Molecular Probes of the Cosmic Background Radiation

P. CRANE, ESO

1. Introduction

In the late 1930's observers at the Mount Wilson observatory using the 100-inch telescope and the Coudé Spectrograph discovered absorption lines of the interstellar molecules CH, CH^+, and CN. In the case of CN, an absorption line from an excited rotational state in addition to the ground rotational state was also seen. In fact, an excitation temperature of about 2.3 K was deduced, but the connection to cosmology and the cosmic background radiation was not realized. The full significance of these observations only became obvious in 1964 when the cosmic background radiation (CBR) was finally discovered using radiometers, and found to have a temperature of about 3.1 K.

Subsequently, several investigators reanalyzed old data, or obtained new data on the interstellar absorption lines of CN as well as of CH and CH^+. This work was well summarized in 1972 by Thaddeus (1972) who emphasized the importance of studying these interstellar molecules in connection with the short wavelength portion of the CBR spectrum. Nevertheless, the subject lay dormant for several years until modern electronic detectors permitted about a factor of 10 increase in the precision with which these absorption lines could be measured.

Studying the intensity of the CBR at different wavelengths allows us to probe the thermal history of the Universe back to redshifts of about 1,000, or, in more prosaic terms, to times before the formation of stars and galaxies. Intensities in the short wavelength region of the CBR are particularly interesting since it is here that departures from a pure blackbody spectrum due to energetic events in the early Universe might first become evident. Figure 1 shows a 2.79 K blackbody spectrum, and indicates several recent measurements.

Interstellar molecules permit us to study the intensity or equivalently the temperature of the CBR at specific wavelengths determined by the separation of the rotational levels of the particular molecule involved (see Fig. 2). For CN, these wavelengths are 2.64 mm and 1.32 mm. For CH, this is 0.56 mm. All that is required is that an interstellar cloud containing the molecules lie along the line of sight to a star. If the star is bright enough and of the correct type so that the stellar continuum can be precisely determined, then the molecular absorption lines will show up prominently (see Fig. 3).

This technique for determining the CBR temperature is particularly simple and free from major systematic corrections that could give false answers. The relative intensities of visible absorption lines, representing electronic transitions of the molecule, give a direct measurement of the populations of the rotational states. For the stars we have studied, it is a very good assumption that the CN molecule is in thermal equilibrium with the CBR, and therefore the CBR temperature can be determined from the Boltzmann equation.

$$\frac{N_u}{N_l} = exp(- \frac{hc}{\lambda k T_{exc}})$$

where N_u is the upper state population, and N_l is the lower state population. λ is the wavelength of the rotational line splitting and T_{exc} is the CBR temperature.

In order to make a 1% determination of T_{CBR}, it is necessary to test the assumption that CN is in thermal equilibrium with the CBR or, in other words, to show that $T_{exc} = T_{CBR}$ to better than 1%. Also, the ratio N_u/N_l must be measured with the necessary precision. This requires that the observed absorption line strengths be corrected for saturation effects. (This is basically a correction for the fact the molecules on the near side of a molecular cloud see less radiation at the appropriate wavelength because molecules on the far side have already absorbed it.)

Two groups have recently taken up this approach to measuring the CBR temperature. One group headed by David Meyer at Northwestern University has used primarily the Lick Coudé. The other group at ESO has used the ESO 1.4-m CAT telescope and the Coudé Echelle Spectrograph. This group includes in addition to the author, N. Mandolesi (Bologna), E. Palazzi (Bologna), D.J. Hegyi (Ann Arbor), M. Kutner (RPI, Troy), J.C. Blades (STScI, Baltimore), and A.C. Danks (ARC, Landover). In the

