

# A search for interstellar anthracene toward the Perseus anomalous microwave emission region

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## ABSTRACT

We report the discovery of a new broad interstellar (or circumstellar) band at  $7088.8 \pm 2.0$  Å coincident to within the measurement uncertainties with the strongest band of the anthracene cation ( $C_{14}H_{10}^+$ ) as measured in gas-phase laboratory spectroscopy at low temperatures (Sukhorukov et al. 2004). The band is detected in the line of sight of star Cernis 52, a likely member of the very young star cluster IC 348, and is probably associated with cold absorbing material in an intervening molecular cloud of the Perseus star forming region where various experiments have recently detected anomalous microwave emission. From the measured intensity and available oscillator strength we find a column density of  $N_{an^+} = 1.1(\pm 0.4) \times 10^{13} \text{ cm}^{-2}$  implying that  $\sim 0.008$  % of the carbon in the cloud could be in the form of  $C_{14}H_{10}^+$ . A similar abundance has been recently claimed for the naphthalene cation (Iglesias-Groth et al. 2008) in this cloud. This is the first location outside the Solar System where specific PAHs are identified. We report observations of interstellar lines of CH and  $CH^+$  that support a rather high column density for these species and for molecular hydrogen. The strength ratio of the two prominent diffuse interstellar bands at 5780 and 5797 Å suggests the presence of a “zeta” type cloud in the line of sight (consistent with steep far-UV extinction and high molecular content). The presence of PAH cations and other related hydrogenated carbon molecules which are likely to occur in this type of clouds reinforce the suggestion that electric dipole radiation from fast spinning PAHs is responsible of the anomalous microwave emission detected toward Perseus.

**Key words:** ISM:molecules—ISM:lines and bands—ISM:abundances

## 1 INTRODUCTION

Several regions in the Perseus molecular complex display a strong continuum microwave emission in the frequency range 10–60 GHz that is correlated with dust thermal emission (Watson et al. 2005, Tibbs et al. 2010). The spectral dependence of this emission cannot be explained by synchrotron, free-free or thermal dust radiation processes and represents one of the best known examples of the so-called anomalous microwave emission (Kogut et al. 1996, Leitch et al. 1997, de Oliveira et al. 1999, 2002). This kind of microwave emission is also detected in other molecular clouds (Casassus et al. 2006) and there is increasing statistical evidence supporting its existence at high Galactic latitudes (Hildebrandt et

al. 2007). Draine and Lazarian (1998) suggested a possible explanation for this emission based on electric dipole radiation from rapidly spinning carbon based molecules (see also Iglesias-Groth 2005, 2006). Polycyclic aromatic hydrocarbons (PAHs) proposed as the sources of interstellar mid-infrared emission (Puget & Léger 1989, Allamandola, Tielens & Barker 1989) and diffuse interstellar bands (Puget & Léger 1989, Allamandola, Tielens & Barker 1989) are also potential carriers for the anomalous microwave emission. It is likely that anomalous microwave emission surveys reveal interstellar regions of enhanced PAH abundance and therefore further studies of these regions may facilitate the identification of individual PAHs. Recent progress in the laboratory measurements of optical and near infrared bands of the most simple PAHs and their cations under conditions

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resembling the interstellar medium is a key step to this aim (e.g. Salama 2008).

Here, we report results on a search for interstellar bands in the line of sight of the maximum anomalous microwave emission detected toward the Perseus clouds (Tibbs et al. 2010). We obtained high resolution optical spectroscopy of Cernis 52 (BD+31° 640), a reddened star ( $E(B-V)=0.9$ , Cernis 1993) located in this line of sight at a distance of 240 pc where most of the dust extinction is in the Perseus OB2 dark cloud complex. This is the brightest hot star that we could identify as a suitable background object to study the interstellar absorptions in the intervening cloud. Very recently, evidence was reported for absorption bands of the naphthalene cation  $C_{10}H_8^+$  in the line of sight of this star (Iglesias-Groth et al. 2008). A detailed chemical composition study of this star has been published by González Hernández et al. (2009). We report now evidence in this line of sight for the next PAH in terms of complexity, the anthracene molecule which is composed of three aromatic rings. Laboratory spectroscopy of the anthracene cation ( $C_{14}H_{10}^+$ ) obtained using supersonic jet-discharge cavity ring-down spectroscopy (Sukhorukov et al. 2004) to resemble the conditions of the interstellar medium has provided an accurate measurement of the strongest vibronic band for the  $D_2\leftarrow D_0$  system of this molecule. The laboratory band is measured at the wavelength of  $7085.7 \pm 1.3 \text{ \AA}$  (in standard air) with a full width at half maximum of  $\sim 47 \text{ \AA}$ . We obtained spectra of Cernis 52 and found a new broad interstellar feature with wavelength and width consistent with the measurements for the strongest optical transition of the anthracene cation. We also present new measurements of interstellar absorption lines of CH and  $CH^+$  and of the most prominent diffuse interstellar bands providing insight on the physical and chemical processes in the intervening medium.

## 2 OBSERVATIONS

We report spectroscopy of Cernis 52 obtained with: a) the ISIS spectrograph (grating R1200B and R1200R for the blue and red arm, respectively) at the 4.2 m William Herschel Telescope (WHT), at the Roque de los Muchachos Observatory (La Palma, Spain) on December 2007 and December 2008; b) the High Resolution Spectrograph (HRS) of the 9.2 m Hobby-Eberly Telescope at McDonald Observatory (Texas, USA) on several nights during 2008.

