible through QSO absorption lines seems to be valid mainly for galaxies significantly fainter than R = 25.5 (Fynbo et al. 1999; Haehnelt et al. 2000). In order to select and study galaxies fainter than the current spectroscopic limit, one has to rely on other selection criteria than the Lyman-Break. Two promising possibilities are (i) to select galaxies with Ly-α emission lines, and (ii) to study the host galaxies of Gamma-Ray Bursts (GRBs).

Ly-α Selected Galaxies

Ly-α selection of high-redshift galaxies has been attempted for many years, but only recently with significant success (Møller and Warren 1993; Francis et al. 1995; Cowie and Hu 1998; Pascarelle al. 1998; Kudritzki et al. 2000; Fynbo et al. 2000a; Steidel et al. 2000; Kurk et al. 2000). In 1998 we detected 6 candidate Ly-α emitting galaxies (called S7–S12) in the field of the QSO Q1205-30 at *z* = 3.036 with deep NTT narrow-band imaging (Fynbo et al. 2000b). In March 2000 we carried out follow-up Multi-Object Spectroscopy with FORS1 on the 8.2-m Antu telescope (UT1). We also obtained deeper broad-band B and I imaging reaching 5 (2)σ detection limits in 1 arcsec^2 circular apertures of 25.9 (26.9) in the I-band and 26.7 (27.7) in the B-band (both on the AB system). The results of these observations are presented in Fynbo et al. (2001a), and summarised here.

Imaging

In Figure 1 we show image sections with Ly-α (top), VLT B-band (middle) and VLT I-band (bottom) for S7–S12. As seen, despite the faint detection limits, only for S7 and S9 is there a corresponding source detected in the broad bands (B(AB) = 25.6 and 25.4 respectively). For the sources S8 and