Astronomy 405: Introduction to cosmology
Section A01, Spring 2021

Jon Willis, Elliot 211, Tel. 721-7740, email: jwillis@uvic.ca

Website for lecture notes and assignments: http://www.astro.uvic.ca/~jwillis/Jon%20Willis%20Teaching.html

Lectures: Lectures will take place online on Mondays and Thursdays 10.00 – 11.20am. A private link will be emailed to all registered students before the start of the semester.

Office hours: Office hours will take place online and by request.

Course text: Introduction to cosmology by Barbara Ryden. See over for additional reading.

Course outline:

Topic	Description	Textbook
1	A mathematical model of the universe	Chapters 3 to 6 inclusive
2	Measuring the universe	Chapter 7
3	The cosmic microwave background	Chapter 9
4	Big Bang Nucleosynthesis	Chapter 10
5	Dark Matter in the universe	Chapter 8
6	Large-scale structure	Chapter 12
7	Lambda	Chapters 4 and 6

Course assessment:

Assignments:	15%
Mid-term exams:	15+15%
Final exam:	55%

Approximately six assignments will be issued through the semester. Assignments will typically be due one week after the issue date. Late assignments will not be accepted. The first mid-term exam will take place in class at 10am on Thursday February 11th, the second mid-term will take place in class at 10am on Monday March 22nd.

Use of calculators: On all examinations the only acceptable calculator is the Sharp EL-510R. This calculator can be bought in the Bookstore for about $10.
DO NOT bring any other calculator to examinations

Astronomy 405: Introduction to cosmology
Section A01, Spring 2021

Additional reading: not compulsory, just useful. All texts should be available in the UVic library

1) Carrol and Ostlie: An Introduction to Modern Astrophysics (excellent general textbook).

2) Peebles: Physical Cosmology (excellent general textbook).

3) Gunn, Longair and Rees: Observational Cosmology, 1978 Saas-Fe conference proceedings (good description of basic cosmological ideas, some sections are rather dated).

4) Rees: Perspectives in Astrophysical Cosmology (though not employed directly in the course, this book provides excellent additional reading).

5) Mo, van den Bosch and White: Galaxy formation and evolution. Very comprehensive graduate text.

6) Weinberg: The First Three Minutes (excellent reading material for early Universe physics).

7) Berry: Principles of Cosmology and Gravitation (a good introductory text for cosmology and GR).

1. A mathematical model of the universe

Properties of the observed universe:

1. The night sky is dark. Is the universe therefore bounded in space or time?
2. General relativity describes gravity accurately on Solar System scales.
3. The universe is expanding uniformly and isotropically according to Hubble's law. We assume that peculiar velocities can be described by local gravitational effects.
4. The Hubble time, H^{-1}, the ages of the oldest stars and the radioactive dating of terrestrial elements all approximately agree, i.e. of order a few billion years in each case.
5. The observed universe is isotropic on very large scales.
6. We observe a statistically isotropic background of microwave radiation with a blackbody spectrum of T = 2.73 K. The is the Cosmic Microwave Background (CMB).

Properties of the observed universe:

7. The observed abundance of H, He, Li (and their isotopes) agree with the predictions of nucleosynthetic reactions occurring within the early universe.

8. The present day universe is structured (galaxies, clusters, superclusters) - note that this point does not contradict point 5.

9. Dynamical, X-ray and gravitational lensing studies imply that most of the matter in the universe is dark.

10. The CMB displays temperature anisotropies or fluctuations of order $(dT/T) \sim 10^{-5}$ on scales of order one degree.

11. Observations of supernovae type 1a (SNe1a) and the CMB indicate that the universe is spatially flat and expanding at an accelerating rate.

Basic principles:

- The observed universe is isotropic.
- The cosmological principle (an extension of the Copernican principle) assumes that we occupy no special place in the universe.
- The combination of observed isotropy with the cosmological principle implies that the universe is homogeneous.

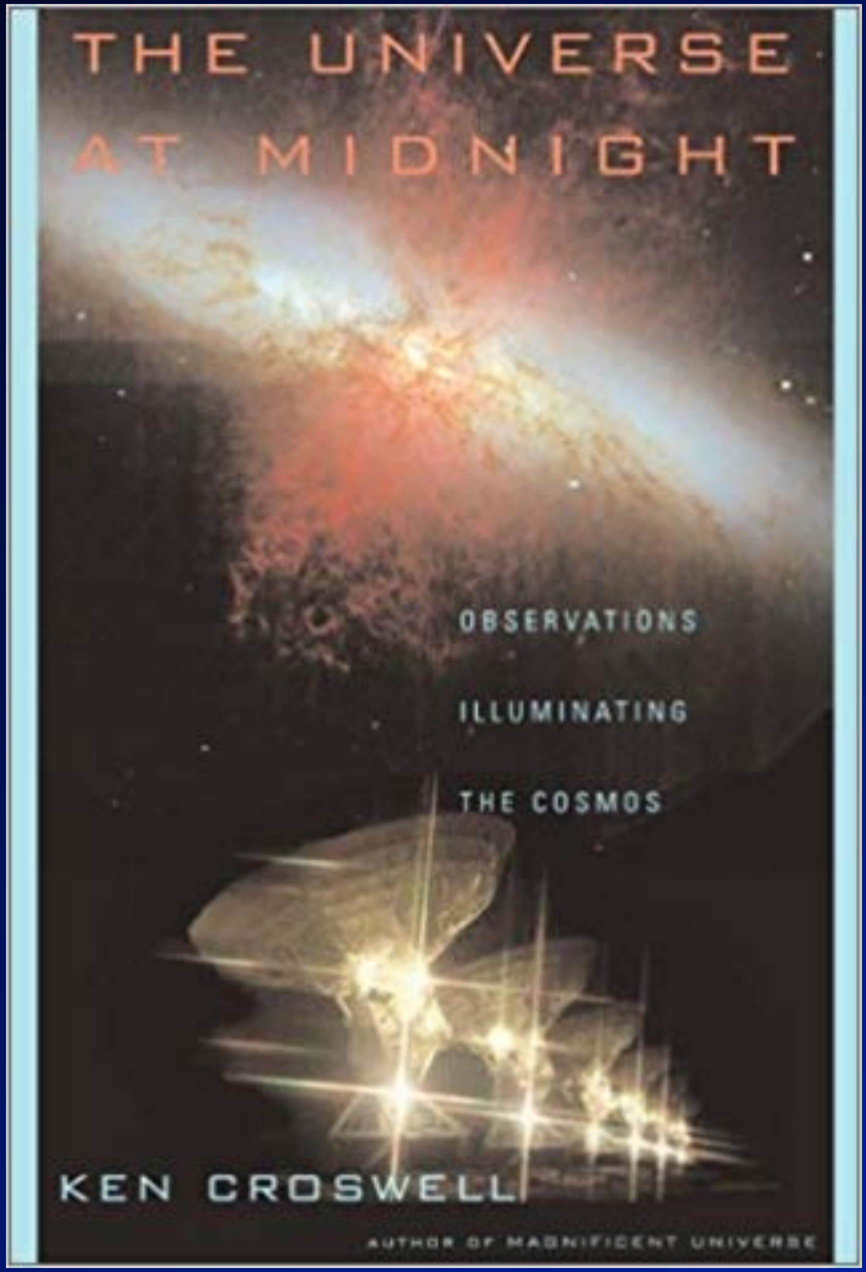
Understanding what the metric represents using Pythagoras' Theorem as an example

