

# Distance measures in cosmology

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## 1 Introduction

In cosmology (or to be more specific, *cosmography*, the measurement of the Universe) there are many ways to specify the distance between two points, because in the expanding Universe, the distances between comoving objects are constantly changing, and Earth-bound observers look back in time as they look out in distance. The unifying aspect is that all distance measures somehow measure the separation between events on radial null trajectories, ie, trajectories of photons which terminate at the observer.

In this note, formulae for many different cosmological distance measures are provided. I treat the concept of “distance measure” very liberally, so, for instance, the lookback time and comoving volume are both considered distance measures. The bibliography of source material can be consulted for many of the derivations; this is merely a “cheat sheet.” Minimal *C* routines (KR) which compute all of these distance measures are available from the author upon request. Comments and corrections are highly appreciated, as are acknowledgments or citation in research that makes use of this summary or the associated code.

## 2 Cosmographic parameters

The *Hubble constant*  $H_0$  is the constant of proportionality between recession speed  $v$  and distance  $d$  in the expanding Universe;

$$v = H_0 d \tag{1}$$

The subscripted “0” refers to the present epoch because in general  $H$  changes with time. The dimensions of  $H_0$  are inverse time, but it is usually written

$$H_0 = 100 h \text{ km s}^{-1} \text{ Mpc}^{-1} \tag{2}$$

where  $h$  is a dimensionless number parameterizing our ignorance. (Word on the street is that  $0.6 < h < 0.9$ .) The inverse of the Hubble constant is the *Hubble time*  $t_H$

$$t_H \equiv \frac{1}{H_0} = 9.78 \times 10^9 h^{-1} \text{ yr} = 3.09 \times 10^{17} h^{-1} \text{ s} \tag{3}$$

and the speed of light  $c$  times the Hubble time is the *Hubble distance*  $D_H$

$$D_H \equiv \frac{c}{H_0} = 3000 h^{-1} \text{ Mpc} = 9.26 \times 10^{25} h^{-1} \text{ m} \tag{4}$$

These quantities set the scale of the Universe, and often cosmologists work in geometric units with  $c = t_H = D_H = 1$ .

The mass density  $\rho$  of the Universe and the value of the cosmological constant  $\Lambda$  are dynamical properties of the Universe, affecting the time evolution of the metric, but in these notes we will treat them as purely kinematic parameters. They can be made into dimensionless density parameters  $\Omega_M$  and  $\Omega_\Lambda$  by

$$\Omega_M \equiv \frac{8\pi G \rho_0}{3 H_0^2} \quad (5)$$

$$\Omega_\Lambda \equiv \frac{\Lambda c^2}{3 H_0^2} \quad (6)$$

(Peebles, 1993, pp 310–313), where the subscripted “0”s indicate that the quantities (which in general evolve with time) are to be evaluated at the present epoch. A third density parameter  $\Omega_k$  measures the “curvature of space” and can be defined by the relation

$$\Omega_M + \Omega_\Lambda + \Omega_k = 1 \quad (7)$$

These parameters completely determine the geometry of the Universe if it is homogeneous, isotropic, and matter-dominated. By the way, the critical density  $\Omega = 1$  corresponds to  $7.5 \times 10^{21} h^{-1} M_\odot D_H^{-3}$ , where  $M_\odot$  is the mass of the Sun.

Most believe that it is in some sense “unlikely” that all three of these density parameters be of the same order, and we know that  $\Omega_M$  is significantly larger than zero, so many guess that  $(\Omega_M, \Omega_\Lambda, \Omega_k) = (1, 0, 0)$ , with  $(\Omega_M, 1 - \Omega_M, 0)$  and  $(\Omega_M, 0, 1 - \Omega_M)$  tied for second place.<sup>1</sup> If  $\Omega_\Lambda = 0$ , then the *deceleration parameter*  $q_0$  is just half  $\Omega_M$ , otherwise  $q_0$  is not such a useful parameter. When I perform cosmographic calculations and I want to cover all the bases, I use the three world models

name	$\Omega_M$	$\Omega_\Lambda$
Einstein–de-Sitter	1	0
low density	0.05	0
high lambda	0.2	0.8

These three models push the observational limits in different directions. Some would say that all three of these models are already ruled out, the first by mass accounting, the second by anisotropies measured in the cosmic microwave background, and the third by lensing statistics. It is fairly likely that the true world model is somewhere in-between these (unless the  $\Omega_M, \Omega_\Lambda, \Omega_k$  parameterization is itself wrong).

### 3 Redshift

The *redshift*  $z$  of an object is the fractional doppler shift of its emitted light resulting from radial motion

$$z \equiv \frac{\nu_e}{\nu_o} - 1 = \frac{\lambda_o}{\lambda_e} - 1 \quad (8)$$

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<sup>1</sup>This sentence, unmodified from the first incarnation of these notes, can be used by historians of cosmology to determine, at least roughly, when they were written.

where  $\nu_o$  and  $\lambda_o$  are the observed frequency and wavelength, and  $\nu_e$  and  $\lambda_e$  are the emitted. In special relativity, redshift is related to radial velocity  $v$  by

$$1 + z = \sqrt{\frac{1 + v/c}{1 - v/c}} \quad (9)$$

where  $c$  is the speed of light. In general relativity, (9) is true in one particular coordinate system, but not any of the traditionally used coordinate systems. Many feel (partly for this reason) that it is wrong to view relativistic redshifts as being due to radial velocities at all (eg, Harrison, 1993). I do not agree. On the other hand, redshift is directly observable and radial velocity is not; these notes concentrate on observables.

The difference between an object's measured redshift  $z_{\text{obs}}$  and its *cosmological redshift*  $z_{\text{cos}}$  is due to its (radial) *peculiar velocity*  $v_{\text{pec}}$ ; ie, we define the cosmological redshift as that part of the redshift due solely to the expansion of the Universe, or *Hubble flow*. The peculiar velocity is related to the redshift difference by

$$v_{\text{pec}} = c \frac{(z_{\text{obs}} - z_{\text{cos}})}{(1 + z)} \quad (10)$$

where I have assumed  $v_{\text{pec}} \ll c$ . This can be derived from (9) by taking the derivative and using the special relativity formula for addition of velocities. From here on, we assume  $z = z_{\text{cos}}$ .

