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AN UPPER LIMIT ON THE MICROWAVE BACKGROUND TEMPERATURE AT $z = 1.776$[1]

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ABSTRACT

We present observations of C I lines in the $z = 1.776$ absorption-line system toward the QSO 1331+170 which indicate a 2 σ upper limit of 0.67 on the $N(^3P_1)/N(^3P_0)$ fine-structure population ratio. Even in the presence of other excitation mechanisms in C^0, this value provides an upper limit of 16 K on the cosmic microwave background (CMB) temperature at 0.61 mm at $z = 1.776$. Based on the present-day 2.7 K blackbody spectrum for the CMB, the CMB temperature (T_b) at $z = 1.776$ should be 7.5 K according to the standard Big Bang model prediction that $T_b(z) = 2.7(1 + z)$ K. The prospects for improving our upper limit on T_b through observations at higher redshift and a better understanding of the local C^0 excitation are briefly discussed. We also report a 2 σ upper limit of 4.5×10^{12} cm^{-2} for the column density of C^0 in the $z = 2.309$ absorption-line system toward PHL 957.

Subject headings: cosmic background radiation — quasars

I. INTRODUCTION

The simplest Big Bang cosmologies make three fundamental predictions about the cosmic microwave background radiation (CMB) (Peebles 1971): (1) it should be isotropic, (2) it should have a blackbody spectrum, and (3) its brightness temperature (T_b) should increase with redshift (z) such that $T_b(z) = T_b(0)(1 + z)$. The current upper limit of 0.005% on the (nondipole) anisotropy of the CMB (Uson and Wilkinson 1984; Lubin *et al.* 1985) and its well-determined 2.7 K blackbody spectrum (Meyer and Jura 1985; Peterson, Richards, and Timusk 1985; Smoot *et al.* 1985) testify to the effort that has been expended in testing the first two predictions with observations of increasing sensitivity over the past two decades. Indeed, the primary goal of the *Cosmic Background Explorer* (*COBE*) satellite (Weiss 1980) will be to search with high sensitivity for CMB anisotropies and spectral deviations which might help to explain phenomena such as the formation of galaxies not accounted for by the simplest Big Bang models. However, the third prediction listed above cannot be tested by *COBE* or any other direct measurement of the CMB since it concerns the CMB temperature in the past.

Fortunately, nature has provided a time-traveling "thermometer" in the form of neutral carbon atoms whose ground-state fine-structure excitation should be sensitive to the CMB at the large redshifts of some QSO absorption-line systems (Bahcall and Wolf 1968; Khersonskii 1981). The ground term ($2s^2\ 2p^2\ ^3P_J$) of C^0 is split into three levels ($J = 0, 1, 2$) with $J = 0$–1 and $J = 1$–2 energy separations of 23.6 K (0.61 mm) and 38.9 K (0.37 mm). Since the flux of a 2.7 K blackbody is quite weak at 0.61 mm, collisions with hydrogen atoms are much more important than the CMB in exciting Galactic interstellar C^0 (de Boer and Morton 1974). However, C^0 should be appreciably excited by the CMB at large redshifts where the CMB temperature is presumably higher and the peak of its flux is nearer to 0.61 mm. Consequently, by comparing the strengths of C I absorption lines arising from the $J = 0$ and $J = 1$ fine-structure levels in a QSO absorption system, an interesting upper limit on the CMB temperature at 0.61 mm at that system's redshift could be established independent of any assumptions about other excitation mechanisms.

In an effort to probe the CMB at large redshifts, we have obtained high signal-to-noise ratio (≈ 50) observations of C I absorption in the low-ionization absorption-line system at $z = 1.776$ toward the QSO 1331+170. Prior to this study, the only QSO absorption system found to exhibit unambiguous C I absorption was that toward the BL Lac object 0215+015 at $z = 1.345$ (Blades *et al.* 1982, 1985). Unfortunately, Blades *et al.* could not derive a C^0 $J = 0$–1 excitation temperature for this system because their spectral resolution was inadequate to separate the $J = 0$ and $J = 1$ components. The only

[1]Data presented here were obtained with the Multiple Mirror Telescope, a joint facility of the Smithsonian Institution and the University of Arizona.

previous attempt to measure the CMB at large redshifts was performed by Bahcall, Joss, and Lynds (1973) who estimated an upper limit of 45 K for the CMB temperature at $z = 2.309$ from the C^+ fine-structure excitation toward PHL 957. Although C II absorption is common in QSO absorption-line systems, it is a much less sensitive probe of the CMB at large redshifts than C I due to the larger energy separation (91 K) of its fine-structure levels and its greater susceptibility to saturation, collisional excitation, and line crowding.

