redshift z can be described by the usual linear perturbation of the cosmic number density,

$$n=n_0(1+z)^3[1+(1+y)/(1+z)] \tag{1}$$

where y is the redshift at which the density perturbation reaches unity.

Under these assumptions, the expectation value of the factor β by which the projected area of a galaxy increases due to an encounter is $\beta\propto r^{-2}v^{-1}\propto r^{-3/2}$, and because $r\propto n^{-1/3}$ we obtain

$$\beta=\varepsilon(n(z)/n_0)^{1/2}=\varepsilon(1+z)(2+y+z)^{1/2} \tag{2}$$

The parameter ε is estimated by noting that numerical simulations[13] give at least a fivefold area increase for a collision with a periapsis of a few galactic radii. Thus, if the mean distance between galaxies with a mass of 10^{41} kg is 1.5 Mpc, one has $\varepsilon\simeq 5(0.1/1.5)^{3/2}=0.07$. Observations of the interacting system M81/M82 show[14] a hydrogen envelope having a projected surface area of about 10 times the combined Holmberg areas of the individual galaxies. This suggests $\varepsilon\simeq 0.2$, but the collision may be atypical. With equation (2), the probability P that the line of sight from us to a QSO with redshift z cuts a galaxy or a tidal extension is given by

$$P\propto\int_0^z(1+z')(1+\beta(z'))\mathrm{d}z'$$

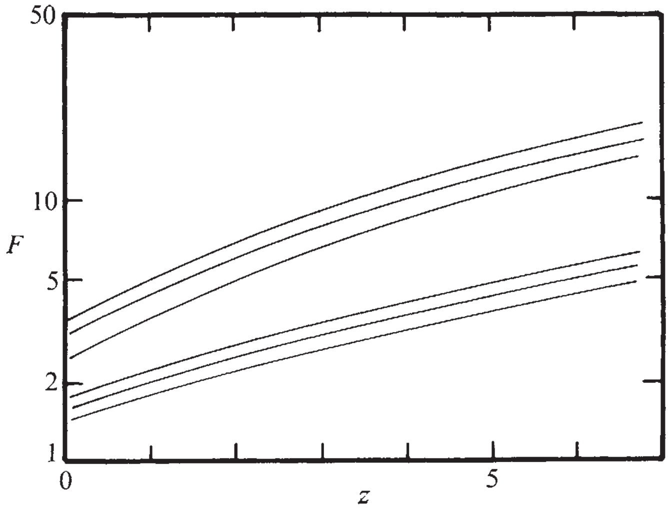
$$=\left[\tfrac{1}{2}(1+z')^2+\varepsilon\tfrac{2}{3}(2+y+z')^{3/2}\left\{(1+z')^2-\tfrac{4}{5}(1+z')(2+y+z')+\right.\right.$$

$$\left.\left.+\tfrac{8}{35}(2+y+z')^2\right\}\right]_0^z \tag{3}$$

It has been assumed that $q_0=0$, which avoids complicated functions in (3) and is for the present purposes sufficiently near the value $q_0=0.05$ that corresponds to the mean cosmic density implied above.

In Fig. 1 we have drawn the function (3) for $\varepsilon=0$ (see ref. 10) and in Fig. 2 the factor with which this must be multiplied to obtain the solution for various values of ε and y. This factor equals the relative proportion of lines due to bridges and tails of all absorption line systems. The optical depth[10] of the lines in absorption systems due to a bridge or a tail will be smaller than those due to galaxies proper. The ionisation state of the tidal extensions could be caused by the higher ultraviolet background radiation expected[7,8] at higher values of z. As appears from the figure, tidal extensions could contribute significantly to the interception cross section of galaxies at large redshifts.

Fig. 2 Factor F with which the number of intercepting galaxies expected for $q_0=0$ (see text) must be multiplied in order to obtain the number expected when tidal interaction is taken into account. Upper triple: tidal distortion parameter $\varepsilon=1$, lower triple $\varepsilon=0.3$. Of each triple, the upper curve has clustering parameter $y=4$, middle curve $y=2$, lower curve $y=0$.



