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Letter to the Editor

Far UV nonlinear rise extinction in relation to CH and CH$^+$ abundances

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Abstract. The amount of FUV non-linear rise in the interstellar extinction curve is found to be proportional to the CH abundance in the line of sight. The CH^+ abundance shows, if any, a negative trend with the FUV non-linear rise. Implications for the carrier of the FUV non-linear rise are discussed.

Key words: Dust, extinction – Interstellar medium: abundances – Interstellar medium: molecules.

1. Introduction.

The interstellar extinction curve depicts absorption and scattering of various interstellar dust components from the near infrared to the far ultraviolet. It has been suggested that the far ultraviolet (FUV) rise consists of a linear and an unrelated non-linear part (Fitzpatrick & Massa 1988).

Greenberg & Chlewicki (1983) have found that, in the diffuse medium, the shape of the interstellar extinction curve in the far UV ($0.12 < \lambda < 0.17\mu$m) is remarkably constant from one line of sight to another. But deviations in the functional form occur for some HII regions and in the lines of sight that cross dense clouds, which typically show an abnormal linear rise. Fitzpatrick & Massa (1988) extrapolated the linear rise that underlays the 220nm bump in a search for a more general characterisation of the extinction curve and showed that the remaning non-linear curvature in the far UV (Fig. 1) has a characteristic shape. In terms of $k(x) = E(\lambda - V)/E(B-V)$ the FUV non-linear rise (c_4) is given by:

$$f(x) = 0.5392(x - 5.9)^2 + 0.0564(x - 5.9)^3 + ... \quad (1)$$

$$k(x) = c_4 \times f(x)$$

for $5.9 < x < 8.3\mu\text{m}^{-1}$, where $x = \lambda^{-1}(\mu\text{m}^{-1})$. Greenberg & Chlewicki (1983) argued that the constant shape implies that the FUV non-linear rise is a pure absorption feature. This is confirmed by the lack of a FUV non-linear rise in the scattering amplitude of dust in reflection nebulae (see: Witt 1989) and in the polarisation curve of light from reddened stars (Clayton et al. 1992).

The carrier of the FUV non-linear rise has not yet been identified. At present even the physical significance of the FUV non-linear rise is questioned (i.e. Cardelli et al. 1989), because there is a priori no reason for extrapolating the linear rise to shorter wavelengths. On the other hand the decomposition is justified because the linear and non-linear rise do not correlate (Fitzpatrick & Massa 1988), and the linear rise is closely related to the shape of the extinction curve in the visual (Cardelli et al. 1988).

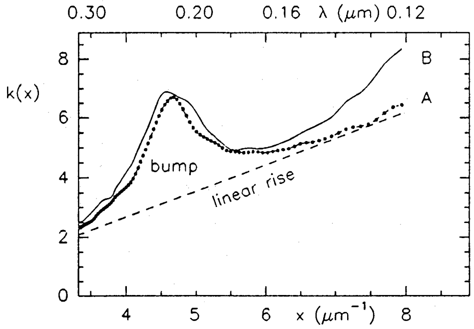

Fig. 1. Examples of extinction curves with high and low FUV non-linear rise (from: Aiello et al. 1988). HD190603 (A) has $c_4 = 0.04$ and HD61827 (B) has $c_4 = 0.83$. Both have the same amount of linear rise.

The FUV non-linear rise has not been related to any extinction or emission parameter of interstellar dust. There is a weak trend that broader 0.22 μm bumps have stronger FUV curvature and the FUV non-linear rise tends to be high in dense media (Fitzpatrick & Massa 1988). An attempt to correlate the FUV non-linear rise with near infrared excess emission at 12 and 25 micron has not been successful (Leene & Cox 1987; Hackwell et al. 1991).

Joseph et al. (1989) have reported a correlation of the 0.22 μm bump with the abundance of the CN molecule in the gas phase. In the process of a diffuse band survey we observed very strong CH^+ absorption at 4232.5 Å and weak CH absorption at 4300.3 Å in two lines of sight with almost absent FUV non-linear rise (HD190603 and HD30614). Even when the formation of CH^+ is a much debated subject currently, any correlation of gas phase abundances with continuum extinction may lead to new clues about the carrier of this extinction feature. This lead

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us to observe the optical absorption lines of *CH* and CH^+ of 22 lines of sight for which IUE extinction curves are published. Similar data for 7 more lines of sight are reported in the literature.

