

Interstellar CO in the direction of the runaway star AE Aurigae

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Summary. We report the detection of absorption by interstellar $^{12}\text{C}^{16}\text{O}$ in a high-dispersion *IUE* spectrum of AE Aur. Relative to an estimated total hydrogen column density, $\log N(\text{H} + 2\text{H}_2) \sim 21.62$, in the line-of-sight, the measured CO column density, $\log N(\text{CO}) = 14.76 \pm 0.10$, is consistent with the theoretical model of Federman *et al.* for gas-phase chemistry in low density diffuse clouds. Arguments are presented for locating the principal cloud in the direction of AE Aur close to the star.

1 Introduction

AE Aur (HD 34078) is a runaway star with a space velocity of 106 km s^{-1} (Blaauw 1961). Herbig (1958) postulated that IC405, the bright nebula around AE Aur, is the result of a chance encounter of the star with a diffuse interstellar cloud. In considering the reflection properties of the nebula he suggested that, as a consequence of the high space velocity of the star, dust grains in certain parts of the diffuse cloud have been modified by radiation from AE Aur while in other regions of the cloud there has been insufficient time for such modification to occur.

Of the 62 stars listed by Adams (1949) as having spectra that show absorption by the interstellar molecules detectable at that time, strongest absorption by CH and CH^+ occurs in the spectra of AE Aur and ζ Oph, both sight-lines also showing absorption due to interstellar CN. Conditions in the line-of-sight to AE Aur, perhaps in the vicinity of the star, are clearly conducive to the formation of these molecules and possibly others.

In view of the importance of CO for theories of molecule formation we have used high-dispersion spectra obtained with the *International Ultraviolet Explorer (IUE)* satellite in a search for interstellar absorption by this molecule in the direction of AE Aur.

2 Observations and results

AE Aur has a very low projected rotational velocity, $V \sin i \sim 5 \text{ km s}^{-1}$ and, as a consequence, the profiles of interstellar absorption lines are indistinguishable from those of weak stellar lines. To facilitate identification of the interstellar lines in the spectrum of

this star, *IUE* high-dispersion images of two other stars of similar spectral type were obtained for comparison. One of these stars, ν Ori (HD 36512), is a slow rotator with consequently a sharp-line stellar spectrum; as this star is only slightly reddened its spectrum would not be expected to show absorption due to interstellar CO. The other comparison star, ζ Oph (HD 149757) has a high velocity of rotation resulting in a smeared stellar spectrum against which the interstellar lines are easily identifiable; the spectrum of ζ Oph is known to show absorption by interstellar CO (Morton 1975). Details of the three stars and of the *IUE* images obtained from the World Data Centre are given in Table 1; a description of the *IUE* satellite has been given by Boggess *et al.* (1978).

The STARLINK programs STAK and TRAK were used to extract the spectra which were then analysed with the aid of the data reduction package known as DRP. Wavelength calibration was checked against the known radial velocities of the stars AE Aur and ν Ori and the principal component containing CO in the line-of-sight to ζ Oph (Morton 1975); for all spectra calibration proved good to within the wavelength resolution of the spectrograph, $\Delta\lambda \sim 0.2 \text{ \AA}$.

In the spectrum of ζ Oph six of the seven strongest bands of the fourth positive system ($A^1\Pi - X^1\Sigma^+$) of $^{12}\text{C}^{16}\text{O}$ are clearly seen; at $\lambda = 1544.3 \text{ \AA}$ the spectrum is very weak as a result of the broadening of the stellar C IV line and identification of the (0–0) band of CO is uncertain. Of the six bands visible in the spectrum of ζ Oph, four have distinct counterparts in the spectrum of AE Aur and the other two are detectable on large-scale plots, although they are severely blended with stellar lines as the comparison with the spectrum of ν Ori shows.