Predictions of our model are (1) because the probability of tidal deformation increases with z, the fraction of QSOs with shallow absorption lines also increases with z, (2) the abundances of the absorbing atoms are typical for the interstellar medium: (3) absorption line splitting of the order of a few hundred kilometers per second (that is, the velocity at periapsis of slightly hyperbolic orbits) is possible, but the splitting should not be 'magic'. Observational tests on the basis of existing data are not yet possible for (1), confirm[1,2] (2) and are inconclusive[15] for (3). We feel that the third one is the acid test: it is, of course, a key prediction of our model that the absorption line splitting will not be constrained to certain 'magical' intervals in frequency.

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Theoretical maximum for energy from direct and diffuse sunlight

SCHEMES for the conversion of sunlight to useful (electrical, mechanical, chemical) energy all make use of the high spectral temperature of solar radiation relative to the terrestrial ambiance. Some schemes, but not others, also make use of the high directivity of the solar flux. For example, focusing mirror arrays require direct sunlight, while photovoltaic devices are indifferent to the directness or diffuseness of light of a given intensity. In biological systems, photosynthesis evidently makes little use of sunlight directivity, since it is not observed to depend strongly on plant orientation on angular scales as small as half a degree (the size of the Sun); on the other hand, Kevan[1] reports some heliotropic, arctic flowers whose corollas are nearly paraboloidal and focus direct (but not diffuse) radiation on the sporophylls.

The maximum thermodynamic efficiency permitted for extracting energy from direct sunlight must be higher than that permitted for diffuse sunlight of the same intensity, since loss of directivity is evidently an irreversible process. But what are the numerical values of these two maximum efficiencies? Are they different enough to justify *a priori* a concentration of effort by man or plant on the exploitation of direct solar radiation only? These are the questions to be considered briefly here, somewhat more specifically than can be found in the literature[2,3]. The answers are in some ways surprising. For example, neither direct nor diffuse light yields the efficiency formula $(T_{\odot}-T_{\odot})/T_{\odot}$ that one might naively expect (where $T_\odot$ is the equivalent black-body solar temperature, ~5,800 K, T_e is the ambient temperature on Earth, ~300 K.

We take the input thermodynamic system to be a volume sample of the ambient radiation field at the Earth's surface, including fluxes from the Sun, sky and ambient surroundings. Per unit volume suppose that this radiation field has energy E and entropy S. Since a black-body (maximum entropy) distribution has an energy density $a(S/(4/3)a)^{4/3}$, an amount of work equal to $E - a(S/(4/3)a)^{4/3}$ can be extracted isentropically, leaving a black-body distribution of temperature $T_\star = (S/(4/3)a)^{1/3}$. (Here a is the usual radiation constant.) Adiabatic expansion or contraction of the unit volume now extracts further work, until the radiation temperature is brought to equilibrium with the ambient temperature T_e. This amount of work is easily computed to be $aT_\star^4 + (1/3)aT_e^4 - (4/3)aT_\star^3 T_e$. The total useful work is thus

$$R = E - ST_e + \frac{1}{3}aT_e^4 = G(T_e) \quad (1)$$

where $G(T_e)$ is the Gibbs free energy[4] of the original unit volume evaluated relative to the ambient temperature T_e and its external radiation pressure $(1/3)aT_e^4$.

We must now compute S and E for the examples of interest: If $N\mathrm{d}\nu\mathrm{d}\Omega$ is defined to be the volume density of photons in a frequency interval $\mathrm{d}\nu$ and solid angle $\mathrm{d}\Omega$, then (taking units with $c = 1$),

$$E = \int Nh\nu \,\mathrm{d}\nu\mathrm{d}\Omega$$

$$S = \iint\left[2\nu^2 \ln\left(1+\frac{N}{2\nu^2}\right) + N \ln\left(1+\frac{2\nu^2}{N}\right)\right]\mathrm{d}\nu\mathrm{d}\Omega \quad (2)$$

The integration extends over all angles, and from 0 to ∞ in ν. Equation (2) goes back to Planck[5] and others[6].

