membrane domain of HA at the pH of fusion might be able to bend with respect to the plane of the membrane. Such bending could allow the opposed membranes to approach more closely than the length of $TBHA_2$. In addition, increased orientational flexibility of the HA extramembrane domain might facilitate higher-order assembly of trimers, as proposed to be necessary for HA-mediated fusion[35], perhaps in the formation of a fusion pore structure[36]. Studies to date have not ruled out the possibility that other parts of the polypeptide, such as the membrane-proximal region inferred to be disordered from the $TBHA_2$ structure, are directly active in membrane fusion, as suggested for the C-terminal anchor region[37]. ☐

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LETTERS TO NATURE

# Measurement of the microwave background temperature at a redshift of 1.776

**A. Songaila*, L. L. Cowie*, S. Vogt†, M. Keane†, A. M. Wolfe‡, E. M. Hu*, A. L. Oren‡, D.-R. Tytler‡ & K. M. Lanzetta§**

* Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive,
Honolulu, Hawaii 96822, USA
† Lick Observatory, University of California, Santa Cruz,
California 95064, USA
‡ Department of Astrophysics and Space Science,
University of California, San Diego, La Jolla, California 92093, USA
§ Astronomy Program, Department of Earth and Space Science,
State University of New York, Stony Brook, New York 11794, USA

**HOT Big Bang cosmology predicts that the temperature of the cosmic microwave background radiation will increase linearly with increasing redshift to early in the history of the Universe. The local background temperature (2.7 K) is known very accurately from direct measurements[1–3], but other techniques must be used to estimate it at non-zero redshifts. One way is to determine the excitation of atomic transitions in absorbing clouds along the lines-of-sight to distant quasars[4]. When the transitions are in equilibrium with the microwave background radiation, the radiation will populate the fine-structure levels of the ground states of certain atoms, and the relative populations of the levels can be used to calculate its temperature. Here we report the detection of absorption from the first fine-structure level of neutral carbon atoms in a cloud at a redshift of 1.776, towards the quasar Q1331 + 170. The population ratio yields a temperature of 7.4 ± 0.8 K, assuming that no other significant sources of excitation are present. This agrees with the theoretical prediction of 7.58 K.**

The cosmic microwave background radiation (CMBR) will populate excited levels of atomic and molecular species when the energy separations involved are not too different from the CMBR peak frequency. The first measurement of the local CMBR temperature was in fact made using this method[5] with fine structure lines in the cyanogen (CN) molecule, although it was not recognised as such until after Penzias and Wilson identified the CMBR[6]. Cyanogen excitation can now be used to measure $T_{\mathrm{CMBR}}$ very precisely. Roth *et al.*[7], who measured the rotational excitation of CN toward five Galactic stars and carefully corrected for local sources of excitation, found a value of $T_{\mathrm{CMBR}}$ at 2.64 mm of $2.729(^{+0.023}_{-0.031})$ K, in agreement with the COBE result[2] of $2.726 \pm 0.010$ K.