For small  $v/c$ , or small distance  $d$ , in the expanding Universe, the velocity is linearly proportional to the distance (and all the distance measures, eg, angular diameter distance, luminosity distance, etc, converge)

$$z \approx \frac{v}{c} = \frac{d}{D_{\text{H}}} \quad (11)$$

where  $D_{\text{H}}$  is the Hubble distance defined in (4). But this is *only true for small redshifts!* It is important to note that many galaxy redshift surveys, when presenting redshifts as radial velocities, *always* use the non-relativistic approximation  $v = cz$ , even when it may not be physically appropriate (eg, Fairall 1992).

In terms of cosmography, the cosmological redshift is directly related to the scale factor  $a(t)$ , or the “size” of the Universe. For an object at redshift  $z$

$$1 + z = \frac{a(t_o)}{a(t_e)} \quad (12)$$

where  $a(t_o)$  is the size of the Universe at the time the light from the object is observed, and  $a(t_e)$  is the size at the time it was emitted.

Redshift is almost always determined with respect to us (or the frame centered on us but stationary with respect to the microwave background), but it is possible to define the redshift  $z_{12}$  between objects 1 and 2, both of which are cosmologically redshifted relative to us: the redshift  $z_{12}$  of an object at redshift  $z_2$  relative to a hypothetical observer at redshift  $z_1 < z_2$  is given by

$$1 + z_{12} = \frac{a(t_1)}{a(t_2)} = \frac{1 + z_2}{1 + z_1} \quad (13)$$

## 4 Comoving distance (line-of-sight)

A small *comoving distance*  $\delta D_C$  between two nearby objects in the Universe is the distance between them which remains constant with epoch if the two objects are moving with the Hubble flow. In other words, it is the distance between them which would be measured with rulers at the time they are being observed (the *proper distance*) divided by the ratio of the scale factor of the Universe then to now; it is the proper distance multiplied by  $(1+z)$ . The total line-of-sight comoving distance  $D_C$  from us to a distant object is computed by integrating the infinitesimal  $\delta D_C$  contributions between nearby events along the radial ray from  $z=0$  to the object.

Following Peebles (1993, pp 310–321) (who calls the transverse comoving distance by the confusing name “angular size distance,” which is *not* the same as “angular diameter distance” introduced below), we define the function

$$E(z) \equiv \sqrt{\Omega_M (1+z)^3 + \Omega_k (1+z)^2 + \Omega_\Lambda} \quad (14)$$

which is proportional to the time derivative of the logarithm of the scale factor (ie,  $\dot{a}(t)/a(t)$ ), with  $z$  redshift and  $\Omega_M$ ,  $\Omega_k$  and  $\Omega_\Lambda$  the three density parameters defined above. (For this reason,  $H(z) = H_0 E(z)$  is the Hubble constant as measured by a hypothetical astronomer working at redshift  $z$ .) Since  $dz = da$ ,  $dz/E(z)$  is proportional to the time-of-flight of a photon traveling across the redshift interval  $dz$ , divided by the scale factor at that time. Since the speed of light is constant, this is a proper distance divided by the scale factor, which is the definition of a comoving distance. The total line-of-sight comoving distance is then given by integrating these contributions, or

$$D_C = D_H \int_0^z \frac{dz'}{E(z')} \quad (15)$$

where  $D_H$  is the Hubble distance defined by (4).

In some sense the line-of-sight comoving distance is the fundamental distance measure in cosmography since, as will be seen below, all others are quite simply derived in terms of it. The line-of-sight comoving distance between two nearby events (ie, close in redshift or distance) is the distance which we would measure locally between the events today if those two points were locked into the Hubble flow. It is the correct distance measure for measuring aspects of large-scale structure imprinted on the Hubble flow, eg, distances between “walls.”

## 5 Comoving distance (transverse)

The comoving distance between two events at the same redshift or distance but separated on the sky by some angle  $\delta\theta$  is  $D_M \delta\theta$  and the transverse comoving distance  $D_M$  (so-denoted for a reason explained below) is simply related to the line-of-sight comoving distance  $D_C$ :

$$D_M = \begin{cases} D_H \frac{1}{\sqrt{\Omega_k}} \sinh \left[ \sqrt{\Omega_k} D_C / D_H \right] & \text{for } \Omega_k > 0 \\ D_C & \text{for } \Omega_k = 0 \\ D_H \frac{1}{\sqrt{|\Omega_k|}} \sin \left[ \sqrt{|\Omega_k|} D_C / D_H \right] & \text{for } \Omega_k < 0 \end{cases} \quad (16)$$

where the trigonometric functions  $\sinh$  and  $\sin$  account for what is called “the curvature of space.” (Space curvature is not coordinate-free; a change of coordinates makes space flat; the only coordinate-free curvature is space–time curvature, which is related to the local mass–energy density or really stress–energy tensor.) For  $\Omega_\Lambda = 0$ , there is an analytic solution to the equations

$$D_M = D_H \frac{2 [2 - \Omega_M (1 - z) - (2 - \Omega_M) \sqrt{1 + \Omega_M z}]}{\Omega_M^2 (1 + z)} \text{ for } \Omega_\Lambda = 0 \quad (17)$$

(Weinberg, 1972, p. 485; Peebles, 1993, pp 320–321). Some (eg, Weedman, 1986, pp 59–60) call this distance measure “proper distance,” which, though common usage, is bad style.<sup>2</sup>

(Although these notes follow the Peebles derivation, there is a qualitatively distinct method using what is known as the *development angle*  $\chi$ , which increases as the Universe evolves. This method is generally preferred by relativists; eg, Misner, Thorne & Wheeler 1973, pp 782–785).

The comoving distance happens to be equivalent to the *proper motion distance* (hence the name  $D_M$ ), defined as the ratio of the actual transverse velocity (in distance over time) of an object to its proper motion (in radians per unit time) (Weinberg, 1972, pp 423–424). The proper motion distance is plotted in Figure 1. Proper motion distance is used, for example, in computing radio jet velocities from knot motion.

## 6 Angular diameter distance

The *angular diameter distance*  $D_A$  is defined as the ratio of an object’s physical transverse size to its angular size (in radians). It is used to convert angular separations in telescope images into proper separations at the source. It is famous for not increasing indefinitely as  $z \rightarrow \infty$ ; it turns over at  $z \sim 1$  and thereafter more distant objects actually appear larger in angular size. Angular diameter distance is related to the transverse comoving distance by

$$D_A = \frac{D_M}{1 + z} \quad (18)$$

(Weinberg, 1972, pp 421–424; Weedman, 1986, pp 65–67; Peebles, 1993, pp 325–327). The angular diameter distance is plotted in Figure 2. At high redshift, the angular diameter distance is such that 1 arcsec is on the order of 5 kpc.

