most distant observable galaxies. Velocities are measured in kilometres per second and distances in megaparsecs, so it is convenient to express H_0 in the units km per s per Mpc. Hubble's own best estimate of H_0, given in 1935, was about 530, but we now accept that H_0 is much smaller than this, because, since 1935, estimates of the distances d of galaxies have increased. This revision of the distance scale has happened in many small steps over the intervening years, although the largest single change came in 1952 when Walter Baade realized that the Cepheid and RR Lyrae variable stars do not have the same period-luminosity relation. As a result of Baade's revision, the extragalactic distance scale was doubled, and, whereas before 1952 the Andromeda galaxy (M 31) was thought to be distinctly smaller than our Galaxy, since 1952 it has been known to be distinctly larger.

The use of the most modern instrumentation, especially CCD equipment (see page 235), has enabled us to observe even more distant galaxies and obtain their spectra. At the time of writing the most distant known galaxy (as distinct from a quasar) is one associated with the radio source 3C 324, where z is 1·21, but the vast majority of galaxies which can be studied easily have redshifts lower than 0·1.

The galaxian distance scale

Hubble's law relating distance to the observed redshift means that the scale of galaxian distances can be expressed by stating the numerical value of Hubble's constant H_0. However, to determine H_0 means determining the distances of a suitable sample of galaxies, and this is not easy. In fact, such astronomical distances must be determined step-by-step, starting with radar ranging of planets which gives the scale of the Solar System. Distances to nearby open clusters of stars may then be found using the cluster method (page 174), which leads to absolute magnitudes for main-sequence stars. We are then in a position to find distances for more distant open clusters which contain Cepheid variables, and this allows the Cepheid period-luminosity relation to be calibrated. This is important because Cepheids can be observed and used to establish distances to galaxies within about 4 Mpc. (See Fig. 7·4)

A recent systematic study to determine H_0 has been made by Allan Sandage and Gustav Tammann. They use Cepheid distances to determine the absolute diameters of the largest H II regions in the galaxies concerned, then, assuming that the diameters of large H II regions are much the same in different galaxies, distances to others can be found. It is a useful technique because H II region diameters can be measured out to about 25 Mpc. The next step is to use these H II region distances to find the absolute magnitude for Sc I galaxies; for, being of the same luminosity class, all Sc I galaxies have the same absolute magnitude. Finally, samples of more distant Sc I galaxies, whose distances are known from this absolute magnitude, are used to establish the relation between distance and redshift and so provide the value of H_0. According to Sandage and Tammann H_0 is 55 km per s per Mpc, with a probable error of ± 5 km per s per Mpc. (In this context, probable error is a measure of the internal consistency in a determination, and does not give the full range of possible inaccuracy of the result.)

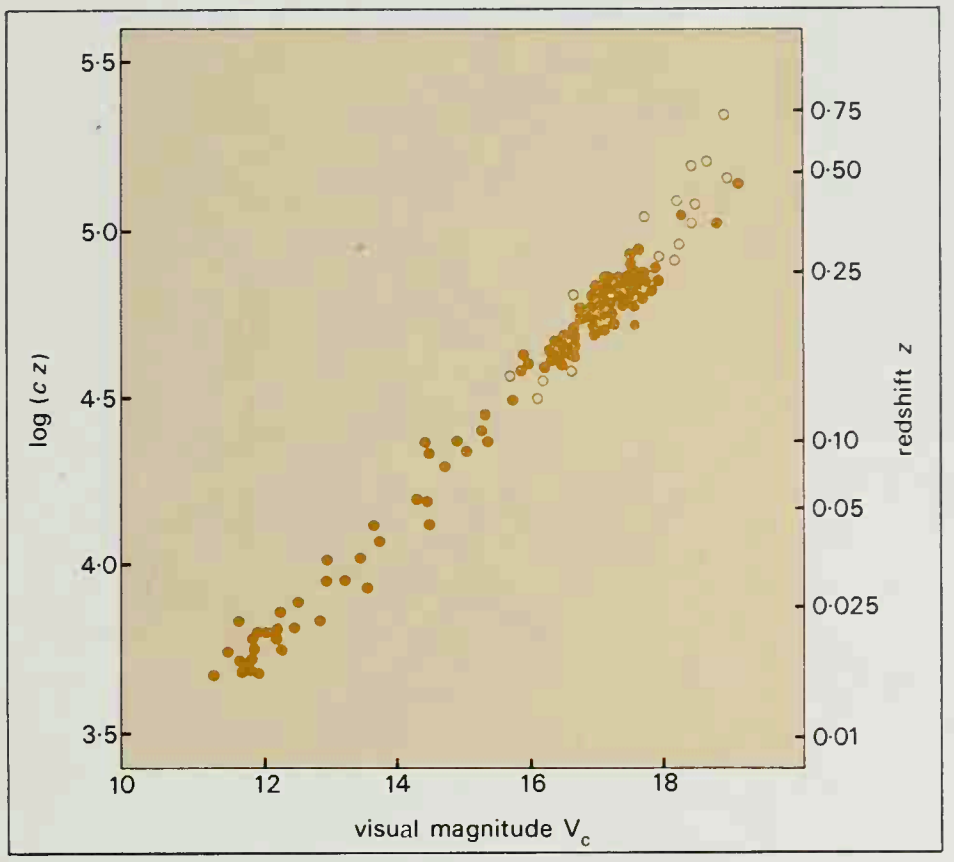

Fig. 7·3 above: The Hubble relation for the brightest galaxies in large clusters. z is the redshift and V_c is a corrected apparent visual magnitude. If it is assumed that all these galaxies have the same absolute magnitude, V_c is related to distance. The open circles come from more recent observations and suggest that for larger z the plot departs slightly from a straight line.

This is the best value available at present, in the sense of having the smallest probable error, and it is quite widely accepted, but some other recent determinations disagree with it. Certain details of the work have been questioned, and several other workers deduce that H_0 is about 77 km per s per Mpc, using the same observational data.

Alternative methods can be used at different stages in the determination. Cepheid calibrations can be confirmed and extended using novae, for which the absolute magnitude at maximum and the subsequent rate of decline in intensity are related, and bright