Bahcall and Wolf[4] first suggested that the method could be extended to high redshift, where $T_{\mathrm{CMBR}}$ could be presumed to be larger, using atomic fine-structure transitions in absorbing clouds toward high-redshift quasars. Useful transitions for this purpose include those of $C^0$, $C^+$ and $N^+$, with $C^0$ being particularly well suited[4,8]. This measurement has been attempted several times, but has generally been limited by the resolution and signal-to-noise available in reasonable exposure times at the very faint magnitudes involved, and, in the case of $C^0$, the intrinsic weakness of the line. $C^+$ and $N^+$ have strong lines, common in the spectra of quasars, but their relatively high fine-structure splitting makes them rather insensitive probes of the temperature. Furthermore the $N^+$ line lies in the region of quasar spectra confused by the Ly-$\alpha$ 'forest' of intergalactic neutral hydrogen lines. Nevertheless, Bahcall, Joss and Lynds[9] found an upper limit of $T_{CMBR} < 45$ K at redshift $z = 2.309$ toward the quasar PHL957 from $C^+$ absorption. The most recent measurement of Songaila *et al.*[10], with very high signal-to-noise observations from the Keck telescope (Mauna Kea, Hawaii), achieved a limit of $T_{CMBR} < 13.5$ K at $z = 2.909$ towards the quasar Q0636+680 based on upper limits to $C^+$ fine structure. $C^0$ excitation is inherently more sensitive, because of the small splitting of 16.4 $cm^{-1}$ of the $J = 0$ and $J = 1$ levels of the ground state, but $C^0$ absorption is very rare in quasar spectra. The best measurement to date with $C^0$ is that of Meyer *et al.*[11] in the spectrum of Q1331+170. Their upper limit on the column density of carbon atoms in the $J = 1$ level (C I*) implies that $T_{CMBR} < 16$ K at $z = 1.776$. We now report the first detection of C I* at high redshift, toward this same system in Q1331+170.

Our measurements were made with the HIRES high-resolution spectrograph[12] at the Keck 10-m telescope on 16–18 April 1994 (UT). Thirteen 60-min exposures of the quasar Q1331+170 were used, taken with a measured resolution $R = 47,000$, which corresponds to an instrumental '$b$-parameter' of 3.6 km $sec^{-1}$. ($b \equiv (2kT/m)^{1/2}$, where $m$ is the atomic mass and $T$ the temperature.) The data were reduced as described in ref. 10 and the resulting spectra near the $C^0$ multiplets at 1,656 Å and 1,560 Å are shown in Fig. 1. An energy level diagram showing the transitions in the relevent multiplets is given in Fig. 2. The $J = 0$ (C I) and $J = 1$ (C I*) absorption occurs in two main velocity components with (vacuum heliocentric) redshifts of 1.77638 and 1.77654, as well as some weak higher-velocity absorption, giving a weighted mean redshift of 1.77644±0.00002, in good agreement with the 21-cm redshift[13] of 1.77642±0.00002. We fitted Voigt profiles simultaneously to all the observable transitions in the two multiplets to obtain the column densities in the C I and C I* lines. The fitting parameters of the two main components are detailed in Table 1. Absorption from the $J = 2$ level is not detected with a 1$\sigma$ upper limit of $5 \times 10^{11}$ $cm^{-2}$. Component 1 is strongest, both in the ground state, where the $C^0$ column density, $N = 1.25 \times 10^{13}$ $cm^{-2}$, and in the $J = 1$ state, where $N = 3.9 \times 10^{12}$ $cm^{-2}$. Component 2 is weaker in the ground state, with $N = 7.2 \times 10^{12}$ $cm^{-2}$, but very weak in the $J = 1$ state. In the individual lines it is detected only at the (1–2)$\sigma$ level, and in the weighted mean it is present only at the 3$\sigma$ level, with $N = (9 \pm 3) \times 10^{11}$ $cm^{-2}$. Component 2 is very narrow and is only marginally resolved at our resolution, with $b \leqslant 2.6$ km $sec^{-1}$, which corresponds to an upper limit on the cloud kinetic temperature of 6,500 K. Multiplet equivalent-width ratios show that $b \geqslant 1$ km $sec^{-1}$, and that the lines are unsaturated. The column