There is also an angular diameter distance  $D_{A12}$  between two objects at redshifts  $z_1$  and  $z_2$ , frequently used in gravitational lensing. It is *not* found by subtracting the two individual angular diameter distances! The correct formula, for  $\Omega_k \geq 0$ , is

$$D_{A12} = \frac{1}{1 + z_2} \left[ D_{M2} \sqrt{1 + \Omega_k \frac{D_{M1}^2}{D_H^2}} - D_{M1} \sqrt{1 + \Omega_k \frac{D_{M2}^2}{D_H^2}} \right] \quad (19)$$

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<sup>2</sup>The word “proper” has a specific use in relativity. The *proper time* between two nearby events is the time delay between the events in the frame in which they take place at the same location, and the *proper distance* between two nearby events is the distance between them in the frame in which they happen at the same time. In the cosmological context, it is the distance measured by a ruler at the time of observation. The transverse comoving distance  $D_M$  is *not* a proper distance—it is a proper distance divided by a ratio of scale factors.

where  $D_{M1}$  and  $D_{M2}$  are the transverse comoving distances to  $z_1$  and  $z_2$ ,  $D_H$  is the Hubble distance, and  $\Omega_k$  is the curvature density parameter (Peebles, 1993, pp 336–337). Unfortunately, the above formula is *not correct* for  $\Omega_k < 0$  (Phillip Helbig, 1998, private communication).

## 7 Luminosity distance

The *luminosity distance*  $D_L$  is defined by the relationship between bolometric (ie, integrated over all frequencies) flux  $S$  and bolometric luminosity  $L$ :

$$D_L \equiv \sqrt{\frac{L}{4\pi S}} \quad (20)$$

It turns out that this is related to the transverse comoving distance and angular diameter distance by

$$D_L = (1+z) D_M = (1+z)^2 D_A \quad (21)$$

(Weinberg, 1972, pp 420–424; Weedman, 1986, pp 60–62). The latter relation follows from the fact that the surface brightness of a receding object is reduced by a factor  $(1+z)^{-4}$ , and the angular area goes down as  $D_A^{-2}$ . The luminosity distance is plotted in Figure 3.

If the concern is not with bolometric quantities but rather with differential flux  $S_\nu$  and luminosity  $L_\nu$ , as is usually the case in astronomy, then a correction, the *k-correction*, must be applied to the flux or luminosity because the redshifted object is emitting flux in a different band than that in which you are observing. The k-correction depends on the spectrum of the object in question, and is unnecessary only if the object has spectrum  $\nu L_\nu = \text{constant}$ . For any other spectrum the differential flux  $S_\nu$  is related to the differential luminosity  $L_\nu$  by

$$S_\nu = (1+z) \frac{L_{(1+z)\nu}}{L_\nu} \frac{L_\nu}{4\pi D_L^2} \quad (22)$$

where  $z$  is the redshift, the ratio of luminosities equalizes the difference in flux between the observed and emitted bands, and the factor of  $(1+z)$  accounts for the redshifting of the bandwidth. Similarly, for differential flux per unit wavelength,

$$S_\lambda = \frac{1}{(1+z)} \frac{L_{\lambda/(1+z)}}{L_\lambda} \frac{L_\lambda}{4\pi D_L^2} \quad (23)$$

(Peebles, 1993, pp 330–331; Weedman, 1986, pp 60–62). In this author’s opinion, the most natural flux unit is differential flux per unit log frequency or log wavelength  $\nu S_\nu = \lambda S_\lambda$  for which there is no redshifting of the bandpass so

$$\nu S_\nu = \frac{\nu_e L_{\nu_e}}{4\pi D_L^2} \quad (24)$$

where  $\nu_e = (1+z)\nu$  is the emitted frequency. These equations are straightforward to generalize to bandpasses of finite width.

The *apparent magnitude*  $m$  of an astronomical source in a photometric bandpass is defined to be the ratio of the apparent flux of that source to the apparent flux of the bright star

Vega, through that bandpass (*don't* ask me about “AB magnitudes”). The *distance modulus*  $DM$  is defined by

$$DM \equiv 5 \log \left( \frac{D_L}{10 \text{ pc}} \right) \quad (25)$$

because it is the magnitude difference between an object’s observed bolometric flux and what it would be if it were at 10 pc (this was once thought to be the distance to Vega). The distance modulus is plotted in Figure 4. The absolute magnitude  $M$  is the astronomer’s measure of luminosity, defined to be the apparent magnitude the object in question would have if it were at 10 pc, so

$$m = M + DM + K \quad (26)$$

where  $K$  is the k-correction

$$K = -2.5 \log \left[ (1+z) \frac{L_{(1+z)\nu}}{L_\nu} \right] = -2.5 \log \left[ \frac{1}{(1+z)} \frac{L_{\lambda/(1+z)}}{L_\lambda} \right] \quad (27)$$

(eg, Oke & Sandage, 1968).

## 8 Parallax distance

If it were possible to measure parallaxes for high redshift objects, the distance so measured would be the *parallax distance*  $D_P$  (Weinberg, 1972, pp 418–420). It may be possible, one day, to measure parallaxes to distant galaxies using gravitational lensing, although in these cases, a modified parallax distance is used which takes into account the redshifts of both the source and the lens (Schneider, Ehlers & Falco, 1992, pp 508–509), a discussion of which is beyond the scope of these notes.

## 9 Comoving volume

The *comoving volume*  $V_C$  is the volume measure in which number densities of non-evolving objects locked into Hubble flow are constant with redshift. It is the proper volume times three factors of the relative scale factor now to then, or  $(1+z)^3$ . Since the derivative of comoving distance with redshift is  $1/E(z)$  defined in (14), the angular diameter distance converts a solid angle  $d\Omega$  into a proper area, and two factors of  $(1+z)$  convert a proper area into a comoving area, the comoving volume element in solid angle  $d\Omega$  and redshift interval  $dz$  is

$$dV_C = D_H \frac{(1+z)^2 D_A^2}{E(z)} d\Omega dz \quad (28)$$

where  $D_A$  is the angular diameter distance at redshift  $z$  and  $E(z)$  is defined in (14) (Weinberg, 1972, p. 486; Peebles, 1993, pp 331–333). The comoving volume element is plotted in Figure 5. The integral of the comoving volume element from the present to redshift  $z$  gives

