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NEAR-INFRARED SPECTROSCOPY AND THE PHOTOSPHERES OF YOUNG STELLAR OBJECTS

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RESUMEN

Presentamos resultados preliminares de observaciones de las bandas del cercano infrarrojo del ^{12}CO en estrellas jóvenes de baja luminosidad muy oscurecidas. Se han obtenido espectros de baja resolución de 44 objetos localizados en diferentes regiones de formación estelar. El CO, cuando se detecta, se observa en absorción. Espectros de alta resolución de nueve objetos muestran bandas no resueltas, confirmando que la absorción es de origen fotosférico. La intensidad de la banda de CO está correlacionada con algunos parámetros estelares. En particular, existe una correlación muy buena entre el índice del CO y la pendiente de la distribución de energía, indicando que este índice puede utilizarse para diferenciar fuentes de Clase I y Clase II.

ABSTRACT

We present preliminary results of an observational study of the ^{12}CO near-IR bands in young embedded stars of low luminosity. Low-resolution spectra of 44 objects located in different star formation regions have been obtained; CO, when present, is observed in absorption. High resolution spectra of 9 objects show unresolved bands and confirm a photospheric origin of the absorption. The CO band strength is correlated with several stellar parameters. In particular, there is a good correlation between the CO index and the slope of the spectral energy distribution, which indicates that the CO index is an excellent discriminator between Class I and Class II sources.

Key words: **STARS: FORMATION — STARS: PRE-MAIN-SEQUENCE — INFRARED: STARS**

1. INTRODUCTION

IR cameras with 2-D detectors have enabled us to detect a large number number of young stellar objects (YSOs) deeply embedded in molecular clouds. In fact, the study of PMS clusters and their properties, such as luminosity and mass functions, have experienced a noticeable progress. One of the problems we are confronting is the correct identification of embedded young objects, since background field stars can be easily detected with the IR cameras. Independently of this, the IR images and photometry do not provide criteria to make a physical description and classification of YSOs.

An attempt in that direction has been the classification scheme based on the 2-25 μm index of the spectral energy distribution, SED (Lada 1987). This scheme basically distinguishes three types of objects with the working idea that the slopes represent an evolutionary sequence, the youngest being those with steepest SED. However, the information of this classification concerning the physical nature of YSOs is poor. In fact, spectroscopic observations are the only reliable way of detecting photospheric features, which would allow us to estimate physical quantities in YSOs as spectral types, abundances, rotation, etc. These kinds of studies have been carried out successfully on visible PMS stars for many years. However, the studies dealing with the more embedded objects only visible at $\lambda \geq 1$ μm have been inferior due to the shortcomings of near-IR spectroscopic methods used in the past.

The new generation of IR spectrometers equipped with 2-D detectors has largely overcome these limitations, since it is now possible to obtain high sensitive, high spectral resolution spectra of deeply embedded YSOs. Thus, Casali & Matthews (1992) showed that 2.3 μm ^{12}CO absorption bands are common in young stars - note that traditionally the presence of this absorption in the spectra of IR objects has been used to identify them as background giant or supergiant stars. Hodapp & Deane (1993) used those bands and NaI and CaI lines as a first attempt at deriving spectral types for embedded objects from near-IR spectra alone. Since embedded objects detected in the near-IR may well be the youngest objects with well-defined photospheres, their accurate placement on the HR diagram is a very important test of models for PMS evolution. Summarizing, the present near-IR spectroscopic capabilities do represent a significant step towards a deeper and more consistent understanding of the nature and evolution of embedded YSOs.