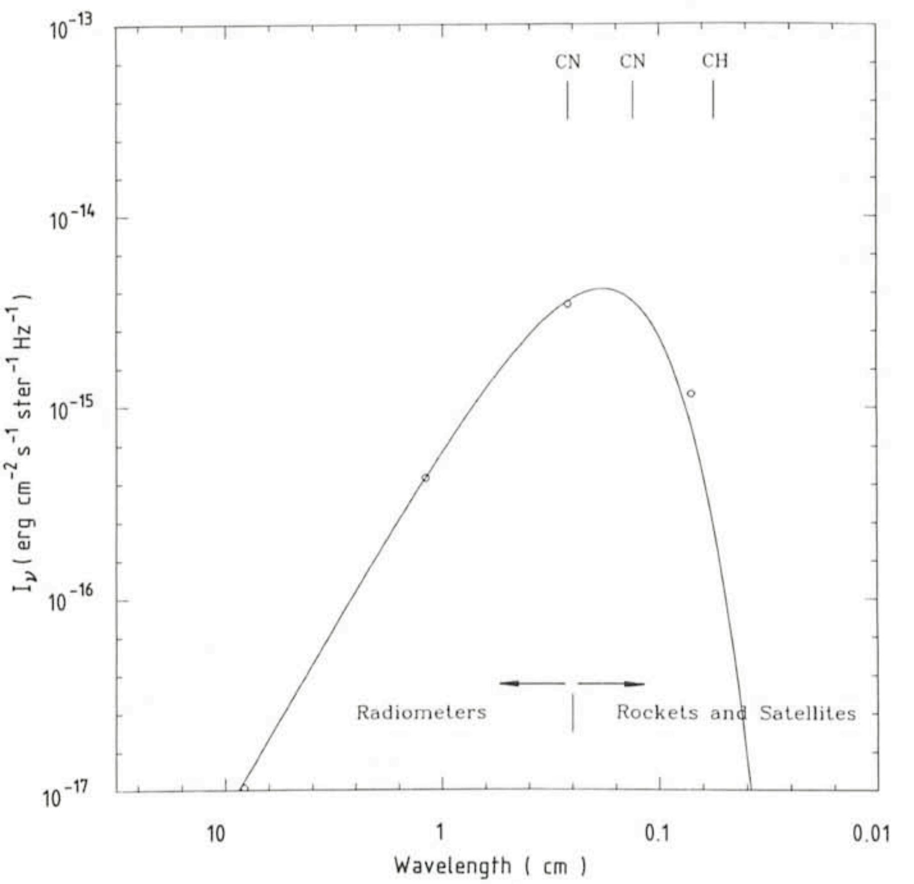

Figure 1: *2.79 K blackbody spectrum. The positions of the CN and CH lines are indicated. The indicated measurements are from Smoot et al. 1987 and from Matsumoto et al., 1988. The regions where ground based radiometers and rockets and satellite technology are most effective are also indicated.*

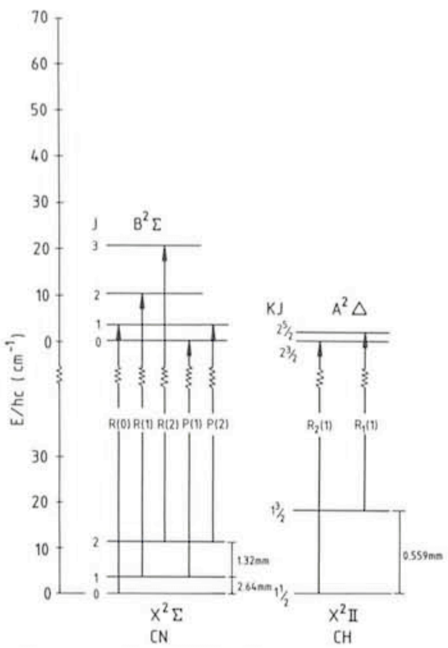

Figure 2: *Term diagram for CN and CH. The vertical lines show the observed optical transitions. The lower horizontal lines represent the various rotational levels and their relative separation in wavelength.*

paragraphs below, the recent work of the ESO group is dicussed.

2. Measurements at 2.64 mm

Previous work published in 1986 (Crane et al., 1986) on the absorption lines of CN toward ζ Ophiuchi yielded a value of $T_{CBR} = 2.74 \pm 0.05$ K. Recent work has aimed at reducing the uncertainty in this measurement. The uncertainty is made up of the three parts: uncertainty in the measurement of the optical absorption lines, uncertainty in the saturation correction, and uncertainty on the extent to which CN is in thermal equilibrium with the CBR. Each element of this uncertainty has been studied in detail, and a value for T_{CBR} with an uncertainty approaching 1% seems to be probable.

Improving the precision of the optical absorption line measurements required developing a new technique for analysing the spectra (Crane and Hegyi, 1988). This procedure gave a much better understanding of the origin of the noise in the data and hence greater faith in applying standard statistical procedures to the results. Currently, the uncertainty in T_{CBR} due to the optical absorption lines is about 19 mK. or 0.7%.

The value of T_{CBR} from the 1986 result contained a correction due to local excitation processes in the interstellar cloud,

$$T_{corr} = -0.060 \pm 0.040 \text{ K}$$

This was based on a theoretical calculation of collisional excitation of CN by electrons, and an estimate of the electron density in the cloud. However, if the CN is not in thermal equilibrium with the CBR, then it would be expected to emit radiation at 2.64 mm. Thus it is possible to measure the correction to T_{CBR} directly rather than to depend on an estimate. We have made such a direct measurement, and find that the correction must be less than 30 mK. This translates into an uncertainty of at most 0.6% in T_{CBR}.

