**The Acceleration of the Universe**

Values of the Hubble constant H0 measured in the 1920s and 1930s suggested the expansion rate of the universe is about 500 km/sec/Megaparsec. Refinements in our ability to measure H0 have improved our measurements since then. The most recent and best measurement now comes from the recently announced analysis of 15 months of data from ESA’s Planck satellite mission, which measures the intensity of the cosmic microwave background radiation around the sky. Planck data put the value of the Hubble constant at 67.8 ± 0.77 km/sec/Mpc.

The data in the table on the next page are measurements of the redshifts and distance moduli of Type Ia supernovae in distant galaxies. Remember that the recession velocity is not actually the velocity of the galaxy, but rather the factor by which space has expanded since the light we observe originally left the galaxy.

The distance modulus is just the difference between the apparent and absolute magnitude of each observed Type Ia supernova. Recall that Type Ia supernovae are standard candles, with an absolute magnitude of about -19. A distance modulus of 35 means that the apparent magnitude of the supernova was +16, easily observable with a mid-size research telescope.

The table on the left includes average values for large samples of supernovae out to redshifts up to z = v/c =1.0 (a distance of about 6 billion light years, or about 1.8 billion parsecs. The table on the left includes redshifts and distance moduli for individual galaxies at even larger redshifts (z > 1.0) and distances.

Plot the quantities in the tables onto the chart below it, plotting redshift (z) on the horizontal axis and galaxy distance modulus on the y-axis.

The dashed line in the chart is the expected curve for a simple, expanding model of the universe in which galaxies are slowing down due to the gravitational pull of matter in the universe.

A. Over what redshift range do the data follow the simple model of the universe shown by the dashed line?

B. At what redshift do the observed galaxy distance moduli begin to deviate clearly from the simple model shown by the dashed line?

C. At a redshift of 1.5, is a typical Type Ia supernova brighter or fainter than predicted by the simple model? (Think this through... Are the distance moduli larger or smaller than predicted by the simple model?) Does this mean the supernovae (and their host galaxies) at redshift z=2 closer or more distant than predicted by the simple model?

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| **Average Data for Type Ia Supernovae** **at z < 1** |  | **Data for Individual Type Ia Supernova** **at z >1** |
| **Redshift****(v/c)** | **Galaxy Distance Modulus (Megaparsecs)** |  | **Redshift****(v/c)** | **Galaxy Distance Modulus (Megaparsecs)** |
| 0.034 | 35.7 |  | 1.056 | 44.25 |
| 0.170 | 39.7 |  | 1.140 | 44.84 |
| 0.383 | 41.6 |  | 1.190 | 44.19 |
| 0.537 | 42.7 |  | 1.265 | 45.20 |
| 0.811 | 43.6 |  | 1.300 | 45.27 |
| 0.986 | 44.1 |  | 1.305 | 44.70 |
|  |  |  | 1.340 | 45.05 |
|  |  |  | 1.400 | 45.09 |
|  |  |  | 1.551 | 45.30 |
|  |  |  | 1.755 | 45.53 |