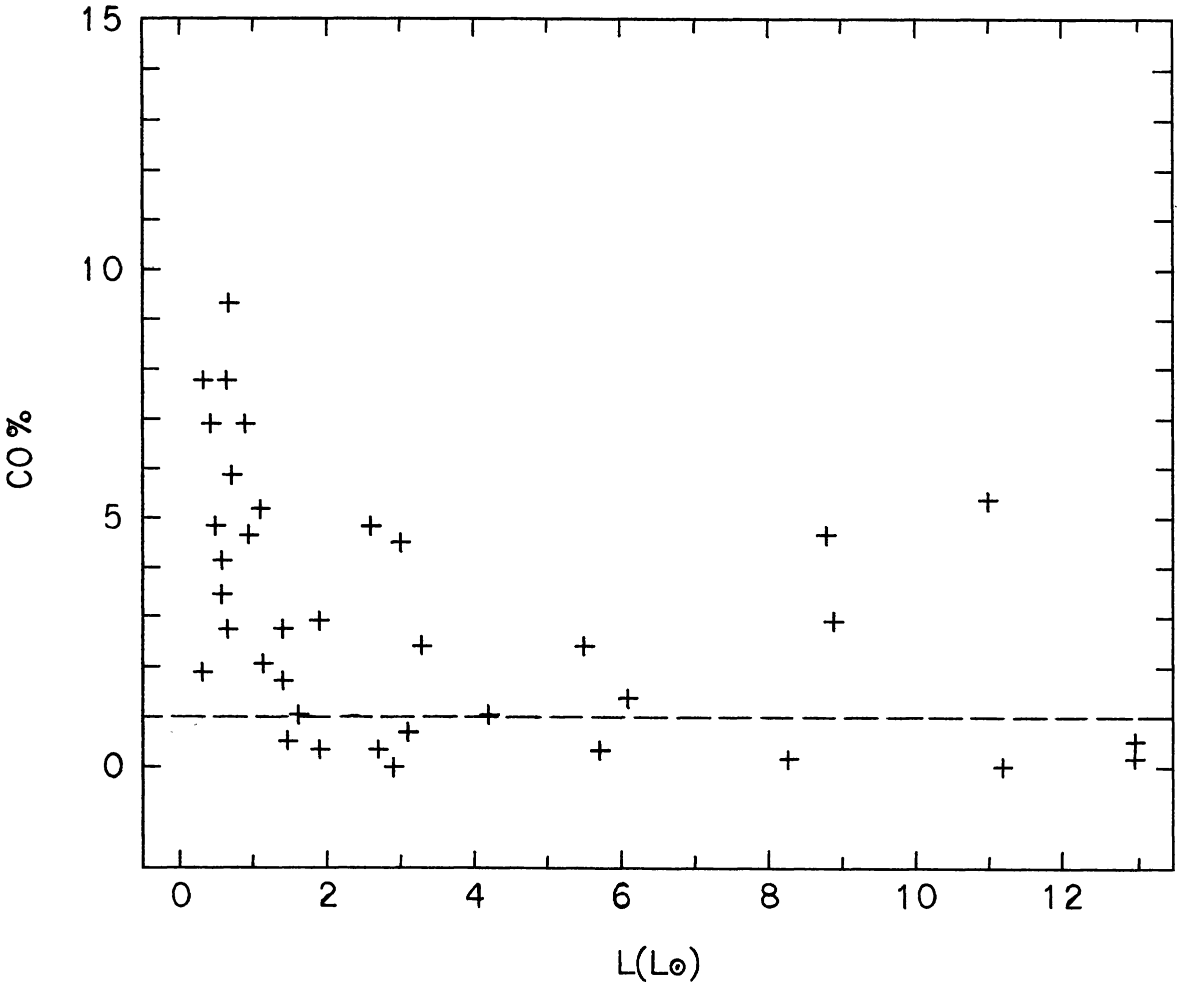

Fig. 1.— Observed CO band strength vs luminosity. The horizontal dashed line approximately indicates the CO detection limit.

We must, however, be aware that the use of IR absorption spectra for the study of YSOs is a relatively new concept and there are many potential problems. For instance, we have to consider the possible dilution of absorption features due to veiling by dust emission. Furthermore, it is not certain that absorption lines exclusively form in the photospheres. Strong CO absorption is believed to occur in disks around FU Orionis objects (Kenyon et al. 1993), and Calvet et al. (1991) have shown that CO absorption can be formed in accretion disks around young objects.

2. OBSERVATIONS

Observations were made in May and October 1993 using the United Kingdom Infrared Telescope (UKIRT) on Mauna Kea, with the common user 1-5 μm spectrometer CGS4 equipped with a 62 x 58 InSb detector (Mountain et al. 1990).