II. OBSERVATIONS

The observations of 1331+170 were obtained in the spring of 1985 at the Multiple Mirror Telescope Observatory using the MMT spectrograph and a photon-counting Reticon detector (Latham 1982). Complete spectral coverage from 3200 Å to 6900 Å at 1 Å resolution (as measured from the FWHM of calibration lamp lines) was achieved with exposures at several settings of the 832 lines mm^{-1} grating. Our observational and data reduction procedures are discussed by Chaffee, Foltz, and Black (1986). Using the same equipment in the autumn of 1985, we also searched for C I absorption in the $z = 2.309$ system toward PHL 957. We observed PHL 957 from 3200 Å to 5600 Å at 1 Å resolution with the 832 lines mm^{-1} grating and from 5200 Å to 5600 Å at 0.5 Å resolution with the echellette grating. These spectra reveal no evidence of C I absorption at the expected wavelength (5483 Å) of the strongest C I ground-state ($J = 0$) line redshifted from 1656.928 Å. Our 2 σ upper limit of 15 mÅ for the rest-frame equivalent width of this feature yields an upper limit of 4.5×10^{12} cm^{-2} on the C I column density. This absence of C I and other details of the $z = 2.309$ system toward PHL 957 are discussed further by Black, Chaffee, and Foltz (1986).

Table 1 lists the rest wavelengths and f-values for the strongest C I multiplets one might expect to observe in QSO spectra. Both the empirical (f_{emp}) and the theoretical (f_{the}) values for the oscillator strengths are given. The former derive from the compilation of Morton and Smith (1973) for UV multiplets 2, 3, and 7 and from the analyses of interstellar absorption line data by de Boer and Morton (1979) and Jenkins, Jura, and Loewenstein (1983) for UV multiplet 4, while the latter result from the calculations of Nussbaumer and Storey (1984). The empirical values incorporate line strengths within multiplets based on the assumption of LS coupling while the theoretical values were obtained in intermediate coupling. Oscillator strengths for UV multiplets 2, 3, and 7 are consistent and can be considered well-established, but there is an unresolved discrepancy in the value for the 1329 Å multiplet. A fairly recent experimental measurement implies $f(\mathrm{UV}\ 4) = 0.063$ (Brooks, Rohrlich, and Smith 1977) which is 30% larger than the theoretical value and 30% smaller than the astronomically determined value. Table 1 also lists the expected wavelengths of these C I transitions in 1331+170 corresponding to the H I 21 cm absorption-line redshift of 1.77642 (Wolfe and Davis 1979). All redshifts and wavelengths quoted in this paper are vacuum, heliocentric values.

Figure 1 illustrates our spectra of 1331+170 in the vicinity of the four C I multiplets listed in Table 1. This figure shows that C I $J = 0$ absorption is clearly present in UV multiplets 2 and 3 at the wavelengths expected from H I absorption

TABLE 1

THE EXPECTED WAVELENGTHS FOR C I IN 1331+170

Multiplet	J	λ(rest) (Å)	$\lambda(z = 1.77642)$ (Å)[a]	f_{emp}	f_{the}
2..........	0	1656.9282	4600.33	0.136	0.136
	1	1656.2665	4598.49	0.057	0.057
	1	1657.3797	4601.58	0.034	0.034
	1	1657.9070	4603.05	0.045	0.045
	2	1657.0078	4600.55	0.102	0.102
	2	1658.1222	4603.64	0.034	0.034
3..........	0	1560.3095	4332.08	0.081	0.076
	1	1560.6832	4333.11	0.061	0.057
	1	1560.7079	4333.18	0.020	0.019
	2	1561.3407	4334.94	0.012	0.011
	2	1561.3670	4335.01	0.001	0.001
	2	1561.4382	4335.21	0.068	0.064
4..........	0	1328.8332	3689.40	0.082	0.049
	1	1329.0863	3690.10	0.027	0.017
	1	1329.1001	3690.14	0.034	0.020
	1	1329.1230	3690.20	0.021	0.013
	2	1329.5775	3691.47	0.062	0.037
	2	1329.6005	3691.53	0.021	0.012
7..........	0	1277.2454	3546.17	0.090	0.089
	1	1277.2823	3546.27	0.068	0.067
	1	1277.5130	3546.91	0.022	0.021
	2	1277.5496	3547.02	0.075	0.074
	2	1277.7229	3547.50	0.014	0.015
	2	1277.9538	3548.14	0.001	0.001

