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INTERSTELLAR CO IN THE ULTRAVIOLET SPECTRUM OF ζ OPHIUCHI

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One of the most important characteristics of interstellar molecules is the sensitivity of their internal energy to the ambient gas and radiation field. Consequently, the molecules make good monitors of such physical parameters as particle density, gas temperature, radiation field energy density, and radiation field spectrum. Until recently, all observations of interstellar molecules have been made by radioastronomical techniques, which because of the large volumes of space sampled afford great sensitivity. This sensitivity, however, is accomplished at the expense of spatial resolution and, where the signal is saturated, spectral sensitivity.

Within the past year using optical methods in the vacuum ultraviolet, Carruthers at NRL (Ref. 1) has detected interstellar H_2 in the spectrum of ϵ Persei and we at Goddard have observed CO in the spectrum of ζ Ophiuchi. By contrast with radio results the regions sampled are small, being one or a few clouds in the line of sight, and, in addition, isotopic effects may be detected in the spectrum.

Let me now discuss the second of these observations further.

Figure 1 shows portions of the ζ-Ophiuchi spectrum in which the spectral resolution is about 0.05 nm and the linear dispersion is 0.4 f nm mm^{-1}. Wavelengths are plotted on the abscissa where each division is 1 nm; the stellar flux in relative units is plotted on the ordinate. Vibrational transitions in the fourth positive system ($A^1\ \pi$-$X^1\ \Sigma^+$) of $^{12}C^{16}O$ are indicated by the vertical solid lines and in the case of $^{13}C^{16}O$ by the vertical dashed lines. The vibrational quantum numbers are shown in parentheses. It is noteworthy that this system of bands is very strong when observed in the laboratory. Although there are easily identified stellar features, e.g., the lines of C-IV (154.82, 155.08 nm) Si-IV (139.37 nm), and O-I (130.22 nm) that blend with the CO lines, we feel that the correlation of observed features with laboratory-measured lines in the CO spectrum is good and that the presence of this molecule in some interstellar cloud or clouds between us and ζ Ophiuchi may be observed.

Figure 2 illustrates the curve-of-growth analysis by which column densities of the $^{12}C^{16}O$ and $^{13}C^{16}O$ molecules were estimated. On the abscissa is plotted the log of the optical depth in the center of the line; and on the

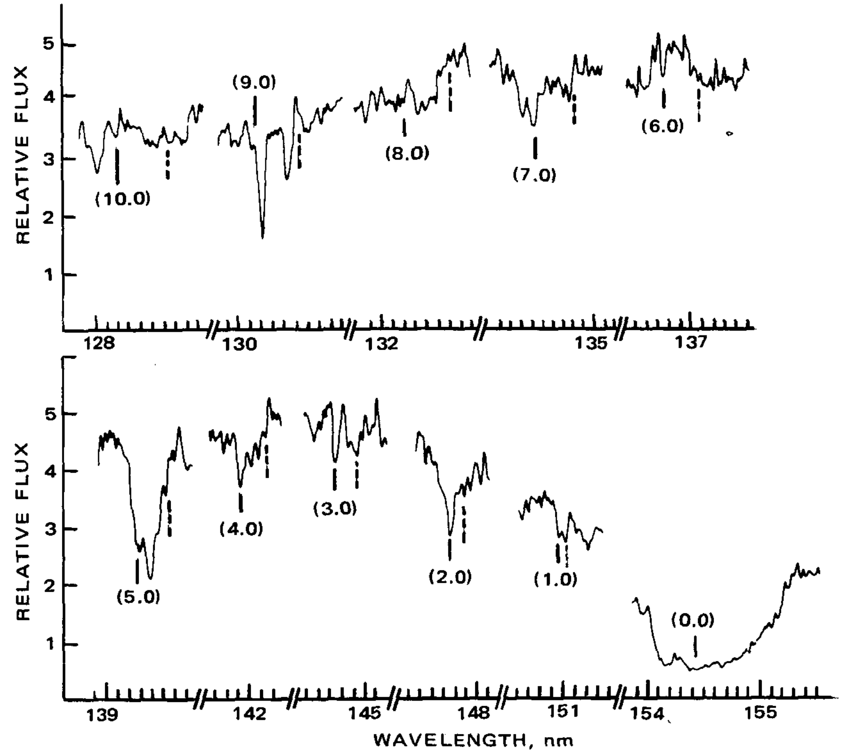

Figure 1–Portions of the ζ-Ophiuchi spectrum.

ordinate, the log of the equivalent width in units of the doppler width. The solid curve is computed assuming that the molecules are in thermodynamic equilibrium with a fossil 2.7 K blackbody radiation field. Thus, three rotational levels in the ground state molecules are excited giving rise to six lines in each vibrational transition. Equivalent widths of eight lines in the $^{12}C\,^{16}O$ spectrum were measured and were plotted against their corresponding oscillator strengths. This array, indicated by the black dots, was then fitted to the computed curve-of-growth at the "knee," and a turbulence parameter b, related to the Doppler width b_λ by the relation $b = c/\lambda\, b_\lambda$, and the column density n, which is proportional to τ_0, were derived. The values of these parameters are 1.5 km s^{-1} and 1.8×10^{15} cm^{-2}, respectively. These results are consistent with the results obtained by both rocket and ground-based observations of interstellar lines arising in different atoms and ions. Such

