

LETTER TO THE EDITOR

2.3 μm CO emission and absorption from young high-mass stars in M 17 $\star, \star\star$

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ABSTRACT

Aims. We are studying the extremely young cluster of M 17 to investigate the birth of high-mass stars and the initial mass function.

Methods. Deep *JHKL* imaging and *K*-band spectroscopy from the VLT of 201 stars toward the cluster is presented.

Results. The majority of 104 stars show the CO band-head in absorption. Half of them emit X-rays and/or have infrared excess, indicative of very young objects. Their intrinsic IR luminosity is compatible with intermediate and high-mass pre-main sequence stars. Nine additional stars have the CO feature in emission, while sixty sources are lacking any stellar spectral feature due to veiling by circumstellar dust.

Conclusions. We suggest that CO absorption is – as in the case of low-mass stars – also a common feature during the early evolution of stars with higher masses. According to model calculations the observed CO absorption is most likely a sign of heavily accreting protostars with mass accretion rates above $10^{-5} M_{\odot} \text{yr}^{-1}$.

Key words. infrared: stars – ISM: H II regions – Galaxy: open clusters and associations: individual: M 17 – Galaxy: open clusters and associations: individual: NGC 6618 – stars: early-type – stars: circumstellar matter

1. Introduction

Numerous young stellar objects (YSOs) display the CO band-heads at 2.3–2.4 μm in emission. There is consensus that this CO emission originates in extremely dense ($n_{\text{H}} \geq 10^{10} \text{cm}^{-3}$) and warm ($1500 \text{K} < T < 4500 \text{K}$) regions associated with YSOs and is likely a result of the disk accretion process during early stellar evolution. A variety of mechanisms and models have been proposed to explain their precise origin. These include circumstellar disks, stellar winds, magnetic accretion mechanisms, and inner disk instabilities (e.g., Carr 1989; Carr et al. 1993; Chandler et al. 1993; Biscaya et al. 1997). Recently, the CO emission has been used to infer properties of the associated circumstellar disks (Bik & Thi 2004; Blum et al. 2004).

CO band-heads in absorption, in contrast, are typical of the photospheres of cool, mostly evolved stars. Nevertheless, initial surveys of star-forming regions (e.g., Casali & Eiroa 1996) have demonstrated that low-luminosity Class II sources, i.e., stars with flat or decreasing spectral energy distributions (SEDs), such as T Tauri stars, may also display strong CO absorption features. Sources with steeply rising SEDs (Class I) showed much weaker, or even undetectable, CO absorption. Greene & Lada (1996) also found that the CO bands are much weaker in Class I sources. On the other hand, CO absorption arising from an expanding shell

or from an accretion disk has been discussed in the context of FU Orionis objects (Hartmann et al. 2004).

Models have shown that variations in the strength and the appearance of the CO feature – either in emission or in absorption – depend on parameters like the stellar temperature, the geometry of the circumstellar material, and the mass accretion rate onto the protostellar object (Carr 1989; Calvet et al. 1991). The weakness or even the absence of any CO feature may therefore be a complex combination of various competing mechanisms.

We investigate the stellar content of the extremely young cluster NGC 6618 that is exciting the luminous H II region of M 17 at a distance of 1.9 kpc (Schmidt et al., in prep.). As we will show in the following, we have found a considerable population of CO sources in this cluster. Only a few of them show the CO band-head in emission (COES); the majority of objects display CO in absorption (COAS). Associated X-ray emission and IR excess suggest that the youngest generation of intermediate and high-mass stars is in the process of heavy accretion.

2. Observations

We have performed both near-infrared imaging and spectroscopy of the M 17 cluster. The images have been obtained with ISAAC (*JHK_s* and *L_p*, hereafter *JHKL*) at the ESO VLT in September 2002 and September 2004, respectively. Details of the observation and reduction procedures will be described elsewhere (Hoffmeister et al., in prep.; Scheyda et al., in prep.). The 1.00–1.04 μm spectra were obtained from May to August 2005, and the 2.0–2.4 μm spectra in August 2004 as well as from

* Based on observations made with ESO telescopes at the Paranal Observatory under programme IDs 069.C-0303, 073.C-0170, and 075.C-0381.

