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THE DIFFUSE INTERSTELLAR BANDS

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RESUMEN. Se discuten la estructura de las bandas difusas interestelares y sus relaciones con otros rasgos interestelares.

ABSTRACT. The structure of the diffuse interstellar bands and their relations to other interstellar features are discussed.

Key words: INTERSTELLAR-BANDS

Understanding the interstellar medium (ISM) is of fundamental importance for understanding the evolution of galaxies. Much interest has been paid to its composition and its interaction with the stars. The importance of the molecular clouds for star formation has been shown during the past few years, and the contribution of young massive stars as well as of old red giants by mass loss to the ISM has been well established. One would perhaps then expect all the most important facts to be known. However, this is not so. The interrelation between the various components of the ISM is poorly known and even the frequently established "good" relations between the interstellar reddening (the dust grains) and various of the ISM components do not hold for a close scrutiny. Still worse is probably the fact that some features originating in the ISM are not yet identified, i.e. the agents causing these features are unknown. I refer here to the diffuse interstellar bands (DIBs) known since the 1920's and still not identified. Most studied among the DIBs are the 4430 band and the yellow bands at 5780 and 5797 Å with the superposed very wide 5778 band. Much of the fundamental work on the DIBs has been done by Herbig; I refer to his 1975 paper for an extensive list of DIBs together with extremely useful descriptions of the spectral ranges involved.

Here, I shall mainly deal with the yellow and a few of the red bands. All the spectra used by us are taken at La Silla with the ESO Coudé Echelle spectrograph (CES) combined with the Coudé Auxiliary Telescope (CAT) with a resolution of about 100 000. Each pixel corresponds to about 0.025 Å; the resolution is then about 0.05 Å, corresponding to 2.3 - 2.6 km/sec for the ranges covered (5780 - 6380 Å).

If we look at some of the spectra taken of SN 1987 A (Andreani, Vidal- Madjar 1987, Vladilo, Molaro 1987), we see that a large number of interstellar sodium- line components exist with galactic as well as LMC velocities and maybe a few "in between". There are obviously a still higher number of interstellar CaII lines. A comparison of the distribution of these components with the observed diffuse bands in the SN spectrum shows that the major D- line components group in the centres of the galactic and the LMC bands. The observed DIBs, even though rather weak, are possibly composed; each component may correspond to a D- line component.

Vladilo and Molaro identify the following main components of the diffuse bands:

Band	Galaxy		LMC
5780	+ 24		+ 283 km/sec
5797	+ 23	+ 195	+ 287
6284	+ 19		+ 262

They find the galactic components stronger than the LMC ones, contrary to the result for sodium. They see no fine structure in the bands at their resolution of 3 km/sec. This is not surprising. As we will show below the intrinsic widths of the bands are so large that the overlap of slightly shifted components virtually all occurs inside the bands themselves. This makes it also impossible to draw any conclusions about the relations between the D- line components and the bands - or the possible components of the bands - directly from these observations. In the 6284 DIB the telluric lines add to the confusion and are probably responsible for the differences seen between the velocities determined for this band and the other two.

In order to obtain full information from spectra of diffuse bands it is necessary:

a) to correct properly for the telluric and stellar lines in the spectral ranges of the bands, and

b) to establish for each band an intrinsic profile, i.e. a band profile formed in a single interstellar cloud. It would be extremely valuable if the chemistry and physics of such a cloud was also known. This may eventually be derived by combining theory and observations.

The observations of the sodium lines and the DIBs in the direction of SN 1987 A show how complicated the situation really is. Even in a direction with as low reddening as this (estimated to about E(B-V) = 0.2) there are many interfering clouds.

We may describe the ISM in any direction in the Galaxy or in any other galaxy as consisting of a number of elements or clouds, each one with its own particular conditions. The medium in one cloud may be clumpy or uniform and have its particular density, temperature and content (of dust, atoms, molecules, ions and radicals). The grain structure may vary from cloud to cloud. Some clouds may be expanding, thus adding to the Doppler shifts observed as a result of galactic rotation. Between us and a star belonging to a distant stellar association we have to count with i) our local interstellar medium (LISM), ii) a number of the ISM clouds just considered, iii) the interassociation medium, and, in many cases, iv) a circumstellar cloud.