TABLE 1 Fitting parameters and $T_{CMBR}$

| | Component 1 | Component 2 |
|---|---|---|
| Redshift | 1.77638 | 1.77654 |
| Multiplet 2 | | |
| $b$ (km $s^{-1}$) | 6.4 | 2.1 |
| $N(\times 10^{12}\ cm^{-2})$*: | | |
| $J = 0$, $\lambda = 1,656.928$ Å | 12.6±0.7 | 6.7±0.5 |
| $J = 1$, $\lambda = 1,656.267$ Å | 5.5±1.0 | 0.9±0.8 |
| $J = 1$, $\lambda = 1,657.379$ Å | 5.6±2.7 | 1.9±1.6 |
| $J = 1$, $\lambda = 1,657.907$ Å | 6.4±2.1 | 1.0±1.2 |
| $\langle J = 1 \rangle$ (weighted mean) | 5.6±0.9 | 1.1±0.6 |
| $N(J = 1)/N(J = 0)$ | $0.44(^{+0.08}_{-0.07})$ | $0.16(^{+0.09}_{-0.09})$ |
| $T_{excitation}$ (K) | $12.3(^{+1.2}_{-1.1})$ | $8.0(^{+1.5}_{-1.7})$ |
| Multiplet 3 | | |
| $b$ (km $s^{-1}$) | 6.4 | 2.6 |
| $N(\times 10^{12}\ cm^{-2})$*: | | |
| $J = 0$, $\lambda = 1,560.309$ Å | 12.5±0.5 | 7.5±0.4 |
| $J = 1$†, $\lambda = 1,560.695$ Å | 3.4±0.5 | 0.75±0.4 |
| $N(J = 1)/N(J = 0)$ | $0.27(^{+0.04}_{-0.04})$ | $0.10(^{+0.05}_{-0.05})$ |
| $T_{excitation}$ (K) | $9.8(^{+0.6}_{-0.6})$ | $7.0(^{+0.9}_{-1.2})$ |
| Weighted mean of multiplets | | |
| $N(J = 0)$ ($\times 10^{12}$ $cm^{-2}$) | 12.5±0.4 | 7.2±0.3 |
| $N(J = 1)$ ($\times 10^{12}$ $cm^{-2}$ | 3.9±0.4 | 0.9±0.3 |
| $T_{excitation}$ (K) | 10.4±0.5 | 7.4±0.8 |

Symbols used: $N$ is the column density and $b$ the width of the line ($\equiv (2kT/m)^{\frac{1}{2}}$ where $m$ is the atomic mass and $T$ the temperature). $T_{excitation}$ is the excitation temperature inferred from the relative populations of the $J = 1$ and $J = 0$ levels of the ground state.

* Errors are based on random fitting to 20 surrounding positions. Dropping the continuum level by 1% (an extreme case) would decrease the ratio of component 2 an amount comparable to the 1$\sigma$ error.

† The average of the $J = 1$ lines at 1,560.6832 Å and 1,560.7079 Å, with combined oscillator strength $f = 0.081$. The C I* lines are blended at our resolution. All rest wavelengths and oscillator strengths are from Morton[19].