the total comoving volume, all-sky, out to redshift  $z$

$$V_C = \begin{cases} \left( \frac{4\pi D_H^3}{2\Omega_k} \right) \left[ \frac{D_M}{D_H} \sqrt{1 + \Omega_k \frac{D_M^2}{D_H^2}} - \frac{1}{\sqrt{|\Omega_k|}} \operatorname{arcsinh} \left( \sqrt{|\Omega_k|} \frac{D_M}{D_H} \right) \right] & \text{for } \Omega_k > 0 \\ \frac{4\pi}{3} D_M^3 & \text{for } \Omega_k = 0 \\ \left( \frac{4\pi D_H^3}{2\Omega_k} \right) \left[ \frac{D_M}{D_H} \sqrt{1 + \Omega_k \frac{D_M^2}{D_H^2}} - \frac{1}{\sqrt{|\Omega_k|}} \operatorname{arcsin} \left( \sqrt{|\Omega_k|} \frac{D_M}{D_H} \right) \right] & \text{for } \Omega_k < 0 \end{cases} \quad (29)$$

(Carroll, Press & Turner, 1992), where  $D_H^3$  is sometimes called the *Hubble volume*. The comoving volume element and its integral are both used frequently in predicting number counts or luminosity densities.

## 10 Lookback time

The *lookback time*  $t_L$  to an object is the difference between the age  $t_o$  of the Universe now (at observation) and the age  $t_e$  of the Universe at the time the photons were emitted (according to the object). It is used to predict properties of high-redshift objects with evolutionary models, such as passive stellar evolution for galaxies. Recall that  $E(z)$  is the time derivative of the logarithm of the scale factor  $a(t)$ ; the scale factor is proportional to  $(1+z)$ , so the product  $(1+z)E(z)$  is proportional to the derivative of  $z$  with respect to the lookback time, or

$$t_L = t_H \int_0^z \frac{dz'}{(1+z')E(z')} \quad (30)$$

(Peebles, 1993, pp 313–315; Kolb & Turner 1990, pp 52–56, give some analytic solutions to this equation, but they are concerned with the age  $t(z)$ , so they integrate from  $z$  to  $\infty$ ). The lookback time and age are plotted in Figure 6.

## 11 Probability of intersecting objects

Given a population of objects with comoving number density  $n(z)$  (number per unit volume) and cross section  $\sigma(z)$  (area), what is the incremental probability  $dP$  that a line of sight will intersect one of the objects in redshift interval  $dz$  at redshift  $z$ ? Questions of this form are asked frequently in the study of QSO absorption lines or pencil-beam redshift surveys. The answer is

$$dP = n(z) \sigma(z) D_H \frac{(1+z)^2}{E(z)} dz \quad (31)$$

(Peebles, 1993, pp 323–325). The dimensionless differential intersection probability is plotted in Figure 7.

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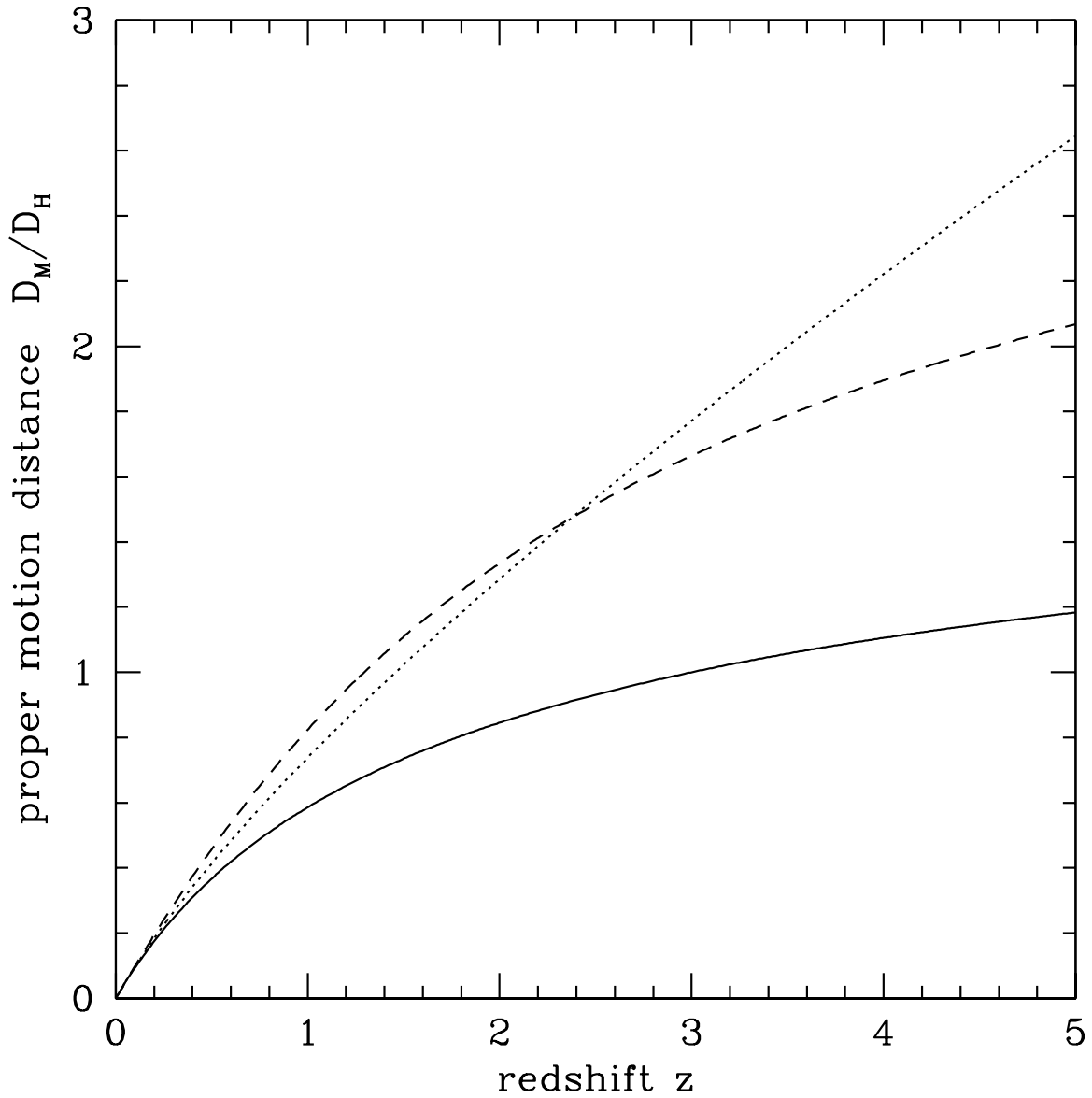


Figure 1: The dimensionless proper motion distance  $D_M/D_H$ . The three curves are for the three world models, Einstein-de Sitter ( $\Omega_M, \Omega_\Lambda = (1, 0)$ ), solid; low-density,  $(0.05, 0)$ , dotted; and high lambda,  $(0.2, 0.8)$ , dashed.