The relevant sections of the spectra of the three stars are shown in Fig. 1. In constructing this figure the known radial velocities of AE Aur and ν Ori have been used in establishing a laboratory wavelength scale for the stellar absorption features in the spectra of these stars. On this scale the positions of the interstellar lines in the spectrum of AE Aur are shifted to lower wavelengths by an amount corresponding to the radial velocity of the star; an appropriate shift has therefore been given to the observed spectrum of ζ Oph. As a result, in Fig. 1 the stellar absorption lines common to AE Aur and ν Ori are vertically aligned as are the interstellar lines common to AE Aur and ζ Oph.

Equivalent widths of the CO bands that are measurable in the spectrum of AE Aur are given in Table 2. The measurements were made at a graphics-supported terminal by interactive use of the EW routine in the DRP package, the continuum in the region of each band being fitted by eye. Repeat measurements with estimated upper and lower limits to the continuum setting gave a range of values of $W\lambda$ for each band. The best estimate of $W\lambda$ and probable limits are given in the table. In order to determine a column density of carbon monoxide we have used the observations of de Boer & Pottasch (1974) who detected two diffuse clouds of neutral sodium in the line-of-sight to AE Aur, the clouds

Table 1. Stellar data and *IUE* high-dispersion images.

Name	HD	Spectral type	$E(B-V)$	$V \text{ rad}^*$ (km s^{-1})	$V \sin i^*$ (km s^{-1})	<i>IUE</i> image	Exposure time (s)
AE Aur	34078	O9.5 V	0.52†	+59	5	SWP 3999	1499
ζ Oph	149757	O9.5 V	0.32‡	–15	379	SWP 2910	39
ν Ori	36512	B0 V	0.03‡	+17	20	SWP 3997	75

Sources:

* Hoffleit (1982); quoted radial velocities are heliocentric.

† Crawford (1975).

‡ Neckel (1967).