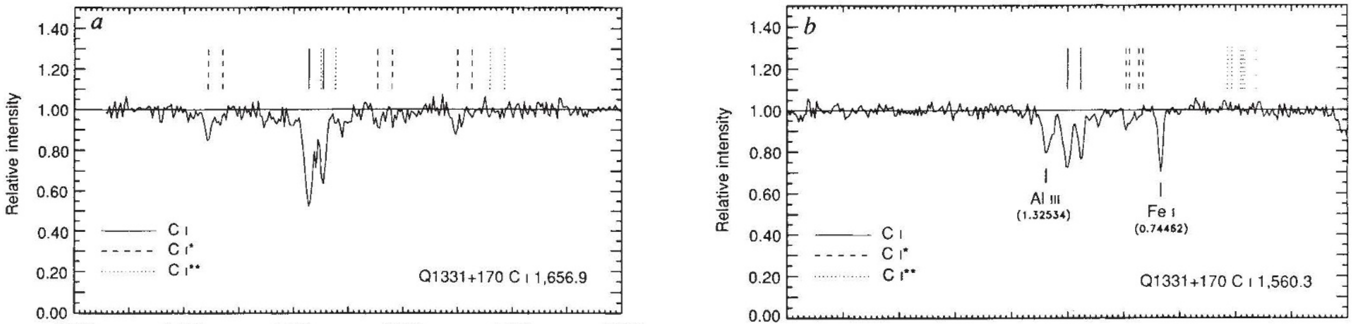

FIG. 1 Portions of the spectrum of the quasar Q1331+170: *a*, near C I multiplet 2 at rest wavelength 1,656.9 Å (orders 77 and 78); *b*, near C I multiplet 3 at rest wavelength 1,560.3 Å (order 82) in the $z = 1.77642$ absorption-line system. Two main velocity components are seen, at vacuum heliocentric redshifts of 1.77638 and 1.77654, as well as some weak higher-velocity absorption. Vertical solid lines show the positions of the ground-state transitions of components 1 and 2, dashed lines the C I*, and dotted lines the C I** fine-structure lines. Individual positions for the C I* lines in multiplet 3 are given, although these are blended at our resolution of $R = 47,000$. The neighbourhood of multiplet 3 contains lines of Al III (1,862.790 Å) at $z = 1.32534$ and Fe I (2,484.021 Å) at $z = 0.74462$ whose positions are marked. The $z = 0.74462$ system contains many strong lines and is well known[20]. The $z = 1.32534$ system has not been reported before, but is confirmed by the identification of the other line of the Al III doublet (1,854.716 Å) at 4,312.0 Å in order 82, by Mg II (2,795.528 Å) absorption at 6,501.1 Å and weak Fe II absorption (2,344.214, 2,382.765 and 2,600.173 Å) at 5,448.4, 5,539.5 and 6,045.1 Å, respectively.

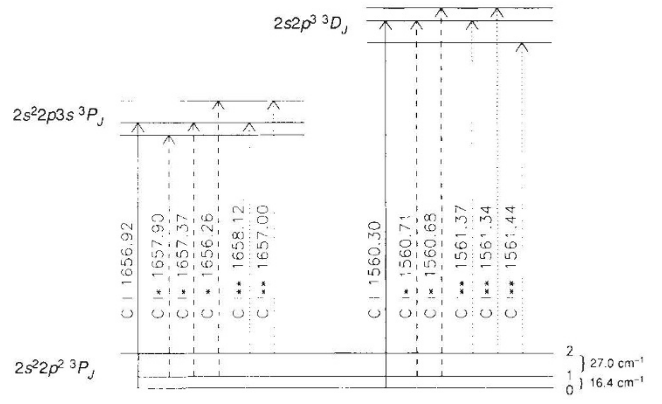

FIG. 2 Schematic energy-level diagram showing the ground state and fine-structure transitions of the two C$^0$ multiplets at 1,656 and 1,560 Å. The fine-structure energy splittings of the ground state are also shown (16.4 cm$^{-1}$, $J=1$–0; 27.0 cm$^{-1}$, $J=2$–1).

densities are therefore insensitive to the $b$ values. If there were unseen narrow saturated components that do not dominate the equivalent width, the ground-state column density would be larger and our measured excitation temperature would be lowered. Our measured ratios of population in the $J=1$ and $J=0$ levels, $N(J=1)/N(J=0)=0.31\pm0.03$ in component 1 and $0.125\pm0.04$ in component 2, imply excitation temperatures of $10.4\pm0.5$ K in component 1 and $7.4\pm0.8$ K in component 2. The predicted value of the temperature at this redshift is $T_{\rm CMBR}=7.58$ K.

