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Discovery of a very cool object with extraordinarily strong Hα emission*

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Abstract. We report on the finding of the strongest Hα emission – pseudoequivalent width of 705 Å – known so far in a young, late type dwarf. This object, named as S Ori 71, is a substellar candidate member of the 1–8 Myr star cluster σ Orionis. Due to its overluminous location in color-magnitude diagrams, S Ori 71 might be younger than other cluster members, or a binary of similar components. Its mass is in the range 0.021–0.012 $M_{\odot}$, depending on evolutionary models and possible binarity. The broad Hα line of S Ori 71 appears asymmetric, indicative of high velocity mass motions in the Hα forming region. The origin of this emission is unclear at the present time. We discuss three possible scenarios: accretion from a disk, mass exchange between the components of a binary system, and emission from a chromosphere.

Key words. open clusters and associations: individual: σ Orionis – stars: low-mass, brown dwarfs – stars: individual: S Ori 71 – stars: pre-main sequence

1. Introduction

Both mass accretion and chromospheric activity have Hα emission as a signature. Chromospheric activity appears as a consequence of the low density, the inverted temperature profile and the strong magnetic field present in K- and M-type dwarfs. Other Balmer lines, as well as Ca II H&K and the Ca II infrared triplet can appear in emission too. The activity detected in some brown dwarfs (objects incapable of burning hydrogen stably, with masses below 0.075 $M_{\odot}$, Chabrier at al. 2000 and references therein) have, probably, this origin (Martín et al. 1999a), although so far there is no theoretical model capable of explaining this phenomenology (e.g., Mohanty et al. 2002). In addition, the Hα emission line of these cool objects often has an intrinsic variability, and strong flares are commonly detected in M dwarfs. On the other hand, accretion can appear in interacting binaries (during the transfer process of material) or in accreting objects with circumstellar disks, such as the young T Tauri stars. These pre-main sequence stars are normally classified as classical T Tauri (CTT) stars or weak-line T Tauri (WTT) stars. The first group is characterized by strong Hα emission (larger than 10 or 20 Å, Appenzeller & Mundt 1989; Martín 1997), asymmetric and broad Hα profiles (sometimes with double peaks), presence of forbidden emission lines (arising from shocks produced by jets and outflows), blue/UV and infrared excesses, and a strong Li I 6708 Å line in absorption (indicative of youth). On the contrary, WTT stars lack most of these properties due to the absence of an active disk, and show smaller Hα emissions while keeping strong lithium lines. In addition, WTT stars display a lower degree of variability (e.g., Herbst et al. 2002).

The σ Orionis cluster (Walter et al. 1997) is a young (1–8 Myr, Zapatero Osorio et al. 2002a) stellar association with low reddening ($E(B-V) = 0.05$, Lee 1968), and located at a Hipparcos distance of 352^{+166}_{-85} pc. Many substellar members of this cluster show Hα emission in their optical spectra (Barrado y Navascués et al. 2002, and references therein). This paper presents the discovery of a brown dwarf with likely membership in σ Orionis, which has the strongest Hα emission line ever detected in a T Tauri late-type star or active very cool object. We discuss the origin of this extraordinary emission.

2. Observations and analysis

The object studied in this paper, named S Ori 71, was discovered in an optical IZ survey using LRIS at the 10-m Keck I telescope, USA (Zapatero Osorio et al. 2002b). Near-infrared

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* These observations were collected at the VLT of the ESO (Chile), the Keck I telescope (USA), and the 3.5-m telescope at Calar Alto Observatory (Spain).

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Table 1. Photometric and spectroscopic data of S Ori 71 (S Ori J053900.2–023706). Photometric errors: ±0.10 mag.

