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ON THE TEMPERATURE OF THE MICROWAVE BACKGROUND RADIATION AT A LARGE REDSHIFT

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ABSTRACT

It is shown that the temperature of the microwave background radiation at a redshift of the order of 2.5 is certainly less than 200° K and probably less than 45° K. Further detailed studies of the absorption spectra of large-redshift quasars can improve these limits.

Subject headings: cosmic background radiation — quasi-stellar sources or objects

The intensity of the microwave background radiation in our Galaxy has been measured by many investigators at a variety of wavelengths (see Penzias and Wilson 1965 and for recent reviews Peebles 1971 and Thaddeus 1972). Some time ago, Bahcall and Wolf (1968) suggested that one could investigate the temperature of the microwave background radiation at much earlier epochs by studying the absorption spectra of quasars with large redshifts. For abundant atomic species such as C, N, O, Si, and Fe, the relative strengths of absorption lines from excited and ground fine-structure states are sensitive to the ambient radiation temperature.

We report an analysis of the absorption spectrum of PHL 957, which has a very prominent absorption redshift at $z = 2.31$ that contains many lines from ground fine-structure states (Lowrance *et al.* 1972; Bahcall and Joss 1973). Our results are based on a series of five relatively high-resolution spectra (resolution $\leqslant 2$ Å) of PHL 957 taken with the Kitt Peak 84-inch (213-cm) telescope by one of us (R. L.). The spectra cover the range 3200–7100 Å; the complete line list and details of the spectra will be published separately (Lynds 1973). Our main result is that the ambient radiation temperature in the region in which the most prominent absorption system is formed is not more than one order of magnitude greater than the extrapolated local radiation temperature [$T(z) = (1 + z)\ T_{\text{local}}$]. We are unable to say definitely whether the absorption lines are formed at the distance indicated by the absorption redshift [$z_{\text{abs}} = 2.3$; $T(2.3) = 9°$ K] or at the distance indicated by the emission redshift [$z_{\text{em}} = 2.7$; $T(2.7) = 10°$ K].

For matter in equilibrium with radiation of temperature T, the ratio of the number N_{ex} of atoms in an excited fine-structure state to the number N_g in a ground fine-structure state is $N_{\text{ex}}/N_g = (g_{\text{ex}}/g_g) \exp(-\Delta E/k_{\text{B}}T)$, where ΔE is the energy difference between the ground and excited states. If only the background radiation contributes to the population of the excited fine-structure states,[1] then the radiation temperature can be determined from the relation

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[1] The absence, in the absorption spectra of several quasars, of conspicuous lines from excited fine-structure states has previously been shown to imply that the electron density in the absorbing medium is less and 10^3 cm^{-3} and that the distance between the source of continuum radiation and the absorbing region exceeds 1 kpc; see Bahcall and Wolf (1968), Bahcall and Goldsmith (1971), and references quoted therein.

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$$T(z) = \left[1.44\, k/\ln \left(\frac{g_{\mathrm{ex}}N_g}{g_g N_{\mathrm{ex}}} \right) \right] {}^\circ\,\mathrm{K}, \qquad (1)$$

where $k(=\Delta E/k_{\mathrm{B}}c)$ is the wave number (in cm^{-1}) between the two states. If, as appears to be the case for PHL 957, the population of the excited fine-structure states is unobservably small, then one can place an upper limit on $T(z)$ by estimating from observation an upper limit to N_{ex}/N_g. For example, if we can detect values of $N_{\mathrm{ex}}/N_{\mathrm{g}}$ in excess of $\frac{1}{3}$ [or equivalently, for the cases considered, ln $(g_{\mathrm{ex}}N_{\mathrm{g}}/g_{\mathrm{g}}N_{\mathrm{ex}}) \lesssim 2$], the characteristic temperature that can be studied with the aid of equation (1) is (see Bahcall and Wolf 1968 for a more complete discussion): 10° K for C I ($k = 16\ \mathrm{cm}^{-1}$), 35° K for N II ($k = 49\ \mathrm{cm}^{-1}$), 45° K for C II ($k = 64\ \mathrm{cm}^{-1}$), 115° K for O I ($k = 159\ \mathrm{cm}^{-1}$), 200° K for Si II ($k = 287\ \mathrm{cm}^{-1}$), 275° K for Fe II ($k = 385\ \mathrm{cm}^{-1}$), and 315° K for Fe III ($k = 436\ \mathrm{cm}^{-1}$).

The absorption system at $z = 2.3$ in the spectrum of PHL 957 is the best-identified absorption system for a quasar with an emission redshift greater than 2 ($z_{\mathrm{em}} = 2.69$ for PHL 957) and contains the most lines (at least 7) from ions with excited fine-structure states. We show in table 1 only the *most reliable* identifications made for this redshift system using the five best Kitt Peak spectra. Our results are in agreement with previous analyses (Lowrance *et al.* 1972; Bahcall and Joss 1973). In addition, the Kitt Peak spectra extend to shorter wavelengths (which enables us to also identify Lγ at an observed wavelength $\lambda_{\mathrm{obs}} = 3217$ Å and possibly C III λ977.0 at $\lambda_{\mathrm{obs}} = 3231$ Å) and are of higher resolution throughout most of the spectrum (which enables us to identify Si III λ1206.5 at $\lambda_{\mathrm{obs}} = 3992$ Å).