Comparison stars were observed with the same instruments on the same nights for correction of telluric lines and control of the instrumental response. All the spectra were reduced using IRAF, wavelength calibrated with less than  $20 \text{ m\AA}$  rms error, and individual spectra were co-added after correction for telluric lines. The adopted slit width for ISIS (1.00 arcsec) led to a spectral resolution of 0.8 and 0.6  $\text{\AA}$  for the blue and red arm of ISIS, respectively. The fiber used to feed HRS led to a spectral resolution of 0.25  $\text{\AA}$  in the spectral regions of interest. The zero-point of the adopted wavelength scale was set by assigning the laboratory wavelength to the KI 7698.974  $\text{\AA}$  interstellar absorption line. We plot in Fig. 1 one of the spectra of Cernis 52 obtained at the WHT. This spectrum was extracted using the IRAF routine “apsun” after bias and flatfield correction of the original spectral image. We show the spectrum with no normaliza-

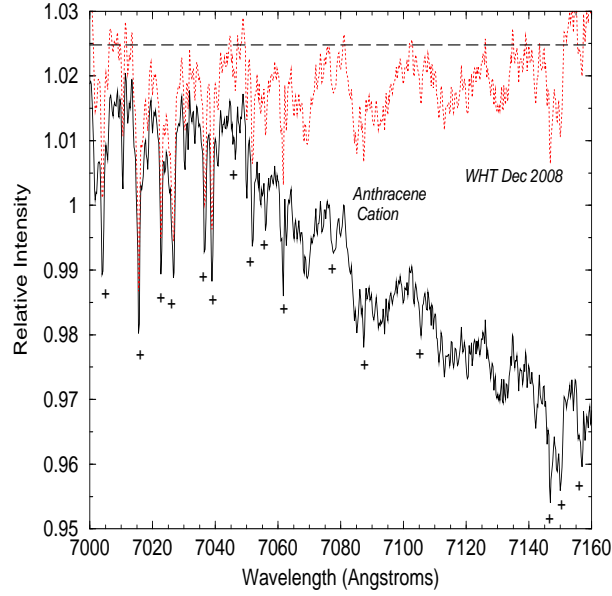
tion applied, only division by a constant and we also show the result of normalization using a low order polynomial fit. We note the smooth behaviour of the continuum and the presence of several broad absorption features and narrow telluric lines. The continuum correction does not affect these features. The WHT spectra help to define the continuum regions used for normalization of the echelle spectra obtained at HET.

The Cernis 52 spectra from both telescopes were corrected for telluric line contamination and possible instrumental effects dividing each individual spectrum (15 were recorded at HET) by the almost featureless spectrum of a much brighter, hot and fast rotating star in a nearby line of sight observed with the same instrument configuration. After this correction, individual spectra were normalized using a polynomial fit to the continuum regions and then combined to improve S/N. The final WHT and HET spectra are plotted at the top of Fig. 2 (red and blue solid lines, respectively). We remark the good agreement between the WHT and HET spectra (both with  $S/N \geq 300$  per pixel). These two spectra contain stellar photospheric features as well as bands associated with circumstellar or diffuse interstellar material in the line of sight (Iglesias-Groth et al. 2008, González Hernández et al. 2009). Cernis 52 is embedded in a cloud responsible for significant visible extinction ( $A_V \sim 3$ ) and the presence of absorption bands caused by the intervening interstellar material were therefore expected.

## 3 RESULTS AND DISCUSSION

In both spectra of Cernis 52 plotted in Fig. 2 we note the presence of a broad absorption in the range 7075-7105  $\text{\AA}$ . This is the range where absorption from the most intense band of the anthracene cation is expected. As we can see there is no similar absorption feature in the spectrum of the nearby hot star HD 23180 (Cernis 67, also known as o Per) plotted at the bottom. This star is located in Perseus close but outside the region of anomalous microwave emission. It was observed with the same instruments and with similar signal to noise ratio to Cernis 52 at both telescopes. The HD 23180 and the Cernis 52 spectra were divided by the same spectra of fast rotating stars to correct for telluric absorptions. The rather flat spectra of HD 23180 indicate that the broad absorption feature in the range 7075-7105  $\text{\AA}$  found in Cernis 52 is not an artefact introduced by the instrument or the reduction procedure. In Fig. 2 we can see the absence of broad absorptions in the spectrum of the A0V star HIP 91262 taken from the database by Allende-Prieto et al. (2004). The very narrow absorptions are telluric lines. The most significant photospheric absorption in this star is located in the range 7110-7120  $\text{\AA}$  where we also see absorption in the spectrum of Cernis 52. This is mostly caused by photospheric C I lines.

In what follows we show in more detail that the broad absorption in the range 7075-7105  $\text{\AA}$  does not originate in the photosphere of Cernis 52. We computed a synthetic spectrum of Cernis 52 using the atmospheric parameters and metallicity derived for this star by González Hernández et al. (2009). We adopted  $T_{eff} = 8350 \text{ K}$ ,  $\log(g/cm s^{-2}) = 4.2$  and  $[Fe/H] = -0.01$ . The synthetic spectrum was broadened to match the rotational velocity of the star ( $v \sin i = 65$



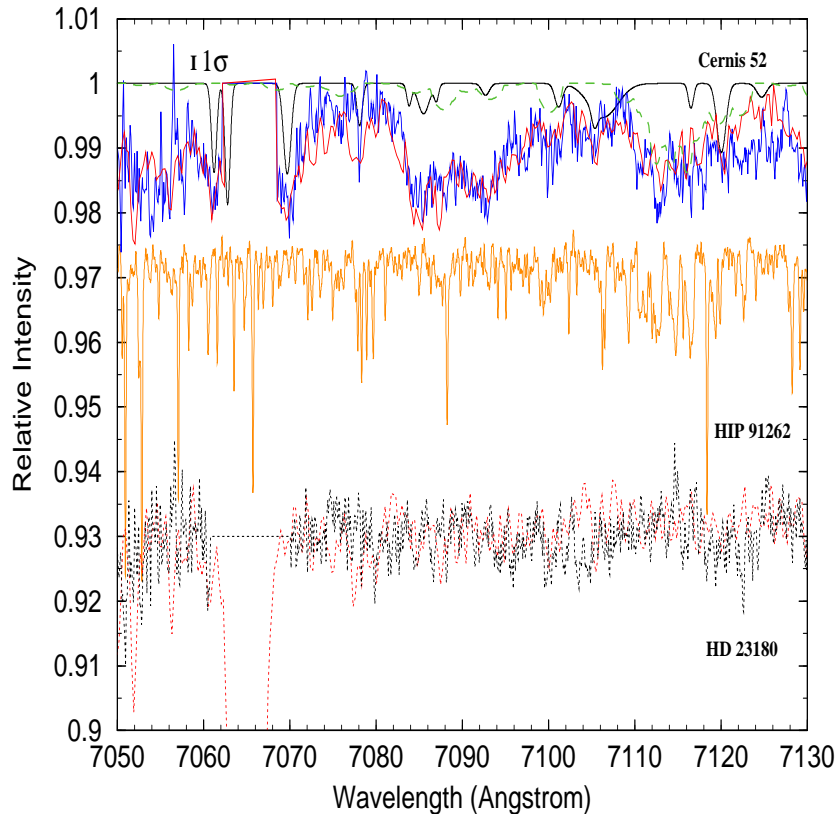
**Figure 1.** Spectrum of Cernis 52 obtained at WHT with ISIS (grating R1200R) on December 2008 before (solid black line) and after (red dotted line) normalization of the continuum. The strongest telluric lines are marked. The dashed line indicates the location of the continuum.

