obtained by summing up the contributions of clouds at different distances from the ionizing source. This is justified since the emission in LINERs is spatially resolved and known to cover hundreds of parsecs in diameter. Because most spectrophotometric data were obtained through circular or square apertures, the spectrum likely represents a mixture of high and low ionization lines emitted at different radii, an effect taken into account in the present models. The filling factor (or number) of ionized clouds has been assumed to decrease exponentially with distance from a centrally located ionizing source; the cloud density was fixed at 400 cm^{-3}. It was assumed that the clouds were individually optically thick but because the observed filling factor is very small, the covering factor of (intervening) clouds was always considered negligible. This method, described in more detail in ref. 10, is obviously applicable to the gas-limited geometries thought to prevail in LINERs (cf. Keel (1)) rather than to radiation-limited geometries. Adopting a spherical distribution of clouds, the resulting models will hereafter be labelled "integrated". They are characterized by an effective U_e which is simply a weighted average of the ionization parameter. Fiducial marks along the continuous lines indicate successive values of Log U_e with a step of −0.3 between integer values (e.g. −3.0, −3.3, −3.6 . . .). In order to show the relative position of "non-integrated" models, calculations at values of Log U of −3.0 and −3.6 are represented by asterisks (left and right respectively). It is clear from Fig. 1 that integrated or discrete U sequences overlap quite well but with a systematic shift in the value of U between the two sequences.

The two dotted curves in Figs. 1 and 2 show the effect of varying the abundances (the asterisks are actually part of these curves) and the fiducial marks from left to right correspond to successive increases by factor two of all elements' abundances (except He) relative to hydrogen (from 1/8 to 8 times the reference set). The reference set of abundances was chosen to reflect the observed radial increase in metallicity in spirals as determined by supernova remnants' and H II regions' abundance analysis. Its main characteristics (by number) are as follows: He/H = 0.10, O/H = 0.001, O/N = 3.0 and O/S = 45 (for comparison, solar abundances would give: 0.085, 0.0008, 8 and 41 respectively). A mild depletion of the refractory elements C, Mg, Si has been allowed for.

In Figs. 1 and 2, the index $\alpha = -2.0$ appears the best choice for the objects as a whole and is adopted. In support of this we note that the observed upper envelope in Fig. 1 is probably a consequence of a moderately steep ionizing spectrum since, as shown by the dotted lines, varying abundances only populate a region below the maximum in O III/Hβ that occurs around solar values. It must be emphasized that with the flatter indices used in previous work, this turnaround in the [O III] intensity would only occur at very high metallicity so that with reasonable abundances [O III] is then simply proportional to metallicity. This could explain how previous calculations favoured anomalous abundances of 0.3 solar since otherwise the majority of objects were found to be below the locus of their solar abundances' models.

As for the metallicity of the nuclear interstellar medium, the two dotted lines in Fig. 1 show the filled-symbol objects to be consistent with abundances that are roughly solar with variations in these probably confined to between solar and three times solar. This range of variations is smaller than in Keel (8) who derived an (N + O) abundance index that ranges from 0.88 to 4.7 times solar. Concerning nitrogen, the N II/O III ratio of Fig. 2 scales almost linearly with the N/O abundance ratio and, therefore, the filled-symbol objects are considered consistent with variations in N/O not exceeding a factor three. It is to be noted that the determined average value (<N/O> = 1/3) is definitely above solar. Since many factors, such as observational errors, differences in the ionizing spectrum or reduced optical thickness, could account for part of the scatter in the figures, it is plausible that abundances are actually even more uniform than suggested here.

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Absorption Lines of Interstellar C_2 and CN Molecules

E.F. van Dishoeck, Sterrewacht Leiden, the Netherlands, and
J.H. Black, Steward Observatory, Tucson, USA

Introduction

A considerable part of our knowledge about interstellar clouds stems from observations of their constituent molecules. In particular, diffuse interstellar clouds—i.e. clouds which do not entirely obscure the light from the stars which lie behind them—may be conveniently studied by the resonance absorption lines of the molecules superposed on the spectra of background stars. Already more than 40 years ago, the first three interstellar molecules CH, CH^+ and CN were discovered in this way at visible wavelengths. However, the next discovery of a molecule in the visible, C_2 (Souza and Lutz, 1977, *Astrophysical Journal* **216,** L 49), had to wait for the advent of high-resolution spectrographs with detectors that are very sensitive in the red part of the spectrum. At present, one of the best instruments in the world for these observations is the ESO Coudé Echelle Spectrometer (CES). The instrument has been described previously in the *Messenger* by Enard (**17,** 32 and **26,** 22), and its excellent performance has been demonstrated by the multitude of enthusiastic papers on CES observations in the last few issues of the *Messenger* (see e.g. Ferlet, **30,** 9; Andersen et al., **34,** 26).