** Figure 4 is only available in electronic form at <http://www.edpsciences.org>

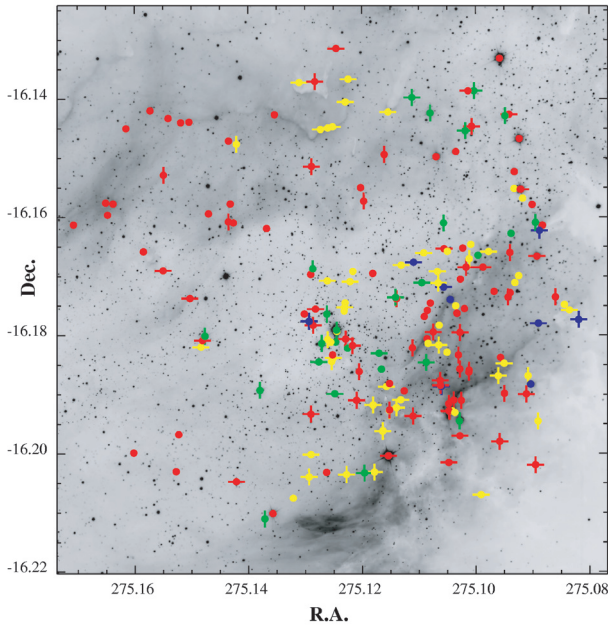


Fig. 1. *K*-band mosaic of the cluster region in M 17. All sources with *K*-band spectra are marked. Red: CO absorption, blue: CO emission, yellow: featureless, green: others. X-ray emission is indicated by a vertical bar, IRE by a horizontal bar.

Table 1. Number statistics of the four groups.

Objects	COAS	COES	Featureless	Others
Total	104	9	60	28
IRE	34 (33%)	7 (78%)	32 (53%)	10 (36%)
X-ray	39 (38%)	4 (44%)	19 (32%)	19 (68%)
IRE and X-ray	19 (18%)	4 (44%)	10 (17%)	6 (21%)
IRE and/or X-ray	54 (52%)	7 (78%)	41 (68%)	23 (82%)

May to July 2005 with ISAAC; the spectral resolutions are 5700 and 1500, respectively.

The selection of the sources across the cluster field was fairly arbitrary. We centred one or two sources onto the 120'' slit, while on average two to three additional sources happened to be covered by the same slit position. In this way, we obtained *K*-band spectra for 201 stars of which two-thirds appear in our sample by pure chance. As such, this survey can be regarded as fairly unbiased.

3. Results

Figure 1 shows a *K*-band image of the cluster field in M 17 (FOV 330'' × 342'') with about 18.000 sources down to a limiting magnitude of *K* = 19.0 mag (Hoffmeister et al., in prep.). The region was also observed in the *L*-band (Scheyda et al., in prep) with a limiting magnitude of *L* = 16.2 mag and contains about 3700 *L*-band sources. Those 201 sources for which we have obtained *K*-band spectroscopy are marked and divided into four groups: i) COES (blue), ii) COAS stars (red), iii) featureless (yellow), and iv) others (green). Additionally, we have marked stars with X-ray emission seen by Chandra by a vertical bar, and those with infrared excess (IRE) by a horizontal bar. The number statistics is summarised in Table 1. The spatial coverage of our spectroscopy is not homogeneous across the region, but focussed toward the cluster centre and the southwestern interface between the H II region and the molecular cloud.