Considering this complexity of the ISM it is not surprising that observations of stars of virtually the same reddening may result in the differences shown in Fig.1 (stars b,c,d). Two of the stars have about the same D- line intensities (a and b -- Note, one component in a) is stellar.) but star a) lacks completely DIBs. The star a) is less reddened but in principle sufficient to be expected to have DIBs.

In comparing stars b) and c) we see that the sodium lines have about the same strengths (but do not agree completely in velocity) and so have the 5797 bands, whereas the 5780 band is much weaker in star b). The star d) has very complex sodium lines with at least nine components. It has also strong DIBs, but the 5780 band does not appear much wider than in star c).

It appears possible to draw already now the conclusion that at least three different types of interstellar clouds may exist:

i) causing reddening but no DIBs,

ii) causing reddening and/or 5797, and

iii) causing reddening and/or 5797 and/or 5780.

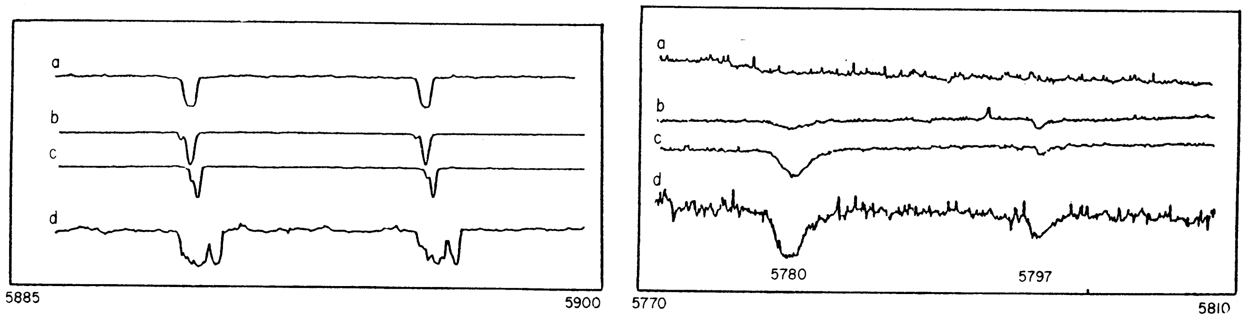

Fig.1.- Sodium lines and diffuse bands in the spectra of
a) HD139094, B8IV, V = 7.40, E(B-V) = 0.19, Sco OB2 association;
b) HD149757, O9.5V, 2.56, 0.33; Sco OB2 ;
c) HD147165, B1III, 2.90, 0.35; Sco OB2 ;
d) HD102997, B5Ia, 6.55, 0.38; Cru OB1 .

We will see below that there are also interstellar clouds causing the "5780 family of bands" to form but not 5797.

In Fig.1 all terrestrial lines have been eliminated by dividing the spectrum of each program star with that of an almost unreddened and DIB free star. Fig.2 exemplifies this for the heavily disturbed 6284 band. The uppermost spectrum is of a DIB star, the middle is of the program star with the oxygen bands still dominating. The result of the successful division is presented in the bottom spectrum.

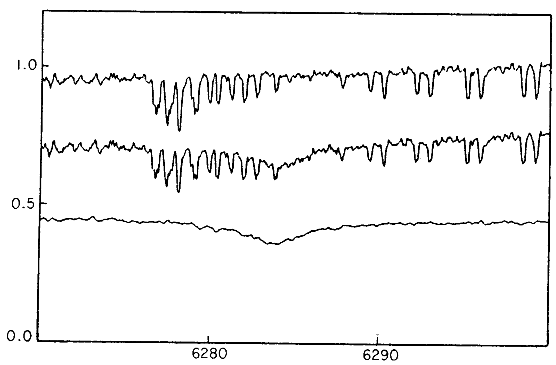

Fig.2.- The elimination of the oxygen bands in the DIB 6284 by division of the spectrum of the program star by that of a DIB free comparison star