[a] In vacuum.

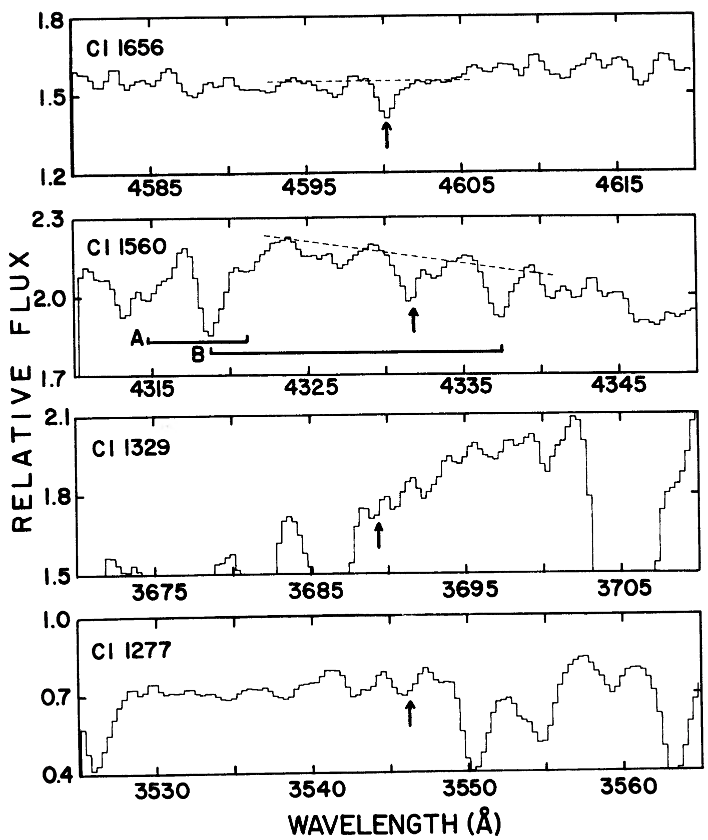

FIG. 1.—Portions of the spectrum of the QSO 1331+170 in the vicinity of the four C I multiplets listed in Table 1. The labeled wavelengths are vacuum, heliocentric values. The expected positions of the ground-state ($J = 0$) features are indicated by arrows which correspond especially well with the absorption features at 4600.2 Å and 4331.8 Å in the top two panels. The dashed lines indicate our continuum placement for the equivalent width measurement of these C I features. In the second panel from the top, the doublet marked A at 4314.6 Å and 4321.2 Å corresponds to C IV λλ1548,1551 at a redshift of 1.787 and the doublet marked B at 4318.5 Å and 4337.2 Å corresponds to Al III λλ1855, 1863 at a redshift of 1.328.

within our calibration uncertainty of ±0.3 Å. The identification of these two features as C I is also consistent with the redshifts of the other metal lines in the $z = 1.776$ system (Foltz, Chaffee, and Black 1986). In fact, an identification of these features as anything other than C I at $z = 1.776$ is unlikely in that they are far redward of the 1331+170 ($z_{em} = 2.091$) Lyman-α forest and do not correspond to any expected transition in the other absorption-line systems known toward 1331+170 (Carswell *et al.* 1975). In order to emphasize the reality of the C I line at 4332 Å and the sensitivity of our spectra, we have identified the other spectral features in the second panel of Figure 1 as the C IV (A) and Al III (B) doublets corresponding to the absorption-line systems at $z = 1.787$ and $z = 1.328$ toward 1331+170. The case for C I absorption in UV multiplets 4 and 7 is much more ambiguous due to the line crowding and continuum uncertainties produced by the Lyman-α forest. Nevertheless, the absorption features at 3689 Å and 3546 Å in Figure 1 are consistent with our identification of C I from UV multiplets 2 and 3.