Observations of molecules are not only interesting because they provide the abundance of the species in the interstellar

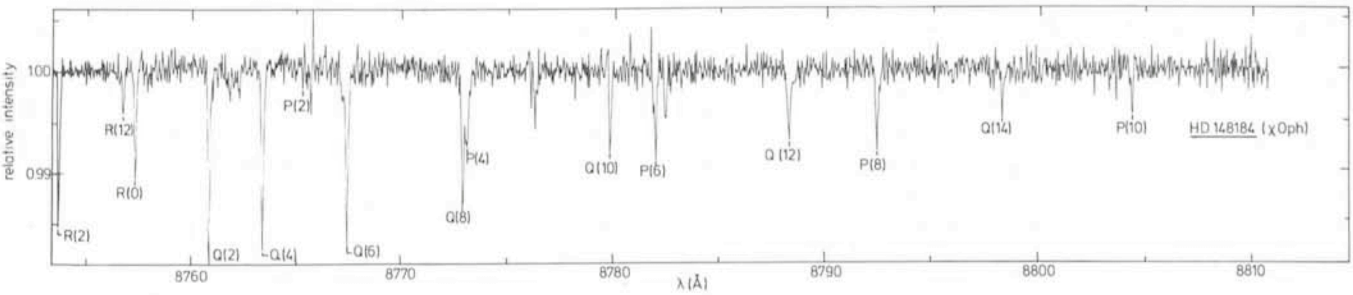

Fig. 1: *The spectrum of χ Oph in the region of the (2,0) Phillips band of C_2, obtained with the ESO CES fed by the CAT telescope. In addition to the lines shown in this figure, the R(4)-R(10) lines also appear shortward of the R(2) line. They are superposed on a broad stellar feature and are therefore not shown. Note that the strongest line absorbs less than 2 % of the starlight at this resolution.*

medium: they also may give valuable information on the physical conditions (such as temperature and density) prevailing in the cloud. C_2 is a particularly interesting molecule in this respect because it is a symmetric species with no permanent dipole moment. As a result, its excited rotational levels have long radiative lifetimes and may be highly populated in interstellar clouds by collisional and radiative processes. In contrast, molecules with a permanent dipole moment (such as CH and CN) are mainly in their ground rotational state.

What is Observed?

Fig. 1 shows part of the spectrum of the star χ Oph (V = 4.4, $A_v \simeq 1$ mag) in the region of the C_2 lines around 8750 Å, obtained with the CES fed by the 1.4 m CAT telescope (van Dishoeck and de Zeeuw, 1984, *M.N.R.A.S.* **206,** 383). A total of 10 hours of integration time at a resolving power of 80,000 was needed to obtain the high signal-to-noise ratio. No fewer than seventeen interstellar C_2 lines can be identified in the spectrum! The lines originate in the various rotational levels J of the ground vibrational state v = 0 of the molecule. They end in the v = 2 vibrational level of the first excited singlet electronic state, the so-called A state, of C_2. From each level J > 0 of the lower state, three different lines can arise, namely those for which the J quantum number in the upper state differs by −1, 0 or 1; they are designated by the P, Q or R lines, respectively. Thus the notation Q (2) indicates the Q line originating from J = 2 of the lower state. Fig. 2 illustrates the energy levels of the molecule involved and several observed transitions. Note that even a line arising in J = 14 has been observed: this level has an excitation energy corresponding to a temperature of more than 500 K — i.e. much larger than the kinetic temperature in the cloud! The equivalent widths of the strongest lines, e.g. the Q(2) line, are about 2 mÅ, those of the weaker observed lines only 0.5 mÅ.