2. New absorption line measurements.

The data were obtained with the 1.52m f/27.6 Coudé telescope at the Observatoire de Haute Provence (OHP) in France, on June 29th, September 10th and December 23rd, 25th and 26th, 1991. The resolving power of the spectrograph "Aurelie" was set to R = 15,000 or $\Delta\lambda = 0.3$ Å, using a 1200 lines/mm grating with a blaze angle at 5000 Å and a dispersion of 8.1 Å/mm. Both the transition from the $A^2\Delta - X^2\Pi$ system of *CH* at 4300.321 Å and the R(0) (0,0) transition of the $A^1\Pi - X^1\Sigma$ system of CH^+ at 4232.539 Å were recorded in a single spectrum, which was centered at 4260 Å. The interstellar lines have a Doppler width of typically less than 0.1 Å (7 km/s) and are therefore unresolved.

The program stars were selected from the lists of Aiello et al. (1988) and Fitzpatrick & Massa (1988), to cover a wide range of extinction curve parameters and be bright enough in order to reach a S/N > 100 in the continuum within one hour of integration time. The resulting S/N in the equivalent widths is of the order of 2-10.

The spectra were reduced with the IHAP package at O.H.P. and the ***Institut d' Astrophysique de Paris.*** The equivalent width (W) of the absorption lines is given in Tab. 1, and compared with values from the literature. A significant deviation occurs only for the measurement of CH^+ for HD2905. However, Federman (1982) does not include a broad absorption component at $V_r \sim +2$ km/s. The (1 σ) error is at least $\Delta W \sim 0.22$ rms/px, but is affected by uncertainties in the baseline level. From a number of independent measurements of the same star we estimate the error to be about $\Delta W \sim 0.4$ rms/px. Upper limits in Fig. 2 are set to 2σ.

Stellar line contamination is present in late B type stars, like HD183143, but easily recognized because the stellar lines are usually well resolved, contrary to the interstellar lines. The only exception here is HD34078 (O9.5V). Close to the position of CH^+ a line of *Fe*I is found at 4232.724 Å (f.e. figures in Hawkins & Meyer 1989) and close to the position of *CH* two lines of *Ca*I are found at 4298.986 Å and 4302.527 Å (f.e. Fig. 7 of van Dishoeck & Black 1989).

Column densitites are calculated for an oscillator strength of 0.0053 for *CH* and 0.0056 for CH^+ respectively, values which have an uncertainty of about 10% (Brzozowski et al. 1976; Cardelli & Wallerstein 1986; van Dishoeck & Black 1989). In the weak line limit $N(CH) = 1.20 \times 10^{12}$ $[W_{CH}/\mathrm{m\AA}]$ cm^{-2} and $N(CH^+) = 1.13 \times 10^{12}$ $[W_{CH^+}/\mathrm{m\AA}]$ cm^{-2}.

For equivalenth widths larger than 10 mÅ significant saturation occurs. We have adopted curve of growths from van Dishoeck & Black (1989) that relate equivalenth width and column density for Doppler parameters between 0.7 and 1.5 km/s. For *CH* a Doppler parameter of b=1.0 km/s is adopted (e.f. Gredel et al. 1992) and the curve of growth for a blended Λ doublet. For CH^+ we extrapolated the given curves of growth for a single line to a Doppler parameter of b=2.5 km/s (e.f. Lambert & Danks 1986).

The column densities are normalised to unit reddening, in the same way as the extinction curve parameters. Thus they are transformed into ***abundances***, where the reddening refers to the total amount of matter in the line of sight.

3. Results.

The extinction curves of Aiello et al. (1988) were put in the parameterisation scheme of Fitzpatrick & Massa following the approach of Fitzpatrick & Massa (1990). Tab. 1 lists values of c_4. The extinction curve parameters for bump strength and linear rise are published elsewhere (Fitzpatrick & Massa 1990; Jenniskens 1992).

