ζ Ophiuchi: A stellar and interstellar Pandora's box

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The broadening of the photospheric lines in ζ Ophiuchi by very rapid rotation allows not only mapping of its surface velocities and temperature distribution, but makes the star an excellent probe for a profusion of sharp interstellar lines. Being bright, it is a good object for smaller telescopes. Apart from discovering nonradial oscillations in its atmosphere over twenty years ago and a significant temperature differential between pole and equator (the von Zeipel effect), I have recently assisted in the discovery of some 30 lines of interstellar C_3 near 405 nm – the first carbon chain to have been found in a diffuse interstellar cloud and at a much higher concentration than expected.

Keywords: hot emission-line (OBAe) stars – interstellar lines – spectral changes

1 Introduction

I should have looked more closely at the legend of Pandora's Box before invoking it. Pandora was the first woman, according to the Greeks, who was made out of earth as the god's revenge on man for obtaining fire from Prometheus. Despite being forbidden to open her Box she disobeyed thereby releasing all the ills that beset mankind, leaving only hope. Perhaps the revelations from ζ Ophiuchi would be better described as a Cornucopia, the reader can decide! ζ Ophiuchi does have one 'ill', it is single which may explain why Mirek never got around to writing a paper about it!

2 ζ Ophiuchi: the star

ζ Ophiuchi (V=$2^{\mathrm{m}}.56$, E_{B-V}=$0^{\mathrm{m}}.30$, $v \sin i$ ~400 km s^{-1}) is classified as a O9.5 V and has long been known to be rotating at close to break-up velocity. Its lines have a classical elliptical profile caused by rotational distortion and in 1979 together with my colleagues Yang and Fahlman I reported that there were distinct sub-features travelling through these profiles on time scales of hours (Walker et al. ?). Vogt & Penrod (?) made a good analytical case that these sub-features were caused by velocity distortions introduced by sectorial ($l = |m|$) non-radial pulsations (nrp) while Harmanec (?) championed shadowing by spokes in a circum-stellar disc. These two possible interpretations led to a lively debate which sharpened the analysis and provoked even higher quality observations using the high fidelity solid-state detectors then coming into use.

It is probably fair to say that the non-radial pulsation explanation for the travelling sub-features is now generally accepted but not fully understood. ζ Ophiuchi has been the object of several global campaigns which have more clearly defined two principal periods of 2.018 and 3.337 hours implying a super-period of some 10.5 hours but there are still other as yet unexplained periods (Kambe et al. ?).

I also demonstrated that by looking at the variance rather than the individual profile variations in a series of spectra, one could demonstrate the effect of gravity darkening for this star (Walker ?). The variance inreases within each stellar line as a result of the nrp but the relative magnitude of the variance depends strongly on the excitation potential of the line. The lower the EP the larger the variance, to the extent that the highest excitation lines with EP~50 eV such as He II do not vary perceptibly. Further, the extent in wavelength of the variation becomes narrower with increasing excitation potential. Both of these indicate a minimum temperature in the equatorial region where the sectorial mode amplitudes are greatest. A piece of work I must complete some day.

3 Interstellar C_3

Carbon chains play a central role in the chemistry and spectroscopy of interstellar space. The detection of cyanopolyacetylenes in dense interstellar clouds (Kroto **?**) led to the suggestion by Douglas (**?**) that carbon chain species be considered as candidates for the diffuse interstellar bands (DIBs) (Herbig **?**), which are found in the 4000-8500Å spectral region of stars reddened by interstellar dust. Since then, many other molecules with a carbon chain backbone have been identified at radio frequencies in dense clouds (Kawaguchi et al. **?**). Meanwhile, advances in laboratory measurements have provided an understanding of the types and sizes of carbon chains which have strong electronic transitions in the DIB range (Maier **?**). It is thus somewhat surprising that as yet among the bare carbon species only diatomic C_2 has been identified with certainty in interstellar clouds.

The 4052Å electronic band system of C_3 was first detected in comets (Swings **?**) and then in circumstellar shells by infrared spectroscopy (Hinkle et al. **?**). Most recently Cernicharo et al. (**?**) identified it in a dense cloud using sub-mm measurements of its low frequency bending mode to obtain an estimate of $N_{tot}(C_3) \sim 10^{13}$ cm^{-2}. Snow et al. (**?**) established an upper limit of 5×10^{10} cm^{-2} for the column density of C_3 in the direction of ζ Oph, some two orders of magnitude lower than that set by Clegg & Lambert (**?**). Haffner & Meyer (**?**) made a tentative detection of C_3 towards an eighth magnitude star in the same part of the sky, HD 147889, at a column density of 4×10^{12} cm^{-2}. Unfortunately, the star turned out to be a (previously unknown) double-lined spectroscopic binary which limited their sensitivity.