The conversion of equivalent widths into column densities is a simple task for the C_2 lines, since the lines are unsaturated so that there are no curve-of-growth effects. As Fig. 1 shows, for several J values not only the stronger Q line, but also the weaker P and R lines have been detected. Since these lines originate from a common lower level J, they should yield the same column density for that level. In this way we have an excellent independent check on the reliablility of the results.

Interpretation

The column densities N_J indicate the number of C_2 molecules in the various rotational levels J. These populations are a measure of how internal energy is distributed on average within the molecule. In microscopic terms, temperature is a measure of the rate and force with which molecules strike each other in the gas; if the gas is in equilibrium these collisions govern the distribution of internal energy within the molecules as well. In that case, the rotational level populations in C_2 might provide a sort of remote thermometer. When N_J is plotted against the excitation energy E_J of level J, however, it appears that the populations cannot be characterized by a single (rotational) temperature. For χ Oph, the lower levels give $T_{rot} \simeq$ 65 K, while for the higher levels $T_{rot} \simeq 150$ K. Both of these "internal" temperatures are higher than the kinetic temperature of the gas $T \simeq 40$ K. Thus some mechanism other than collisions with gas particles is populating the excited J levels, and the C_2 molecules are not in complete equilibrium with the gas.

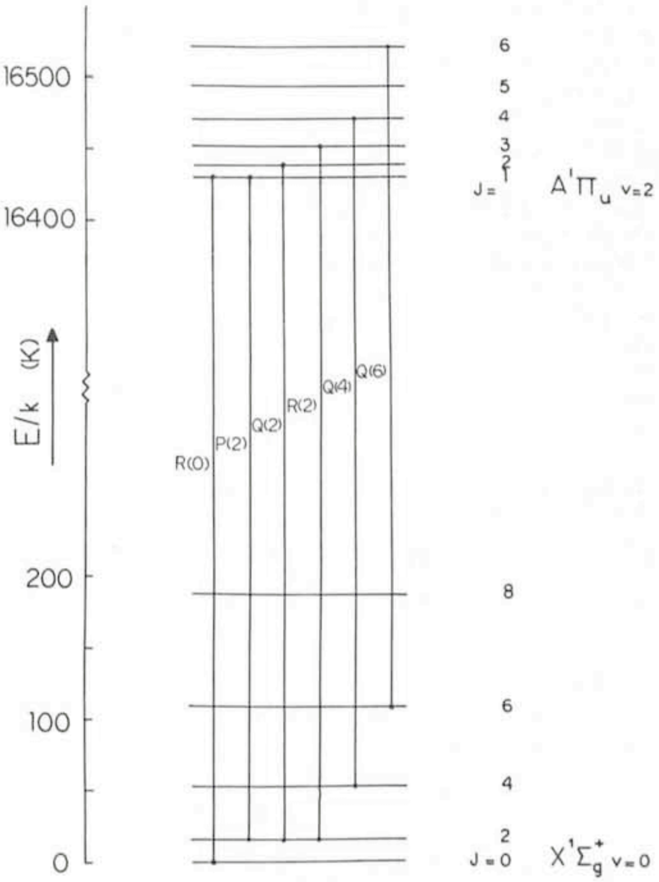

Fig. 2: *Energy level diagram of the A-X (2,0) Phillips band of C_2. Some of the observed transitions are indicated. Note that, because of symmetry considerations, only even J levels exist in the ground state of $^{12}C_2$. The energy scale has been converted to a temperature scale for convenience.*