RA (J2000) (h m s)	Dec (° ′ ″)	I_c	$I_c - J$	SpT.	pW (Hα) (Å)	$T_{\rm eff}$ (K)	$\log L/L_\odot$	Mass (single) ($M_\odot$)	Mass (binary) ($M_\odot$)
05 39 00.2	−02 37 06	20.02	2.88	L0 ± 0.5	705 ± 75	2200–2500	−2.66 ± 0.15	0.014–0.021	0.012–0.017

data (J-band) were collected with the Omega Prime detector attached at the 3.5-m telescope of the Calar Alto Observatory, Spain. The combination of optical and infrared datasets produced several brown dwarf and isolated planetary-mass candidates (unable to fuse deuterium) of the σ Orionis cluster. Many of them have been followed-up spectroscopically in order to assess their nature and study their properties (Barrado y Navascués et al. 2001; Martín et al. 2001). The spectrum presented in this paper was collected with the 8-m VLT/UT1 telescope at the Paranal Observatory of the European Southern Observatory, Chile, using FORS1 (2451904.056 JD). It was processed and analyzed as in Barrado y Navascués et al. (2001). The VLT spectrum of S Ori71 (6200–9300 Å) is shown in Fig. 1. The spectral type of our object was derived by comparing its pseudo-continuum to that of various M- and L-type dwarf spectra, and by comparing several spectral ratios in different bands following Kirkpatrick et al. (1999) and Martín et al. (1999b). The final classification, L0, has a uncertainty of half a sub-class. Coordinates, photometric and spectral measurements, and other parameters of S Ori 71 are listed in Table 1. A finding chart can be provided upon request. Both photometric and spectroscopic data support S Ori 71's being a likely member of the σ Orionis cluster.

Figure 2 illustrates the known spectral sequence of the σ Orionis cluster. S Ori 71 lies above this sequence, which might indicate that, either it is younger than other cluster members, or that it contains two components of rather equal mass. A similar case is that of S Ori 47 (Zapatero Osorio et al. 1999; Barrado y Navascués et al. 2001), a slightly cooler (L1), substellar object of the cluster. S Ori 71 also appears overluminous in color-magnitude diagrams. Its luminosity (Table 1) is obtained using bolometric corrections of Leggett et al. (2002). Adopting a cluster age of 3 Myr and the evolutionary models of Baraffe et al. (1998), we estimate the mass of S Ori 71 to be between 0.014 $M_\odot$ and 0.021 $M_\odot$ if it were a single object. In case of binarity, each component would be 0.012–0.017 $M_\odot$. From the models, we also infer that the surface temperature of the object is in the range 2200–2500 K, in agreement with its spectral type. Table 1 summarizes these results. Other sets of theoretical models (Burrows et al. 1997; D'Antona & Mazzitelli 1997; Chabrier et al. 2000) produce similar mass and temperature values.