The observed sample consists of 44 YSOs from Perseus, Taurus, L 1641, Ophiuchus and Serpens. Sources were selected according to the following criteria: 1. relatively bright objects at K ($\lesssim$11.5), 2. wide range in near-IR colours (0.1$\lesssim$H-K$\lesssim$3.7), 3. if possible, a reliable IRAS association, 4. wide range in α_{2-25} index (-1.2$\lesssim$ α $\lesssim$1.7), 5. low luminosity sources (L$\lesssim$ 13 $L_\odot$). The sample includes 11 Class I sources, 17 Class II, 5 of which are visible PMS stars, and 16 embedded sources without IRAS counterpart.

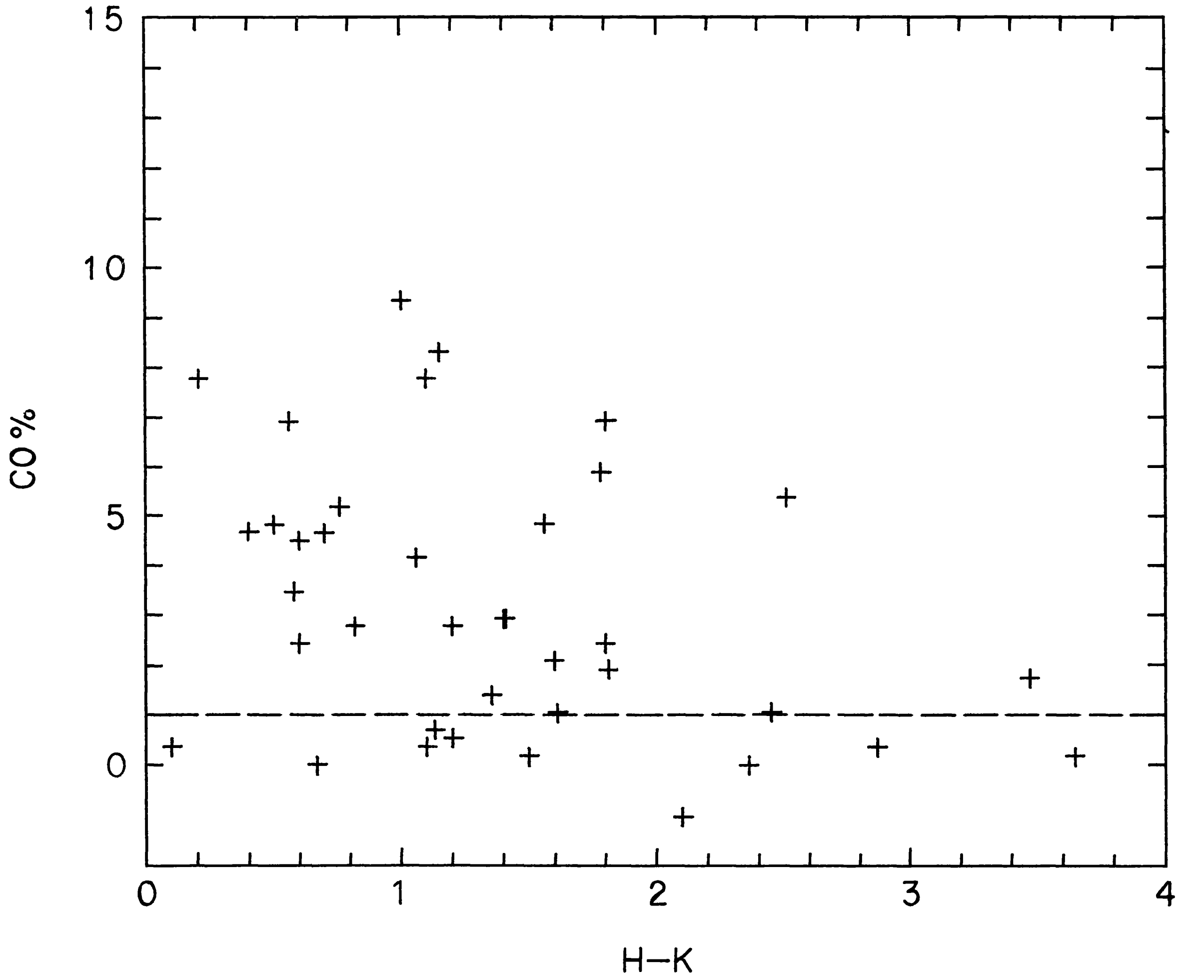

Fig. 2.— CO band strength versus H-K colour.