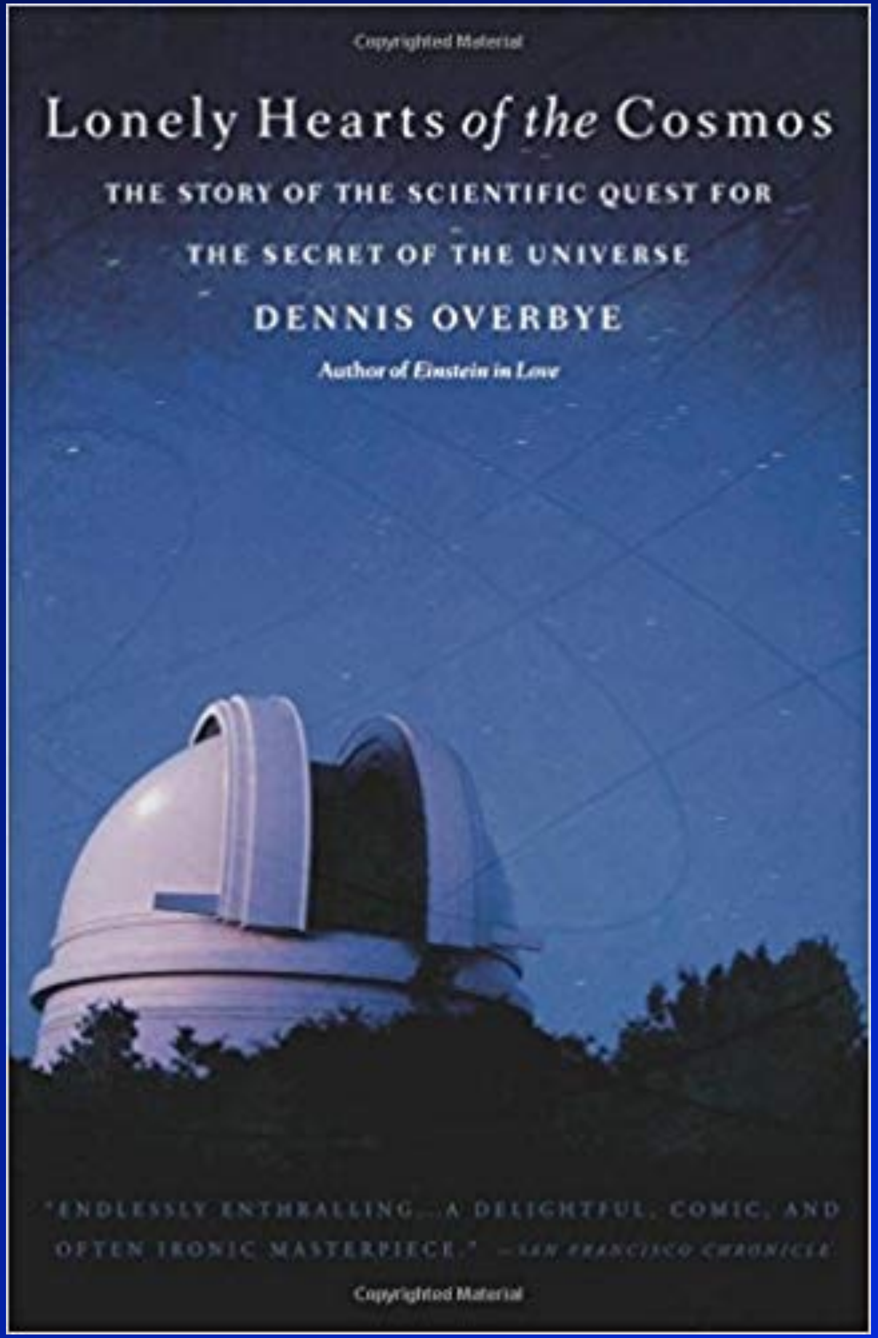
$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$

$$ds^2 = g_{\mu\mu}(dx^\mu)^2 + g_{\nu\nu}(dx^\nu)^2 + 2\, g_{\mu\nu} dx^\mu dx^\nu$$

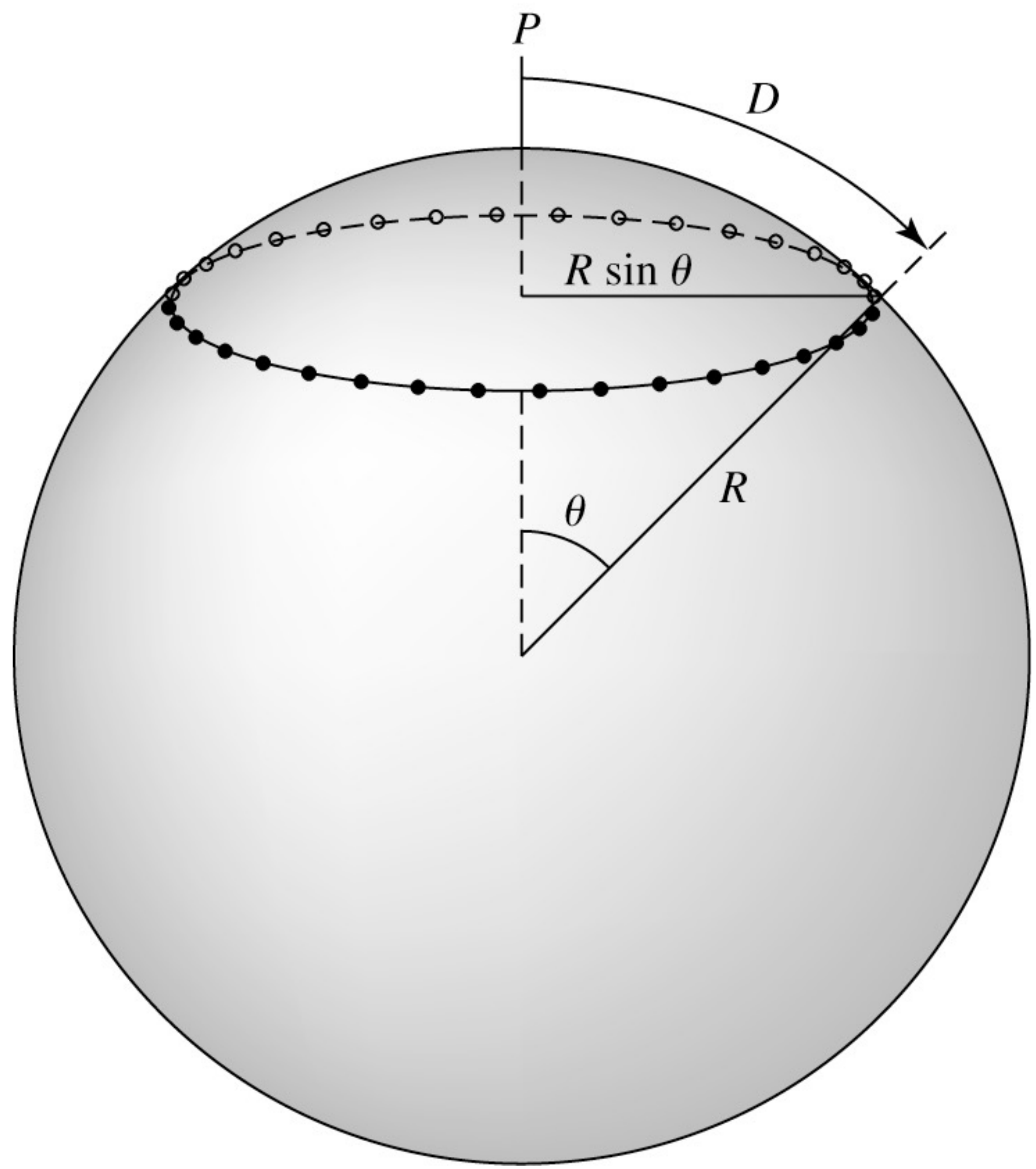
$$g_{\mu\mu} = 1; g_{\nu\nu} = 1; g_{\mu\nu} = 0; x^\mu = \text{“}x\text{”}; x^\nu = \text{“}y\text{”}$$