km/s). In González Hernández et al. evidence is reported for veiling of the photospheric spectrum, they find that almost half of the total observed flux at  $5180 \text{ \AA}$  is contributed by the photosphere of Cernis 52. We also find that the synthetic spectrum has to be veiled by an amount comparable to the flux in the continuum in order to match the photospheric features in the  $7110\text{-}7120 \text{ \AA}$  region. The veiled synthetic spectrum is plotted at the top of Fig. 2 (dashed green line) where we can see there are only very weak photospheric absorptions in the range  $7050\text{-}7110 \text{ \AA}$  which cannot explain the broad feature detected in the spectrum.

As an additional check, we compared our synthetic spectra with stellar spectra available in the compilation by Allende-Prieto et al. (2004) and verified that the photospheric features of stars with spectral type similar to Cernis 52 were properly reproduced. To illustrate this, we plot in Fig. 3 the synthetic spectrum computed for Cernis 52 and compare it with the spectrum of the A3 V star HIP 57632 (corrected for telluric lines) and broadened to the rotational velocity of Cernis 52. The reference star shows no significant photospheric absorptions in the  $7075\text{-}7105 \text{ \AA}$  range. The main photospheric absorption is the C I blend at  $7110\text{-}7120 \text{ \AA}$  which is reasonably well reproduced in the computed spectrum. We trust our spectral synthesis can reproduce the observed features in the spectra of stars similar to Cernis 52 and therefore conclude that photospheric lines cannot explain the broad absorption detected in the range  $7075\text{-}7105 \text{ \AA}$ . We find other possible broad bands in Cernis 52 at  $7050$  and  $7133 \text{ \AA}$  which are not present in the reference stars and cannot be ascribed to known photospheric or interstellar features. The TiO  $\gamma$  system has bandheads at  $7054$ ,  $7088$  and  $7125 \text{ \AA}$  but the atmospheric temperatures of both components of Cernis 52 are much higher than required for the formation of atmospheric TiO molecules and therefore cannot provide an explanation. The potential contribution to these absorptions of circumstellar or protoplanetary disk

material at much cooler temperatures cannot be ruled out neither proved at present and should be further investigated.

In Fig. 2 we also overplot a synthetic spectrum of DIBs computed adopting wavelengths, widths and strengths from a comprehensive compilation in spectra of the stars HD 204827 and HD 183143 (Hobbs et al. 2008, 2009). These stars display extinctions  $E(B-V)$  of 1.11 and 1.27, respectively, slightly higher than Cernis 52 and provide a valuable reference for the strength of the DIBs in our target. The assumption of a gaussian profile was reasonable, in particular given the relatively modest resolution of our spectra, for most of the DIBs in the wavelength range of interest. For DIBs in common among these two works we adopted the equivalent widths by Hobbs et al. (2009) which are of slightly higher quality but also correspond to a higher extinction. Very few DIBs were present only in one of the two reference stellar spectra. We can identify in the spectrum of Cernis 52 absorption features coincident with previously known DIBs located at  $7069.68$ ,  $7078.07$ ,  $7083\text{-}87$ ,  $7092.67$  and  $7106.31 \text{ \AA}$ . For these DIBs we measure equivalent widths of 7, 5, 10, 6 and  $\sim 28 \text{ m\AA}$ , respectively (with errors of order 10 %) which seem to be weaker in Cernis 52 than in the reference stars. We convolved the synthetic DIB spectrum to account for the resolving power of our observed spectra. Then, we scaled the DIB spectrum to provide a reasonable match to the DIBs in Cernis 52 that were located outside the region of the anthracene. In practice we establish the scaling factor from the ratios of equivalent widths for several DIBs adjacent to the anthracene region. We find that the equivalent widths of the DIBs in our spectra compare well in strength with those in HD 204827, while a reduction of  $\sim 30\%$  is required for the DIB spectrum provided by HD 183143. The synthetic DIB spectrum with this factor applied is plotted at the top of Fig. 2. We can see that the DIB spectrum reproduces reasonably well several absorptions in our spectra of Cernis 52, in particular the stronger DIBs at

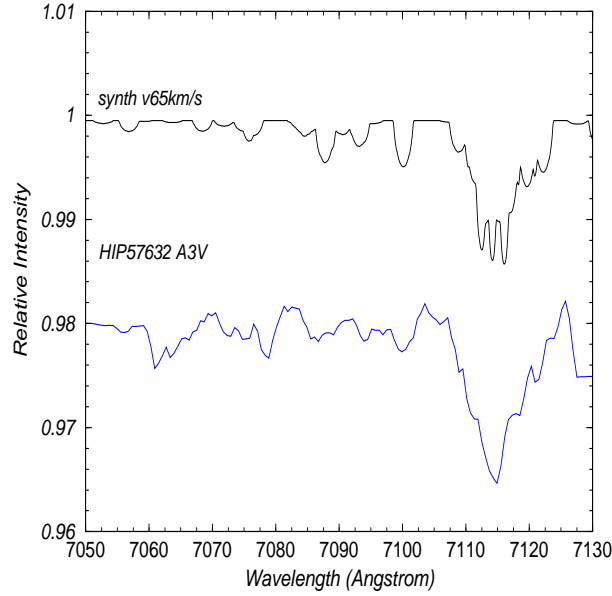


**Figure 2.** Top. Final spectra of Cernis 52 (WHT: red line; HET: blue line) showing two independent detections of the new 7088.8 Å band ascribed to the anthracene cation.  $1\sigma$  error bars are indicated. Both spectra have been corrected for telluric lines using rapidly rotating hot stars observed with the same instrumental configuration. Telluric absorptions were divided out except in the range 7060-7070 Å where a He line present (see spectrum at the bottom) prevents this correction. The uncorrected spectral region has been set at unity. A photospheric spectrum (dashed green line) computed for the stellar parameters of Cernis 52 (see text for details) and a DIB synthetic spectrum (solid thin black line) based on data from Hobbs et al. (2008, 2009) are overplotted. Middle. Spectrum of the comparison AO-type star HIP 91262 (thin red line) from Allende-Prieto et al. (2004). The narrow absorptions indicate the location of telluric lines which were largely corrected for Cernis 52. Bottom. Spectra of the reference hot star HD 23180 (WHT: red line; HET: dotted black line) observed with the same instrumentation than Cernis 52. The HET spectrum was divided by the same fast rotator used for Cernis 52. No division was applied to the WHT data in order to show the He 7065 Å absorption and the strength of telluric lines.