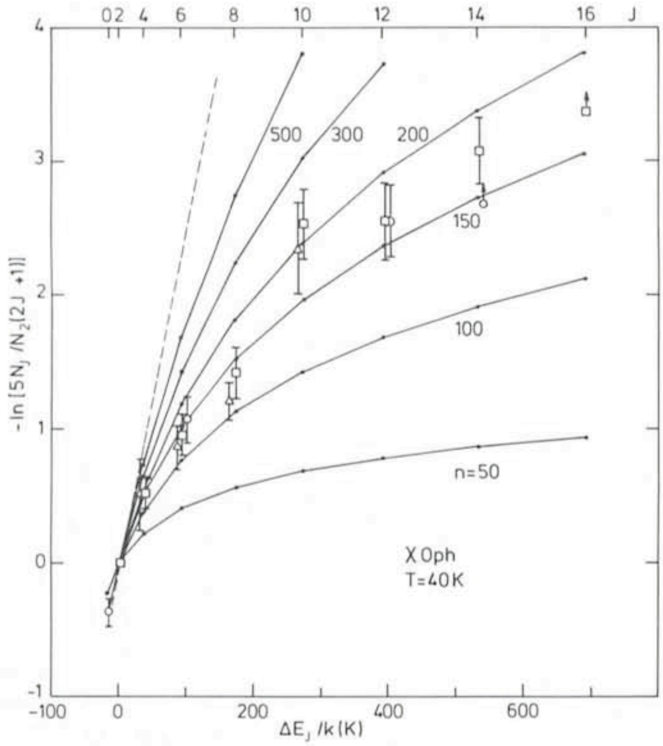

Fig. 3: *The theoretical relative rotational populations of C_2 as functions of the excitation energy (or rotational quantum number J). The solid curves were calculated for a kinetic temperature T = 40 K and several densities n (in cm^{-3}). The dashed line indicates the thermal distribution at 40 K. The observed populations for the cloud in front of χ Oph are indicated by various symbols. △: the column density N_J is obtained from the P line; □: N_J obtained from the Q line; ○: N_J obtained from the R line. Note the good agreement in general between the N_J's obtained from the different lines. Theory and observations are in harmony for T ≃ 40 K and n ≃ 160 cm^{-3}.*

How does this enhanced population arise? A radiative pumping theory has been suggested by Chaffee et al. (*Ap. J.*, 1980, **236,** 474), and developed in detail by the present authors (*Ap. J.*, 1982, **258,** 533). In this mechanism, the C_2 molecules first absorb photons from the interstellar radiation field at a high rate. The absorptions are primarily at wavelengths 8000–12000 Å with excitations into the first excited singlet electronic state, the A state. In Fig. 2, this process has been illustrated for the v = 2 vibrational level of the A state (corresponding to the observed absorption lines), but excitations may also occur into v = 0, 1, 3, etc. The molecules, however, will not stay long in the excited electronic state, but they will radiate spontaneously back into the various levels of the ground electronic state, the X state. In particular, the spontaneous emission occurs not only back into the levels from which the absorptions originated, but also into higher vibration-rotation levels of the ground state. These excited levels cannot decay subsequently through fast dipole transitions, because the C_2 molecule has no dipole moment. They may, however, cascade down into the rotational levels of the lowest vibrational state through slow quadrupole transitions and through intercombination transitions with a nearby triplet state. These radiative processes, governed by the strength of the interstellar radiation field in the (infra) red part of the spectrum, compete with the collisional (de-)excitation processes, governed by the interstellar temperature and density, in establishing the steady-state populations of the rotational levels J of the ground state. Theoretical rotational populations can thus be calculated for a given temperature, density and radiation field, provided all the molecular parameters entering the analysis (such as oscillator strengths and collisional cross sections) are well known. Unfortunately, even for a simple diatomic molecule as C_2, many of these molecular properties are still poorly determined! However, with the help of modern quantum chemical techniques at least some of the crucial parameters can be computed from first principles (see e.g. van Dishoeck, 1984, thesis Leiden).

Theory vs Observations

Fig. 3 shows the theoretical relative rotational population distribution of C_2 as a function of excitation energy $\Delta E_J/k$, for a kinetic temperature T = 40 K and several densities n (where n = n (H) + n (H_2)). Here ΔE_J is the excitation energy of level J relative to that of J = 2 (the level J = 2 is taken as the reference because its observational uncertainties are less than those for J = 0). The calculations are presented in a logarithmic form, with the statistical weights included, so that in the limit of high densities, where the population distribution becomes thermal, a straight line results. It is easily seen that for low densities, n ≃ 50–500 cm^{-3}—i.e. just the range of densities in diffuse clouds!—the population distribution is far from thermal; indeed, the radiative pumping theory correctly reproduces an enhanced population in the higher levels.

Fig. 3 includes the observed C_2 rotational populations toward χ Oph. The observations agree well with the theory for T ≃ 40 K and n ≃ 150–200 cm^{-3}. In this way, the C_2 observations may be used to extract temperatures and densities in the clouds, information which is still difficult to determine otherwise.