In the previous work, we quoted the formal uncertainty in the saturation correction to be 3 mK, but this was based on the assumption that the CN was contained in a single cloud with a gaussian velocity distribution of 0.88 ± 0.02 km s^{-1}. We have reviewed that assumption in the light of recent high resolution CO spectra of this interstellar cloud that show several clouds with small velocity dispersions and which are possibly consistent with the optical measurements. It appears that even the most extreme assumptions concerning the cloud model used to determine the saturation corrections cannot add more than 15 mK to the uncertainty in T_{CBR}. Since the various sources of error add in quadrature, the goal of a 1% measurement of the CBR temperature using the CN molecule seems to be within reach.

3. Measurements at 1.32 mm

The determination of the CBR temperature at 1.32 mm using CN is considerably more difficult than at 2.64 mm because the corresponding absorption lines are considerably weaker in the direction of ζ Oph. However, other stars with more CN along the line of sight can be used if we are willing to concentrate on the 1.32 mm determination. One such star is HD 154368 which was originally observed by Blades (1978) to have large molecular column densities.

We have reobserved this star at the CAT using the short camera plus the CCD. Analysis of the data is still in progress, but preliminary results indicate that a value of T_{CBR} at 1.32 mm with an uncertainty of 10 mK or maybe slightly smaller will be possible. This is more than a factor of two improvement over our result at 1.32 mm from the ζ Oph data. However, since the R(0) line needed to determine T_{CBR} at 2.64 mm is so heavily saturated in this star, we cannot determine a precise value for T_{CBR} at 2.64 mm.

Since the CN column density towards HD 154368 is much higher than toward ζ Oph, there is more concern that the CN may be collisionally excited. To test for possible local excitation of CN in this cloud, we have used the new SEST telescope at La Silla to look for CN emission at 2.64 mm from the diffuse cloud in front of the star HD 154368. We did not detect any emission at 2.64 mm and since collisions would be more effective in exciting emission at 2.64 mm than at 1.32 mm, we feel safe that local excitation is not effecting the observed CN temperature at 1.32 mm.

4. Measurements at 0.56 mm

Figure 2 shows that the separation of the first excited rotational level of CH could be used to probe the intensity of the CBR at 0.559 mm. However, as Figure 1 shows, the intensity of the CBR is falling very quickly in this wavelength range and therefore the excitation of the first rotational level is very small compared to that of CN. Nevertheless, in view of a recent rocket measurement (Matsumoto et al., 1988) which showed a large excess intensity in this region, and because of the broad implications for cosmology, it seemed important to try to see if any excess radiation could be detected using the CH molecule.

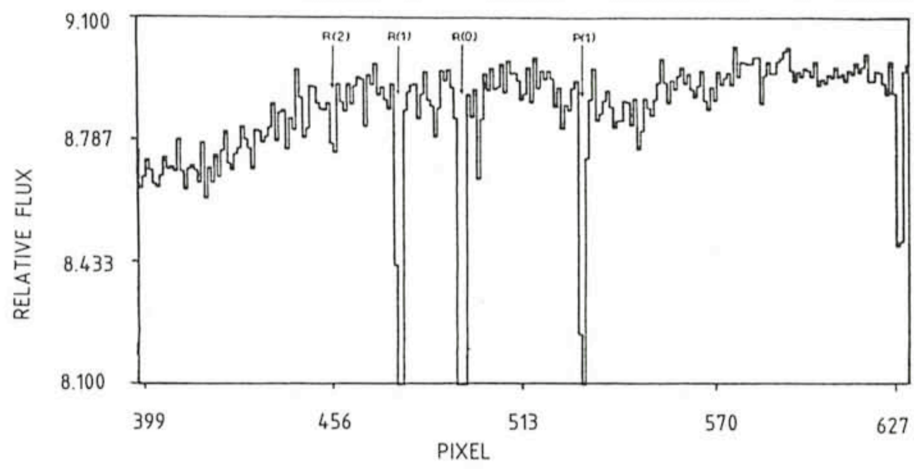

Figure 3: *Spectrum of the star HD 154368 showing the absorption lines R(1), R(0), P(1), and R(2). The ratio of the strength of P(1) or R(1) to R(0) is a measure of the ratio* N_u/N_l *discussed in the text.*

In pursuing this project, we have recently observed ζ Oph using the new combination of the long camera and the CCD detector. Although ζ Oph is quite bright, and the column density of CH is quite high the equivalent width of the CH $R_1(1)$ line is expected to be only about 0.005 mA. Using a spectral resolution of 150,000, such a line would require a signal-to-noise in the stellar continuum of 10,000 : 1 for a 2 standard deviation detection. Needless to say, this is a very difficult project and the results will depend critically on the details of CCD performance.

Even if we don't detect the line, we feel confident that we can provide a useful upper limit on T_{CBR} at 0.559 mm that will serve to constrain the models for the thermal history of the Universe.