From the various possible pairs of *CH* or CH^+ abundance versus one of the extinction curve parameters, we have found a striking result only for the FUV non-linear rise (Fig. 2). The FUV non-linear rise (c_4) is proportional to the CH abundance (r=0.62):

$$\frac{N(CH)}{E_{B-V}} = 1.08(\pm 0.15) \times 10^{14}\ c_4 \qquad (2)$$

There is no such correlation with the linear rise (r=0.04) neither with the bump height (r=0.04). There is also no correlation with the total extinction at $x = 10\mu\mathrm{m}^{-1}$ (r=0.15). The CH^+ abundance shows, if any, a negative trend with c_4. Notable exceptions are *ζOph* (HD149757) and the stars in the Orion Nebula (triangles in the lower left part of the figure).

The line of sight towards HD34078 falls significantly above both trends. Because the star is of late O type, stellar line contamination is unlikely, but can not be ruled out because the stellar lines are not resolved.

4. Discussion

4.1. CH.

The *CH* column density is proportional to the H_2 column density (Federman 1982, Danks et al. 1984): $N(H_2) = 2.5 \times 10^7 N(CH)$. The observed *CH* abundances are well understood from a gas phase reaction scheme of molecular hydrogen. The primary reaction is that of C^+ with H_2 to form CH_2^+ and CH_3^+. Subsequent dissociative recombinations with electrons produce the neutral *CH* radical. From this we infer that the FUV non-linear rise is proportional to the fractional abundance of molecular hydrogen in the line of sight:

$$c_4\ [mag/E(B-V)] = 3.7(\pm 0.2) \times 10^{-22}\ \frac{N_{H_2}}{E(B-V)} [cm^{-2}] \qquad (3)$$

The correlation with molecular gas suggests that the carrier may be some small gas phase molecule. In some environments absorption by molecular hydrogen in its ground state, and photoionisation of neutral carbon atoms, produce a continuum absorption below $\lambda = 0.11\mu$m, but this has probably no implication for the FUV non-linear rise. Some other small (diatomic) molecules show a smooth absorption for $\lambda < 0.17\mu$m due to direct photodissociation. Note that predissociation or spontaneous radiative dissociation transitions are excluded, because the resulting absorption features are not observed (van Dishoeck 1988). Most candidate molecules have abundances that are too low and thus would need unrealisticaly high oscillator strengths. Molecular hydrogen in vibrationally excited states and the most abundant molecule in low reddening lines of sight, *CO*, have spectra that show discrete absorption features at $\lambda < 0.15\mu$m (van Dishoeck 1988, van Dishoeck & Black 1988) and can therefore be excluded.

Remaining candidates are small dust grains or big molecules. The correlation found with *CH* abundance argues against the

Table 1. Summary of CH and CH^+ observations. Entries marked F82, GDB92, etc., are values from the literature. E(B-V) and c_4 are derived from Aiello et al. (1988) or otherwise from Fitzpatrick and Massa (1988). Component (1) of HD152236 is at -6 km/s, (2) at +4 km/s. Component (1) of HD183143 is at +7 km/s, component (2) at +22 km/s.