Equations (2) and (1) could now be evaluated numerically using the empirically known radiation field near the Earth. A useful approximation, however, is to idealise the field as the sum of various, possibly diluted, black-body contributions. Such a flux with dilution factor ε has $N = 2\varepsilon\nu^2/(\exp(h\nu/kT)-1)$, and if it is from solid angle ω, then the integrals (2) can be done by computer and expressed as an accurate numerical approximation:

$$E = aT^4(\omega/4\pi)\varepsilon \quad (3)$$

$$S = (4/3)aT^3(\omega/4\pi)\varepsilon(0.9652 - 0.2777\ln\varepsilon - (0.0348 + f(\varepsilon))\varepsilon)$$

where $f(\varepsilon)$ is a smooth function which can be neglected for $\varepsilon < 0.01$; $f(1) = 0$, $f(0.1) = 0.0114$, $f(0.01) = 0.012$.

Consider now direct sunlight: The solar black-body contribution is undiluted at temperature $T_\odot$ and occupies a fractional solid angle $\omega/4\pi = 5.4\times10^{-6} \equiv \delta$ (the size of the Sun in the sky). The remaining solid angle is approximately a black-body of temperature T_e, also undiluted. Combining equations (2) and (3) then gives

$$R = \delta a T_\odot^4\left[1 - \frac{4}{3}\frac{T_e}{T_\odot} + \frac{1}{3}\frac{T_e^4}{T_\odot^4}\right] \quad (4)$$

The term in square brackets is seen to be the optimal efficiency, and it has a numerical value 0.93 for $T_\odot = 5,800$ K, $T_e = 300$ K. Next consider diffuse sunlight of intensity identical to the above. Here we set $\omega/4\pi = 1$ for both solar and ambient components, but set ε, the dilution factor, to δ for the solar contribution, and $\varepsilon = 1 - \delta$ for the ambient contribution. Now equations (2) and (3) combine to give (for $1 \gg \delta \gg \exp[-T_\odot/T_e]$)

$$R = \delta a T_\odot^4\left[1 - \frac{4}{3}\left(0.9652 - 0.2777\ln\delta\right)\frac{T_e}{T_\odot} + O\left(\frac{T_e^4}{T_\odot^4}\right)\right] \quad (5)$$

The numerical value of the bracketed efficiency coefficient is here 0.70. Diffuse sunlight, then (or direct sunlight with a conversion scheme which does not make use of its directivity), allows about 25% less conversion of energy. This is not simply the geometrical effect of increased flux on to a normal surface (the radiation being sampled on a volume basis), nor is it the effect of a lower total flux which is the general concomitant of diffuse radiation (since we have equalised the intensities in the above calculation); rather it is a consequence of the fundamentally greater entropy in the diffuse radiation, hence its smaller free energy.

To decide whether this is an important efficiency difference, we can note that even on a cloudless day with the Sun directly overhead, of order 20% of the total solar flux is diffuse, and an average temperate cloud cover raises this fraction towards unity with 60% typical[7]. One concludes that any scheme for using diffuse sunlight at near-maximum efficiency (and direct sunlight therefore at an automatic sacrifice of only ~25%), should dominate a scheme which optimises for direct flux (and, for example, with focusing mirrors, sacrifices diffuse radiation almost completely).

In a sense, we were anticipated in this conclusion by the evolutionary experience of natural plants. The advantage of a differently "designed" photosynthesis at the photomolecular level, one which might use the directionality of the solar radiation on angular scale ~0.5°, does not seem to have been sufficient to have driven terrestrial evolution in this direction. One is left to speculate about whether exobiological evolution under different conditions might be able to find a different chemistry for photosynthesis, one which uses the free energy of directionality in addition to (or instead of!) the free energy of spectral temperature.

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Reduction of visibility by sulphates in photochemical smog

THE relationship between pollutant emissions and the optical haze characteristic of photochemical smog has proved difficult to unravel[1,2]. It is clear that material produced by reaction in the atmosphere is responsible for much of the deterioration in the optical environment, since the ambient aerosol scatters much more light at a given mass concentration than do the primary aerosols emitted by known sources[3,4]. Unfortunately, measurement of the scattering contributed by an individual product species is complicated by the fact that most of this secondary material is deposited on existing particles and