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Infrared properties of barium stars*

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Abstract. We present the results of a systematic survey for IRAS associations of barium stars. A total of 155 associations were detected, and IRAS low-resolution spectra exist for 50 barium stars. We use different color-color diagrams from the visual band to 60 μm, relations between these colors and the spectral type, the barium intensity, and the IRAS low-resolution spectra to discuss physical properties of barium stars in the infrared. It is confirmed that most barium stars have infrared excesses in the near infrared. However, a new result of this work is that most barium stars have no excesses in the far infrared. This fact may imply that infrared excesses of barium stars are mainly due to the re-emission of energy lost from the Bond-Neff depression. It is also shown that the spectral type and the barium intensity of barium stars are not correlated with infrared colors, but may be correlated with $V-K$ color.

Key words. stars: late-type – infrared: stars – stars: chemically peculiar

1. Introduction

Barium stars (also known as Ba II stars) were first identified as a class of peculiar red giants by Bidelman and Keenan (1951). Barium stars are thought to be evolved G, K and M stars with luminosity classes I to IV, and they exhibit strong spectral lines of s-process elements, particularly Ba II at 4554 Å and Sr II at 4216 Å, and carbon-rich molecules such as CH, CN and C_2 (Bidelman & Keenan 1951; McClure 1984). Recently, it was confirmed that barium stars are hotter analogues and progenitors of Tc-poor (also called extrinsic) S stars in binary systems (McClure 1984; Han et al. 1995; Jorissen et al. 1998). With the discovery of the binary nature of barium stars, their chemical peculiarities have been attributed to mass transfer across the binary system. When the current white dwarf (WD) companion of a barium star was a thermal pulsing AGB star, it transferred s-process and carbon-rich material to its companion, which now appears as a barium star (Bergeat & Knapik 1997; Jorissen et al. 1998). The scenario has recently been confirmed by Bohm-Vitense et al. (2000). Most barium stars they studied appear to have excess flux in the UV, which can be attributed to their WD companions. Therefore barium stars are very important to our understanding of nucleosynthesis and stellar evolution in the post-main sequence stage.

The most comprehensive list of barium stars in the literature is that published by Lü et al. (1983) and Lü (1991). In the latter paper, 389 barium stars were listed with barium intensity from 0.1 to 5 (Warner 1965; Keenan & Pitts 1980). In the earlier years, Neugebauer & Leighton (1969, hereafter IRC) observed some bright barium stars in the I and K bands. The first systematic photometry in the JHK bands was given by Feast & Catchpole (1977), who showed that barium stars have infrared excesses in the near infrared, compared to normal giants. After about a decade, Hakkila & McNamara (1987) and Hakkila (1989) made more intensive studies of barium stars in the near and middle infrared. From these studies, it was shown that most barium stars exhibit weak ($<0\overset{m}{.}1$) infrared excesses in the H and M bands, and some barium stars show rather large ($>0\overset{m}{.}2$) infrared excess in the N band. These authors suggested that infrared excesses in such bands may be caused by: (1) redistribution of energy into the infrared from the so called Bond-Neff depression, which is a broad drop in the continuum between 3500 Å and 4500 Å (Bond & Neff 1969) or (2) thermal emission in the circumstellar material caused by mass transfer in the binary system. Hakkila & McNamara (1987) pointed out that it is necessary to study the physical properties of barium stars in the far infrared region in order to test these mechanisms of production of such infrared excesses.

In this paper, a survey of IRAS associations of barium stars is presented. Different color-color diagrams, relations between these colors and the spectral type, and the barium intensity are used to outline the physical properties of barium stars in the infrared.

* Table 1 is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via
http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/372/245

** e-mail: iras@public.km.yn.cn

2. Samples and data processing

As mentioned above, Lü (1991) presented a comprehensive catalog of barium stars, in which a total of 389 barium stars are listed with the HD number and the position from the HD catalog in the epoch of 1900. This is our working sample.

Based on the positions and magnitudes in V from Lü (1991), all barium stars were checked and identified with the *HST Guide Star Catalog* (1992, hereafter GSC). Because all barium stars listed are fairly bright (magnitude in V brighter than $10^{\rm m}_{.}0$), this identification is easily made. Then, using the method for the IRAS identification of stars from Chen (1996), IRAS associations of these barium stars were obtained. This method is as follows: (1) there is a positional error ellipse for each IRAS source in the *IRAS Point Source Catalog* (1988, hereafter PSC), and this error ellipse has a reliability of over 95% (IRAS Catalogs and Atlas: Explanatory Supplement 1988, hereafter IRAS ES); (2) On average, the positional accuracy in the GSC is better than $0''_{.}3$ (GSC 1992) so that if the position of a barium star identified in the GSC is located in a certain error ellipse of an IRAS source, the association is confirmed, otherwise there is no such association between the barium star and the IRAS source.