	E(B-V) mag.	c_4 $\frac{mag.}{E(B-V)}$	W_{CH} mÅ	± mÅ	W_{CH^+} mÅ	± mÅ	ref.
HD2905	0.33	0.44	6.8	1.6	13.3	1.6	-
			6.9	2.0	4.1	1.5	F82
HD21483	0.55	0.66	27.	5.	<	5.	-
HD30614	0.30	0.14	1.6	0.8	18.6	0.8	-
			5.6	2.2	15.7	1.8	F82
HD34078	0.53	0.52	42.	10.	52.	10.	-
HD37022	0.34	0.19	<	3.	<	3.	-
HD37061	0.52	0.25	<	7.	<	7.	-
HD37367	0.40	0.32	8.	3.	20.	3.	-
HD37903	0.35	0.54	6.4	0.3	10.8	0.5	GDB92
HD41117	0.45	0.56	12.	4.	15.	4.	-
HD46150	0.45	0.59	9.	4.	13.	4.	-
HD47129	0.36	0.46	11.	4.	13.	4.	-
			7.4	0.8			DFL84
HD47240	0.33	0.44	<	4.	15.	4.	-
HD53974	0.35	0.43	7.	4.	15.	4.	-
HD73882	0.71	0.63	25.2	1.6	17.2	0.7	GDB92
HD147701	0.72	0.90	32.1	1.7	16.2	1.7	CW86
HD147889	1.08	0.88	51.0	1.5	23.1	1.6	CW86
			40.5	-	20	-	CC85
			38.	3.			DB89
HD147933	0.48	0.39	16.7	0.5	11.1	0.7	DFL84+LD86
HD149757	0.32	0.56	17.8	0.9	23.2	0.7	DFL84+LD86
HD152236(1)	0.67	0.38	7.8	1.0	9.9	0.4	GDB92+LD86
HD152236(2)	-.–	-.–	11.6	1.0	4.7	0.5	GDB92+LD86
HD154445	0.42	0.51	16.	8.	17.	8.	-
HD183143	1.28	0.41	36.	6.	57	6.	-
HD183143(1)	1.28	0.41	10.8	2.2	23.3	1.1	GDB92
					25.	1.	HM89
HD183143(2)	-.–	-.–	19.9	1.3	26.5	0.6	GDB92
					28.	1.	HM89
HD190603	0.72	0.04	12.2	2.8	33.2	2.8	-
HD193322	0.41	0.12	<	7.	28.	7.	-
			12.	6.	22.	6.	-
HD198478	0.54	0.23	19.	2.0	37.	2.0	-
			18.	3.	30.	3.	-
HD199579	0.37	0.71	19.	3.	8.	3.	-
HD206165	0.47	0.56	17.7	1.2	12.4	1.2	-
			18.	-	14.	-	CD79
HD207198	0.59	0.66	28.7	2.4	15.6	2.4	-
			20.	4.	18.	4.	-
			26.	-	11.	-	CD79
HD209339	0.36	0.24	5.0	2.8	8.8	2.8	-
BD+60 497	0.89	0.72	42.4	14.	32.3	14.	-

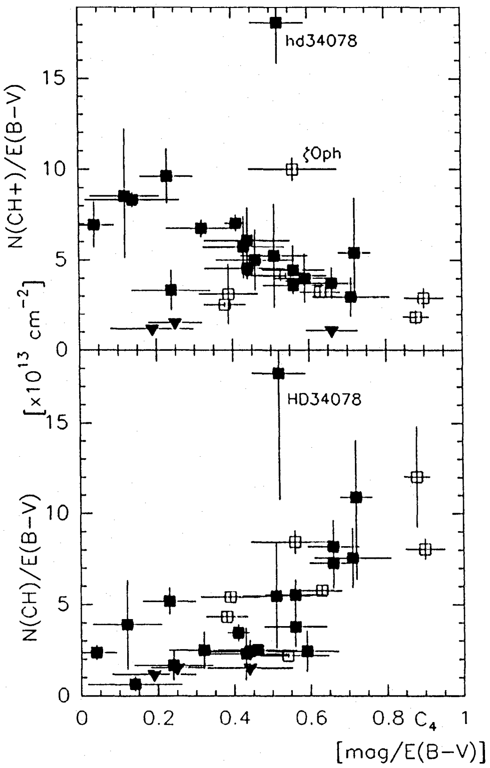

Fig. 2. CH and CH^+ abundances as a function of c_4. Triangles: upper limits. Open symbols: literature data.

suggestion by Hong & Greenberg (1980) that small bare silicate grains are the carrier of the FUV non-linear rise, because such grains are not likely confined to the H_2 medium but will be present in the diffuse atomic gas too. The same argument applies to small amorphous carbon grains (Duley 1984, Mathis & Whiffen 1989), except that hydrogenation may change the absorption properties (see below). Neutral Polycyclic Aromatic Hydrocarbons (PAHs) may be responsible for the FUV non-linear rise. PAHs have been proposed by Leger & Puget (1984) to explain the "unidentified" infrared emission bands. The PAHs should have a clear signature in the extinction curve (Leger et al. 1989), because about 35 % of all the energy absorbed by interstellar dust is emitted in the mid infrared. PAHs do have a rather sharp onset of absorption at 0.178 μm (Leger et al. 1989) and a continuous rise until below 0.0925 μm, as observed for the FUV non-linear rise (Snow et al. 1990). The ionisation potential of neutral PAHs is typically 7 eV (Leach 1986, 1987) and the absorption is thought to be due to ionising transitions.