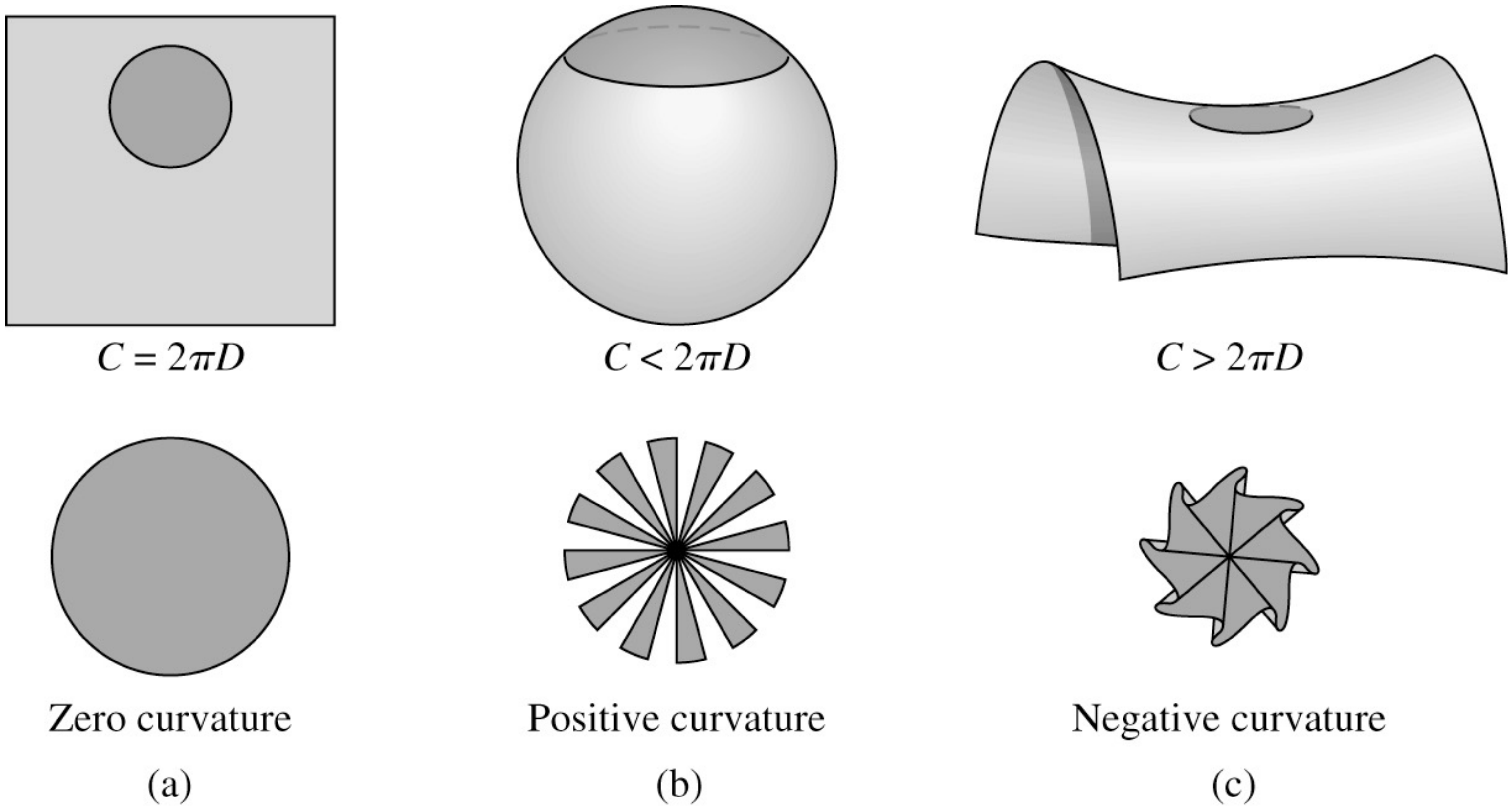
$$ds^2 = dx^2 + dy^2$$

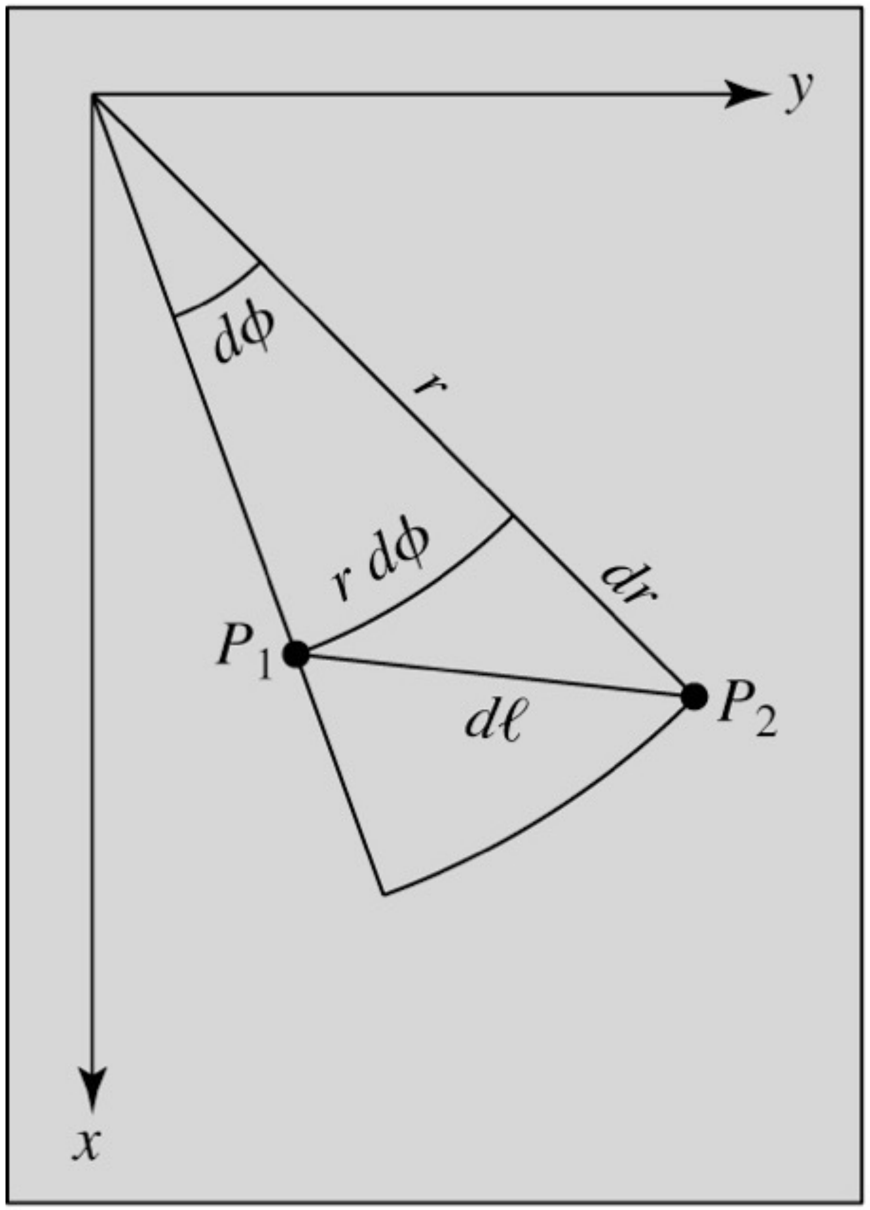




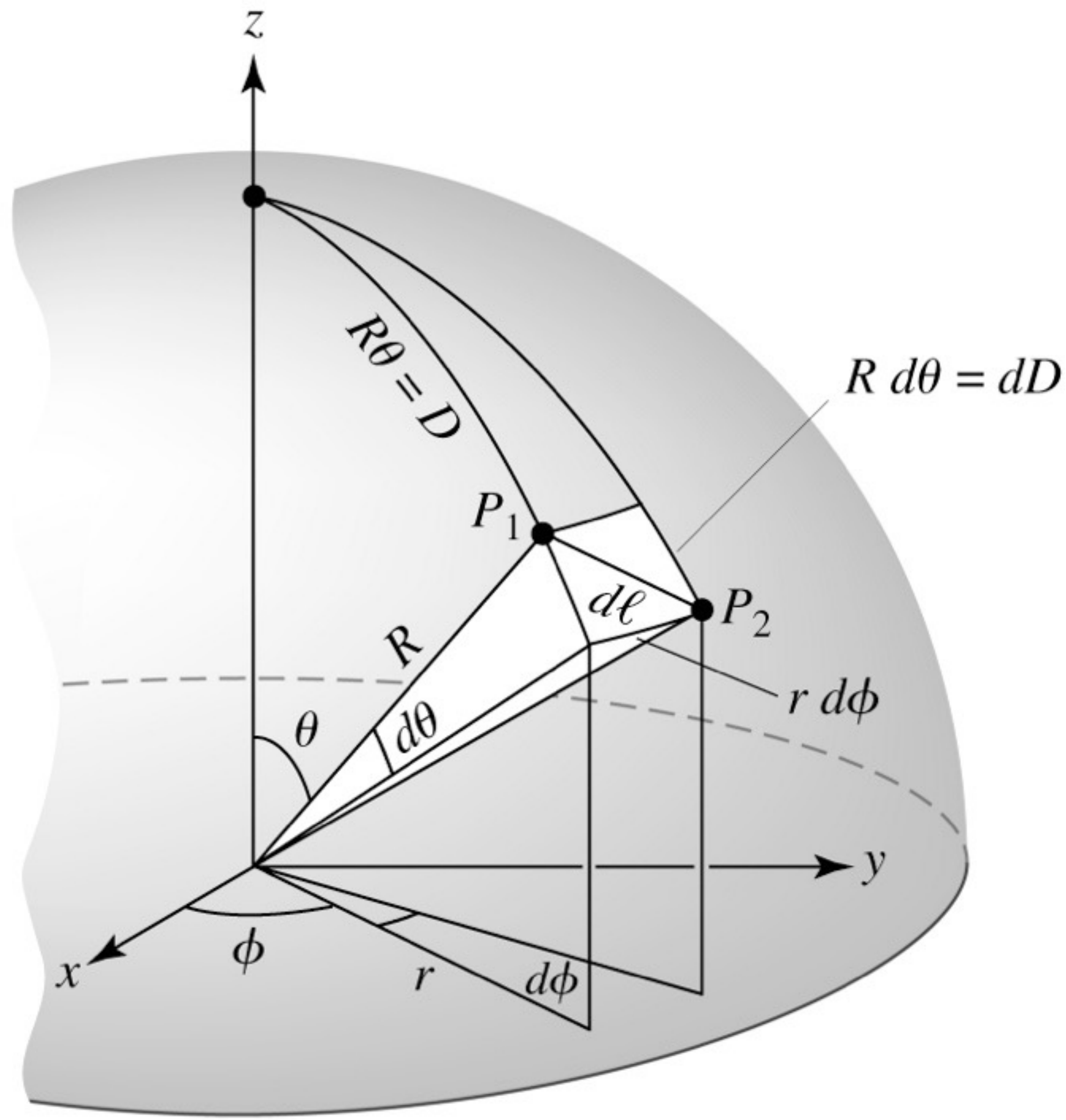
abebooks.com


P
