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B[E] STARS: PRE- VERSUS POST-MAIN SEQUENCE EVOLUTION

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RESUMEN

La clasificación de numerosas estrellas galácticas B[e] está obstaculizada por inciertos o desconocidos parámetros estelares. Además, las estrellas Herbig B[e] y supergigantes B[e], ambas rodeadas por discos de polvo, muestran muchas semejanzas espectroscópicas. Utilizamos el cociente de $^{12}C/^{13}C$, que disminuye drásticamente durante la evolución estelar y demostramos que la forma de la emisión de la banda de ^{13}CO es una prueba inequívoca de una naturaleza supergigante.

ABSTRACT

The classification of numerous Galactic B[e] stars is hampered by uncertain or unknown stellar parameters. In addition, Herbig B[e] stars and B[e] supergiants, both surrounded by dusty disks, show many spectroscopic similarities. We use the $^{12}C/^{13}C$ ratio, which drops drastically during stellar evolution, and show that the appearance of ^{13}CO band emission is an unambiguous proof for a supergiant nature.

Key Words: circumstellar matter — stars: early-type — stars: mass loss — stars: winds, outflows

1. INTRODUCTION

A long-standing problem in B[e] star research is the proper classification of each star showing the B[e] phenomenon (expressed by strong Balmer emission, dust emission, and the presence of permitted and forbidden emission of low-ionized metals) according to its evolutionary phase. While Lamers et al. (1998) made already a great job in splitting B[e] stars into supergiants, Herbig stars, compact planetary nebulae, and symbiotics, more than half of the objects are still gathered under the inconvenient name of "unclassified B[e] stars" (unclB[e]). The problems in classifying the unclB[e] stars arise since (1) they are usually highly reddened with unclear or unknown contributions of circumstellar and interstellar extinction, (2) most of them have not been studied in detail yet resulting in uncertain or even unknown stellar parameters, and (3) they may show features of more than just one class of stars. Especially the latter is the case for a sample of unclB[e] which shows indication for both, a pre-main sequence (Herbig) as well as a post-main sequence (supergiant) nature.

Complications in disentangling the Herbig B[e] from the supergiant B[e] stars are due to the fact that stars in both groups are surrounded by dusty disks, and that the respective pre- and post-main sequence evolutionary tracks overlap substantially in terms of effective temperature and luminosity. The stellar luminosity is thus no sufficient classification criteria, and together with the often huge uncertainties in luminosities of especially the Galactic stars, it is not surprising that we have in the Milky Way to date no confirmed B[e] supergiant, but more than a dozen B[e] supergiant *candidates* (see Kraus 2009). For a proper classification as either supergiant or pre-main sequence star it is necessary to find characteristics that are unambiguously proving the stars' evolutionary phase.

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2. STELLAR EVOLUTION

During the evolution of massive ($\geq 8\,M_\odot$) stars the stellar surface is enriched by processed elements via internal mixing. Consequently, this mixing results in an enrichment of the wind material by processed material. B[e] supergiants have high-density disks formed from their wind material; these disks should thus consist of chemically processed material.

Besides the nitrogen enhancement, the carbon isotopes are ideal evolutionary indicators. For non-rotating stars the $^{12}C/^{13}C$ ratio is drastically decreasing during the post-main sequence evolution, from its initial (interstellar) value of $\sim$ 70 down to values of $10-20$ for stars with initial masses $M_{\rm in} \leq 25\,M_\odot$ and to values ≤ 5 for stars with $M_{\rm in} > 25\,M_\odot$ (Schaller et al. 1992). With such low ratios, ^{13}C should be easily detectable.