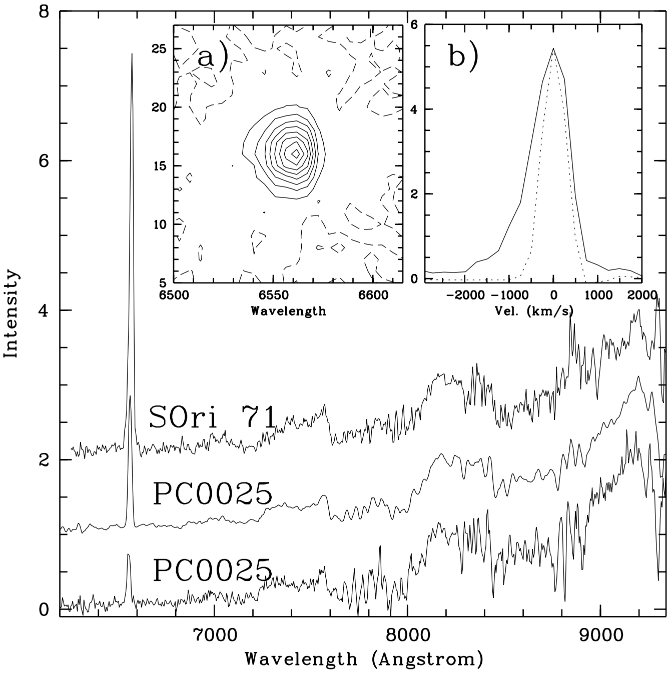

Fig. 1. Spectra of S Ori 71 (this paper) and PC 0025+0047. Two enlargements of the Hα line of S Ori 71 are also shown. **a)** Contour diagram for the 2-D spectrum. Note the asymmetry. Dashed lines correspond to zero level, whereas the peak of the Hα line is at 431 counts. Each contour corresponds to a step of 50 counts. **b)** 1-D spectrum – solid line – and a comparison with the instrumental profile – dotted line.

3. Hα emission and its origin

S Ori 71 displays a broad, incredibly strong Hα emission as compared to other similar type objects. Two blow-ups of the object's spectrum around Hα are depicted in Fig. 1: panel a illustrates the asymmetry of the line in a 2-D plot, while the comparison to the instrumental profile (sky line) is provided in panel b. This broad Hα emission is probably a result of the electron scattering in the Hα formation region as observed in some T Tauri stars (Stahl & Wolf 1980). Figure 1 also includes two spectra of the field dwarf PC 0025+0047 taken from Martín et al. (1999a). With M9.5 spectral type, this field object shows a persistent and variable Hα emission. The line pseudo-equivalent widths (pEWs) of the two spectra of the figure are ~200 Å and 400 Å, although Martín et al. (1999a) have reported Hα variability in the range 100–400 Å in a 4 yr timespan. Other few field objects with similar spectral types also have strong Hα emissions up to $pEW \sim 400$ Å (Liebert et al. 1999; Burgasser et al. 2002). However, the emission of S Ori 71 ($pEW = 705 \pm 75$ Å) stands out due to its huge intensity. Table 2 summarizes the properties of several objects with similar spectral classes both in the field and in the σ Orionis cluster. To our knowledge, in addition to these objects, the largest Hα pEWs correspond to more massive and warmer sources, like LkHα 101, an unusual F-type CTT star (Cohen & Kuhi 1979; Herbig & Bell 1988), and XZ Tau, V573 Ori, HO Lup, Sz 123, Sz 69, Sz 102, WZ Cha and PT Mon, all of them with K and early-M classes and Hα pEWs = 220−377 Å.

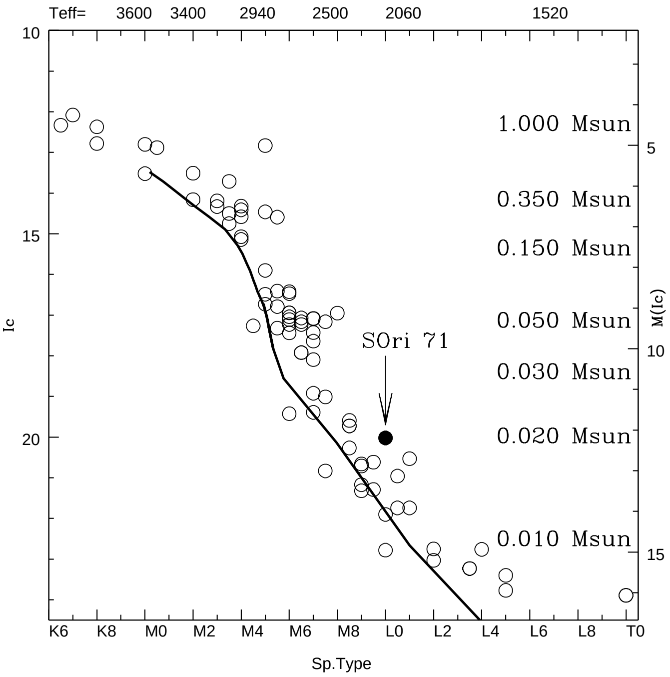

Fig. 2. Spectral type against I_c magnitude of members of the σ Orionis cluster. Data from Barrado y Navascués et al. (2001, 2002), Martín et al. (2001), Béjar et al. (2001) and Zapatero Osorio et al. (2002a). The line represents a 3 Myr-isochrone from Baraffe et al. (1998). Absolute magnitudes and masses are indicated at the right hand side of the diagram, and effective temperatures (in K) are shown at the top.