The observations in May (Ophiuchus) were made with the 150 mm camera and 150 l/mm grating giving a spectral resolution of 1200. The observations in October were made with the 300 mm camera and the 75 l/mm grating. Spectral resolution was 660. The observed spectral range was $\lambda\lambda$ 2.28 - 2.43 μm. In addition, the ^{12}CO(2-0) band of 9 sources were observed in October with the echelle giving a spectral resolution of 17000. A and F standard stars observed at similar air masses to the target objects were used to remove telluric absorption features. Spectra were reduced using the FIGARO package. A completely detailed description of the observations and data reduction is given by Casali & Eiroa (1995).

3. RESULTS

^{12}CO overtone bands from v=2-0 to v=7-5 are clearly visible in the spectra of most of the observed YSOs, while no obvious emission was observed in any of the objects. In addition, ^{13}CO bands are also weakly visible in a few of the spectra.

The echelle spectra of the v=2-0 bandhead show an unresolved drop in 7 out of the 9 observed objects. The spectrum of one object has a poor signal to noise ratio, and only in one case the band could be broadened. By comparison with a spectrum of a late-type giant, we estimate that these 7 objects have less than 17 km/s of velocity broadening.

To quantify the ^{12}CO band strength we have followed a modification of the Kleinmann & Hall (1986) method, which relates the flux in a 10 cm^{-1} band near the head of each absorption band to a clean continuum at λ= 2.290 μm. Our method consisted in estimating the ^{12}CO band strength in each object relative to that of a K2 III star, by using a least square procedure. Then, this relative strength was converted to the KH system by multiplying it by the value of the CO index of the K2 III giant (Casali & Eiroa 1995).