We measure equivalent widths of 120 ± 30 mÅ (1 σ) for the C I $J = 0$ line at 4600 Å and 90 ± 30 mÅ for the $J = 0$ line at 4332 Å. The 1 σ error of 30 mÅ in these measurements was evaluated in the manner described by Chaffee *et al.* (1985). Although the 4600 Å feature is actually a blend of the $J = 0$ (4600.32 Å) line and a $J = 2$ (4600.55 Å) line at our resolution, the consistency of the 4600 Å and 4332 Å line strengths with respect to their relative $J = 0$ f-values and the absence of other $J = 2$ lines implies that the $J = 2$ fine-structure level is negligibly populated. The only evidence for $J = 1$ absorption is a hint of a feature with $W_\lambda = 40 \pm 30$ mÅ at 4333 Å, near the expected wavelength of the blended UV multiplet 3 $J = 1$ lines at 4333.11 Å and 4333.18 Å. Because of the large combined f-value of the lines comprising this blend, its weakness provides a more stringent upper limit on the C^0 $N(^3P_1)/N(^3P_0)$ fine-structure population ratio and, hence, on the temperature of the CMB than do the equivalent transitions in UV multiplet 2. Adopting 60 mÅ as a 2 σ upper limit on the strength of this blend and assuming no saturation of the $J = 0$ line, we derive an upper limit of 0.67 ± 0.22 on the population ratio, where the uncertainty results from the uncertainty of the measured equivalent width of the $J = 0$ line. This population ratio implies a value of the excitation temperature, T_{01}, of less than 16 ± 3 K, where again the uncertainty reflects the measurement error in the $J = 0$ line strength. By contrast, if we adopt the same 60 mÅ limit for the strength of the $J = 1$ transition of UV multiplet 2 at

4598.49 Å, we derive a 2 σ upper limit of 1.19 ± 0.60 for the population ratio yielding a poorer limit on T_{01} of less than 26 ± 16 K. We therefore adopt the UV multiplet 3 limit of 16 K in the discussion that follows.

III. DISCUSSION

Our C I observations provide a firm upper limit on the CMB temperature (T_b) at $z = 1.776$ independent of any assumptions about curve-of-growth effects or the contribution of other excitation mechanisms. In particular, since the presence of saturation or multiple components in the C I line profiles can serve only to decrease further our unsaturated upper limit on the $N(^3P_1)/N(^3P_0)$ ratio, the corresponding upper limit of 16 K derived from the Boltzmann equation for the C^0 $J = 0$–1 excitation temperature (T_{01}) is secure from any curve-of-growth effects. Furthermore, since the presence of local C^0 excitation can serve only to raise T_{01} above T_b, this upper limit on T_{01} directly implies that T_b(0.61 mm) $\leq$ 16 K at $z = 1.776$.

The application of these same ideas (but with much better data on the line profiles and local excitation) to the rotational excitation of interstellar CN in our Galaxy has led to the determination of 2.70 ± 0.04 K for the present-day CMB temperature at 2.64 mm (Meyer and Jura 1984, 1985). Based on this value and the blackbody character of the CMB spectrum, one would expect a CMB temperature of 7.5 K at $z = 1.776$ if $T_b(z) = 2.7(1 + z)$ K. The difference between this temperature and our upper limit of 16 K corresponds to a factor of 5.3 in the population ratio and a factor of 6.6 in the background intensity; thus, it is clear that observations of C I absorption in QSO absorption-line systems with comparable or slightly better sensitivity can provide important cosmological information.

In addition to obtaining better measurements of the C I absorption at $z = 1.776$ toward 1331+170, an obvious way to improve our upper limit on T_b would be to remove the contribution of local C^0 excitation to T_{01}. In a dilute gas, the relative populations of the C^0 fine-structure levels are governed by (1) the rates of spontaneous emission, stimulated emission, and absorption in the local submillimeter radiation field; (2) the rates of inelastic collisions, principally with H atoms, protons, and electrons in the present context; (3) the rates of absorption and fluorescence in the C I ultraviolet transitions; and (4) the rates of photoionization of C^0 and radiative recombination of C^+. In the limits of low density and low ultraviolet intensity, the fine-structure level populations come into equilibrium with the ambient submillimeter radiation field.