5. The Future

Future work on determining the CBR temperature using interstellar molecules will focus on reducing the uncertainty at 1.32 mm and on finding other lines of sight where the results at 2.64 mm can be confirmed with equivalent precision. Reducing the uncertainty at 1.32 mm can be achieved either by continuing to work on the CN lines toward HD 154368, or by working on another, as yet, undetermined line of sight. Finding new lines of sight in which to study the CBR temperature has been one of the ESO group's objectives in the last few years. So far, about 20 stars have been surveyed and several good candidates have been identified. Unfortunately, the ideal candidate has yet to be found.

Although cosmological theory assumes that the CBR is ubiquitous, the only direct evidence we have that it does not have a local origin is through molecular temperature determinations. These show that the CBR is similar to what we see locally out to distances of roughly 200 parsecs. A confirmation of the universal nature of the CBR on a much larger scale would provide further confidence in our cosmological models. This, however, is a project for the VLT and an appropriate spectrograph, since the stars required being further away will be considerably fainter than those studied to date.

On a very different front, if all goes according to plan, the NASA sponsored Cosmic Background Explorer satellite (COBE) should be launched by June 1989. This satellite should provide very accurate measurements of the CBR spectrum from 0.1 to 10 mm. Although COBE will very likely provide definitive data on this problem, the most accurate measurements possible by other means will still be needed to confirm the satellite results.

References

Blades, J.C., 1978, *M.N.R.A.S.* **185,** 451.

Crane, P., Hegyi, D.J., Mandolesi, N., and Danks, A.C. 1986, *Ap. J.* **309,** 1.

Crane, P., and Hegyi, D.J., 1988, *Ap. J. (Letters),* **326,** L35.

Matsumoto, T., Hayakawa, S., Matsuo, H., Murakami, H., Sato, S., Lange, A.E., and Richards, P.L., 1988, *Ap. J.* **329,** 567.

Smoot, G.F., Bensadoun, M., Bersanelli, M., De Amici, G., Kogut, A., Levin, S., and Witebsky, C., 1987, *Ap. J. (Letters),* **3137,** L45.

Thaddeus, P. 1972 *Ann. Rev. Astron. and Astrophys.,* **10,** 305.

The Abundance of Manganese in Halo Stars

R. G. GRATTON, Osservatorio Astronomico di Roma, Italy

1. Introduction

The chemical composition of halo stars provides primary data about the nucleosynthesis processes that built up the metals present in young stars and in the interstellar medium. Theoretical information about the basic mechanisms of metal production are rather scarce. We know that only a tiny amount of metals was produced during the Big Bang; and we think that most of the heavy elements presently observed were manufactured in massive stars, or in intermediate-mass binaries, exploding as supernovae. However, the relative role of type I und type II (and/or type IIb) supernovae is quite unknown. Furthermore, we do not know precisely the composition of the ejecta of such supernovae. Therefore, empirical data are still at the basis of an interpretation of the chemical evolution of our Galaxy.

Considerable progress has been made in the last years in establishing clear runs of the ratios among the abundances of different elements with overall metallicity, as it is testified by a number of recent reviews (Spite and Spite, 1985; Sneden, 1985; Lambert, 1987; Gustafsson, 1988). This progress was mainly made thanks to the advent of arrays of linear detectors, which allowed very high S/N at high resolution, even for relatively faint stars. ESO has a leading position in this field, mainly thanks to the CES spectrograph at the CAT, and the CASPEC at the 3.6-m telescope. In particular, the combination CAT and CES was at least for five years the most efficient instrumention worldwide for high resolution (> 50,000) spectroscopy. This is most noteworthy since only a rather small telescope is used.

Most of the investigations on the composition of metal poor stars concentrated on the interesting light elements, and on the heavier ones, like Barium and the rare earths. However, Fe-group elements merit a particular inspection, since the presence of an enhanced odd-even effect was first reported by Helfer et al. (1959). The investigation of this enhanced odd-even effect was for a long time hampered by the poor knowledge of the hyperfine structure of lines of elements like Vanadium, Manganese, Cobalt and Copper, which have appreciable nuclear magnetic momenta. However, two papers from the Oxford group (Booth et al., 1983, 1984) provided detailed hyperfine structure and oscillator strengths for quite a large number of Manganese lines. This allowed a preliminary investigation of the abundance of Manganese in 13 metal-poor stars (mainly giants) using blue CASPEC spectra (Gratton, 1988). This investigation showed that Manganese is indeed deficient in metal-poor stars, as originally proposed by Helfer et al. However, the use of the resonance lines, which are located in a crowded spectral region, required a careful consideration of synthetic spectra and of (uncertain) damping parameters. Furthermore,

Erratum

Dust in Early-Type Galaxies. M.P. Véron-Cetty and P. Véron. *The Messenger,* No. 52, June 1988, p. 41.

In Figure 1, the names of two galaxies have been interchanged; the picture of NGC 4526 is labelled NGC 4696, while the picture of NGC 4696 is labelled NGC 4526.