Variations in the strength of the FUV non-linear rise probably do not reflect variations in abundance of the carrier, but physical or chemical alteration. The FUV non-linear rise behaves more erratic than other components of the extinction curve (e.f. Cardelli et al. 1988, 1989). And although on a small scale strong abundance variations in the interstellar medium have been infered from mid infrared observations (Boulanger et al. 1990), no correlation has been established between FUV non-linear rise extinction and mid infrared excess emission (Leene & Cox 1987; Hackwell et al. 1991).

Hydrogenation of small amorphous carbon grains affect local and medium range order in the grains, which affects the absorption properties. The argument is that tetrahedral (diamond like) sp^3 σ bonds tend to absorb at somewhat longer wavelength than trigonal (graphite like) sp^2 σ bonds (Robertson 1986). Hydrogenation induces tetrahedral bonding. The balance between hydrogenation and dehydrogenation may be pushed towards the former in the weak radiation field environment of the H_2 medium. An objection to this hypothesis could be that the shape of the absorption does not remain constant.

Apart from a chemical alteration mechanism as described above, which might apply to PAHs too, we propose an explanation in which variations in the ionisation fraction of big molecules are responsible for variations in the FUV non-linear rise. Since the ionisation threshold from single to double ionisation of PAHs is close to the Lyman limit (12.7-15 eV; Leach 1986, 1987) we do not expect ionized PAHs to show an onset of absorption below 10 eV like for neutral PAHs. The FUV non-linear rise in this hypothesis indicates the ionisation fraction of PAHs. In the H_2 medium the UV field is weak, which will result in a lower ionisation fraction and therefore in a stronger FUV non-linear rise. In reflection nebulae the PAH ionisation fraction can rise to 100%. The two extreme cases with low FUV non-linear rise mentioned in the introduction, HD190603 and HD30614, indeed are such reflection nebulae. However, not all known reflection nebulae have a low FUV non-linear rise. It is possible that H_2 rich matter located further away from the exciting star contributes to the extinction curve. The ionisation fraction of the diffuse medium is currently estimated at 10% (Verstraete et al. 1991). The hypothesis suggests an ionisation fraction of about 45%, because in the diffuse medium the FUV non-linear rise peaks at about $c_4 = 0.50$ while the strongest values are of order 0.90.

4.2. CH^+.

The abundance of CH^+ is less well understood. Elitzur & Watson (1978, 1980) proposed that CH^+ is formed in hot postshock gas by the endothermic reaction: $C^+ + H_2 - > CH^+ + H -$ 0.39eV. Lambert & Danks (1986) found that the CH^+ abundance correlates with H_2 in rotationally excited states. The warm H_2 molecules are thought to be tracers of such warm postshock gas and not directly responsible for the CH^+ formation.

If shock excitation is important we would have expected, but did not find, a correlation between CH^+ and the linear rise. The linear rise is proportional to the fraction of small grains relative to big classical grains in the line of sight, and this fraction should be affected by shocks (Seab & Shull 1987).

Some other possible mechanisms for the formation of high CH^+ abundances are discussed by Duley et al. (1991). A.o. they considered the formation of CH^+ from the photoionisation of small molecular fragments that are formed by the disruption of organic grains or grain mantles. However, the maximum abundances calculated from this mechanism are an order of magnitude less than found in our lines of sight. Furthermore, both CH and CH^+ are expected to be formed.

5. Conclusions.

The correlation with CH abundance is the first evidence for a correlation of the FUV non-linear rise with any parameter in the line of sight normalised to unit reddening. The result emphasizes the significance of decomposing the FUV rise in the extinction curve into a linear and a non-linear part. Because CH is closely related to the presence of molecular hydrogen, we conclude that the carrier of the FUV non-linear rise is confined to the medium containing molecular hydrogen. The absence of a correlation between the CH^+ abundance and linear rise is an argument against shock induced formation of CH^+.