D
R sin θ
θ
R

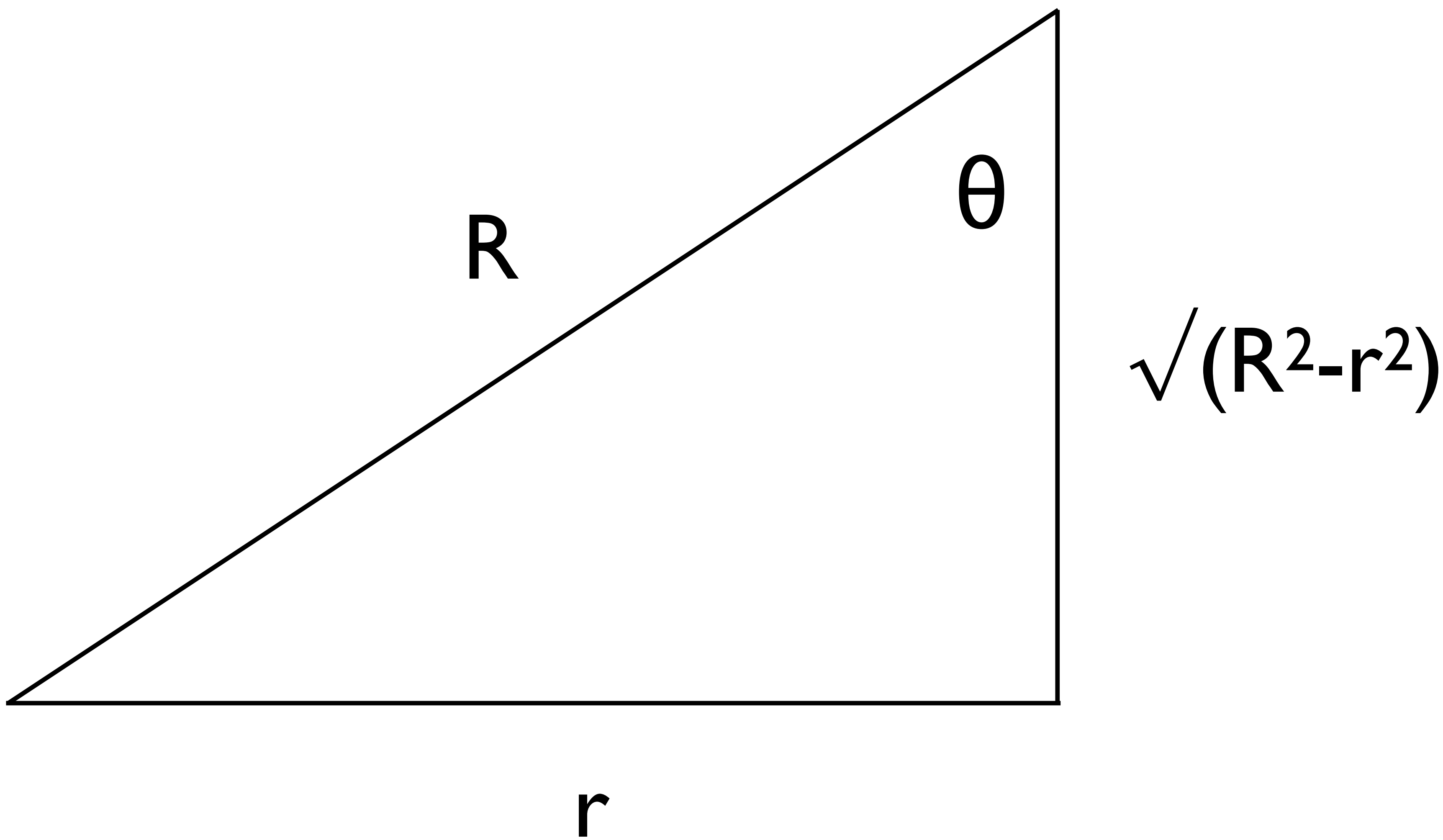

$C = 2\pi D$
$C < 2\pi D$
$C > 2\pi D$
Zero curvature
Positive curvature
Negative curvature
(a)
(b)
(c)



(a)