7061, 7063, 7070, and 7120 Å. It is also clear that the DIB spectrum cannot explain the broad feature in the 7075-7105 Å range. We conclude that this feature in the spectrum of Cernis 52 cannot be of photospheric origin since it is at least 10 times broader and much stronger than photospheric lines and cannot be explained by known DIBs which are 10 times narrower and much weaker in this spectral range. To our knowledge, no such broad band has been reported in spectra of similar stars, so we suggest that it could be associated with molecular material of circumstellar or interstellar origin.

In order to better quantify the shape and strength of a potential anthracene cation feature, we have applied corrections for both the photospheric bands and the DIBs present in the spectra. First, we removed the photospheric lines from the spectra of Cernis 52 by dividing by the synthetic photospheric spectrum of Fig. 2. Then, the resulting spectrum was divided by either the synthetic DIB spectrum of Fig. 2 or by the publicly available “average” spectrum of stars of comparable extinction to Cernis 52 (Galazutdinov et al. 2000). These corrections were applied to the spectra of Cernis 52 obtained at both telescopes. The results obtained with each

of the two DIB reference spectra are plotted in Fig. 4 where we can see that independent from the telescope (WHT or HET) and from the DIB reference spectrum used for correction (the synthetic spectrum based on data by Hobbs et al. or the Galazutdinov et al. “average” spectrum) we obtain as a result a broad band remarkably close in wavelength and width to the laboratory measurements of the strongest band of the anthracene cation. Spectra “b” and “c” allow us to compare the use of a “synthetic” DIB spectrum versus a real one. The latter may describe more properly the profile of the bands but may also introduce photospheric contamination from the hot reference star. As we can see, using one approach or the other does not make a significant difference for the shape and strength of the band we are interested. Apparent minor differences in the resulting spectra can be attributed to uncertainties in the scaling and differential behaviour of DIBs with  $E(B-V)$  and to the presence of small atmospheric features in the hot stars used to outline these DIBs. We caution that the “average spectrum” used as divisor can introduce features which are difficult to trace. It is unfortunate that the blue wing of our band is affected by a He line present in hot stars (see HD 23180 spectra in Fig. 2)



**Figure 3.** Top: Synthetic spectrum computed for the stellar parameters of Cernis 52. Bottom: Spectrum of the star HIP 57632 (A3 V) from Allende-Prieto et al. (2004) box-car smoothed to match the rotational velocity of Cernis 52. Telluric lines are corrected.

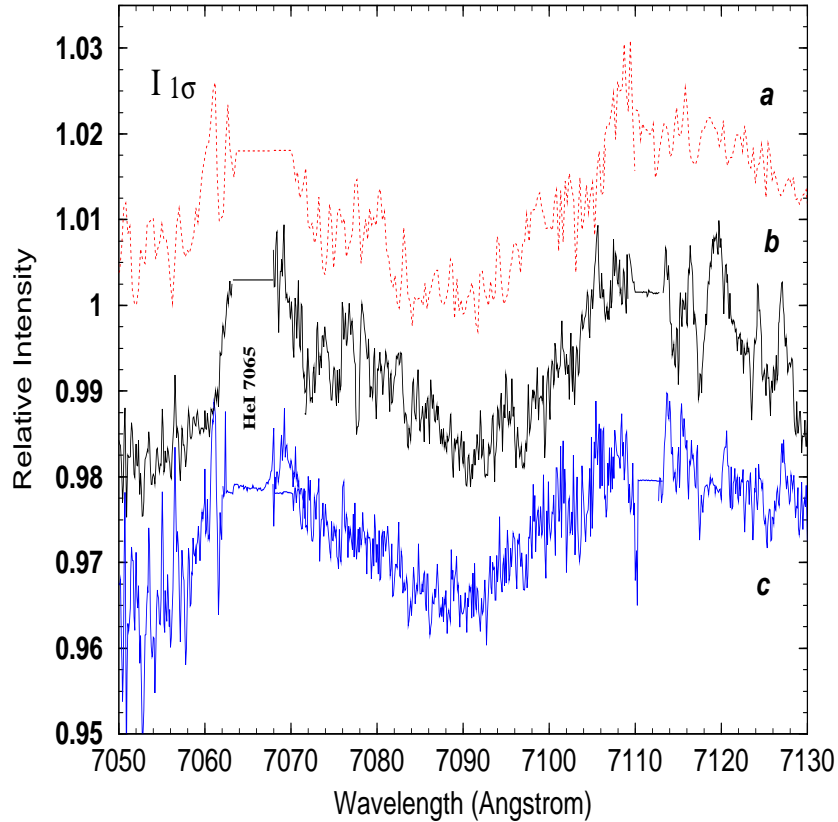
and certainly in the "average reference spectrum" limiting our ability to obtain suitable corrections at a wavelength bluer than 7070 Å. This region is also closer to the edge of the order in the HET echelle data where the S/N decreases quickly.

In summary, we find in each of the three spectra plotted in Fig. 4 a broad band with a maximum depth of about 1.5% of the continuum, and a central wavelength close to 7088 Å. The differences between these spectra give an idea of the uncertainties involved in the measurement of this band which is traced in the spectra of both telescopes by more than 40 resolution elements at  $3\sigma$  from the continuum, leading to a very solid overall detection. In Fig. 5 we plot overlaid the three spectra of the previous figure. The combined WHT(a) and HET (c) spectrum can be fitted using a Lorentzian of FWHM of  $40 \pm 5$  Å centred at 7088.8 Å. The equivalent width of the interstellar band was measured integrating the combined spectrum and resulted  $W = 600 \pm 200$  mÅ where the error takes into account the differences in width and strength of the bands resulting from the various corrections applied and is largely dominated by the uncertainty in the location of the continuum.