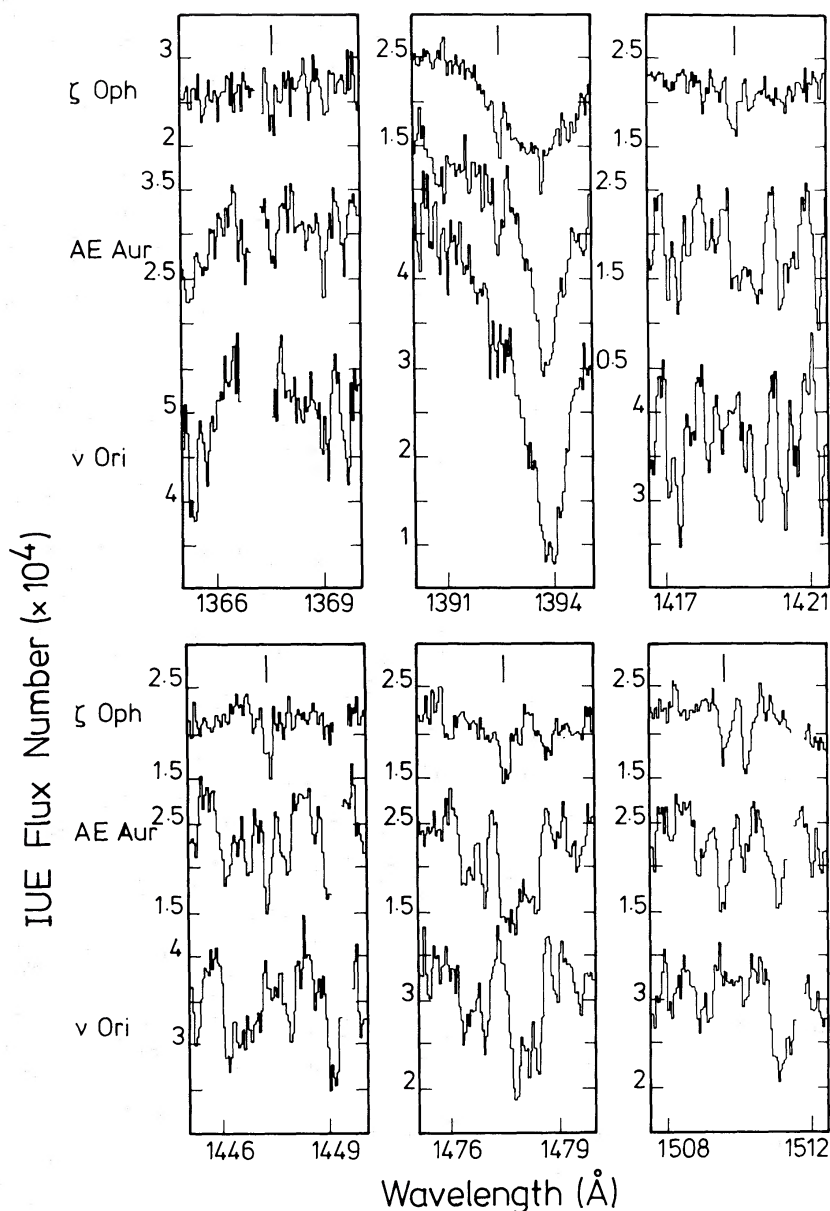


Figure 1. Sections of the spectra of ζ Oph, AE Aur and ν Ori. Bands of the fourth positive system ($A^1\Pi - X^1\Sigma^+$) of carbon monoxide in the spectrum of ζ Oph (top) are indicated by vertical lines. The extent of blending of these bands with stellar lines in the spectrum of AE Aur (middle) can be gauged by reference to the spectrum of ν Ori (bottom) in which the CO bands are absent.

having log column densities 14.0 and 13.3 and heliocentric radial velocities of 15 and 4 km s⁻¹ respectively. As these velocity components are not resolved by *IUE* and as CO and Na I are believed to coexist in diffuse clouds that have column densities of neutral sodium $N(\text{Na I}) > 10^{12} \text{ cm}^{-2}$ (Federman 1981), it is assumed that both clouds contribute towards the observed absorption by CO. It is also assumed that CO, Na I and K I have the same curve of growth in this line-of-sight; at the low temperatures, $T \leq 100 \text{ K}$, of shielded diffuse clouds the three species may be considered to have the same value of the velocity-spread parameter $b = 1.29 \times 10^4 (T/A)^{1/2} \text{ cm s}^{-1}$. Accordingly, our CO equivalent widths have been combined with the Na I data of de Boer & Pottasch (1974) and the K I observations of Chaffee & White (1982) to define an empirical curve of growth for these

Table 2. Bands of the fourth positive system ($A^1\Pi - X^1\Sigma^+$) of $^{12}\text{C}^{16}\text{O}$ measured in the spectrum of AE Aur.

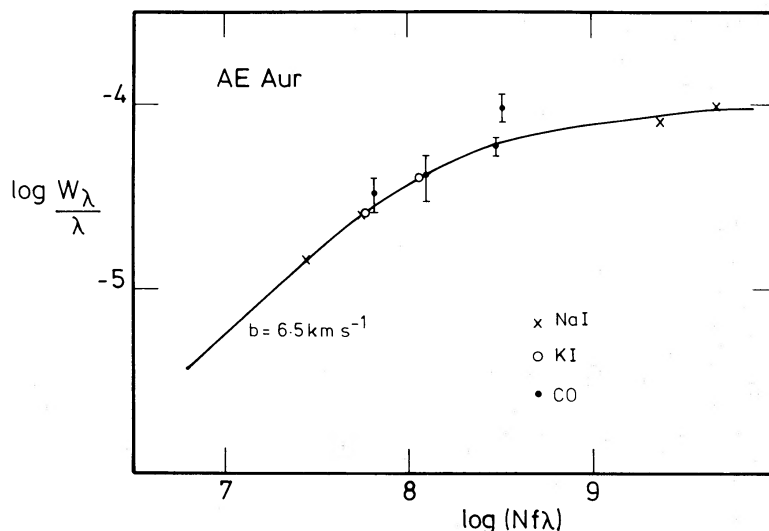
v'	v''	$\lambda^* \text{ lab } (\text{\AA})$	$\lambda \text{ obs } (\text{\AA})$	$f(v', v'')^*$	$W_\lambda \text{ (m\AA)}$
1	0	1509.74	1509.72	0.0380	145 ± 25
3	0	1447.35	1447.33	0.0360	85 ± 10
5	0	1392.52	1392.48	0.0155	58 ± 17
6	0	1367.61	1367.69	0.0085	45 ± 10