In passing we note that the relationship between c_4 and CH column density can be used to predict FUV non-linear rise extinction from observations in the visual.

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Aiello S., Barsella B., Chlewicki G., Greenberg J.M., Patriarchi P., Perinotto M., 1988, A & AS **73**, 195 Boulanger F., Falgarone E., Puget J.L., Helou G., 1990, ApJ **364**, 136
Brzozowski J., Bunker P., Elander N., Erman, P., 1976, ApJ **207**, 414
Cardelli J.A., Wallerstein G., 1986, ApJ **302**, 492 (CW86)
Cardelli J.A., Clayton G.C., Mathis J.S., 1988, ApJ **329**, L33
Cardelli J.A., Clayton G.C., Mathis J.S., 1989, ApJ. **345**, 245
Chaffee, F.H., Dunham T., 1979, ApJ **233**, 568 (CD79)
Clayton G.C., Anderson C.M., Magalhaes A.M., et al., 1992, ApJ 385, L53
Crutcher R.M., Chu Y.-H., 1985, ApJ **290**, 251 (CC85)
Danks A.C., Federman S.R., Lambert D.L., 1984, A& A **130**, 62 (DFL84)
van Dishoeck E.F., 1988, in *Rate coefficients in Astrochemistry*, T.J. Millar and D.A. Williams (eds.), p. 49.
van Dishoeck E.F., Black J.H., 1988, ApJ **334**, 771
van Dishoeck E.F., Black J.H., 1989, ApJ **340**, 273 (DF89)
Duley W.W., 1984, ApJ **287**, 694
Duley W.W., Hartquist T.W., Sternberg A., Wagenblast R., Williams D.A., 1991, MNRAS, in press
Elitzur M., Watson W.D., 1978, ApJ 222, L141
Elitzur M., Watson W.D., 1980, ApJ 236, 172
Federman S.R., 1982, ApJ **257**, 125 (F82)
Fitzpatrick E.L., Massa D., 1988, ApJ **328**, 734
Fitzpatrick E.L., Massa D., 1990, ApJS **72**, 163
Greenberg J.M., Chlewicki G., 1983, ApJ **272**, 563
Gredel R., Dishoeck E.F., Black J.H., 1992, ApJ, in prep. (GDB92)
Hackwell J.A., Hecht J.H., Tapia M., 1991, ApJ **375**, 163
Hawkins I., Meyer D.M.,1989, ApJ **338**, 888
Hong S.S., Greenberg J.M., 1980, A& A, **88**, 194
Jenniskens P., 1992, in preparation for A& A
Joseph C.L., Snow T.P., Seab C.G., 1989, ApJ 340, 314
Lambert D.L., Danks A., 1986, ApJ **303**, 401 (LD86)
Leach S., 1986, J. of Electron Spectr. and Rel. Phen. 41,427
Leach S., 1987, in *Polycyclic Aromatic Hydrocarbons and Astrophysics*, Leger, d'Hendecourt and Boccara eds., p. 99
Leene A., Cox., P., 1987, A& A **174**, L1
Leger A., Puget J.L., 1984, A& A **137**, L5
Leger A., Verstraete L., D'Hendecourt L., Défourneau D., Dutuit O., Schmidt W., Lauer J.C., 1989, in *Interstellar Dust*, IAU Symp. 135, 173
Mathis J.S., Whiffen G., 1989, ApJ **341**, 808
Robertson J., 1986, Adv. Phys. 35, 317
Seab C.G., Shull J.M., 1983, ApJ **275**, 652
Snow T.P., Allen M.M., Polidam R.S., 1990, Ap.J. **359**, L23
Verstraete L., Leger A., d'Hendecourt L., Dutuit O., Defourneau D.,1990, A& A **237**, 436
Witt A.N., 1989, in *Interstellar Dust*, IAU Symp. 135, L.J. Allamandola and A.G.G.M. Tielens eds., p. 87

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