Many attempts have been made to interprete the profiles of the 5780 and 5797 DIBs and to decompose them. As frequently rather distant stars have been studied the observed profiles result from DIB formation in a number of clouds with different radial velocities, and the identification of the components becomes extremely difficult. A decomposition of the 6613 DIB in HD183143 into two equal components was carried out by Herbig and Soderblom (1982). However, it is by no means certain that two components are enough. The intrinsic (= one cloud) profile has first to be found. We have approached this problem in several ways. Fig.3 shows the spectra of four rather nearby stars of moderate reddening.

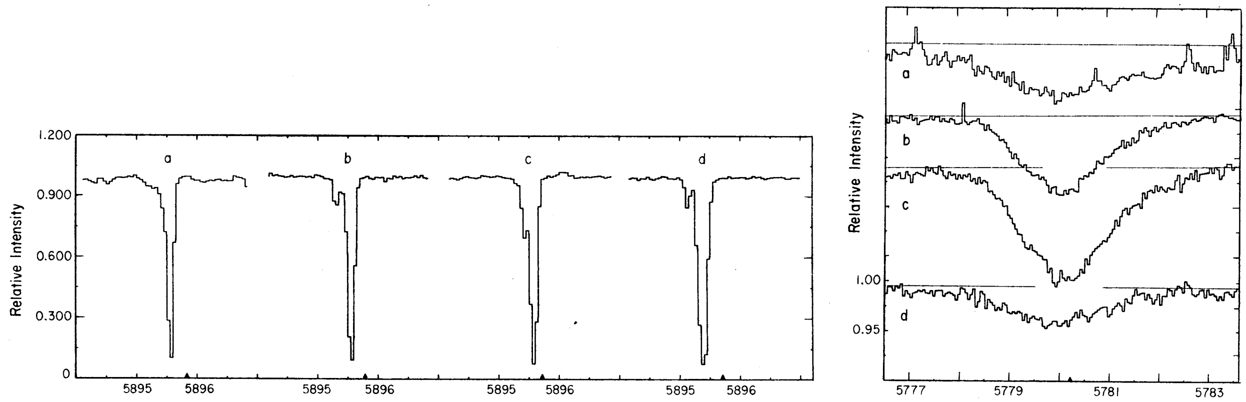

Fig.3.- The sodium D_1 line and the 5780 DIB in four Sco OB2 stars.
a) HD142096, B3V , E(B-V) = 0.18 ;
b) HD144217, B0.5V , 0.19 ;
c) HD147165, B1III , 0.35 ;
d) HD149757, O9.5V , 0.33 .

Note that the 5780 DIB is too weak in HD149757 for its reddening and sodium- line strength.

From the sodium lines one would expect two to three (major) clouds in the line- of- sight, and, as the D- lines are not too different, one would hope to find rather similar profiles of the DIBs in the four stars. The differences are, however, rather pronounced and do not show a direct correspondance to the strengths of the D- lines. We have resolved the D- lines into a number of well defined components and determined their equivalent widths and radial velocities. We have then assumed that any component of a DIB must exist at one of these velocities and that their relative intensities correspond to those of the D- line components. We are then able to isolate the strongest component in each observed band and, by determining a mean profile, obtain an intrinsic profile. The derived profiles are presented in Fig.4 for the 5780 and 5797 DIBs; for other DIBs I refer to Westerlund and Krełowski (1988b).