155 IRAS associations of barium stars were found and are listed in Table 1. In addition, IRAS carried on board a slitless spectrometer which recorded the low-resolution spectra of many sources in the 8–23 μm region with the spectral resolution of about 20–60 (IRAS ES). The *IRAS Atlas of low-resolution spectra* (LRS) (IRAS Science Team 1986, hereafter LRS Atlas) contained spectra of 5425 sources. This database was extended by Kwok et al. (1997) to a total of 11 224 sources. Therefore LRS spectra of these 155 barium stars were checked and extracted from Kwok et al. (1997). 50 barium stars were found to have IRAS LRS spectrum, also listed in Table 1.

The structure of Table 1 is as follows (in the column sequence):

1. Star number from Lü (1991);
2. Star names in the *HD Catalog* and the IRAS PSC;
3. RA and Dec. at the epoch of 1950 from the GSC and IRAS;
4. Magnitudes in V or B from the GSC and Lü (1991);
5. Magnitudes in K from the IRC or from others (indicated in the Note);
6. Spectral type from Lü (1991);
7. Barium intensity from Lü (1991);
8. LRS classification from Kwok et al. (1997), and the LRS Atlas (1986) in brackets;

9–12. IRAS flux densities at 12, 25, 60 and 100 μm (only good quality ones are presented);

13. In the Note there are: related IRC name, K magnitude origination, except for those from IRC.

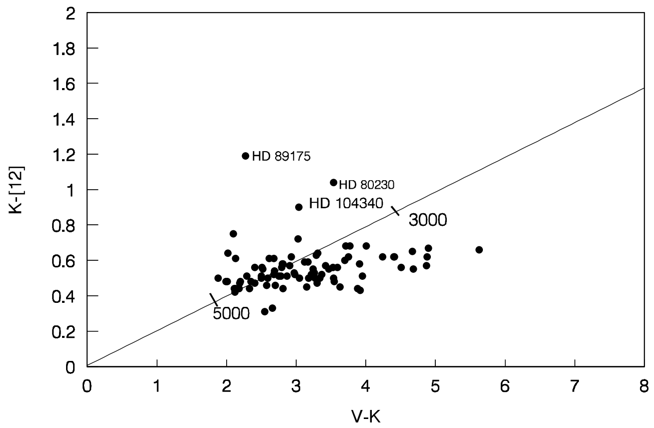

Fig. 1. $K-[12]$ versus $V-K$ diagram for barium stars.

3. Discussion

3.1. Color-color diagrams

From Table 1, the flux densities at 12, 25 and 60 μm can be transferred into magnitudes according to the following expressions without color correction (IRAS ES):

$$[12] = 3.63 - 2.5 \log F_{12} \quad (1)$$

$$[25] = 2.07 - 2.5 \log F_{25} \quad (2)$$

$$[60] = 0.19 - 2.5 \log F_{60}. \quad (3)$$

If V magnitudes from the GSC observations and K magnitudes from the IRC or others in Table 1 are taken into account, the $K-[12]$ versus $V-K$ color-color diagram can be plotted in Fig. 1. The blackbody line is also shown in Fig. 1 with some temperature indications. It can be seen from Fig. 1 that the objects of our sample cover a large interval in $V-K$ but only a small $K-[12]$ interval with about $2 < V-K < 5$ and $0.4 < K-[12] < 0.7$, and corresponding to color temperature between 3000 K and 5000 K. The distribution of barium stars in Fig. 1 indicates that most sources have infrared excess in the K band, but have no infrared excess at 12 μm, except for a few sources (for instance, HD 80230, 89175 and 104340). From Hakkila et al. (1987) and Hakkila (1989), together with our results, it may be concluded that most barium stars do have infrared excesses in the near infrared region, but only a few have infrared excesses in the far infrared. We show the $[12]-[25]$ versus $K-[12]$ color-color diagram and the $[25]-[60]$ versus $[12]-[25]$ color-color diagram in Figs. 2 and 3 respectively. In these figures, the blackbody line is also indicated with some temperature indications. It is obvious from Fig. 2 that almost all sources are concentrated in a small region with $0.4 < K-[12] < 0.7$ and $-0.1 < [12]-[25] < 0.1$, and near the blackbody line with a color temperature around 4000 K. It is also seen from Fig. 3 that most sources are located in a small region with $-0.1 < [12]-[25] < 0.1$ and $-0.2 < [25]-[60] < 0.2$, also near the blackbody line, with a color temperature around 5000 K. If the "standard" IRAS two-color diagram from van der Veen & Habing (1988, Fig. 5b, note that the color