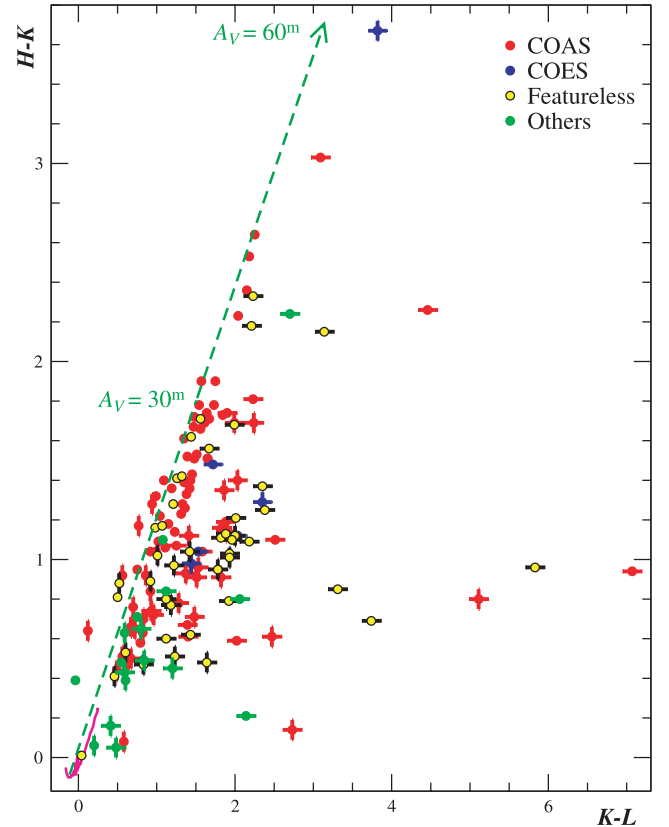


Fig. 2. *HKL* colour-colour diagram for 154 stars from our spectroscopic sample. The notation is identical to that of Fig. 1. The solid curve (magenta) marks the locus of unreddened main sequence stars; the dashed line (green) denotes the reddening vector.

CO features – Altogether there are 9 (4%) COES; 4 of them – B331 (CEN 92), B268 (CEN 49), B275 (CEN 24), and B337 (CEN 93) – were previously known (Hanson et al. 1997). We find 104 (52%) COAS; Hanson & Conti (1995) observed 4 of them – B22, B120, B305 (CEN 102), and B324 (CEN 33) – and interpreted them as field stars unrelated to M 17. Two other COAS with IRE (B239, B339) were suggested to be high-mass YSOs (Hanson & Conti 1995). Among these 113 CO sources, 109 do not show any further spectral features. Furthermore, our sample contains 60 stars without stellar features, while the remaining 28 stars show photospheric absorption lines that allow their classification as early-type stars.

Infrared excess – Figure 2 shows the *HKL* colour-colour diagram for 156 stars from our spectroscopic sample; some of the brighter stars are missing because they were saturated at one of the wavebands. Quite a number of stars are located in the excess region below the reddening path indicating thermal emission from dust in a circumstellar disk and/or envelope. The infrared spectral energy distribution for some of these objects has already been investigated until 20 μ m (Chini & Wargau 1998; Nielbock et al. 2001) and corroborates this interpretation. The relative fractions of IRE among the four groups shows a significant trend: IRE is present in 78% of the COES, in 53% of the featureless stars, in 36% of the “others”, and in 33% of the COAS.

X-ray emission – Within the cluster field of Fig. 1, Chandra has detected 521 X-ray sources (Broos et al., in prep.). All of them are coincident with infrared sources from our imaging survey. The Chandra sources with CO features and with sufficient counts to support spectral fits can be reproduced by a simple

thermal plasma model, i.e., there is no need for a flat power law, which is what one would expect if the source were an X-ray binary or a background AGN. None of these sources is anomalously soft and/or bright with a low absorbing column, so they are unlikely to be foreground field stars; typical A_V values range between 5 and 25 mag, consistent with our *JHKL* photometry. None of these sources shows X-ray variability within the short (40 ks) observation. All of them are consistent with being members of the M 17 complex.

Among our spectroscopic sample of 201 stars, there are 81 X-ray sources. The distribution among the four groups is the following: 68% of all stars in the group of “others” display X-ray emission; according to their IR spectra these are mostly early-type stars. The corresponding fractions in the other groups are: 44% (COES), 38% (COAS), and 32% (featureless). The fractions of sources that simultaneously show X-ray emission and IRE are 44% (COES), 21% (others), 17% (featureless), and 18% (COAS).

Sources of special interest – There are only four stars with the CO feature that have further spectral lines at shorter wavelengths: B163, which was reported to be featureless by Hanson & Conti (1995), is a COES that shows Pa δ and Br γ absorption in our spectrum. If this discrepancy is not due to the low *S/N* spectrum by Hanson & Conti (1995) we must assume that the source is variable. Additionally, B163 has both X-ray emission and IRE. Another COES with IRE, CEN 93 (Chini et al. 1980), also has Pa δ and Br γ in absorption. The COAS CEN 57, with X-ray emission and IRE shows Pa δ and Br γ absorption, and He I λ 21130 Å in emission. CEN 30, another COAS with X-ray emission, shows Pa δ , He I λ 10311 Å, and Br γ in absorption. In both cases, the infrared spectra are consistent with early B-type stars.