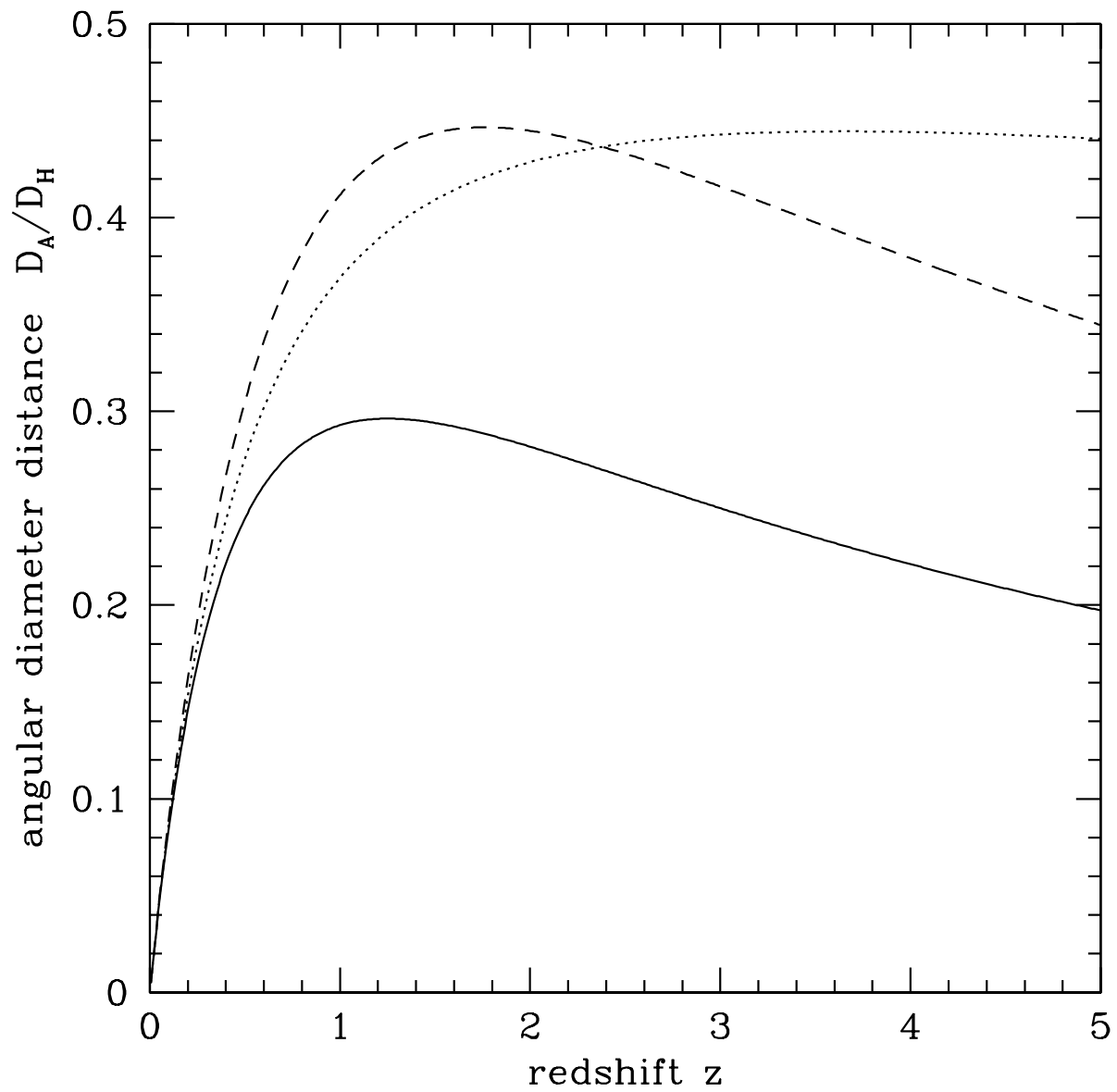


Figure 2: The dimensionless angular diameter distance  $D_A/D_H$ . The three curves are for the three world models,  $(\Omega_M, \Omega_\Lambda) = (1, 0)$ , solid;  $(0.05, 0)$ , dotted; and  $(0.2, 0.8)$ , dashed.