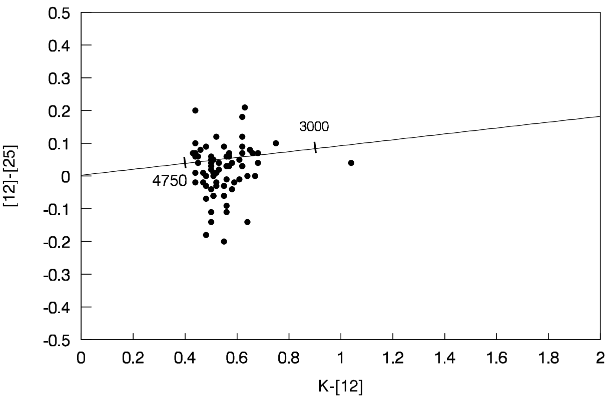

Fig. 2. [12] − [25] versus $K-[12]$ diagram for barium stars.

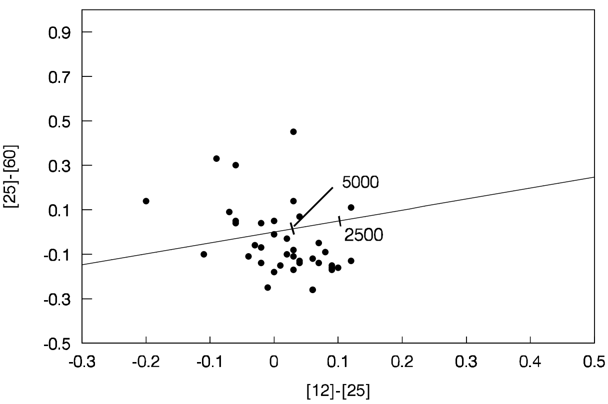

Fig. 3. [25] − [60] versus [12] − [25] diagram for barium stars.

definition in this figure is slightly different from Fig. 3 in this paper) is taken into account to compare with Fig. 3, it is clear that all barium stars here analyzed are located in the region of I in the "standard" IRAS two-color diagram, which is the region of "non-variable stars without circumstellar shells". From the distributions above, it may be concluded that most barium stars have some infrared excesses in the near infrared, but no infrared excesses in the IRAS region can be found.

3.2. Spectral type and colors

Taking the spectral type from Lü (1991), the $V-K$ versus Spectral type (*Sp.*) diagram for barium stars can be plotted (Fig. 4). Here we indicate the intrinsic $V-K$ colors for normal giant stars from Bessell & Brett (1988) with open squares. Compared with the normal giant stars, most barium stars with different spectral types show infrared excesses in the K band. In addition, $V-K$ colors for either barium stars or normal giant stars are all increased as spectral types become later. This mainly may be due to the decrease in the photospheric temperature of the stars. The $K-[12]$ versus spectral type diagram for barium stars can be plotted in Fig. 5. It can be seen from Fig. 5 that there is no correlation between $K-[12]$ color and spectral type for barium stars. The [12] − [25] and [25] − [60] versus spectral type diagrams are similar to Fig. 5.

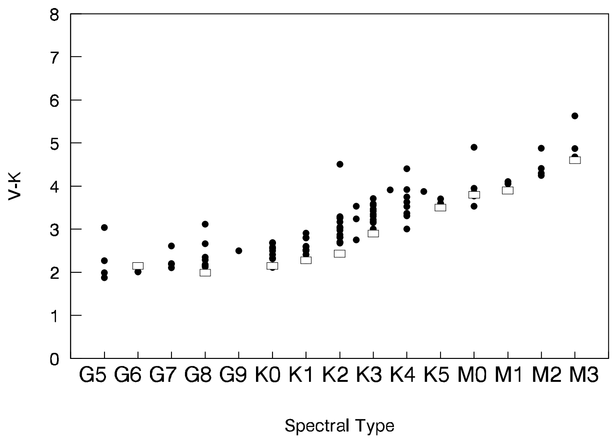

Fig. 4. $V-K$ versus spectral type for barium stars.

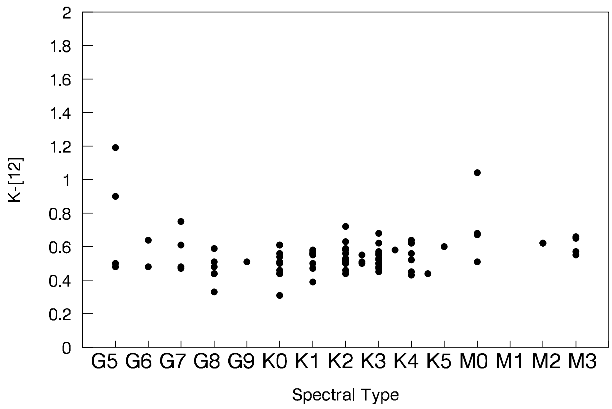

Fig. 5. $K-[12]$ versus spectral type for barium stars.