4. Discussion

Compared to previous CO band-head studies in star-forming regions, the present survey is the most extensive one; in addition, it is the only one that is fairly unbiased. Casali & Eiroa (1996) suggested from their sample of 44 YSOs in six regions that CO absorption is very common in low-mass YSOs; from their Fig. 2 we estimate the fraction of COAS to be about 50%. Likewise, Casali & Eiroa (1996) argue that Class II sources tend to show CO absorption, while Class I sources are featureless. In the following, we will explore the nature of the M 17 sources in more detail.

4.1. Cluster members or field stars?

In accordance with previous studies we interpret the 9 COES as YSOs within M 17. Models for the thermal continuum emission from dusty infalling envelopes around protostars indicate that the envelope emission can exceed the stellar plus disk photospheric emission by almost an order of magnitude (Calvet et al. 1997), thus producing featureless spectra. The veiling of an envelope weakens the CO absorption lines while a disk will only amplify the CO feature. Therefore, the 60 featureless objects are very likely Class I sources within M 17. Those 54 COAS with X-ray emission and/or IRE are also young cluster members, as demonstrated above for the two objects CEN 30 and 57. Only the nature of the 50 remaining COAS is a priori less clear because there is no direct “youth indicator” for classification purposes. However, there are several issues indicating that there might be further YSOs in this group.

The first argument comes from the spatial distribution: most of the COAS are located in the immediate vicinity of other young cluster members and in regions with pronounced nebular emission. This makes it likely that a considerable fraction of them is related to the M 17 cluster. Secondly, the infrared colours of COAS without X-rays are on average redder than for sources with X-ray emission (see Fig. 2); likewise, their apparent IR-brightness is fainter by one or two magnitudes compared to the other stars in the sample. Given that the scatter of intrinsic *HKL* colours for all luminosity classes is fairly small with respect to the observed colours in Fig. 2, one must assume that this large reddening is primarily due to interstellar dust. Thus, all of them have $20 < A_V < 45$ mag, a fact that might explain the non-detections by Chandra and that argues in favour of deeply embedded cluster members, at least for some of them. Finally we want to note that the groups of COES and featureless stars also contain 22% and 32% of objects that neither show X-rays nor IRE; nevertheless, these stars are most likely YSOs. Obviously, the absence of X-ray emission or IRE is no conclusive argument against youth.

4.2. High or low-mass stars?

The question concerning the mass of these YSOs is very important. To estimate their luminosity we use the *J – H* colours, where contamination by dust emission is likely to be small. Dereddening is achieved by adopting $(J - H)_0 \sim 0.16$ mag, the mean intrinsic colour of main sequence stars. As the range of intrinsic colours for dwarf and giant stars is sufficiently small ($-0.1 < (J - H)_0 < 0.3$ mag for types O to K), the dereddening will not be affected much by the stellar temperature. In this way, we obtain absolute magnitudes of $-7.7 < M_H < 2.6$ mag for the stars at the distance of M 17. This transforms into intermediate to high-mass stars, mostly earlier than A0, adopting main sequence luminosities. Some COAS that can be independently dereddened on the basis of their X-ray spectra corroborate this result: most of them appear to be early B-types; this holds also for the COES.

Figure 3 summarises the major statistical findings in the form of an *H*-band luminosity function, adopting main sequence luminosities. Those 50 COAS that do not show unique youth indicators have been omitted from Fig. 3, although there might be further YSOs among them as discussed above. The distribution attains its maximum around B3; there are only 12% A- and 2% F-type stars. The remaining stars have absolute *H*-magnitudes compatible with intermediate and high mass stars, i.e., earlier than A0. Of course, at the faint end this distribution is influenced by the limiting magnitude of our spectroscopy. The faintest source for which a spectrum could be obtained has an apparent *H*-band brightness of 17.6 mag. Thus, it follows that we can see stars of, e.g., type A3 only if their visual extinction is below $A_V \sim 25$ mag; types K6 can only be detected with $A_V \leq 5$ mag.

Concerning the individual groups in Fig. 3, the featureless objects are basically later than B3, while the COES are earlier than B5. The COAS are distributed across the entire luminosity range. The range $-5 < M_H < -2$ mag contains 8 COAS that have X-ray emission and/or IRE. This suggests the presence of YSOs with extremely high luminosity.