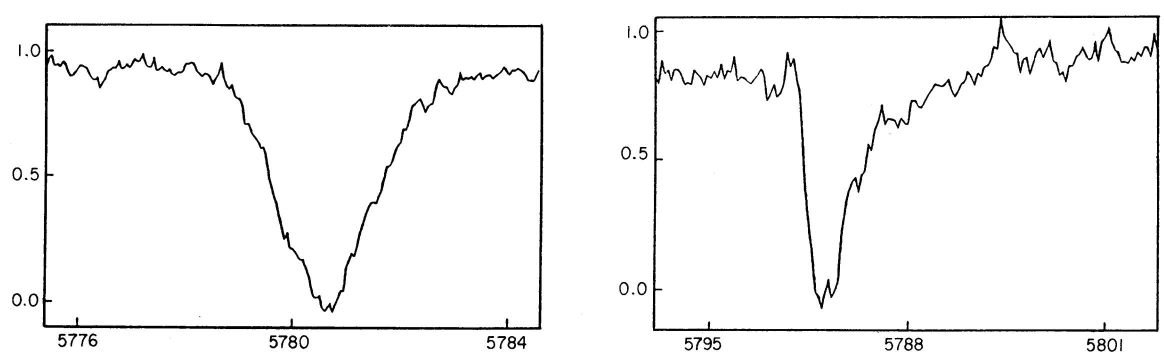

Fig.4.- The intrinsic profiles of the 5780 and 5797 DIBs.

We have used the intrinsic profiles in an analysis of the DIBs in the spectrum of HD157246 (Westerlund and Krełowski 1989) and are applying them in a number of other cases. In the case of HD157246 we found proof for the existence of several families among the DIBs; 5780 and 6196 belong to one, 5797 and 6613 to another.

We began by referring to the interstellar features in the spectrum of SN 1987A. If we attempt to fit our intrinsic profiles of 5780, 5797 and 6284 to the DIBs observed in it, we find a good agreement for 5780 as far as the width is concerned (we have made no attempt to scale for intensity differences); for 5797 the agreement with the LMC band is excellent whereas the galactic band must consist of two components. Due to the existence of the O_2 lines in the SN spectrum of 6284 we have been forced to compare with one of our unreduced spectra. It is evident that weak bands exist in the SN spectrum but we can do little more than state this.

We have shown (Westerlund and Krełowski 1988a, Fig.9,10) how the intrinsic profiles may be fitted also to very complex DIBs.

Another way of analyzing very complex DIBs is illustrated in Fig.5. There, DIBs observed in HD102997 are shown with the D_1- line superposed. The split sodium- line contour has a direct correspondance in the 6196 and 6203 DIBs, but is lost in the apparently wider bands 5780 and 5797 (although the width of the latter at full intensity agrees with the width of the sodium line).

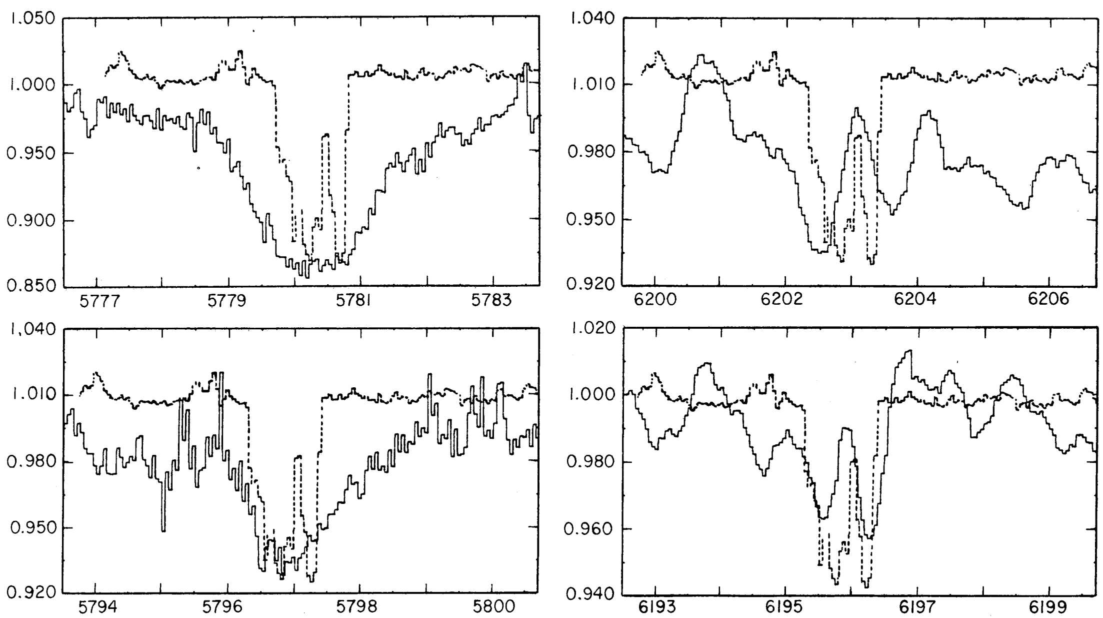

Fig.5.- DIBs in HD102997 with the D_1-line superposed.