The spontaneous transition probability for the C^0 $J = 1$–0 fine-structure transition is 7.93×10^{-8} s^{-1} (Nussbaumer and Rusca 1979) and the corresponding rate of $J = 0$–1 absorption in a radiation field of brightness temperature T is

$$I_\nu B_{01} = (2.38 \times 10^{-7})/[\exp(23.6/T) - 1]\ \mathrm{s}^{-1}. \quad (1)$$

In comparison, the $J = 0$–1 excitation rate due to H impact is 3.8×10^{-10} n(H) s^{-1} at a kinetic temperature of 100 K (Launay and Roueff 1977) and the $J = 0$–1 excitation rate due to pumping by the galactic UV radiation field is 7.55×10^{-10} s^{-1} (Jenkins and Shaya 1979). With these rates and n(H) < 1 cm^{-3}, effects of UV pumping and collisions are small and the limit on the excitation temperature provides a direct limit on the brightness temperature. At a higher density, n(H) $= 20$ cm^{-3} for example, the limit $T_{01} \leq 16$ K corresponds to $T_b \leq 14$ K. The actual density, temperature, and UV field in this system are very uncertain, and values higher than those used in the above example would further lower the upper limit on T_b. In principle, the contribution of collisional processes and UV radiation to the excitation rates can be evaluated directly by means of a thorough interpretation of the absorption lines of many species in various ionization states in the same absorbing region because their strengths are also dependent upon the density, temperature, and local UV field. Such an analysis of the $z = 1.776$ system toward 1331+170 will be presented by Foltz, Chaffee, and Black (1986).

Another improvement to our upper limit of 16 K on T_b at $z = 1.776$ could be realized through the measurement of C I absorption in low-ionization QSO absorption-line systems at higher redshift. Although C I lines have been convincingly detected in only two QSO systems to date, previous observations have generally lacked the resolution, the signal-to-noise, or the coverage necessary to detect the principal C I multiplets redshifted from 1657 Å and 1560 Å. The other C I resonance multiplets are all shortward of 1330 Å and can easily be confused with the Lyman-α forest absorption common toward high-redshift QSOs unless the absorption redshift is very close to the emission redshift. It is important to note that if low-ionization QSO systems are anything at all like Galactic interstellar clouds, the C I absorption observed toward 1331+170 should be the rule, not the exception. Several of these low-ionization QSO systems have been identified at redshifts greater than 3 (Baldwin *et al.* 1974; Hunstead *et al.* 1986). Since the expected CMB temperature at $z = 3$ is 10.8 K, the detection of C I in these systems at the same sensitivity of our 1331+170 observations ($T_b \leq 16$ K) would provide a more stringent test of the prediction that $T_b(z) = 2.7(1 + z)$ K.

Even with corrections for the contributions of collisions and UV pumping, the temperatures derived from the C^0 $J = 0$–1 fine-structure excitation in QSO absorption-line systems will always be upper limits on T_b since there may be other noncosmological contributions to the local radiation fields at 0.61 mm. Nevertheless, an elegant confirmation of our present understanding of the Big Bang and cosmological redshifts would result if upper limits could be measured by C^0 excitation in several QSO systems at different redshifts and were found to be consistently at or above $T_b(z) = 2.7(1 + z)$ K. On the other hand, any QSO system which exhibits C I absorption indicative of a lower than expected CMB temperature (especially with no correction for local C^0 excitation) would be a cause for concern. Although our upper limit of 16 K on T_b at $z = 1.776$ is insufficient for such a test, our observations demonstrate that the physical conditions in at least some high-redshift QSO absorption-line systems are hospitable to C^0 and that current astronomical instrumentation is sensitive enough to detect the C I absorption features in QSOs. Furthermore, with this sensitivity, measurements at high redshift of the fine-structure populations in other species such as C^+ with larger energy separations could help place limits on contributions to the CMB from sources such as protogalaxies and pregalactic stars (Bond, Carr, and Hogan 1986) at wavelengths corresponding to the poorly explored Wien tail of the present-day CMB spectrum.

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