The existence of this redshift seems to us to be beyond doubt. The most conspicuous feature in the absorption spectrum is identified with Lα, and we also observe strong lines associated with Lβ and Lγ. In addition, we identify all five of the expected lines

TABLE 1

IDENTIFICATIONS IN THE SPECTRUM OF PHL 957 AT $z_{\mathrm{abs}} = 2.3084$

Wavelength (Å)	Strength	Identification
3217.4	6.0	Lγ λ972.5 (0.2)
3230.9	2.0	[C III λ977.0](1.5)
3270.6	2.3	[O I λ988.8](0.7)
3275.1	1.9	Si II λ989.9 (−0.2)*
3394.5	15	Lβ λ1025.7 (−1.0)
3428.4	1.2	C II λ1036.3 (0.3)
3437.6	1.2	[O I λ1039.2](0.6)
3787.5	1.3	[Fe II λ1144.95](0.5)
3938.3	2.5	Si II λ1190.4 (0.1)
3947.7	2.7	Si II λ1193.3 (0.2)
3992.3	5.2	Si III λ1206.5 (−0.6)
4022.0	66	Lα λ1215.7 (0.0)
4170.0	2.3	Si II λ1260.4 (0.0)
4308.1	2.1	[O I λ1302.2](0.0)
4415.0	2.7	C II λ1334.5 (0.2)
5050.8	1.7	Si II λ1526.7 (0.3)
5528.2	1.8	Al II λ1670.8 (−0.4)

NOTE.—All observed wavelengths and line strengths are from Kitt Peak spectra (Lynds 1973). The numbers in parentheses indicate wavelength discrepancies, $\lambda_{\mathrm{predicted}} - \lambda_{\mathrm{observed}}$ (in Å). The identifications in brackets are uncertain and were not used in the analysis.

* Coincides with N III λ989.8.

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of Si II, the strong resonance line of Si III, the two expected lines from C II, and the only accessible strong line from Al II. The observed lines are consistent with the requirements of a reasonable ionization equilibrium and have relative strengths that could be expected from atomic physics considerations. Moreover, no such redshift system with so many acceptable identifications could be expected on the basis of accidental coincidence between observed lines and laboratory wavelengths of strong resonance lines. Bahcall and Joss (1973) analyzed 10 separate random-number spectra that resembled the observed spectra of Lowrance *et al.* (1972); no acceptable redshifts were found in any of the random-number spectra which identified more than eight lines. We have analyzed an additional 10 random-number spectra that were constructed to embody the essential characteristics of the Kitt Peak spectra. We found no redshifts among these latter 10 random-number spectra that identified eight more lines with strengths greater than or equal to 2 (on the line-strength scale of Lynds 1973).

We summarize in table 2 the observational results for the excited fine-structure states in the redshift system $z = 2.31$. We obtain, with the aid of equation (1) and table 2, the following limits on the (blueshifted) microwave background radiation temperature in the region in which the absorption lines are formed ($z = 2.3$ or 2.7):

$$T < 200^\circ\ \mathrm{K},\ \text{using the Si II lines,} \tag{2a}$$

and

$$T \lesssim 45^\circ\ \mathrm{K},\ \text{using the C II lines.} \tag{2b}$$

The limit of 200° K is of course more secure since it makes use of the presence of five ground-state lines and the nonobservation of their excited-state companions while the limit obtained with the C II lines depends on the presence of two ground-state lines and the absence of only one unobstructed excited-state line. We note in passing that the very sensitive C I lines are not present in the $z_{\mathrm{abs}} = 2.3$ redshift system. One can, however, make uncertain identifications in the Kitt Peak spectra

TABLE 2

LIMITS ON EXCITED FINE-STRUCTURE TRANSITIONS IN PHL 957 AT $z_{\mathrm{abs}} = 2.3$

Ion	Ground-State Line Wavelength, λ_g (Å)	Excited-State Line Wavelength, λ_{ex} (Å)	Expected Redshifted Separation [$\simeq 3.8(\lambda_{\mathrm{ex}} - \lambda_g)$] (Å)	Observed Strength of λ_{ex} Relative to λ_g
C II	1334.5	1335.7	3.9	$\lesssim \frac{1}{3}$ (weak line present near λ_{ex})
	1036.3	1037.0	2.3	λ_{ex} not observed but spectral region obscured by strong line 1 Å away
Si II	989.9	992.7	9.3	$< \frac{1}{3}$ (λ_{ex} not observed)
	1190.4	1194.5	13.5	$< \frac{1}{5}$ (λ_{ex} not observed)
	1193.3	1197.4	13.6	$\leqslant \frac{1}{4}$ (λ_{ex} not observed)
	1260.4	1264.7	14.3	$< \frac{1}{4}$ (λ_{ex} not observed)
	1526.7	1533.5	22.2	$< \frac{1}{3}$ (λ_{ex} not definitely observed)

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of other ground-state lines, e.g., Fe II λ1144.95, N II λ1084.0, and possibly even O I λλ1302.2, 988.8, and 1039.2. We have no consistent evidence of excited-state lines associated with these ground-state lines, in agreement with the temperature limits given in equation (2), but more and improved spectra in the region of the possible N II and O I lines may be revealing.

The absorption spectra of other quasars should of course be examined for the presence of lines originating on excited fine-structure states. The best-studied case, after that of PHL 957, is 4C 05. 34, which has (Lynds and Wills 1970; Lynds 1971; Bahcall and Goldsmith 1971) an emission redshift of 2.88 and several absorption redshifts larger than 2. Transitions from the ground fine-structure states of C II, N II, Si II, Fe II, and Fe III were among the identified lines in, for example, the eight redshift systems accepted by Bahcall and Goldsmith (1971). No lines from excited fine-structure states were definitely identified (occasional accidental coincidences are expected), in agreement with the temperature limits in equation (2). Detailed studies of the absorption spectra of this and other large-redshift quasars may help establish more stringent limits on the intensity of the microwave background radiation at large z.

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