The characteristics of the observed 7088 Å band agree reasonably well with the laboratory measurements (Sukhorukov et al. 2004) for the strongest band of the anthracene cation which give a central wavelength of  $7085.7 \pm 1.3$  Å and a FWHM of 47 Å. The FWHM measured by Sukhorukov et al. in their direct absorption cavity ring-down spectroscopy seems to be larger than the observed value of the interstellar band, but this may well be the result of differences between the conditions of their experiment and the conditions of the cations in the interstellar medium towards Perseus. The study of the thermal dust emission at millimeter wavelengths indicate temperatures of order 19 K in the region causing the anomalous microwave emission (Watson et al. 2005, Tibbs et al. 2010). The laboratory band of the anthracene cation was measured when the source temperature

was raised to 205 °C. According to Sukhorukov et al., the absorption profile of the anthracene cation depends on the density and this is a function of the temperature. In fact at temperatures lower than 120°C the vapor pressure was too low for these authors to observe the absorption. They concluded that in their experimental setup the anthracene cations may not experience enough collisions to cool down the rotational and vibrational degrees of freedom and therefore that the widths of laboratory bands are likely to be larger than those of interstellar bands. It is interesting to note that with their experimental setup Sukhorukov et al. obtain larger widths by a factor 1.5 for the bands of naphthalene cation than Biennier et al. (2003). The width of the interstellar band of the naphthalene cation in this line of sight is claimed by Iglesias-Groth et al. (2008) to agree well with the laboratory measurements by Biennier et al. (2003). This also supports that the interstellar band of the anthracene cation is narrower than the current laboratory band measurements.

The 7088 Å band is not only one of the strongest bands from the cation's ground state but the sole band for which gas-phase spectroscopy has provided an accurate wavelength. Matrix isolation spectroscopy (MIS) (Szczepek et al. 1993) has provided wavelengths for other bands but these measurements differ from wavelengths for free cations by amounts that are too uncertain to provide a basis for secure identification in an astronomical spectrum. For example, the matrix isolation spectroscopy wavelength for the 7088 Å band is 22 Å to the red of the gas phase measurement. The 7088 Å band is the 0-0 vibrational band of the  $1^2A_u \leftarrow X^2B-3g$  transition. The 0-0 band for  $2^2A_u \leftarrow X^2B_{3g}$  is at 3520 Å from MIS with an f-value probably similar to that of 7088 Å (Niederalt et al. 1995). Then,  $3^2A_u \leftarrow X^2B_{3g}$  is at 3140 Å from MIS with a predicted f-value several times that of the 7088 Å band. With accurate wavelengths from gas-phase spectroscopy, it will be of interest to search for these two bands. Another sequence of transi-



**Figure 4.** HET and WHT spectra of Cernis 52 corrected for the photospheric and DIB contributions. The red solid line shows the results obtained for the WHT spectrum (a) corrected using the “average” DIB spectrum of Galazutdinov et al. (2000). The black solid line shows the HET data (b) corrected using the DIB spectrum in Fig.2. The blue solid line shows the results for the HET data (c) corrected using the “average” DIB spectrum. All the spectra have been normalized in the continuum to unity and shifted vertically for clarity.

tions involves the sequence of  ${}^2B_{1u}$  states. The initial band to  ${}^1{}^2B_{1u}$  is at 6146 Å from MIS but with an  $f$ -value a fraction of the 7088 Å band’s  $f$ -value it is highly unlikely to be detectable in our spectrum even if the wavelength were known accurately. The next member of the series to  ${}^2{}^2B_{1u}$  is at 4279 Å from MIS with an  $f$ -value comparable to that for 7088 Å. The 0-0 band at 7088 Å (and the 0-0 bands of other electronic transitions) will be accompanied by a band to the lowest excited vibrational state of the  ${}^1{}^2B_{1u}$  level. For the 7088 Å band, this band will be about 190 Å to the blue according to the vibrational frequency suggested by MIS and quantum calculations (Szczepanski et al. 1993). With the  $f$ -value suggested by MIS, the band in our spectrum would have a depth of only about 0.2%.

In short, attribution of the new interstellar band at 7088 Å to the anthracene cation is potentially testable when accurate laboratory wavelengths are provided for other electronic transitions. Here we will assume that the 7088.8 Å band is due to anthracene cation molecules in the cloud that causes the extinction in Cernis 52. Adopting for the oscillator strength of the transition at 7088 Å a value of  $f=0.13$  (average of those reported by Hirata et al. 1993, Niederalt et al. 1995, Ruiterkamp et al. 2005) and using 600 mÅ as measured equivalent width of the band, we derive a column density of  $N_{an+} = 1.1 \times 10^{13} \text{ cm}^{-2}$  (with an uncertainty of 40%). This is very similar to the column density estimated for the naphthalene cation in the same line of sight (Iglesias-Groth

et al. 2008). Assuming a ratio  $C/H = 3.7 \times 10^{-4}$  and hydrogen column density per unit interstellar reddening from Bohlin et al. (1978) we obtain  $N(H) = 5.3 \times 10^{21} \text{ cm}^{-2}$  and derive that  $\sim 0.008\%$  of the total carbon in the intervening cloud could be in the form of anthracene cations.

With these low abundances, electric dipole emission of these molecules can explain only a small fraction of the anomalous microwave emission detected in the line of sight, mainly at frequencies higher than 50 GHz (Iglesias-Groth et al. 2008). It is possible that neutral PAHs are more abundant than cations and that larger PAHs exist in the cloud and contribute to the anomalous emission at frequencies in the range 10-50 GHz.