Source:

* Clavel & Flower (1980).

species. This curve of growth, shown in Fig. 2, reproduces the observed total line-of-sight column density of neutral sodium $\log N(\text{Na I}) = 14.08$. Three of the four equivalent widths of CO fit the curve reasonably well and from them we deduce a column density $\log N(\text{CO}) = 14.76 \pm 0.10$, a value that is consistent with the upper limit $\log N(\text{CO}) < 15.0$ implied by the absence of millimetre-wavelength emission from the molecule (Knapp & Jura 1976).

As the relative abundance of CO is not well established we have proceeded to obtain an estimate of the total hydrogen abundance in the same line-of-sight. In order to obtain a column density of atomic hydrogen in the direction of AE Aur, the star was observed with *IUE* in the low dispersion, small aperture mode; the resulting image, SWP 16650, was well exposed in the region of $\text{Ly}\alpha$. The STARLINK program ALAS was used to produce a series of theoretical profiles, convolved with a Gaussian instrumental profile of $\text{FWHM} = 4.2 \text{ \AA}$, for comparison with the observed $\text{Ly}\alpha$ profile. Before the profile matching procedure was executed the observed spectrum was dereddened in order to remove any distortion of the $\text{Ly}\alpha$ profile due to differential reddening across the line which is about $80 \text{ \AA}$ wide at the continuum. In considering the amount of extinction to be compensated for we became aware of an inconsistency in the published value of $E(B-V)$ for AE Aur. Photometric measurements by Crawford (1975) lead to $E(B-V) = 0.52$, a value used by Thuan (1975); other values used have been 0.76 (Knapp & Jura 1976; Chaffee & White 1982) and 0.78 (Cohen 1974). We note that the strengths of the $\lambda 4430$ (Snow, York & Welty 1977) and $\lambda 2200$ (Jamar *et al.* 1976) diffuse bands in the spectrum of AE Aur are consistent with

**Figure 2.** Empirical curve of growth for NaI, KI and CO in the direction of AE Aur.

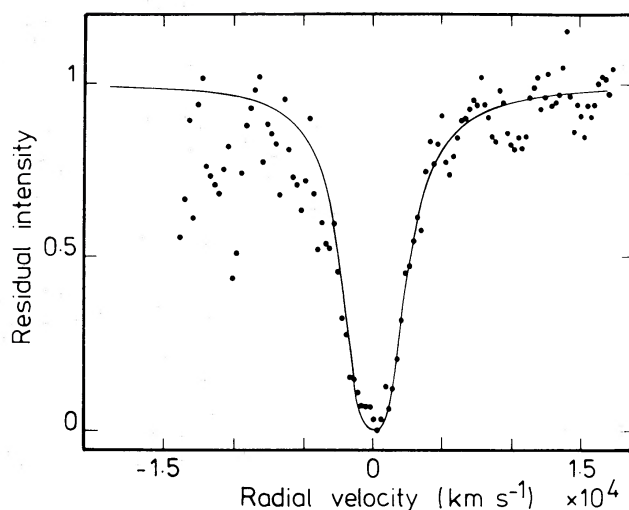


Figure 3. A predicted profile (continuous line) of $\text{Ly}\alpha$, obtained with a column density $N(\text{H I}) = 1.75 \times 10^{21} \text{ cm}^{-2}$, compared with the observed interstellar absorption line.