We have also compared the Hα pEWs of σ Orionis stellar and substellar cluster members (Bejár et al. 1999; Barrado y Navascués et al. 2001; Zapatero et al. 2002a, 2002c) to those values of CTT stars of Orion with less than 1 Myr (Herbig & Bell 1988), WTT stars (Alcalá et al. 1996, 2000), and very low mass stars and brown dwarfs of the α Persei cluster (70–95 Myr, Prosser et al. 1994; Stauffer et al. 1999). Fine details are given in Barrado y Navascués et al. (2002). While Hα emission in CTT stars is very likely originated in accretion disks surrounding the central object, older stars are believed to show less intense Hα emission as a consequence of chromospheric activity and rotation. Resulting from the comparison, we note that besides the very young age of the σ Orionis cluster, Orion CTT stars have stronger Hα lines, and that the emission level of the σ Orionis low mass members is slightly larger or similar to that of the α Persei cluster (late-K to mid-M spectral types). This late cluster is older (Stauffer et al. 1999; Basri & Martín 1999), but its low mass members have high rotation rates (Randich et al. 1996). On the other hand, Hα pEWs of the σ Orionis cluster members, regardless of its origin, increases toward cooler objects, reaching about 100 Å in the planetary-mass domain (Barrado y Navascués et al. 2001). Line variability is also present among the smallest objects: Zapatero Osorio et al. (2002c) measured a variable emission in S Ori 55 (Table 2), with pEWs ranging between 180 Å and 410 Å, whereas few weeks before, Barrado y Navascués et al. (2001) reported almost no activity ($pEW = 5$ Å). Unfortunately, we have a single spectrum of S Ori 71, and cannot reach any conclusion on its variability. However, we remark that S Ori 71 presents a noteworthy Hα pEW among low mass stellar and substellar members of any young cluster. Our literature search covered objects in Upper Scorpius, the Scorpius-Centaurus complex, Taurus, and the IC 348 cluster (Cohen & Kuhi 1979; Herbig & Bell 1988; Alcalá et al. 1996, 2000; Martín 1998; Herbig 1998; Ardila et al. 2000).

Table 2. Properties of S Ori 71 and other similar type objects.

Property	S Ori 71	S Ori 55	PC 0025	LHS 2065
Sp. Type	L0	M9	M9.5	M9
Age (Myr)	2–8	2–8	≤600	?
Mass ($\times 10^{-3}\,M_\odot$)	21–12	16–8	≤70	≥65
Lithium	?	?	Y	N
pW(Hα) (Å)	705	5–410	100–400	7.5–261
Hα asymmetry	Y	N?	N	N
Hα variability	?	Y	Y	Y
Flares	?	Y	N	Y
Forbidden lines	N?	N?	N?	N
He I 6678 Å	N	N	N	Y
Optical veiling	N?	N?	Y	N
IR excess	?	?	N	N

PC 0025 (Martín et al. 1999a); LHS 2065 (Martín & Ardila 2001); S Ori 55, cluster member (Zapatero Osorio et al. 2002c).

If we consider the ratio between the Hα luminosity of the object to its bolometric luminosity, as shown in Fig. 3, S Ori 71 appears to be more active than any other known brown dwarf ($\log L(\mathrm{H}\alpha)/L_{\mathrm{bol}}) = -2.69 \pm 0.16$). In very young star forming regions, strong Hα emission is generally due to disk accretion, and it may be accompanied by emission of forbidden lines, like [O I] at 6300 & 6364 Å, [N II] at 6548 & 6583 Å, and [S II] at 6717 & 6731 Å, which result from jets and outflows. Other lines indicating activity, such as He I at 6678 Å, are not seen. We can impose upper limits of 1–2 Å to the pEW of these lines from our spectrum.