### 3.1 The intervening cloud

We note the existence of a reflection nebula in the line of sight of Cernis 52, clearly seen as extended optical emission in images of the Digital Sky Survey. The radial velocity of the star and of the DIBs in the spectrum agree within 1 km/s, the uncertainty in the measurement, thus this star which is a likely member of the IC 348 cluster (González Hernández et al. 2009) could be embedded in the cloud. Observations of the K I 7698.974 Å line, show only one velocity component, indicative of possibly a single cloud structure in this line of sight (see Fig. 6). Extended mid-infrared emission is also seen in archive images obtained with IRAC

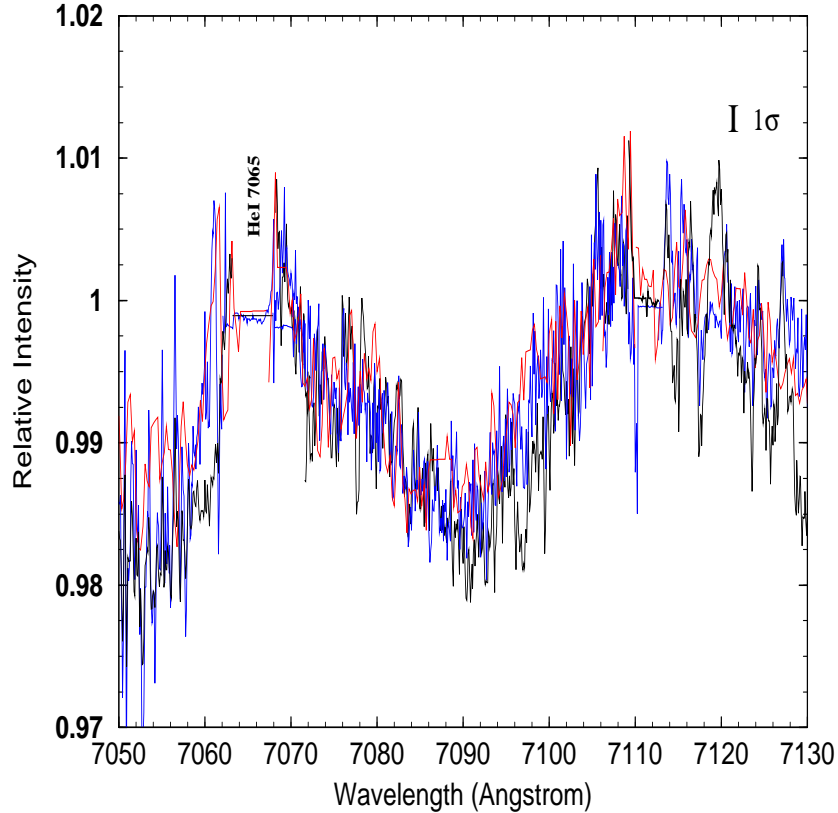


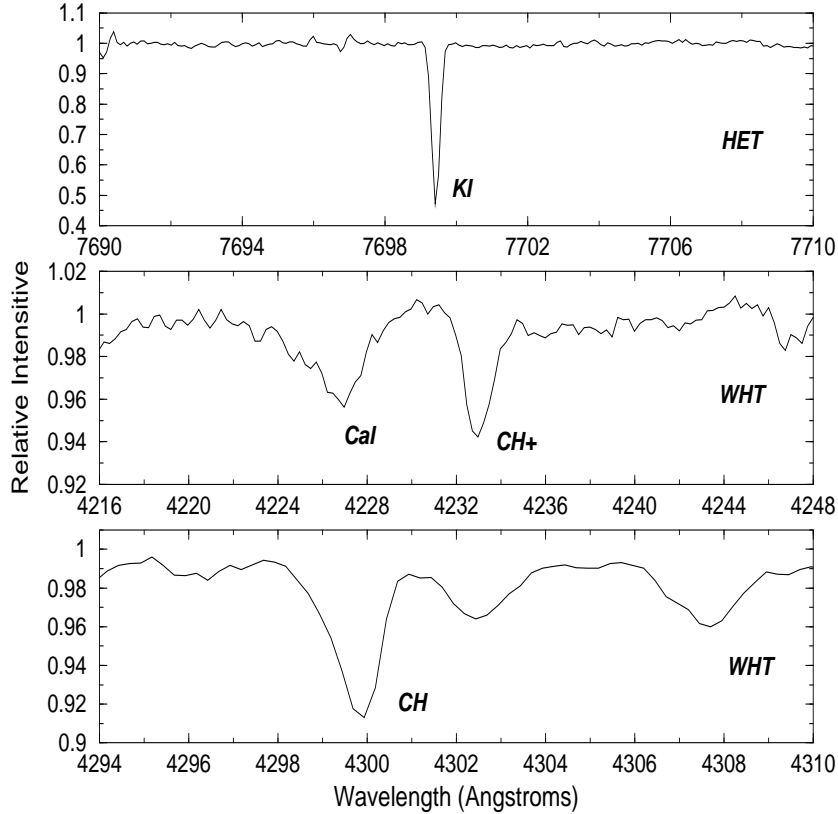
Figure 5. Overlay of the HET and WHT spectra in the previous figure.

onboard the Spitzer satellite in the wavelength range 3 to 9  $\mu\text{m}$ . This emission is much stronger at the 5.8 and 8.0  $\mu\text{m}$  bands than at 3.6 and 4.5  $\mu\text{m}$ . We attribute the high emission at long wavelengths to C-C and C-H stretching and bending modes of PAHs at 6.2 and 7.7+8.6  $\mu\text{m}$ , and note that the weaker emission of the expected 3.3  $\mu\text{m}$  band could be due to a significant ionization of PAHs (Iglesias-Groth et al. in preparation).

In order to provide some insight on the physical and chemical conditions and in particular on the PAH charge state distribution of the cloud in the line of sight of Cernis 52, we have measured the interstellar lines of CH and  $\text{CH}^+$  at 4300.313  $\text{\AA}$  and 4232.548  $\text{\AA}$  available in our ISIS blue arm spectra taken in December 2007 and 2008 at WHT. These lines have been used in the literature to study a large variety of interstellar (diffuse, translucent, dense) clouds including several with extinction similar to that of the cloud under consideration here (see e.g. de Vries and van Dishoeck 1988; Crane, Lambert and Sheffer 1995). We find the blue wing profile of the CH line slightly asymmetric possibly due to contamination by a stellar photospheric feature. We used a synthetic stellar spectrum to take into account potential contributions of photospheric lines from Cernis 52 and correct for them. The  $\text{CH}^+$  line appears consistent with a single Gaussian profile. We measure equivalent widths of  $W=66\pm 8$  m $\text{\AA}$  and  $W=70\pm 8$  m $\text{\AA}$  for the CH and  $\text{CH}^+$  lines, respectively. These errors take into account the uncertainty in the measurement of the equivalent widths which is of order 5-6 m $\text{\AA}$  and the uncertainty associated with the correction of photospheric lines which is driven by the uncertainties in the