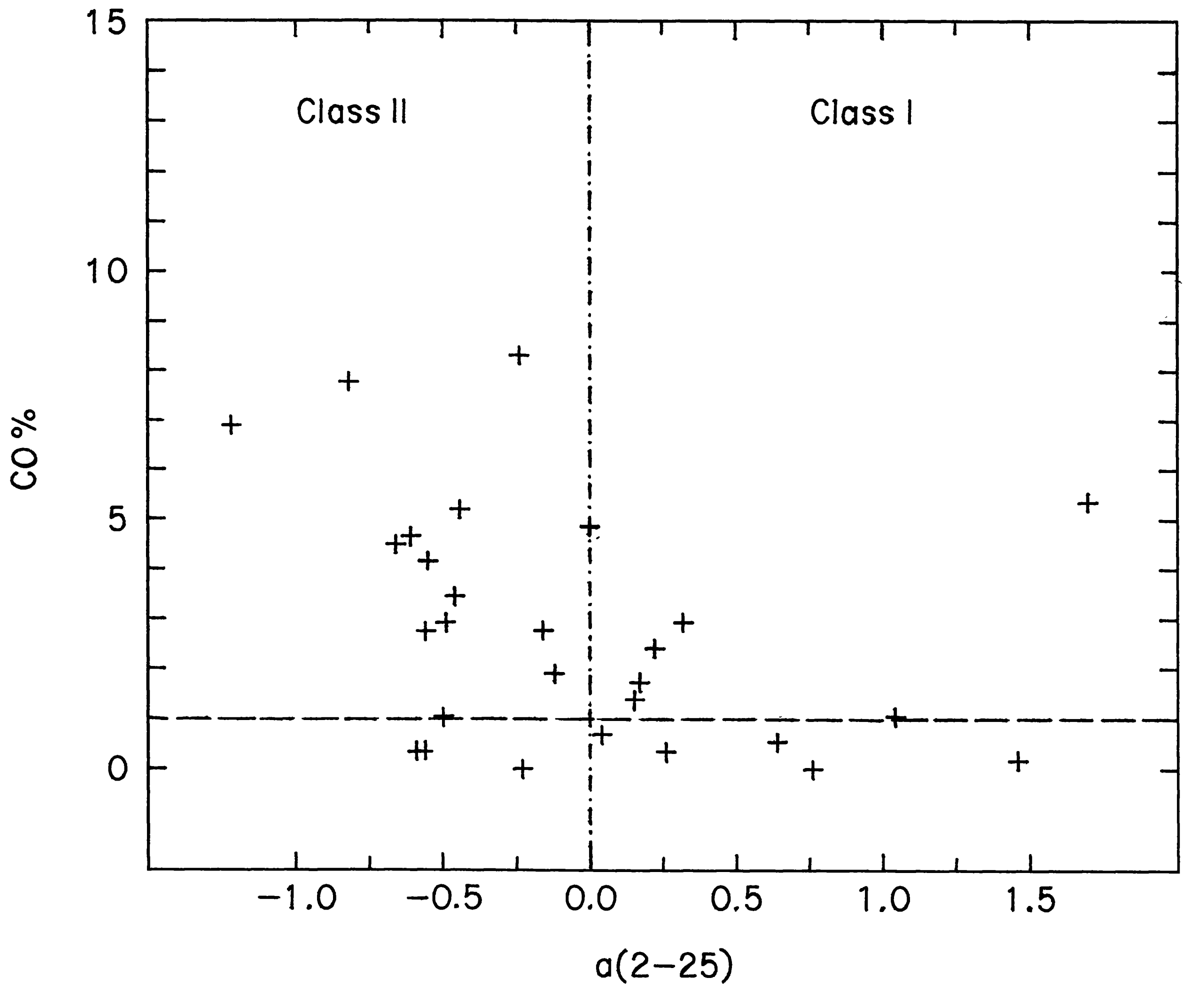

Fig. 3.— CO band strength vs 2-25 μm index of the spectral energy distribution. The dot-dashed line separates Class I and Class II objects.

4. DISCUSSION

The strength of the ^{12}CO absorption can be checked for correlation with a number of the YSO parameters. Fig. 1 shows a weak trend of decreasing CO index with increasing luminosity. This further supports the conclusions of Casali & Matthews (1992) that ^{12}CO are very common in the spectra of low luminosity PMS objects. A better correlation is found with the H-K colour, the redder sources have weaker CO absorption (Fig. 2).

The most interesting plot is that represented in Fig. 3, where the CO index is plotted against the 2-25 μm index of the spectral energy distribution (SED). The regions occupied by Class I and Class II objects are separated in the diagram by a vertical line. 14 out of 17 Class II sources definitively have CO absorption, whereas only 5 out of 11 Class I sources present it. 4 of these 5 objects are transition objects (α_{2-25} close to 0), and the other one is a binary. It seems that CO is an excellent indicator of the SED classes. In addition, the CO spectra of the visible PMS star and the embedded Class II sources are quite similar. This can be taken as a further evidence that both types of objects are essentially the same.

The echelle spectra illustrate which is the most likely physical origin of the observed CO absorption. Under plausible assumptions, it can be demonstrated that if the CO absorption arises in a disk, then a rotational broadening of 50-100 km/s is to be expected (Casali & Eiroa 1995). The echelle results exclude such a rotational broadening for most of the of YSOs; we therefore conclude that the CO bands seem consistent with a photospheric origin and, in addition, the YSO photospheres cannot be rapidly rotating.

The trends of the CO index with the H-K colour and with the SED index suggest a further correlation between the CO absorption and the infrared excess produced by thermal emission from circumstellar dust around young stars. This and the assumption of a photospheric origin of the CO absorption suggest that the CO bands can be veiled by dust emission. In principle, the veiling can be modelled and an intrinsic CO index can be estimated, which would allow us to trace and equivalent HR diagram (Casali & Eiroa 1995).

5. CONCLUSIONS

Near-IR spectroscopy is a very promising tool for studying the photospheres of young embedded objects. Our observations definitively confirm the idea that CO absorption is present in the near-IR spectra of embedded young objects. The CO absorption is photospheric. Only in few cases, the velocity broadening of the bands could imply a rapidly rotating photosphere or a disk as physical origins. The strength of the CO absorption is correlated with different YSO parameters. In particular, CO seems to be a good discriminator between Class I and Class II objects.

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