The fact that S Ori 71 could be a binary formed by similar mass objects, as previously discussed, adds a new possibility to the origin of the Hα emission. Some matter transfer might take place between the components if they are close enough to each other (as proposed by Burgasser et al. 2000 for a T spectral type brown dwarf that has a persistent line emission). However, more data are needed to assess the reliability of this suggestive scenario. In addition, we have considered the possibility of S Ori 71 being an interacting binary formed by one compact object and a very small object. In this case, S Ori 71 would not belong to the σ Orionis cluster. In order to reproduce the observed photometric data of our object, it would be composed of a 0.09 $M_\odot$ main sequence star and a ~0.5 $M_\odot$ white dwarf ($\tau \geq 2$ Gyr) in a very short orbit. However, our optical spectrum does not show any evidence for a contribution from a hot companion (the white dwarf).

It might be possible to classify S Ori 71 as a a CTT substellar analog (i.e., accreting from a surrounding disk), based both on the strength of Hα and its asymmetric profile. It would be very interesting to study the object's K-band and mid-infrared emission and see if there is any flux excess, which would confirm the presence of the disk. At the present time and with the

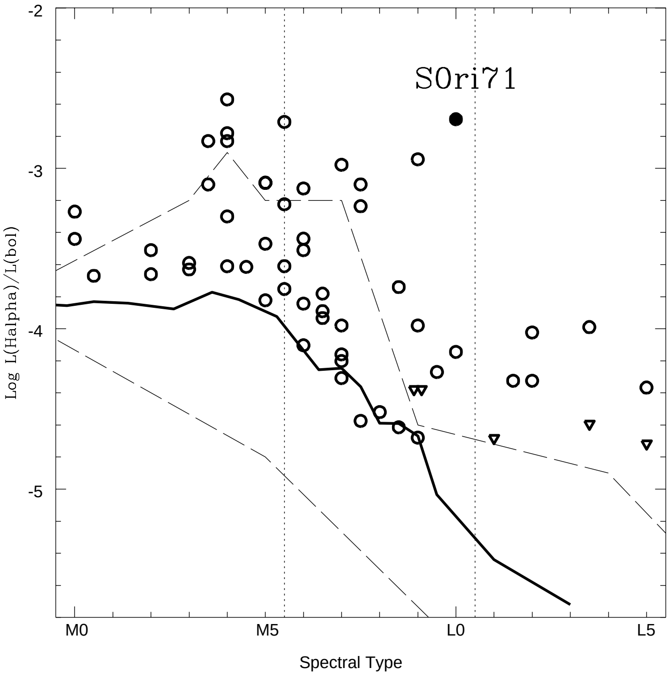

Fig. 3. Ratio between Hα and bolometric luminosities as a function of spectral type for σ Orionis members (open circles; open triangles denote upper limits). The solid-thick line stands for the average for field objects, whereas the area within the dashed lines indicates the region occupied by individual measurements of M- and L-type field dwarfs (Burgasser et al. 2002). Note that most of the L field dwarfs only have upper limits. The vertical dotted lines separates the stellar (left), brown dwarf (centre) and planetary mass (right) regimes in σ Orionis.

available data, we cannot rule out any possible scenario. A further explanation would be the case of an interacting binary with mass exchange or a common chromosphere/corona where magnetic loops would connect both objects and would experience frequent reconnections, producing the very strong Hα emission. The geometry of these loops would be distorted as both components orbit around each other (specially if there is not synchronization between the orbital and the rotational periods), producing a magnification of the magnetic fields by compressing the magnetic lines, and resulting in abrupt releases of energy during flare-like events. Additional infrared, X-ray and radio data would be very valuable to provide new insights on the origin of the Hα emission of objects like S Ori 71.

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