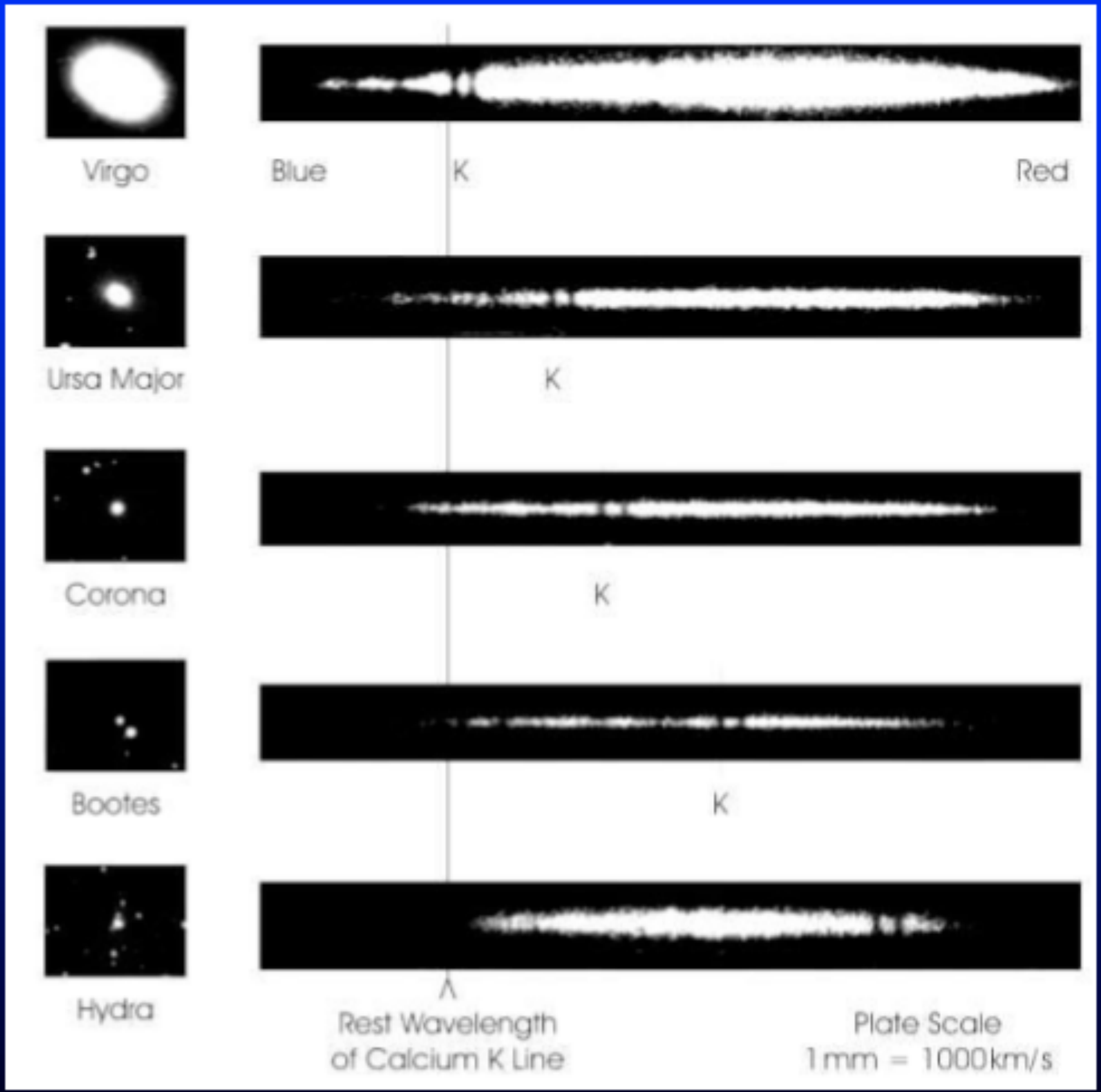


(b)

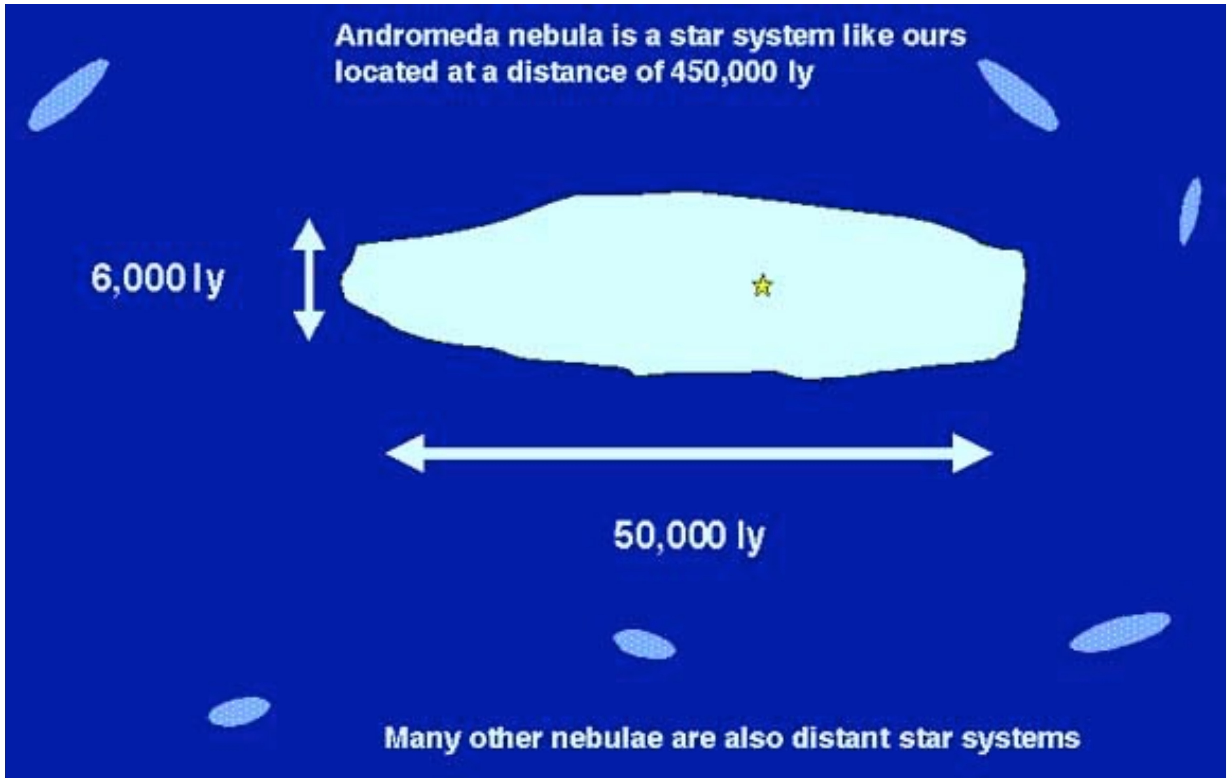

R
θ
√(R²-r²)
r

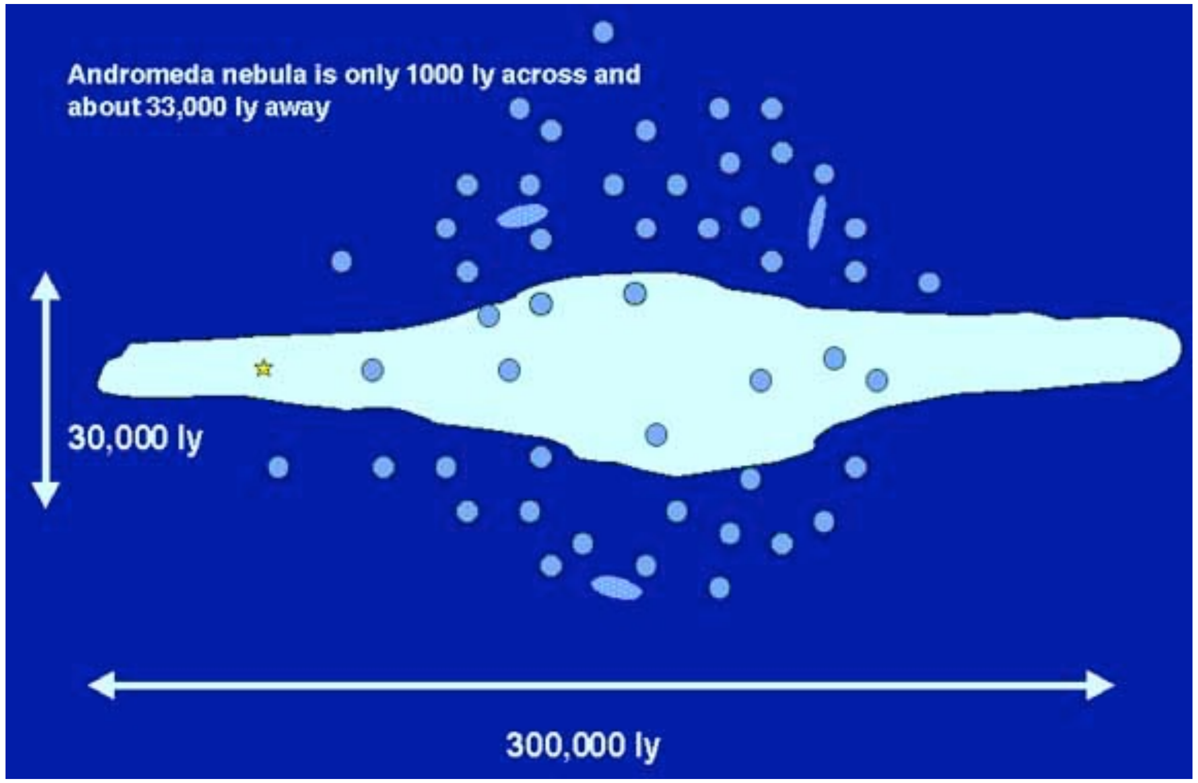
Vesto Melvin Slipher

- Used the Lowell 24” refractor to measure the speeds of approach or recession of galaxies