The above results have assumed the stars to be on the main sequence, although both CO band-heads and IRE indicate pre-main sequence objects. While high-mass stars evolve mainly at constant luminosity and therefore will not alter the overall distribution of spectral types (or masses) in Fig. 3, low-mass pre-main

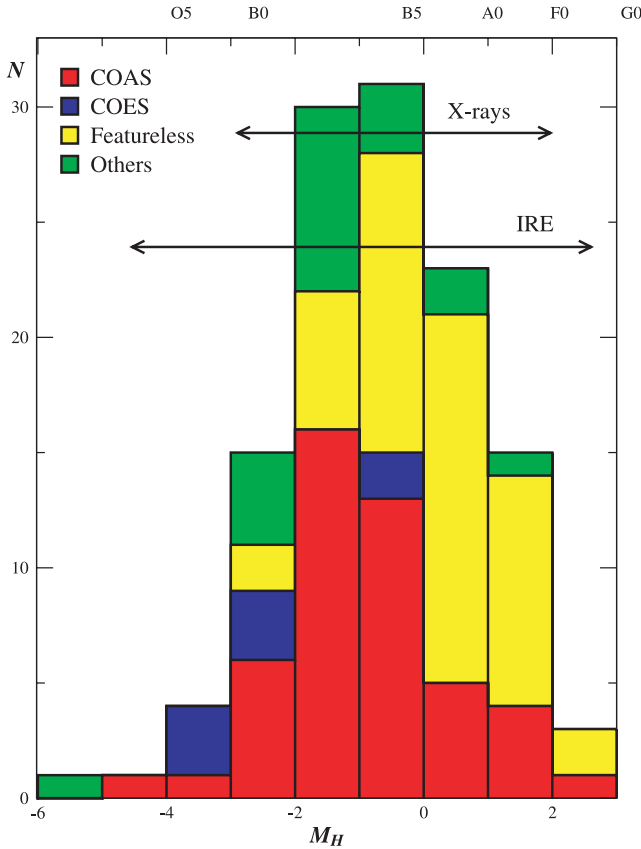


Fig. 3. H -band luminosity function of probable cluster members in M 17. The colour code is identical to that of Fig. 1. The arrows denote the range where stars with X-ray emission or IRE occur.

sequence objects change their luminosity by more than three orders of magnitude and thus will simulate earlier types and higher masses. If it is true that the H -band luminosity function is contaminated by objects of lower masses, these objects must be in an extremely early, i.e., protostellar evolutionary stage (due to their high luminosity).

According to the model by Calvet et al. 1991 the “young” COAS, i.e., those with X-ray emission or IRE, differ from the COES in the sense that either the underlying YSO is cooler or the mass accretion rate is higher. Corroborated by our early-type spectra for CEN 30 and 57, we favour the latter interpretation and identify those COAS as intermediate to high-mass protostars with mass accretion rates above $10^{-5} M_{\odot} \text{yr}^{-1}$. Sources with featureless spectra may be similar to other hot YSOs like the Herbig Ae/Be star AB Aurigae (Hartmann et al. 1989) and may form a population between the CO emission and absorption sources.

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References

- Bik, A., & Thi, W. F. 2004, *A&A*, 427, L13
 Biscaya, A. M., Rieke, G. H., Narayanan, G., Luhman, K. L., & Young, E. T. 1997, *ApJ*, 491, 359
 Blum, R. D., Barbosa, C. L., Damineli, A., Conti, P. S., & Ridgway, S. 2004, *ApJ*, 617, 1167
 Calvet, N., Patiño, A., Magris, C. G., & D’Alessio, P. 1991, *ApJ*, 380, 617
 Calvet, N., Hartmann, L., & Strom, S. E. 1997, *ApJ*, 481, 912
 Carr, J. S. 1989, *ApJ*, 345, 522
 Carr, J. S., Tokunaga, A. T., Najita, J., Shu, F. H., & Glassgold, A. E. 1993, *ApJ*, 411, L37
 Casali, M. M., & Eiroa, C. 1996, *A&A*, 306, 427
 Chini, R., Elsässer, H., & Neckel, T. 1980, *A&A*, 91, 186
 Chini, R., & Wargau, W. F. 1998, *A&A*, 329, 161
 Chandler, C. J., Carlstrom, J. E., Scoville, N. Z., Dent, W. R. F., & Geballe, T. R. 1993, *ApJ*, 412, L71
 Greene, T. P., & Lada, C. J. 1996, *AJ*, 112, 2184
 Hanson, M. M., & Conti, P. S. 1995, *ApJ*, 448, L45
 Hanson, M. M., Howarth, I. D., & Conti, P. S. 1997, *ApJ*, 489, 698
 Hartmann, L., Kenyon, S. J., Hewett, R., et al. 1989, *ApJ*, 338, 1001
 Hartmann, L., Hinkle, K., & Calvet, N. 2004, *ApJ*, 609, 906
 Nielbock, M., & Chini, R. 2001, *A&A*, 377, 273