Observational Programme and Results

Until recently, absorption line observations of C_2 had been made in only a few directions, mainly on the northern hemisphere. Since C_2 appears to be such a useful tool for probing the physical conditions in diffuse clouds, we decided to extend the search to stars in the southern sky. For the first observations, only a few bright (V < 6) southern stars with large column densities of foreground interstellar matter (log N(H_2) > 20.5, A_v > 1 mag) were selected. The initial list contained only three stars in Ophiuchus: ζ Oph, χ Oph and ϱ Oph. Beautiful C_2 spectra, such as the one shown in Fig. 1, were readily obtained in these directions (see also Danks and Lambert, 1983, *Astronomy and Astrophysics,* **124,** 188, and an unpublished paper by Charfman and Aardvark: "We two see C_2 too!"), and the physical conditions in the clouds in front of the stars were inferred.

Detection of the C_2 (3,0) Phillips Band

The results of the C_2 analysis (T ≃ 25 K, n ≃ 200 cm^{-3}) for the well-known cloud in front of ζ Oph were of great interest since previous studies had suggested either a much higher temperature T ≃ 65 K, or a much higher density, n > 1000 cm^{-3}. In order to check the C_2 results, we have very recently performed additional observations of ζ Oph, this time not in the region of the C_2 (2,0) Phillips band around 8750 Å, but of the (3,0) band around 7720 Å (van Dishoeck and Black, in preparation). The (first) detection of interstellar C_2 at these wavelengths is shown in Fig. 4, where several C_2 lines, originating from levels up to J = 10, appear. Because of the smaller oscillator strength for the (3,0) band compared with the (2,0) band, the features are very weak, but reliable column densities can be derived from them. The results appear to be in good agreement with those obtained from the (2,0) band observations, and they strongly suggest a low temperature T ≃ 25 K for the bulk of the ζ Oph cloud.

The pattern of the stronger absorption lines in Fig. 4 belongs to molecular oxygen in the Earth's atmosphere. During the year as the Earth moves in its orbit around the Sun, its velocity relative to ζ Oph changes. Owing to the Doppler effect, this velocity produces a shift in the wavelengths at which the C_2 lines appear, relative to the positions of the stationary oxygen lines. Only at a certain time of year are most of the C_2 lines not directly obscured by oxygen lines: this effect had to be taken into account in preparing our ESO observations request. The second named author, who has a knack for making sign errors in such velocity calculations, was naturally nervous about the prediction, and was greatly relieved when C_2 lines appeared between the oxygen lines as expected.

Observations of Highly-Reddened Stars

Since the C_2 absorption lines lie in the far-red part of the spectrum where the extinction is much smaller than in the blue, they may be observed in thicker interstellar clouds than most other molecules, in particular the H_2 molecule for which only resonance lines in the UV exist. We have therefore extended our search for interstellar C_2 to fainter stars ($V \simeq 8$) with a higher reddening ($A_v \simeq 3$ mag). Such clouds with $A_v \simeq 3$ are very interesting since they are generally dense enough to permit radio observations. They would therefore bridge the gap between the classical diffuse clouds investigated only optically, and the classical dark clouds studied only with radio techniques. The C_2 searches have already been successful for the clouds in front of the stars HD 147889 ($V = 8.1$, $A_v \simeq 3$), HD 29647 ($V = 8.3$, $A_v \simeq 3$) and very recently HD 169454 ($V = 6.6$, $A_v \simeq 3$). The last two clouds appear to be quite cool, $T \simeq 15$ K with $n \simeq 350$ cm^{-3}, in agreement with radio observations. On the other hand, the C_2 data suggest that the HD 147889 cloud is warmer, $T \simeq 70$ K, than the temperature $T \simeq 40$ K, inferred from radio observations. Much remains still to be learned about such clouds.

C_2 Abundances

Apart from the physical conditions, information about the abundance of interstellar C_2 can also be extracted from the observations. For the classical diffuse clouds, such as that in front of ζ Oph, the total C_2 column density is about 2×10^{13} cm^{-2} and its abundance relative to H_2 is about 5×10^{-8}. For thicker clouds, C_2 column densities up to 10^{14} cm^{-2} are found. No comparison with H_2 column densities is possible in these clouds, since the background stars are too faint to permit UV observations of the H_2 lines.