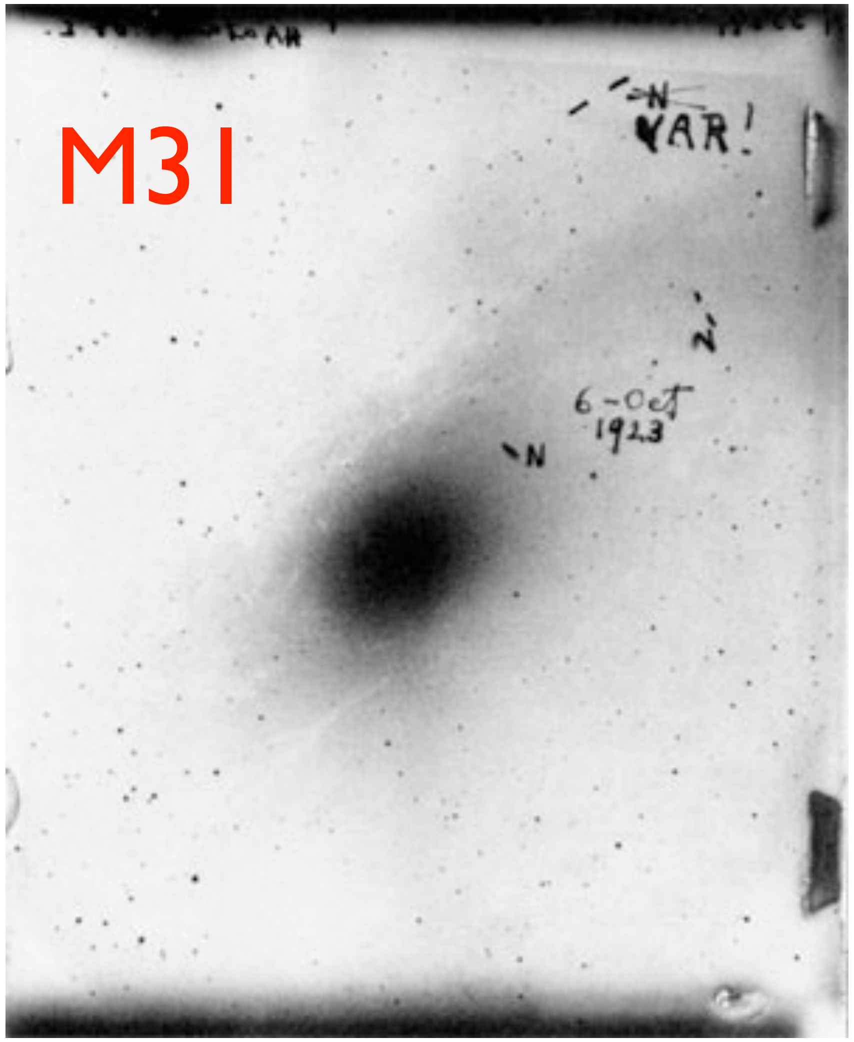
	Curtis	Shapley
Distance to globular clusters?	how do we know that cepheids in globular clusters are like those that are nearby?	cepheids in globular clusters are the same as those nearby
What are the spirals?	novae have been observed in some of these nebulae they must be collections of stars like our own system	rotation of spirals proves they are close they must be true nebulae