Together with John Maier and Nick Lakin of the Institut für Physikalische Chemie, Basel, and David Bohlender of the HIA, Victoria, I have found the first clear evidence of interstellar C_3 towards three stars at column densities comparable to the limit set by Haffner & Meyer (**?**).

The three stars, ζ Oph (HD 149757), ζ Per (HD 24398) and 20 Aql (HD 179406), were observed with the Gecko échellette spectrograph, fiber fed from the Cassegrain focus of the Canada-France-Hawaii 3.6-m telescope (CFHT) (Baudrand & Vitry **?**). All three have a visual extinction, A_v, near 1 and were chosen because they are bright with sharp interstellar K I lines indicating either single clouds or little Doppler distortion (in the case of ζ Oph, Crawford (**?**) resolved the C_2 at 8756 Å into two close velocity components separated by 1.1 km s^{-1}).

Individual spectra were exposed from 5 to 20 minutes and were obtained with continuous fiber agitation to overcome fibre modal noise. The resulting, combined spectra for the individual stars at each wavelength had unusually high signal-to-noise ratios (S/N∼800-4000 per pixel) for CCD observations. Reflex velocities of the λ7699 K I interstellar line was applied to the spectra for each star to put the interstellar features on a laboratory scale for direct comparison.

FIG. 1 MAIER et al.

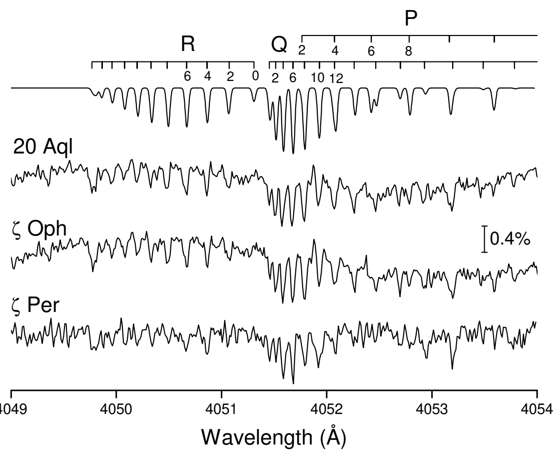

Fig. 1: Rotational lines in the origin band of the C_3 $A^1\Pi_u - X^1\Sigma_g^+$ transition towards ζ Oph, ζ Per and 20 Aql. The bar indicates 0.4% of the continuum. A known, weak stellar absorption line at 4053.2 Å has been removed from the spectrum of ζ Per. The simulated spectrum is for T_{rot} = 80 K at a spectral resolution of 110,000

The $A^1\Pi_u - X^1\Sigma_g^+$ origin band of C_3 is quite clearly detected towards all three stars. Figure **??** compares the observed spectra with an inverted, simulated C_3 emission spectrum based on the spectrograph resolution and assuming a Boltzmann distribution in the ground state rotational levels with a temperature of 80 K. The continuum noise level in the observations is ∼0.1 %. Low order polynomials have been applied to the stellar data to give a level continuum (base line) and, in the case of ζ Per, a weak, broad stellar feature at 4053.2Å has been removed. In the simulation the rotational line intensities were calculated using the Hönl-London factors, while the line positions were taken from the laboratory measurements (this avoids the problem of a perturbation affecting the low J ground state levels which is not accounted for by the fitted spectroscopic constants). The individual rotational P, Q and R lines are clearly resolved in the spectra of all three stars.

Among the lowest rotational levels ($J < 14$) the populations are reasonably approximated by a distribution at 50-70 K, whereas the higher rotational levels correspond to a temperature of 200-300 K. The high temperature component of the distribution is apparent in the astronomical spectra where the R band head and the higher Q lines are more intense than in the simulation in Figure 1.

Lutz & Crutcher (**?**) also found a bimodal population distribution for C_2 in diffuse clouds, with similar characteristic temperatures for the low and high J values. The lower temperature is interpreted as the kinetic energy of the cloud and for both C_2 and now C_3 is comparable to the value used in models of diffuse clouds (van Dishoeck & Black **?**). The higher temperature component is attributed to repopulation of the levels in the ground electronic state by radiative pumping from excited states. In the case of C_3 it is expected that both the $^1\Pi_u$ state and the higher lying $^1\Sigma_u^+$ state contribute to the radiative pumping.

We measure values of $N_J(C_3)$ in the range 0.2-2×10^{11} cm^{-2} for rotational-levels up to $J = 30$. Summing the N_J values then gives a lower limit in the range 1-2×10^{12} cm^{-2} for the total column density, $N_{\rm tot}(C_3)$. With such a high column density it is now reasonable to look for the C_4 and C_5 chains. Which we intend to do!

Our results on C_3 will appear in the 2001 May 10 issue of the Astrophysical Journal.

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