Detection of the Red System of CN

Recent observations of the CN molecule (Federman et al., 1984, ESO preprint no. 336) suggest a very interesting relationship between the abundances of the C_2 and CN molecules. Although ion-molecule reactions are generally thought to control the formation of small interstellar molecules in diffuse clouds, a neutral-neutral reaction must be invoked to explain the observed relationship between the C_2 and CN abundances. Further observational tests of this relationship are clearly needed, especially for denser clouds. So far, all CN observations have been performed in the blue around 3874 Å. However, there also exist resonance lines of CN in the red around 7900 Å, which are more suitable for studying the denser clouds. These lines have been observed extensively in the atmospheres of cool stars and comets, but not previously in the interstellar medium. If the relationship between the C_2 and CN abundances would also hold for the denser clouds with $A_v \simeq 3$ mag, then the clouds which have large C_2 column densities should also show strong CN lines. As a test, we have performed very recently observations (van Dishoeck and Black, in preparation) around 7900 Å toward the star HD 169454, which shows strong interstellar C_2 lines. A two-hour integration produced clearly the strong $R_1(0)$ line of CN with an equivalent width of about 9 mÅ! In addition, the ${}^RQ_{21}(0)$, ${}^SR_{21}(0)$, $R_1(1)$ and ${}^RQ_{21}(1)$ lines have been detected, whereas the $Q_1(1)$ and ${}^QR_{12}(1)$ lines are lost in atmospheric features. These atmospheric absorptions are due to water vapor; in order that they be as weak as possible, it is advantageous to have a very dry observational site like La Silla (see Brand, *The Messenger* **29,** 20).

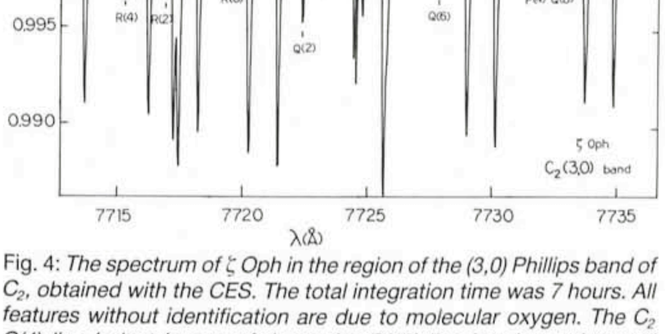

Fig. 4: *The spectrum of ζ Oph in the region of the (3,0) Phillips band of C_2, obtained with the CES. The total integration time was 7 hours. All features without identification are due to molecular oxygen. The C_2 Q(4) line is lost in one of them; the Q(10) line has been detected longward of 7735 Å.*

ESO-IRAM-Onsala Workshop on (Sub)mm Astronomy

In the context of the planned installation at La Silla of the 15 m (sub)mm telescope "SEST", a workshop will be held near Onsala from 17 to 20 June 1985. The scientific aspects will be stressed, and in particular the connection with work at other wavelengths. Further information may be obtained from Dr. P. Shaver at ESO in Garching.

This (first) observation of the red system of interstellar CN is not only interesting for the determination of the CN abundance. It may also provide an important tool for measuring the temperature of the cosmic microwave background radiation at 2.64 mm wavelength by comparing the strengths of the lines originating from $J = 0$ and 1. Because CN has a large dipole moment, the population in $J = 1$ is very small and it can only be maintained by absorption of the cosmic background radiation. This analysis of the rotational population of CN has been done previously using lines in the blue system of CN (see e.g. Meyer and Jura, 1983, *Astrophysical Journal,* **276,** L1) with the result $T_b = (2.73 \pm 0.04)$ K, in agreement with a 2.7 K blackbody spectrum. A preliminary analysis of the red system gives $T_b = (2.6 \pm 0.3)$ K. Although this result is not yet as accurate as for the blue system, it provides an independent measure of T_b. Obviously, the data may be improved upon by using longer integration times or by choosing a more suitable background star, such as HD 147889 or HD 29647.

Concluding Remark

Because the CES affords very high resolution with excellent sensitivity in the far red part of the spectrum, it is now possible to invade the domain of radio astronomers and probe the interior of molecular clouds using optical absorption lines. Because the CES is so convenient to use, it is also possible for theorists like us to masquerade as observers from time to time with some success!