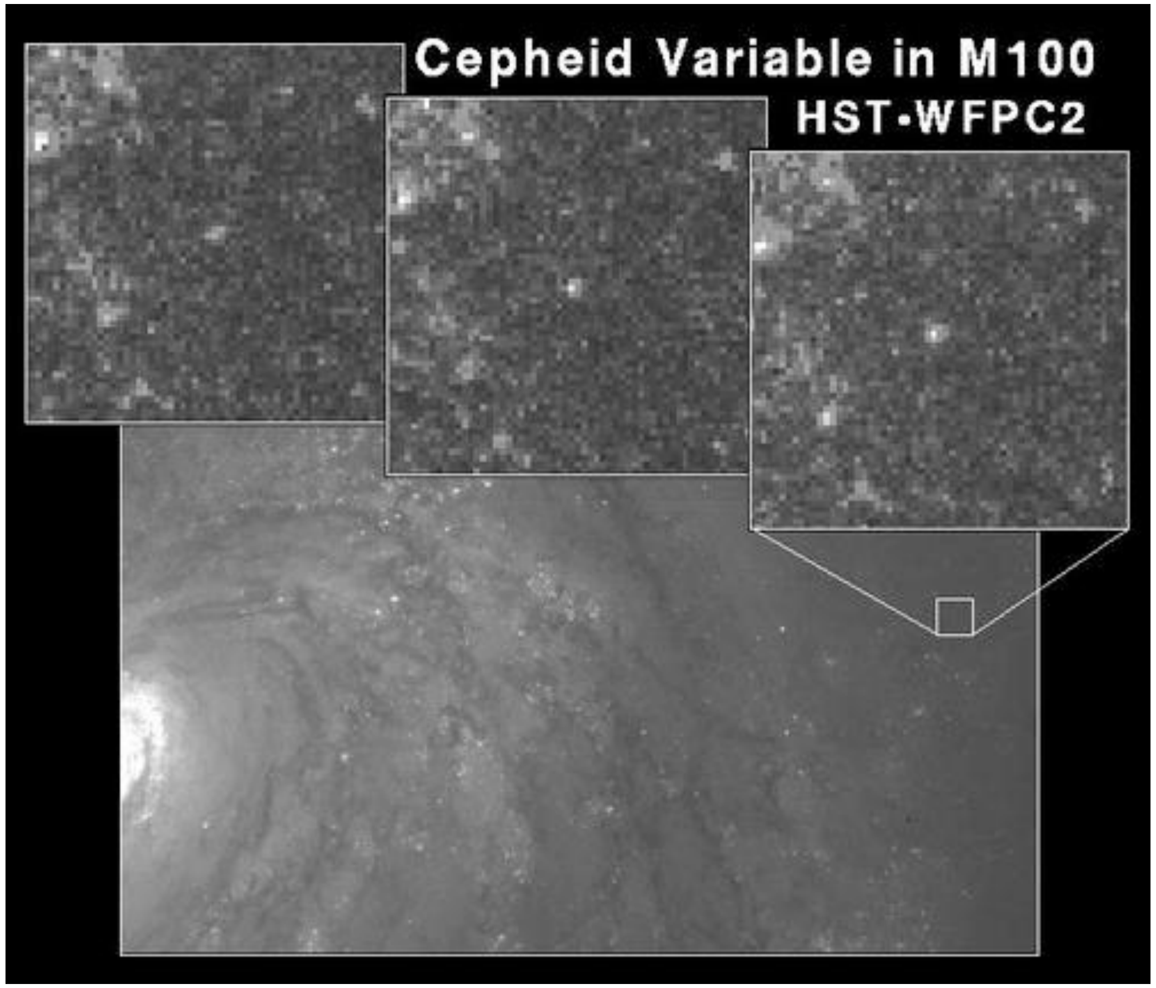


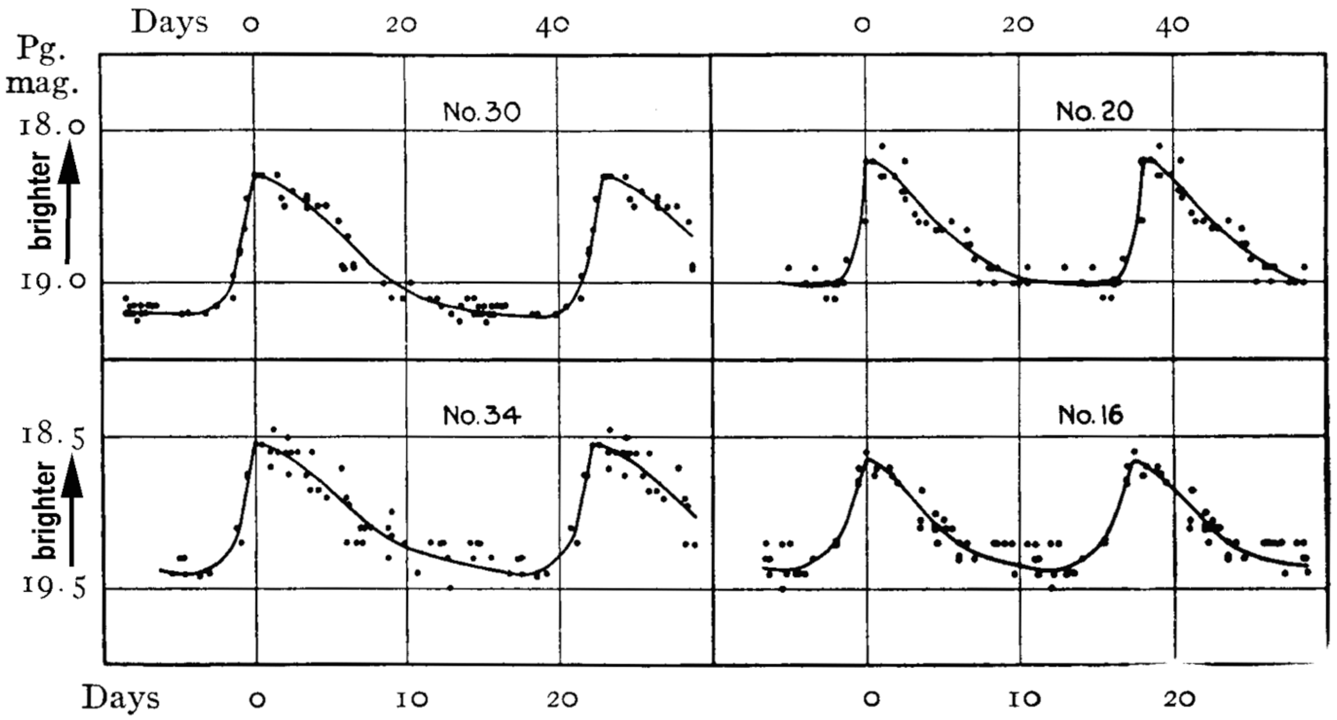


Curtis

Shapley







M31 is much further away than the Galactic Cepheids - it must be a galaxy in its own right.

NGC 6822

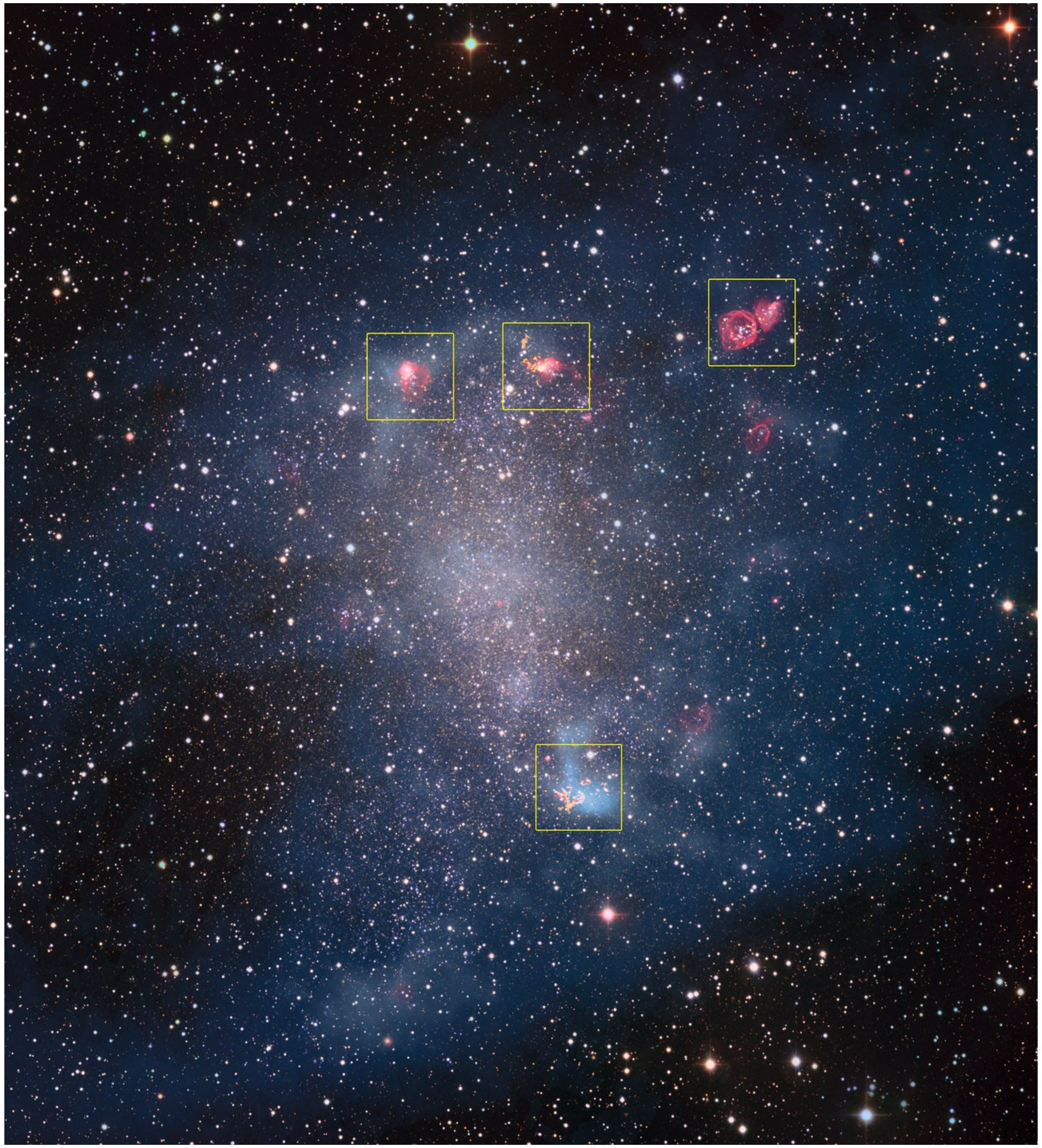
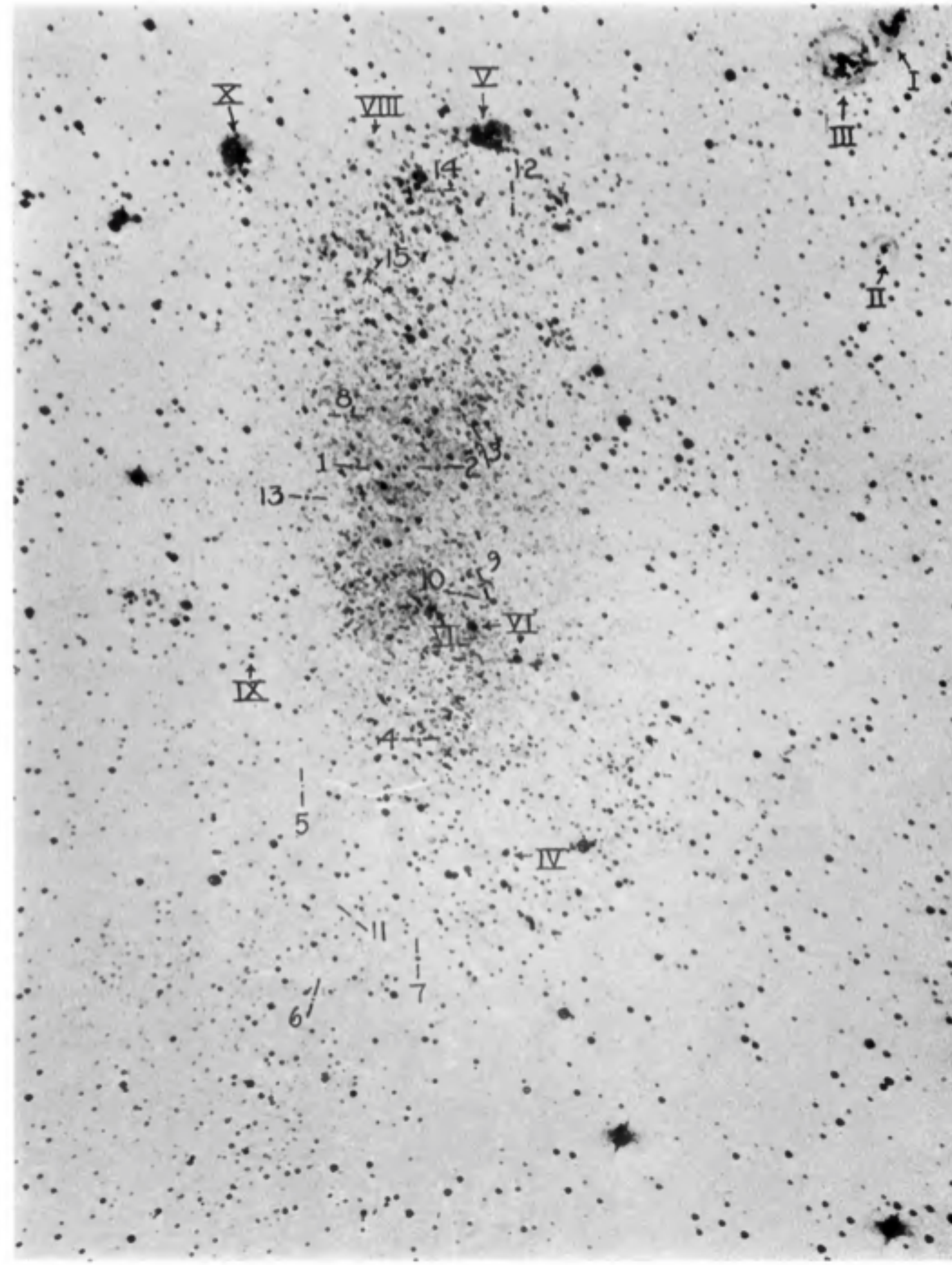