Comparisons between D- lines and DIBs and colour excesses have led to suggestions that correlations exist at least between some of these quantities (See eg Herbig 1975). However, the situation is still so complicated that no universal correlations can be said to have been found. It is necessary to determine the contributions of the individual clouds along any line- of- sight before relations may be established with any degree of certainty. It is evident that information derived from ISM features in the far UV spectrum, such as the far UV colour excess, E(15-B), and the excess of the 2200 Å "Bump" feature, E(Bump), will be of great importance for this. Likewise, other components of the ISM, such as HI and a number of radicals and molecules, must be considered.

We exemplify this by showing in Fig.6 a comparison of the D_1- line strength for a number of stars in Sco OB2 and CMa OB1 and the total hydrogen content in those directions (Bohlin et al. 1978). When the total D_1- line intensities are used the relations for the two regions differ appreciably (Fig.6a). When, however, certain clouds are selected a common relation is obtained.

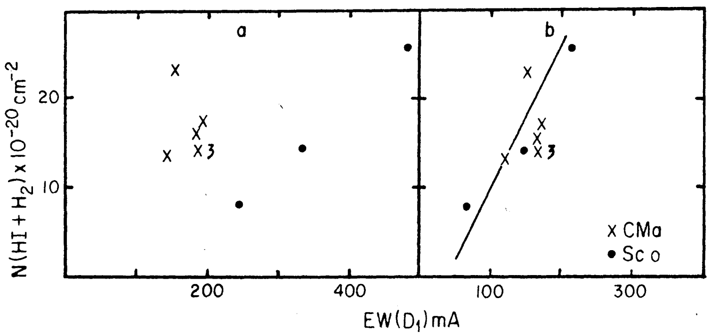

Fig.6.- Comparison of D_1- line strength for stars in Sco OB2 and CMa OB1 with the hydrogen content, HI + H_2:
a) total D1
b) D1 components corresponding to selected velocities:
In Sco OB2 the LISM components are not included;
in CMa OB1 the only components kept are those corresponding to the major CO range (15 - 20 km/sec).
Note that Zeta Oph does not show any deficiency in (HI+H_2). However, this is due to the high amount of H_2 and the HI observed in this direction may be at a greater distance (see Cappa de Nicolau and Pöppel 1986, Fig.21).

We will use the CMa OB1 association for further camparisons between some of the ISM components. This association is rather well studied. It is associated with an R association, Hα nebulosity, dark clouds, CO clouds and HI.

An expanding shell has been suggested to exist there, as well as supernova induced star formation. (See Machnik et al. 1980 for details and references to previous work). I have obtained high- resolution spectra of the sodium lines and the 5780, 5797 DIBs in five stars in the region (See Fig.7), all of them probable members of the association. Direct comparisons between the velocities of the sodium- line components and the gas clouds is thus possible.