stellar parameters of Cernis 52 (González Hernández et al. 2009). We estimate uncertainties of order 20% for the predicted equivalent widths of the photospheric lines which in both cases are minor contributors to the absorption at the wavelength of the CH features. This implies additional uncertainties of order 4-5 m $\text{\AA}$  which combined quadratically with the previous error lead to the final quoted 8 m $\text{\AA}$  error. The two sets of WHT observations taken with a time baseline of one year gave consistent strengths and the observed wavelengths of each set of lines agreed within 50 m $\text{\AA}$  (4 km  $\text{s}^{-1}$ ). Both CH and  $\text{CH}^+$  lines show heliocentric velocities consistent within the uncertainties with that of the KI line observed at higher dispersion with HET. The oscillator strength of the CH transition is  $f=0.00506$  (Larsson and Siegbahn 1983, Brzozowski et al. 1976). In order to account for a slightly saturated line, the column density will be obtained from curves of growth with  $b=1.5$  km  $\text{s}^{-1}$ . The measured equivalent width implies then  $N(\text{CH})=(2\pm 0.2) \times 10^{14}$   $\text{cm}^{-2}$ . Similarly, and adopting the oscillator strength of the  $\text{CH}^+$  line from Larsson and Siegbahn (1983b) we obtain  $N(\text{CH}^+)=(2\pm 0.2) \times 10^{14}$   $\text{cm}^{-2}$ . Both species display rather high column densities.

The average HI column density derived from the LAB map (Karberla et al. 2005) in the direction of Cernis 52 is  $N(\text{HI})=1.2 \times 10^{21}$   $\text{cm}^{-2}$ . Using the relationships between CH and  $\text{H}_2$  in Danks, Federman and Lambert (1984) and Mattila (1986) we obtain from our  $N(\text{CH})$  value two independent estimates of the column density for molecular hydrogen. The average value results  $N(\text{H}_2)=6.3 \times 10^{21}$   $\text{cm}^{-2}$ . The total column density of hydrogen then is  $N(\text{H})=N(\text{HI})+$



**Figure 6.** Top: HET spectrum of Cernis 52 in the region of the KI line at 7699 Å. Middle and bottom: WHT spectra of Cernis 52 in the region of the A-X (0-0) bands of CH<sup>+</sup> and CH.

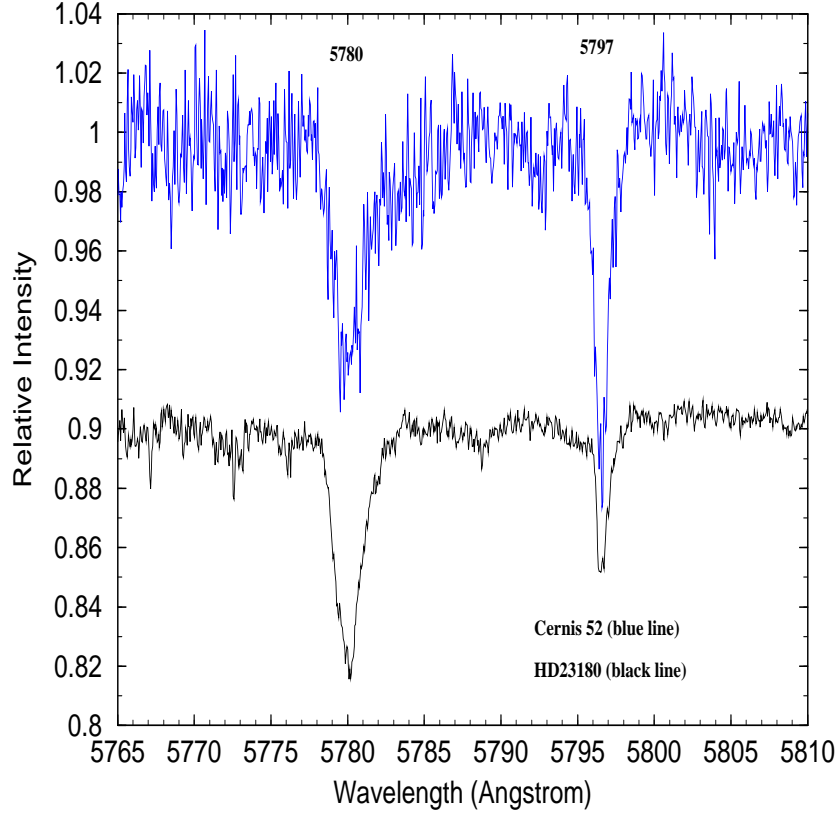
$2N(\text{H}_2)=13.8 \times 10^{21} \text{ cm}^{-2}$ . This is a factor 2.6 larger than the value derived from the excess color  $E(\text{B-V})$  of Cernis 52. Possibly indicating that the  $A_V$  and  $E(\text{B-V})$  relation is steepened in this cloud. It seems that we deal with a cloud that causes a total visual extinction significantly higher than in typical diffuse interstellar clouds and comparable or even higher than translucent molecular clouds (see e.g. van Dishoeck and Black 1989). Models for clouds of similar characteristics can be found for example in Ruiterkamp et al. (2005) who include a detailed treatment of the PAH charge state distribution. It is apparent from their Fig. 3 that PAHs with a low number of carbon atoms are mostly expected in a neutral stage, in particular anthracene and naphthalene cations charge fractions are expected of order 10% while the neutral species could be as abundant as 65% and anions would provide the remaining fraction. Changes in the hydrogen density (in the recombination rate) or in the intensity of the UV radiation field (in the ionization rate) do not affect drastically this result for this type of cloud.

The derived column densities of CH and CH<sup>+</sup> in the cloud toward Cernis 52 are significantly higher than in any other CH surveys of diffuse interstellar clouds, including examples of clouds of higher extinction. The high abundance of these species and also of molecular hydrogen is an indication of a potentially rich chemistry that may convert atoms into organic molecules (see e.g. Millar 2004 for the reaction networks involved) at the observed column densities toward Cernis 52. In less rich clouds previously surveyed in the literature the column density of anthracene and naphthalene

may be considerably lower and their bands weaker. This could explain why the anthracene and naphthalene cation bands discussed here and in Iglesias-Groth et al. (2008) have escaped detection in other lines of sight. Another reason for the lack of previous detections of the anthracene cation is that DIB surveys are frequently conducted using high dispersion echelle spectrographs which have difficulties to detect weak very broad features due to continuum correction.