Recently stellar rotation emerged as an important constituent in the evolution of massive stars (Maeder & Meynet 2000). Rotationally induced mixing brings the processed material to the surface even earlier so that surface compositions of rotating stars

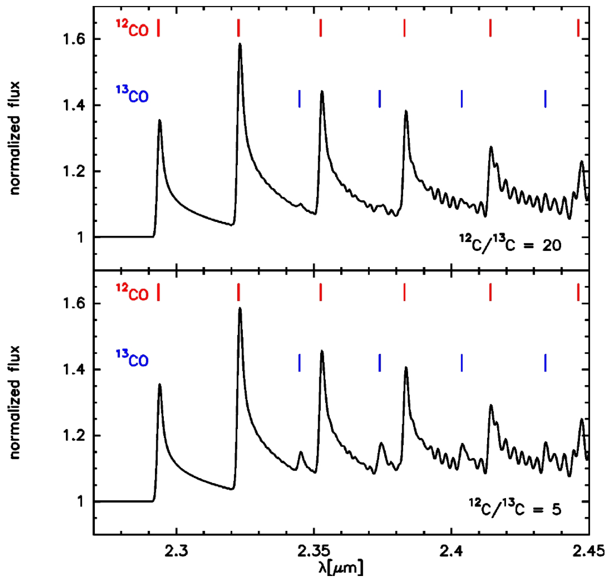

Fig. 1. Synthetic CO band spectra computed for a resolution of $R = 3000$ and two different $^{12}C/^{13}C$ ratios. The wavelengths of the ^{12}CO and ^{13}CO band heads are indicated.

can contain a decreased $^{12}C/^{13}C$ ratio already during their late main-sequence evolution (Meynet & Maeder 2003). Searching for decreased $^{12}C/^{13}C$ ratios thus provides a powerful tool to distinguish between pre- and post-main sequence evolution.

3. ^{12}CO AND ^{13}CO BAND EMISSION

The non-spherical winds of B[e] supergiants result in observable density contrasts between equatorial disk-forming wind and polar wind in the range $100 - 1000$ (Zickgraf et al. 1985). The high-density disk-forming wind is most probably expelled from the equatorial regions of rapidly rotating stars, although it has so far been proven tricky to create such disks. But four B[e] supergiants in the Magellanic Clouds, which rotate at some substantial fraction of their critical velocity, support this hypothesis (see Kraus et al. 2008).

The disk material quickly cools allowing efficient molecule and dust condensation. The most stable molecule is CO with a dissociation temperature of 5000 K, and CO is known to form immediately as soon as temperature and density conditions allow it. To trace hot $(3000 - 5000\,\mathrm{K})$ CO molecules right from their formation location, i.e. close to the star, their band emission longwards of $2.29\,\mu$m, formed by coupled vibration-rotation transitions, is an ideal indicator (see Figure 1). And in fact, several B[e] supergiants in the Magellanic Clouds show strong CO band emission in their K band spectra (McGregor et al. 1988b; Morris et al. 1996), and also for some Galactic B[e] supergiant candidates CO band detection was reported (McGregor et al. 1988a; Morris et al. 1996; Kraus et al. 2000). The ideal way to search for decreased $^{12}C/^{13}C$ ratios in the disk material is thus to search for decreased $^{12}CO/^{13}CO$ ratios.

The slightly higher mass of the ^{13}CO isotope results in a shift of the complete ^{13}CO band structure to larger wavelengths. Its band heads thus peak at different wavelengths with the first ^{13}CO band head falling in between the second and third ^{12}CO band heads. Figure 1 shows the CO band structures calculated for two different $^{12}C/^{13}C$ ratios (for details see Kraus 2009). For a ratio of 5 (bottom), the ^{13}CO peaks clearly out of the spectrum, while for a ratio of 20 (top) a clear detection becomes difficult. An interstellar ratio of 70 will thus hardly be detectable. The detection of ^{13}CO band emission in the K band spectra of unclB[e] is, therefore, an immediate proof of an evolved, i.e. supergiant, nature of the star.

4. THE POWER OF INTERFEROMETRY

The capability with VLTI/AMBER to obtain spectro-interferometric data, makes the study of B[e] supergiant candidates an exciting task. Especially the possibility to spatially resolve the CO gas and dust independently, as recently shown by Tatulli et al. (2008), provides us with a powerful tool to obtain simultaneously information about disk size and geometry *and* the evolutionary stage of the star.

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