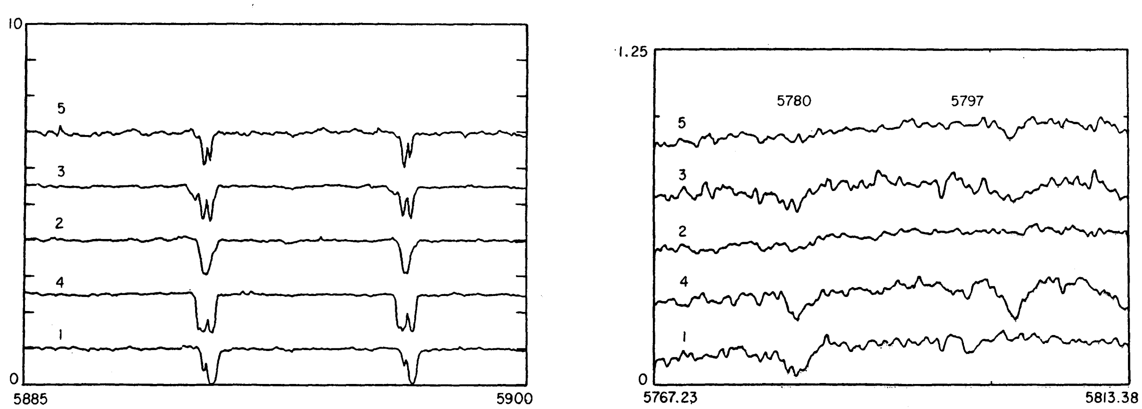

Fig.7.- The sodium lines and 5780, 5797 DIBs in five stars in CMa OB1. 1) HD52382, B1Ib, E(B-V) = 0.44; 2) HD53755, B0V, 0.25; 3) HD53975, O7.5V, 0.22; 4) HD54662, O6.5V, 0.35; 5) HD55879, O9.5III, 0.12.

It is evident in Fig.7 that there are sodium- line components in common to all the stars but that there are also pronounced differences. The measured LSR velocities range from - 13 to + 21 km/sec; Machnik et al. (1980) have CO velocities between - 30 and + 45 km/sec. As far as the DIBs are concerned our present data are not accurate enough to permit analysis of the contours but we will use the total EW:s for a preliminary study.

The mean LSR velocities of the D_1- line components in our five stars are: -13.3 (1 star); -4.7 (3); +5.0 (5); +14.5 (5); +20.8 (4) km/sec. The second and last values are close to those of the expanding shell in the proposed model, and the fourth agrees with the mean velocity of the association as well as with the average CO velocity.

Two of the stars, HD53975 and HD54662, are generally considered as responsible for most of the ionization in the region. The latter is also a run-away star with a velocity of about + 30 km/sec relative to the association. However, this has to be combined with the fact that both stars have the +20.8 km/sec D- line component in their spectra, and thus, must be behind also the far part of the shell. It is necessary to obtain further information by comparing the D- lines with other available ISM measures.

The top figure in a) shows the total D_1- line intensities versus E(B-V). The scatter is evident. If we select the components corresponding to LSR velocities 15 and 21 km/sec an excellent agreement is obtained. Thus, the equivalent widths of the sodium lines in the volume of space occupied by the association is well correlated with the colour excess also mainly caused there (Claria (1974) found the foreground reddening to amount to only 0.08 mag.)

Similar results (Fig.8,b,c) are obtained when the D_1- line strength is compared with E(15-B) and E(Bump) (Savage et al. 1985).

We compare, finally, our DIB measurements and those of Whittet and Blade (1980), after correction to our system, with some colour excess measures.

The position of HD53367 in all the diagrams should be noted. It has been interpreted as a deficiency of the agents causing the DIBs in the direction of this star. The deficiency is completely located to the material in which the star is immersed, circumstellar or not, as all the other stars show a small

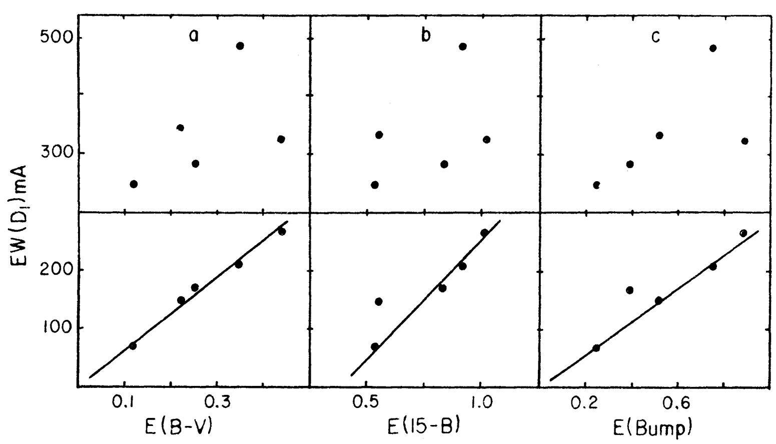

Fig.8.- Comparisons of sodium- line strengths and various extinction measures for the CMa OB1 stars.
Sodium- line equivalent widths (EW) versus a) E(B-V), b) E(15-B), c) E(Bump).