We have examined the behaviour of the major DIBs in the various spectra of Cernis 52 available to us (including those obtained by Iglesias-Groth et al. 2008 at the 3.6m Telescopio Nazionale Galileo (TNG) and the 2.7m at Mc Donald Observatory) with the aim to identify any possible anomalous behaviour which could be related to the dust properties of the cloud. Here, we present results for the two major diffuse bands at 5780 and 5797 Å. These two diffuse bands discovered by Heger (1922) show strength ratios that vary with the shape of the extinction curve (Krelowski et al. 1987). High molecular abundances - as for CH in the line of sight of Cernis 52 - appear in interstellar clouds characterized by a broad UV extinction bump (2175 Å), steep far-UV extinction and low 5780/5797 diffuse band intensity ratio. Such clouds are called “zeta” type clouds (Krelowski and Sneden, 1995) and present strong molecular features in their spectra. Examples of these clouds are found towards stars like ζ Per and HD 23180 in Perseus where the 5780/5797 ratios (equivalent widths of 5780 to 5797) range between 1 and 2 (Krelowski et al. 1996). Such values are much lower than those found by these authors in the so-called “sigma”





**Figure 7.** Spectra of Cernis 52 (blue line) and HD 23180 (black line) in the region of the DIBs at 5780 and 5797 Å.

clouds which present strikingly different extinction curves (see for a discussion Krelowski, Sneden and Hiltgen, 1995). In Fig. 7, we plot our McDonald spectra of Cernis 52 in the spectral range of these DIBs in comparison with HD 23180. It is remarkable the similar strength of the 5780 DIB in both stars while the 5797 DIB is clearly stronger in Cernis 52. This leads to a smaller 5780/5797 ratio than in HD 23180 and fully supports the classification of the intervening cloud towards Cernis 52 as of “zeta” type. To our knowledge the UV extinction curve in this line of sight is unknown but based in the behaviour of the 5780/5797 DIBs we may expect a steep far-UV extinction. It is well established that some diffuse bands like the 5797 Å correlate positively with the overall slope of the extinction curve while others like the 5780 Å show negative correlation (Megier, Krelowski and Weselak 2005). A positive correlation with the overall slope probably indicates an anticorrelation with the UV irradiation and the carrier of the 5797 Å band may benefit from shielding. If this is the case shielding is more effective in the Cernis 52 cloud than in the “zeta” cloud towards the star HD 23180 (also in Perseus but in a region without significant anomalous microwave emission). The band at 5780 Å, known to be more resistant to strong UV fields than the 5797 DIB, shows similar strength in both clouds. The DIB at 5850 Å is known to follow closely the behaviour of the 5797 DIB and correlates with the overall slope of extinction (Megier et al. 2005). We find that the strength of this DIB in Cernis 52 is also a factor two higher than in HD 23180. The extinction in the UV reduces the flux of the UV

radiation that is believed to ionize or destroy the carriers of these bands.

We have scrutinized our spectra to search for bands of other PAHs with reliable gas phase measurements (see Salama 2008) and confirm in our new data the naphthalene band at 6707 Å previously found by Iglesias-Groth et al. (2008). At various wavelengths we find marginal evidence for other broad bands that may correspond to PAH cations, and for relatively narrow absorptions that could be associated to carbon chains and carbon rings but confirmation may require higher quality measurements. The upper limits we can impose on the column densities of these other PAHs do not bring at this stage sufficient information to establish the reaction networks in the cloud. A comprehensive analysis of the DIBs in the line of sight of Cernis 52 may also provide additional information on the UV radiation field in the intervening cloud but this is beyond the scope of this paper and will be subject of a dedicated more comprehensive work.

#### 4 CONCLUSIONS

We report the discovery of a new broad band at  $7088.8 \pm 2$  Å in the spectrum of Cernis 52 with wavelength and width consistent with gas phase measurements of the strongest band of the anthracene cation. This is the only band of the anthracene cation with a wavelength measured from gas phase spectroscopy. We measure an equivalent width

of  $W=600\pm 200$  mÅ. Assigning the observed band to this cation, we infer a column density of  $N_{an^+} = 1.1(\pm 0.4) \times 10^{13}$  cm $^{-2}$ . This value is very close to previous estimates for the column density of naphthalene cations in the same line of sight  $N_{naph^+} = 1.0(\pm 0.6) \times 10^{13}$  cm $^{-2}$  (Iglesias-Groth et al. 2008). It appears that the intervening cloud contains the same amount of cations of anthracene and naphthalene. We also detect bands of CH and CH $^+$  at 4300.313 and 4232.548 Å from which we obtain column densities for these species of  $2(\pm 0.2) \times 10^{14}$  cm $^{-2}$  and infer a rather high column density for molecular hydrogen  $N(H_2) = 6.3 \times 10^{21}$  cm $^{-2}$ . Observations of the KI line are consistent with the existence of a single cloud in the line of sight. Measurements of the major DIBs at 5780 and 5797 Å clearly indicate that the intervening cloud is of “zeta” type, probably with a steep far-UV extinction.

The cloud toward Cernis 52 is likely to be responsible for the anomalous microwave emission reported in this line of sight. The presence of PAHs in a region of strong anomalous microwave emission adds support to the hypothesis that electric dipole radiation by these type of molecules is responsible for the excess emission detected in the 10-50 GHz range. The abundance of PAHs was taken as a free-parameter in models attempting to explain this anomalous microwave emission (Draine and Lazarian 1998). The abundances derived for naphthalene and anthracene cations provide additional constraints for these models.

Laboratory experiments at low temperatures (15 K) have shown that UV radiation on a mixture of naphthalene, ammonia and H $_2$ O ice leads to the formation of a large variety of amino acids (Chen et al. 2008). In the line of sight of Cernis 52 there is evidence for ammonia (Rosolowsky et al. 2008) with a column density quite similar to what we find for the most simple PAHs. The likely presence of H $_2$ O ices combined with the UV radiation from Cernis 52 could make this region in Perseus a potential factory for amino acids. The detection of specific PAHs in the molecular cloud towards Cernis 52 may help to identify a possible path for biogenic compounds from the chemistry of clouds (where new stars form) to the pre-biotic molecules detected in protoplanetary disks. Further studies in this remarkable region have the potential to reveal a very rich interstellar prebiotic chemistry.

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