$E(B-V) = 0.52$. Moreover Somerville *et al.* (1982) have derived a correlation between $\log N(^{12}\text{CO})$ and $E(B-V)$ and reference to their fig. 2 shows that $E(B-V) = 0.52$ is compatible with $\log N(\text{CO}) = 14.76$ whereas, for this column density, $E(B-V) > 0.7$ is less likely. We have, therefore, used $E(B-V) = 0.52$ in dereddening the spectrum of AE Aur. The theoretical absorption line profile arising from a column density $\log N(\text{H I}) = 21.24 \pm 0.05$ gives the best match with the observed $\text{Ly}\alpha$ line and is shown in Fig. 3; in comparing the two profiles greater weight was given to the longer wavelength side of the observed line where the profile is well determined. Because of the early spectral type, O9.5, of AE Aur the stellar contribution to absorption in the $\text{Ly}\alpha$ line is assumed to be negligible.

For an estimate of the line-of-sight column density of molecular hydrogen we have used the observed relationship $N(\text{Na I}) \sim 10^{-7} N(\text{H}_2)$ (Federman 1981) to get $N(\text{H}_2) \sim 1.2 \times 10^{21} \text{ cm}^{-2}$. The total hydrogen column density is therefore estimated to be $\log N(\text{H} + 2\text{H}_2) \sim 21.62$; this is in good agreement with the value obtained from the well-known relationship between $\log N(\text{H} + 2\text{H}_2)$ and $E(B-V)$ (Bohlin, Savage & Drake 1978) which predicts for the AE Aur line-of-sight $\log N(\text{H} + 2\text{H}_2) \sim 21.9$.

3 Discussion

The abundance of CO relative to hydrogen in the sight-line to AE Aur is consistent with the theoretical prediction of Federman *et al.* (1980) for the model parameters: gas density range $70\text{--}300 \text{ cm}^{-3}$ and temperature range $30\text{--}75 \text{ K}$. Knapp & Jura (1976) were unable to detect millimetre-wavelength CO emission from the direction of AE Aur; a gas density less than 1000 cm^{-3} is inferred.

The total line-of-sight column density of neutral hydrogen obtained from $\text{Ly}\alpha$ line agrees within a factor 2 with the column density $\log N(\text{H I}) = 20.9$ derived from 21 cm observations of the $+15 \text{ km s}^{-1}$ cloud (de Boer & Pottasch 1974). This cloud also contains a substantial proportion of the neutral elements Na I and K I and the various molecules identified in the line-of-sight to AE Aur. It is important for interstellar chemistry to establish the relationship, if any, between this cloud and the star.

The mean reddening $E(B-V)$ and distance relation in this direction is $0.5 \text{ mag} \pm 0.1 \text{ kpc}^{-1}$. Since the distance of AE Aur is $\sim 500 \text{ pc}$ an excess of reddening $\Delta E(B-V) \sim 0.25$ indicates

the presence of a dust cloud close to the star, confirming Herbig's (1958) view that IC 405 contains a significant amount of dust. We note that Münch (1964) referred to the emission and reflection features of IC 405 in arguing for the formation of CH and CN in the neighbourhood of NGC 7822 which has similar features. He postulated that the molecules are formed at the boundary between an H II region and an H I region; in the case of AE Aur this boundary occurs at a distance from the star of about 23 pc, the radius of the Strömgren sphere (Elmegreen 1975). Castor, McCray & Weaver (1975) have argued that an early-type star embedded in a dust cloud would cause rapid formation of H₂ which would then be involved in ion–molecule reactions leading to a large variety of other molecules.

It is probable, therefore, that the +15 km s^{−1} cloud is associated with the diffuse cloud encountered by the runaway star and that molecules are being formed in an H I region surrounding the H II region created by the star. From the relationship $N(\text{H}_2) \sim 10^7 N(\text{Na I})$ and the density limits of the low density model the depth of this H I region is estimated to be between 1 and 5 pc.

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