scatter in the EW/E(B-V) diagrams. The surroundings of HD53367 are also, as we will show in a forthcoming paper, underabundant in sodium. Using recently obtained high- resolution spectra we will there also attempt to identify the interstellar clouds in this direction that carry the agents causing the DIBs at 5780 and 5797 Å.

The diagrams in Fig.9 showing the DIBs versus E(15-V) and E(Bump) do not permit any definite conclusions. The correlation between both DIBs and E(Bump) appears better than between them and E(15-V). It is necessary to improve the quality of the observed profiles of the DIBs in these stars so that our intrinsic profiles can be used in the analysis. As I am going from this conference to La Silla to observe the CMa OB1 stars with the CES + CAT I may optimistically end my talk by promising a more complete analysis of the ISM in this direction shortly.

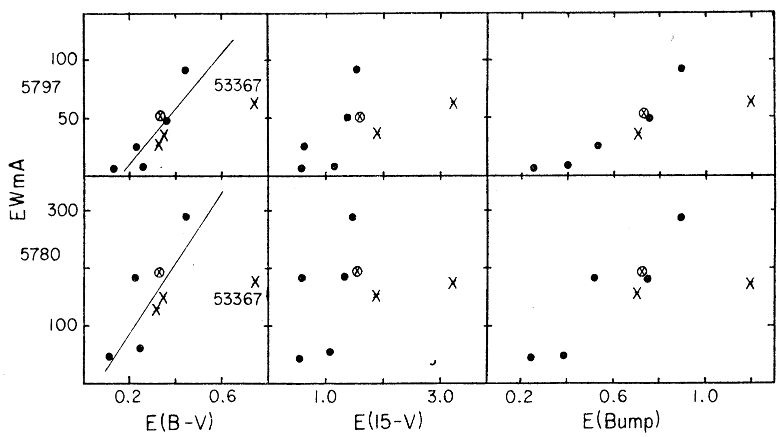

Fig.9.- Comparison of EW(5780) and EW(5797) with E(B-V), E(15-V), and E(Bump) for CMa OB1 stars.
Dots are our stars, x Whittet and Blade's (1980). An x in a circle identifies one of their control stars.

REFERENCES

Andreani, P., Vidal- Madjar, A.: 1987, ESO Workshop on the SN 1987 A, p.517 (ed. J. Danziger)
Bohlin, R.C., Savage, B.D., Drake, J.F.: 1978, Astrophys. J. 224, 132
Cappa de Nicolau, C.E., Pöppel, W.G.L.: 1986, Astron. Astrophys. 164, 274
Claria, J.J.: 1974, Astron. J. 79, 1022
Herbig, G.H.: 1975, Astrophys. J. 196, 129
Herbig, G.H., Soderblom, D.R.: 1982, Astrophys. J. 252, 610
Machnik, D.E., Hettrick, M.C., Kutner, M.L., Dickman, R.L., Tucker, K.D.: 1980, Astrophys. J. 242, 121
Savage, B.D., Massa, D., Meade, M., Wesselius, P.R.: 1985, Astrophys. J. Suppl. Ser. 59, 397
Vladilo, G., Molaro, P.: 1987, ESO Workshop on the SN 1987 A, p.539 (ed. J. Danziger)
Westerlund, B.E., Krełowski, J.: 1988a, Astron. Astrophys. 189, 221
Westerlund, B.E., Krełowski, J.: 1988b, Astron. Astrophys. 203, 134
Westerlund, B.E., Krełowski, J.: 1989 , Astron. Astrophys., in press
Whittet, D.C.B., Blades, J.C.: 1980, Mon. Not. R. astr. Soc. 190, 41P

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