Online Material

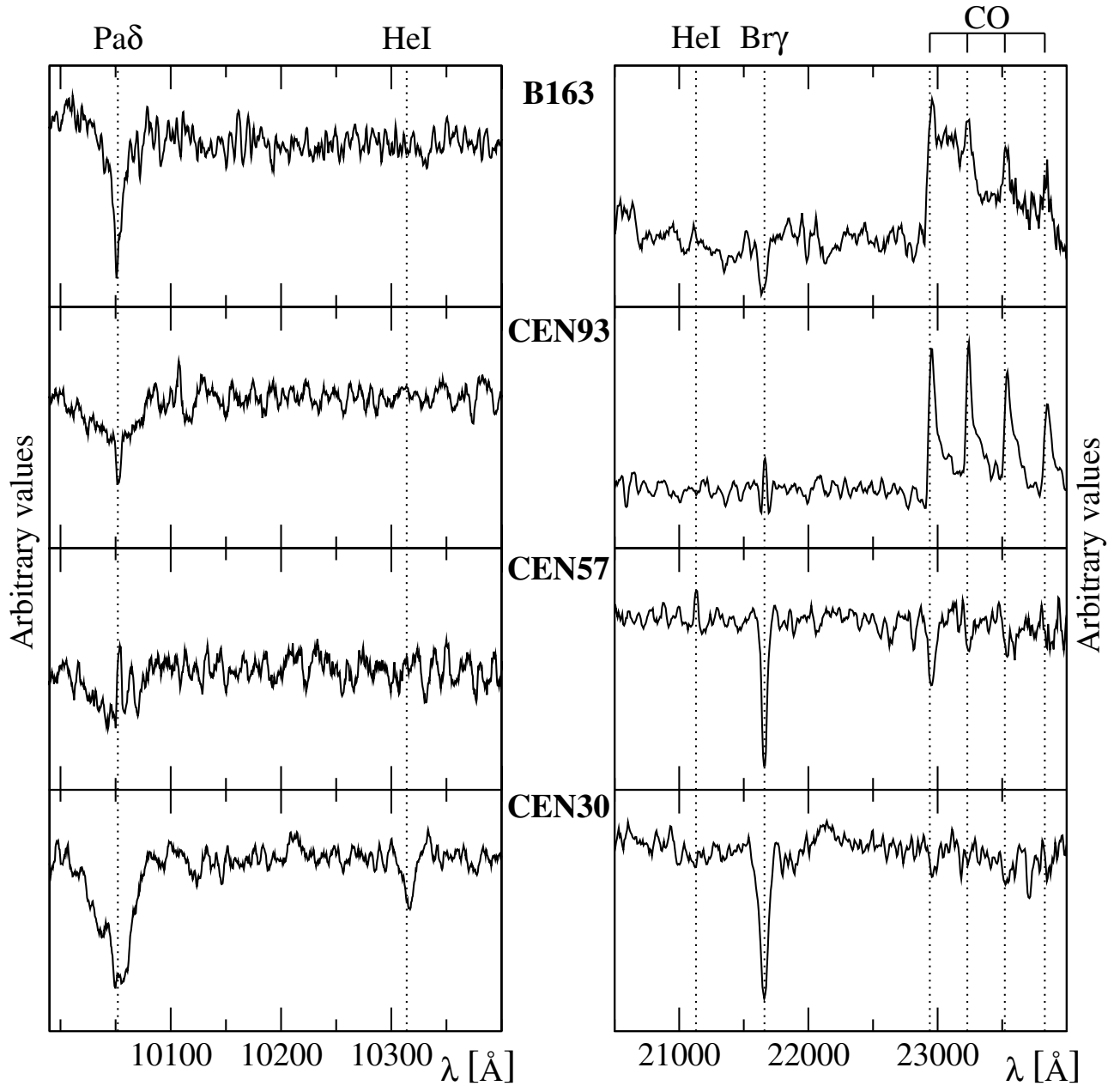


Fig. 4. *J*- and *K*-band spectra of four objects, mentioned in the text in the section “Sources of special interest”. The positions of the CO band-heads and several lines of H and He are marked.