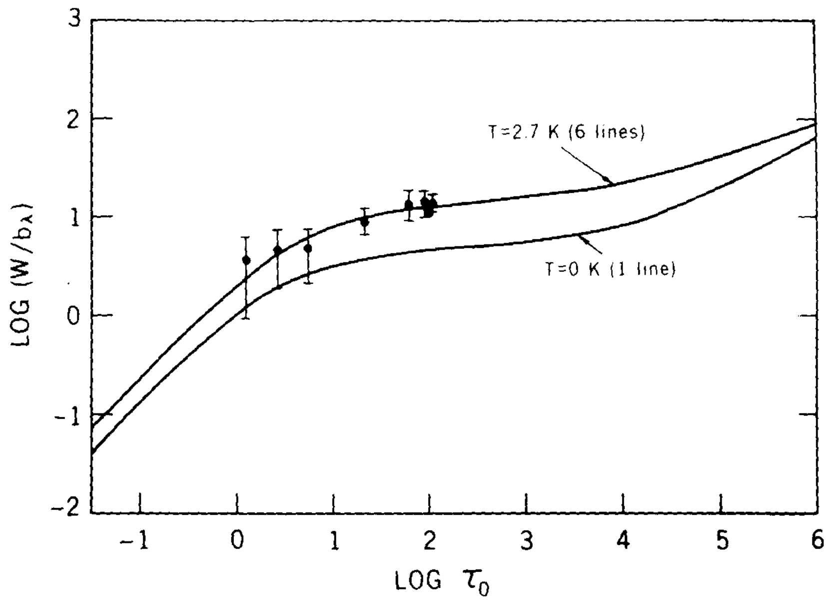

Figure 2–Fit of equivalent widths of $^{12}C^{16}O$ lines to computed curve of growth. The parameters are $b = \sqrt{2KT/Am_0} = 1.5$ km s^{-1} and $n = 1.8 \times 10^{15}$ cm^{-2}

plausible results cannot be obtained if only the lowest rotational level (J = 0) of the ground state is populated; but on the other hand, the higher rotational levels may be excited by collisions with ambient gas particles as well as by the ambient radiation field.

A similar analysis of four lines in $^{13}C^{16}O$ in the interstellar cloud or clouds between here and ζ Ophiuchi is 79, which is close to the terrestrial value of 89.

In summary four points may be made:

(1) Interstellar CO has been observed optically in the ultraviolet spectrum of ζ Ophiuchi, and is probably located in one or a small number of clouds intercepted by the line of sight.

(2) The column density and turbulence parameters are 1.8×10^{15} cm^{-2} and 1.5 km s^{-1}, respectively, and are consistent with observations of other interstellar lines.

(3) The abundance ratio of interstellar ^{12}C to ^{13}C is 79; i.e., nearly terrestrial.

(4) These results are consistent with viewing the interstellar CO molecules as being in thermodynamic equilibrium with a 2.7 K fossil blackbody radiation field.

CHAIRMAN:

Are there any questions?

MEMBER OF THE AUDIENCE:

It seems that you tried to obtain a vertical and horizontal fit of the data points to the computed curve of growth.

DR. SMITH:

Yes.

MEMBER OF THE AUDIENCE:

However, it seems to me that really you can only get one parameter because your data points do not define the shape of your computed curve accurately enough to permit a bit both vertically and horizontally. In other words, if you move the data points up and, say, over to the right, you still fit the computed curve you have drawn there. Thus, it seems that the fit parameters are not independent, and that there is a functional relationship between them.

DR. SMITH:

That's a problem. If you shift the data up and to the right the essential problem that arises is with the turbulence parameter and in this case it becomes quite small. I tried essentially the same thing by seeing what would happen if I assumed the molecules were in thermodynamic equilibrium with a 30° gas. When the data were fitted to this new curve of growth the turbulence parameter came out to be 0.46 km s^{-1}. Why is this not possible? I cannot say exactly that it is not possible. Maybe in the interior of the cloud that is what the case is. But that is not what is observed by Herbig (Ref. 2). Herbig has derived turbulence parameters from roughly 0.8 to 2.4 km s^{-1}, but he has used the value 1.5. What I have tried to do here is to find a fit that produces a value of the turbulence parameter consistent with that found by Herbig.

REFERENCES

1. Carruthers, G. R.: Astrophys. J. Lett., vol. 161, 1970, p. L81.

2. Herbig, G. H.: Z. Astrophys., vol. 68, 1968, p. 243.