In the interstellar medium (ISM) of the Galaxy, because $T_{\rm CMBR}$ is much smaller than the C$^0$ fine-structure separation, the $J=1$ level is populated predominantly by collisions with neutral hydrogen[14]. A small additional contribution is provided by optical pumping by the ultraviolet radiation field, but direct excitation by the CMBR is generally negligible[14]. However, measured values of C I*/C I in the Galactic ISM can be as high as 1.0, which encompasses the values measured in both of the C I components in Q1331+170. In contrast, excitation by the CMBR is substantial at $z=1.78$, and optical pumping is not important unless the ultraviolet radiation field is more than an order of magnitude larger than in the Galaxy[15]. The $J=0$–1 absorption from a background radiation field of $T=7.58$ K is $1.1\times10^{-8}\,{\rm s}^{-1}$ (ref. 15), compared to a $J=0$–1 excitation rate of $3.8\times10^{-10}n_{\rm H}\,{\rm s}^{-1}$ at a cloud kinetic temperature of 100 K and $6.6\times10^{-10}n_{\rm H}\,{\rm s}^{-1}$ at 1,000 K from collisions with neutral hydrogen[16]. ($n_{\rm H}$ is the density of neutral hydrogen in atoms per cm$^3$, and the two temperatures are representative of a reasonable range of kinetic temperatures in a cloud containing C I (ref. 14).) So, given that the CMBR is at its expected temperature, we find 1$\sigma$ upper limits of $n_{\rm H}=7\,{\rm cm}^{-3}$ for $T=100$ K, and 4 cm$^{-3}$ for $T=1{,}000$ K, and the pressure in the system is low compared to that in our own interstellar medium, but not unreasonably so[14]. Unfortunately the excitation of other fine-structure lines, such as those of Si$^+$ and C$^+$, does not usefully constrain $n_{\rm H}$ at these levels.

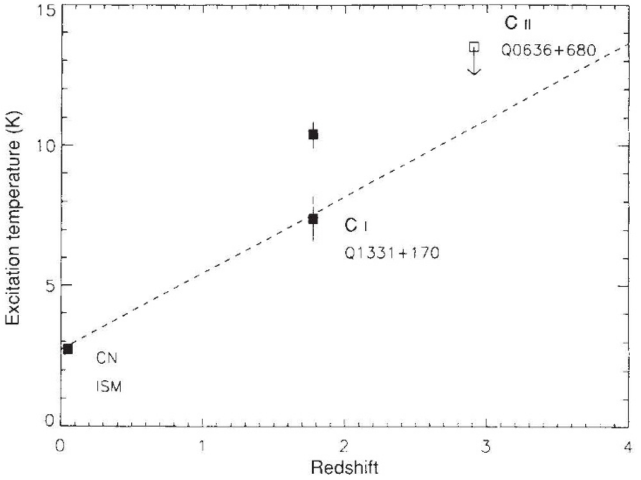

FIG. 3 Measurements of the excitation temperature at various redshifts. The filled square at $z=0$ (offset to $z=0.05$ for clarity) shows the result of Roth, Meyer and Hawkins[7] determined from measurements of interstellar medium (ISM) CN. The upper limit at $z=2.909$ (hollow square) was derived in ref. 10 using C II in an absorption system toward Q0636+680. The present measurements at $z=1.776$ are shown as filled squares. We show 1$\sigma$ error bars (which are smaller than the plotting symbol for the $z=0$ case). The dashed line is the prediction $T_{\rm CMBR}(z)=T_{\rm CMBR}(0)(1+z)$.

Unless the issue of local excitation can be more completely addressed, our $T_{\rm CMBR}$ value must be considered to be an upper limit, although one strikingly close to the standard prediction; if it could be shown that significant other sources of excitation were present, the measured value would be less, possibly leading to a conflict with the Big Bang expectation. In terms of $T_{\rm CMBR}(z)=T_{\rm CMBR}(0)(1+z)^{\alpha}$, we find $\alpha=0.98\pm0.11$ (Fig. 3). Of course, the redshift of Q1331+170 is quite low. It would be very gratifying to find an appropriate C$^0$ absorber at higher redshift to improve existing, much less sensitive, limits from C$^+$. Although the modern steady-state model[17] predicts $T_{\rm CMBR}\propto(1+z)$ until $z\sim6$, other theories[18] make strong claims for a value of $T_{\rm CMBR}$ well below the standard prediction by $z\sim3$, which we could check by such a measurement. ☐

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