3.3. Barium intensity and colors

Taking data from Table 1, the $V-K$ color versus barium intensity diagram is plotted in Fig. 6. For barium intensities less than one, i.e. for so called "weak barium stars" (Lü 1991), there is a wide distribution of $V-K$ color from about 2 to almost 6, but no correlation between the barium intensity and the $V-K$ color. However, as the barium intensity increases from 2 to 5, on average, the $V-K$ color seems to gradually increase, but the statistical significance is small because of the small available sample size. The definition of barium intensity is based on the Ba II line strength at 4554 Å (McClure 1984; Lü 1991), however, this line is out of the range of the pass-band in V for the standard system (Bessell 1990). Therefore, the possible weak correlation between $V-K$ color and barium intensity for barium stars with a barium intensity from 2 to 5 is not easy to explain. The barium line strength is (besides barium abundance) a function of effective temperature and gravity of the star, and the $V-K$ color can be considered as a temperature indicator. However, the situation is very complicated because the cooler barium stars have higher luminosities than the hotter barium stars (Bergeat & Knapik 1997). Thus, it is possible that a very complicated combination of temperature and luminosity/gravity effects taken place. Detailed models are

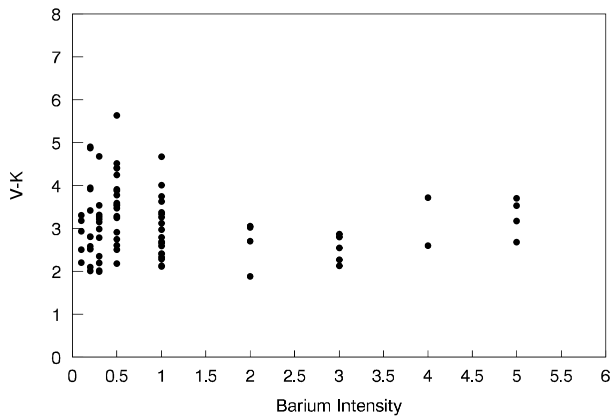

Fig. 6. $V-K$ versus barium intensity for barium stars.

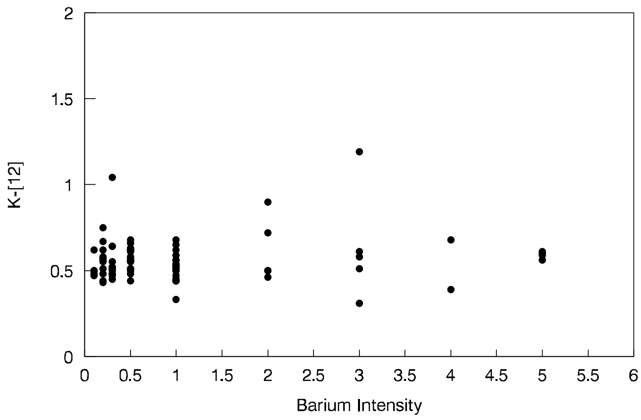

Fig. 7. $K-[12]$ versus barium intensity for barium stars.

required to check this problem. Thus, the weak correlation of barium intensity with $V-K$ color may not reflect a real correlation between barium abundance and $V-K$ color. In addition, the $K-[12]$ color versus barium intensity diagram, shown in Fig. 7, shows no such correlation. The $[12]-[25]$, and $[25]-[60]$ versus barium intensity diagrams are similar to that of Fig. 7.

3.4. LRS spectra

From Table 1 it can be seen that there are 50 LRS spectra for barium stars, among which 45 are classified as S, indicating the Rayleigh-Jeans tails of the stellar photospheric continuum; 4 are in the group F, indicating a featureless continuum with small amounts of circumstellar dust and one belongs to the group I, indicating a noisy or incomplete spectrum (Kwok et al. 1997). Note that $V-K$ and $K-[12]$ colors for F sources and S sources are not very different. From these results it is again confirmed that most barium stars have no infrared excesses beyond the near infrared region (at least in the 8–23 μm range).

4. Conclusions

From the discussion in Sect. 3 we conclude:

(1) Most barium stars have infrared excesses in the near infrared, but not in the IRAS region. This implies that the excess infrared flux is mainly due to the re-emission of energy lost from the Bond-Neff depression. The thermal emission caused by mass transfer in the binary system is not the main contributor;
(2) Spectral types of barium stars are correlated with the color $V-K$, indicating the photospheric temperature difference. However, spectral types of barium stars are not correlated with $K-[12]$, $[12]-[25]$ and $[25]-[60]$ colors;
(3) barium intensities of stars with barium intensity from 2 to 5 may be weakly correlated with $V-K$ color, but not correlated with $K-[12]$, $[12]-[25]$ and $[25]-[60]$ colors.

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