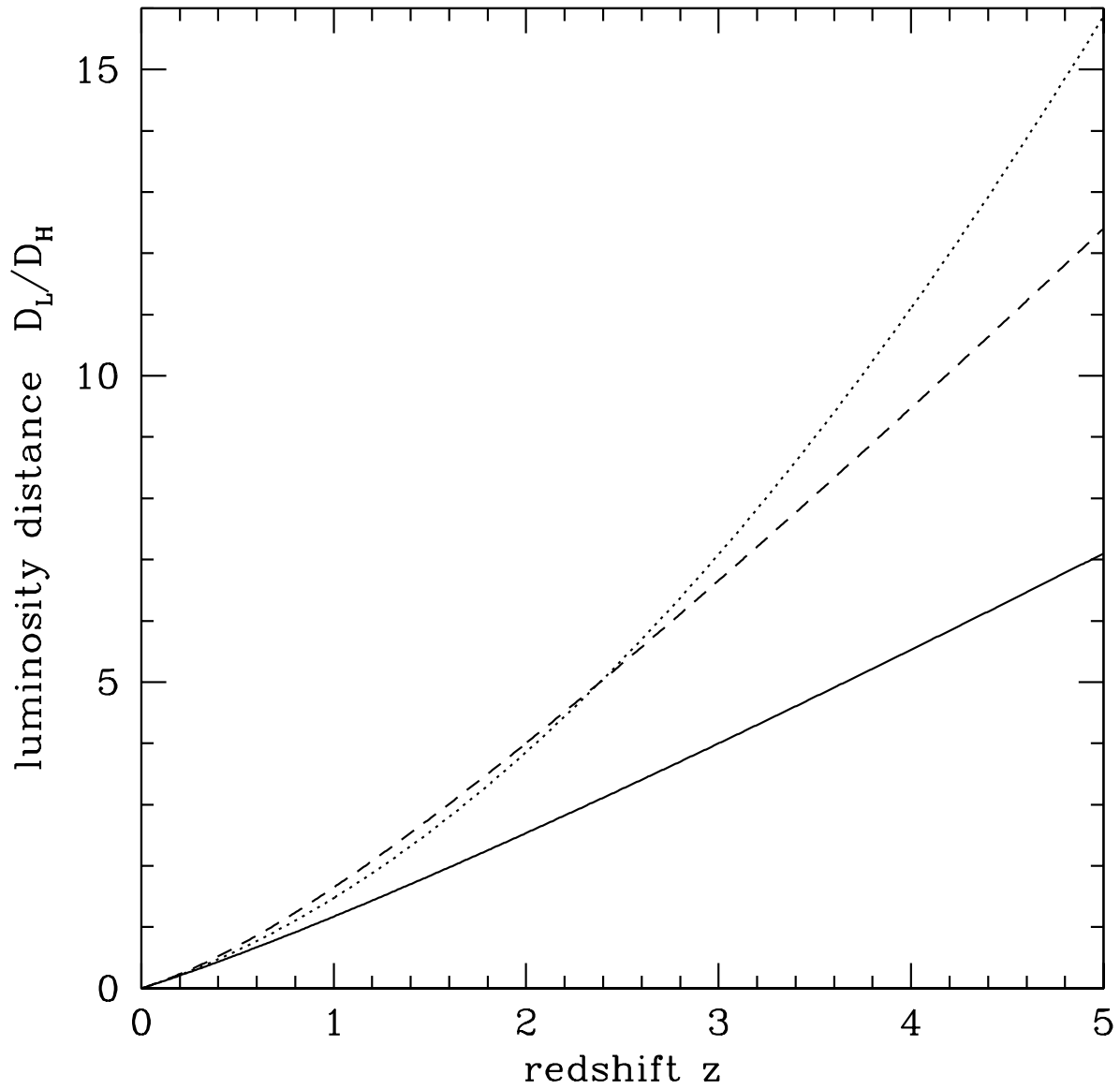


Figure 3: The dimensionless luminosity distance  $D_L/D_H$ . The three curves are for the three world models,  $(\Omega_M, \Omega_\Lambda) = (1, 0)$ , solid;  $(0.05, 0)$ , dotted; and  $(0.2, 0.8)$ , dashed.

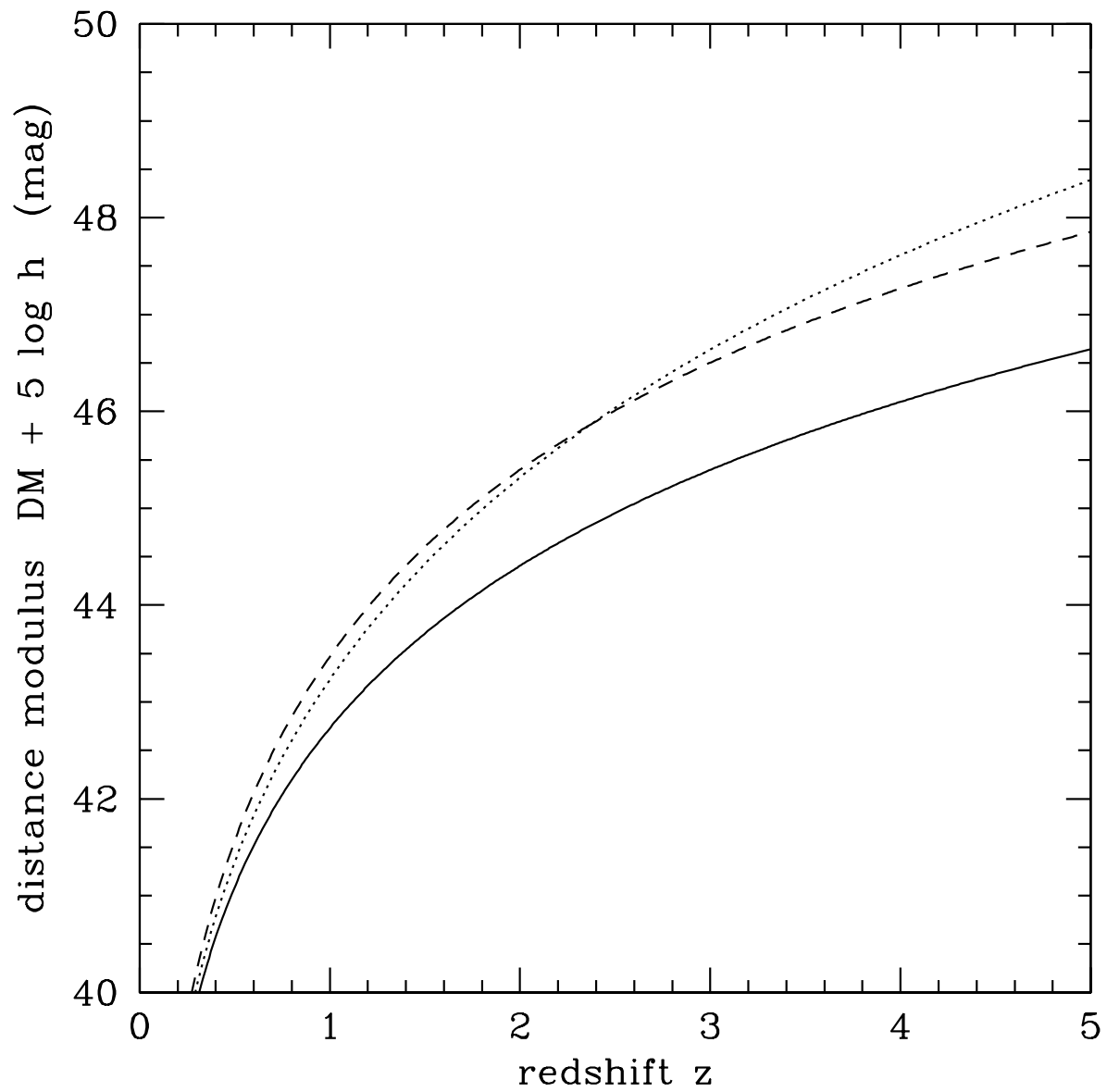


Figure 4: The distance modulus  $DM$ . The three curves are for the three world models,  $(\Omega_M, \Omega_\Lambda) = (1, 0)$ , solid;  $(0.05, 0)$ , dotted; and  $(0.2, 0.8)$ , dashed.

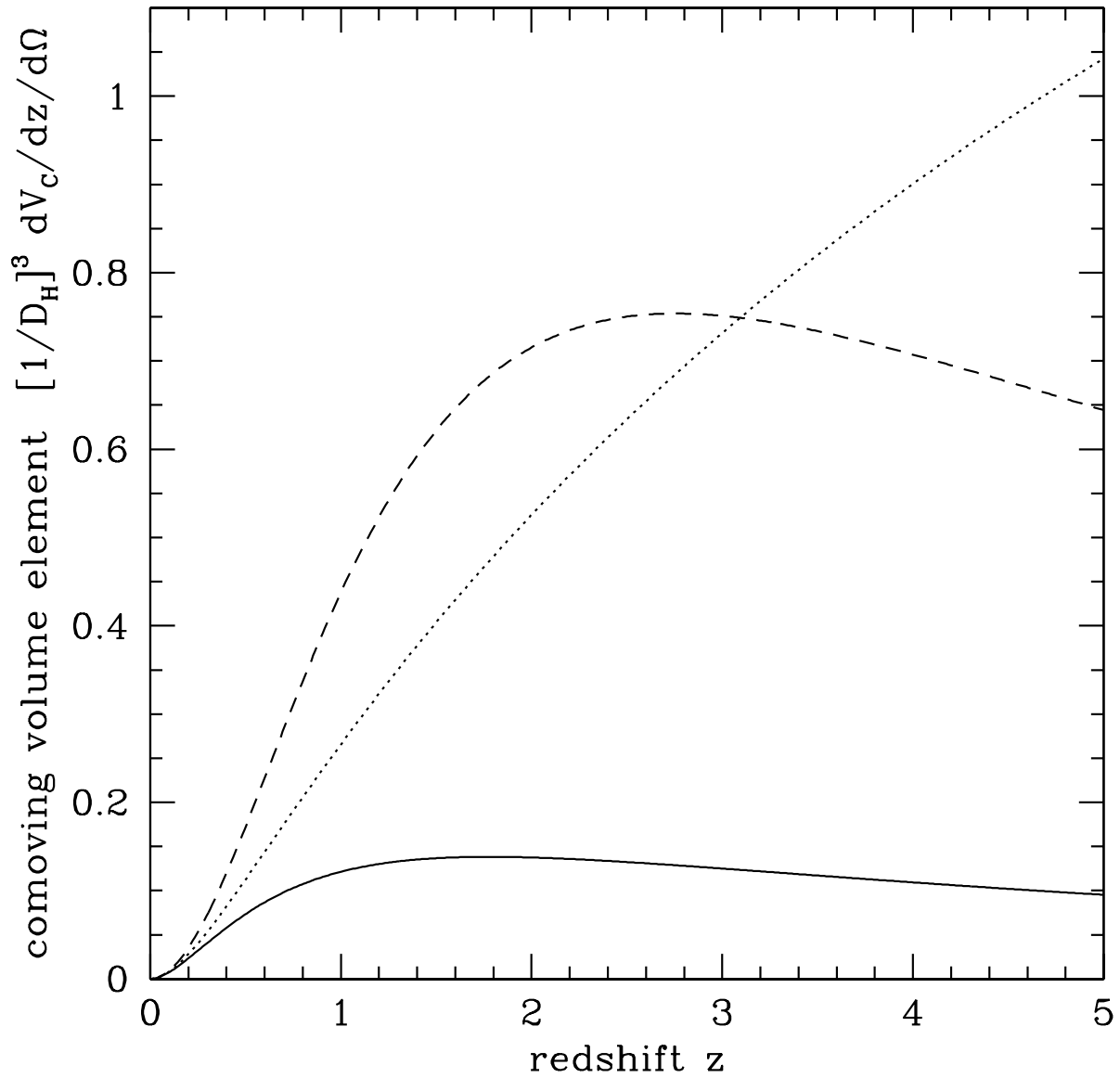


Figure 5: The dimensionless comoving volume element  $(1/D_H)^3 (dV_C/dz)$ . The three curves are for the three world models,  $(\Omega_M, \Omega_\Lambda) = (1, 0)$ , solid;  $(0.05, 0)$ , dotted; and  $(0.2, 0.8)$ , dashed.

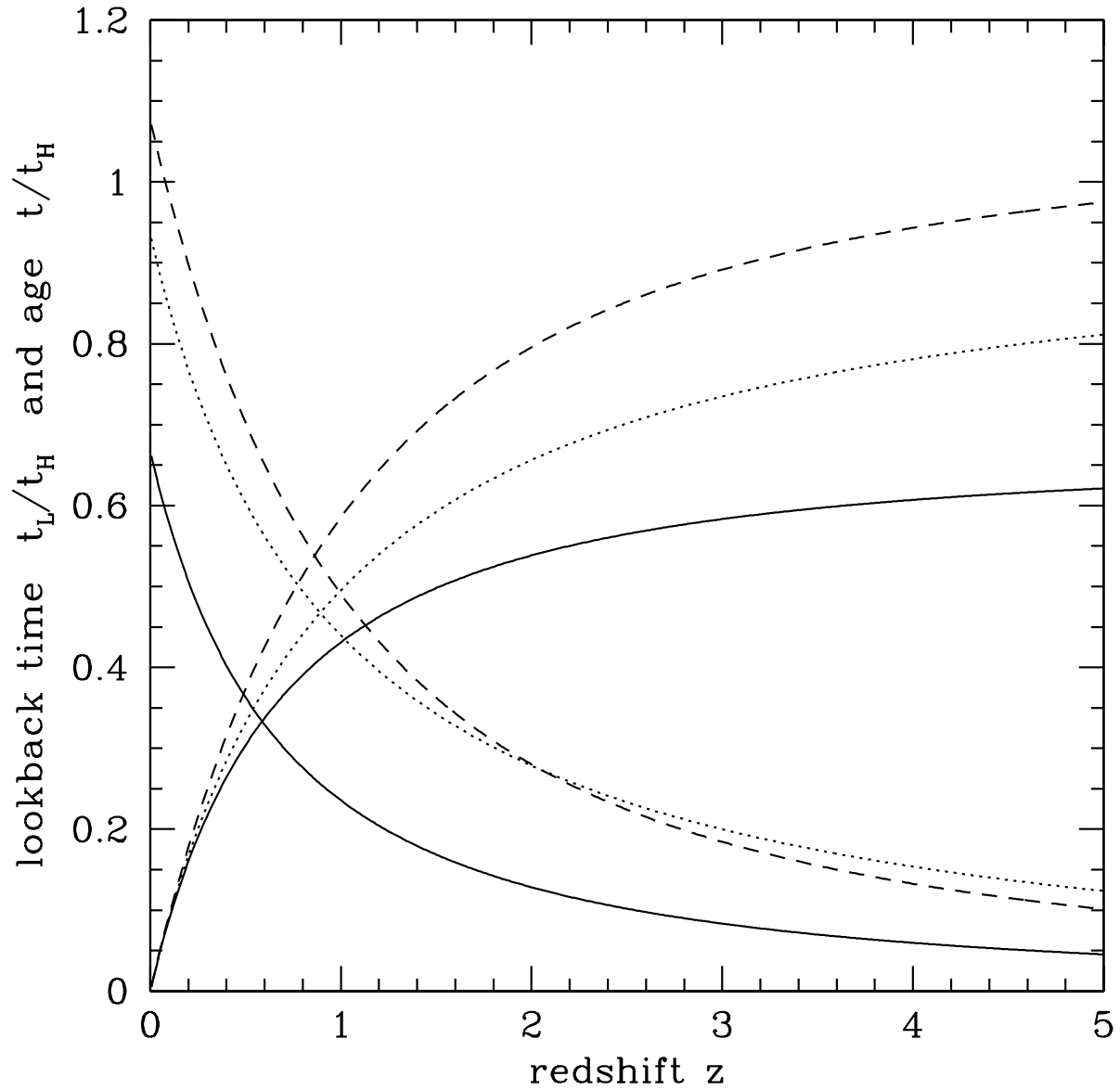


Figure 6: The dimensionless lookback time  $t_L/t_H$  and age  $t/t_H$ . Curves cross at the redshift at which the Universe is half its present age. The three curves are for the three world models,  $(\Omega_M, \Omega_\Lambda) = (1, 0)$ , solid;  $(0.05, 0)$ , dotted; and  $(0.2, 0.8)$ , dashed.

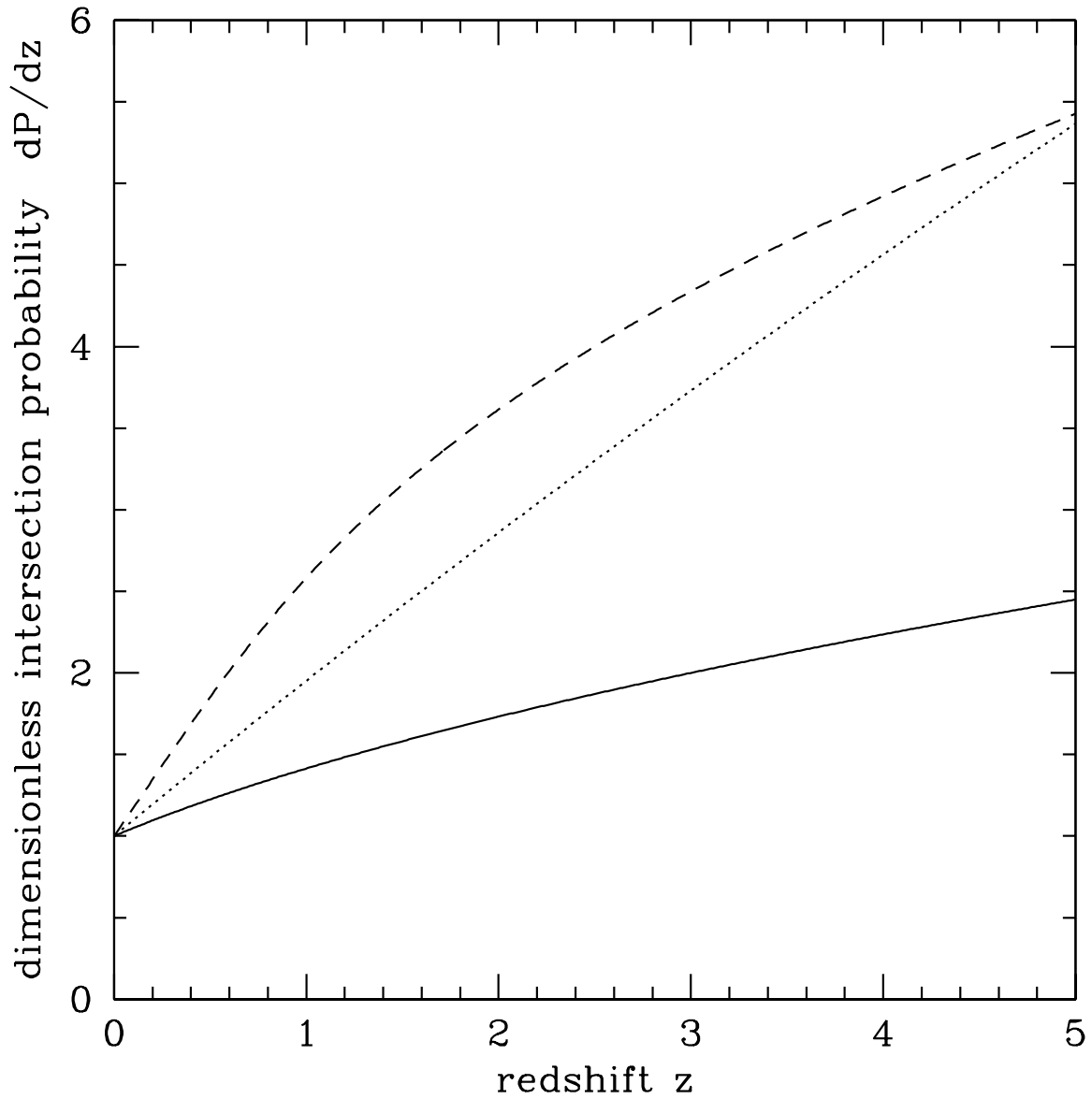


Figure 7: The dimensionless differential intersection probability  $dP/dz$ ; dimensionless in the sense of  $n(z)\sigma(z)D_H = 1$ . The three curves are for the three world models,  $(\Omega_M, \Omega_\Lambda) = (1, 0)$ , solid;  $(0.05, 0)$ , dotted; and  $(0.2, 0.8)$ , dashed.