PLATE XV

N



W

N.G.C. 6822

Negative print of Plate XIV. Variable stars are designated by Arabic figures; nebulae involved in or superposed on the cluster by Roman numerals.

N.G.C. 6822, A REMOTE STELLAR SYSTEM[1]

By EDWIN HUBBLE

ABSTRACT

A study of N.G.C. 6822.—The object is a very faint cluster of stars and nebulae, about $20' \times 10'$, resembling the Magellanic Clouds. Detailed investigations confirm the similarity and show that it extends to many structural features of these systems. Familiar relations such as those connecting periods and luminosities of Cepheids, luminosities of brightest stars involved in diffuse nebulae, and frequencies of the most luminous stars in the systems are consistent when applied to N.G.C. 6822, the first object definitely assigned to a region outside the galactic system.

Variable stars.—Eleven of the fifteen variables found in the cluster are Cepheids. A system of photographic magnitudes has been established from comparisons with the two nearest Selected Areas; and periods, light-curves, and magnitudes have been determined for the Cepheids. The periods range from 12 to 64 days and the magnitudes at maximum, from 17.45 to 19.05. The period-luminosity relation is conspicuous, and a comparison with Shapley's general curve in *Harvard Circular*, No. 280, indicates a distance for N.G.C. 6822 of 214,000 parsecs. $m - M = 21.65$.

Nebulae.—Five diffuse nebulae are involved in the cluster. The four brightest show emission spectra similar to those of the diffuse galactic nebulae. A radial velocity of +25 km/sec., uncorrected for solar motion, has been derived from one slit spectrogram of the brightest nebula. The mean diameter of the diffuse nebula, about 40 parsecs, is comparable with those of the largest nebulae in other systems. In addition to the diffuse nebulae, several small objects are present which are probably non-galactic nebulae whose images are superposed on that of the cluster.

Star counts.—The distribution of apparent photographic magnitudes has been determined down to 19.4, corresponding to absolute magnitude −2.25. The brightest stars in the system are of absolute magnitude about −5.8. When a mean color-index of +1.35 is assigned to the cluster stars, their frequencies are very similar to those of the absolute visual magnitudes in the vicinity of the sun.

Luminosity and space density.—The surface brightness of the central core is about 22.1 photographic magnitudes per square second of arc. This value leads to a total absolute magnitude of −12.0 for the core, or −12.7 for the entire system, and to a space density of about 6.1 absolute magnitudes per cubic parsec for the core, or 8.8 for the entire system.

Cepheid criterion of distance.—Since the Cepheid criterion appears to function normally in N.G.C. 6822, its value as a means of exploring extragalactic space is considerably enhanced.

Influence of instruments on observations of nebulae.—A summary of the early observations of N.G.C. 6822 illustrates the confusion which may arise from disregarding the limitations of various types of instrument and emphasizes the caution required in discussing observations of nebulae.

N.G.C. 6822 is a faint irregular cluster of stars with several small nebulae involved. The position for 1925 is $\alpha = 19^h 40.7^m$, $\delta = -15°$, galactic latitude −20°. The general appearance is shown on Plate XIV, enlarged from an exposure of three hours and a half with the 100-inch reflector. The total area covered by the cluster is about $20' \times 10'$, but the most conspicuous feature is a core about $8' \times 3'$ in

[1] *Contributions from the Mount Wilson Observatory*, No. 304.

the manner described above, with successive steps averaging about 0.2 mag. These furnished easy and accurate means of following the variables. The data for the latter from the separate plates are collected in Table I. The first column gives the Julian Day repre-

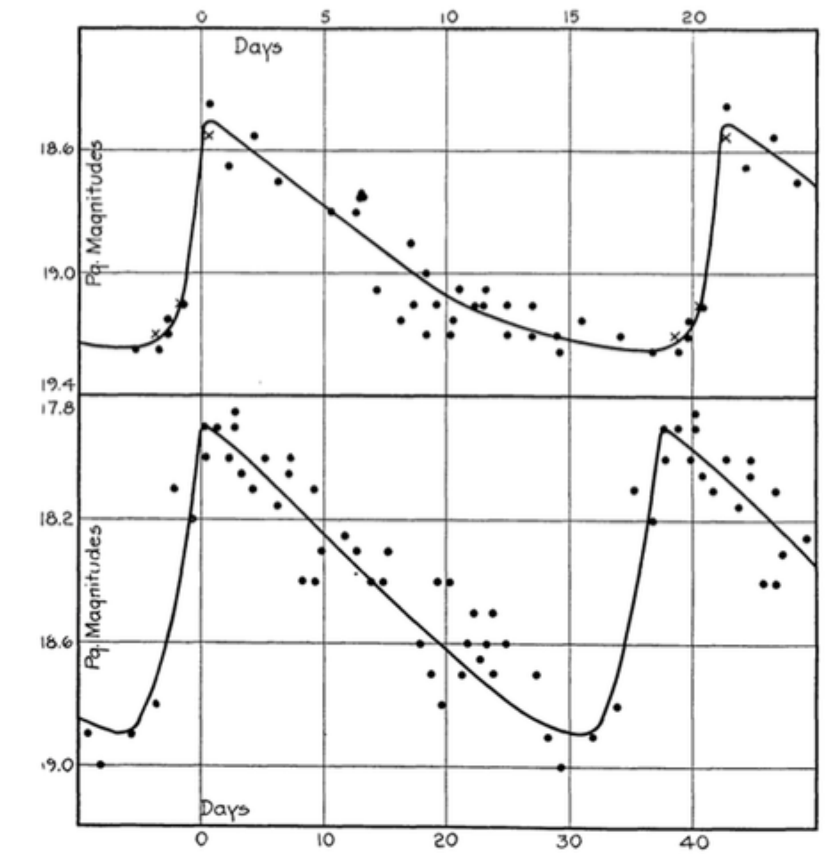


FIG. 1.—Light curves for two Cepheids in N.G.C. 6822. Upper curve, variable No. 6. Period 21.06 days; range 18.5–19.25. Lower curve, variable No. 2. Period 37.45 days; range 17.9–18.9. The three crosses on the rising slope of the upper curve represent observations on successive days and illustrate the rapid brightening of the variables.

senting Pacific mean time; the second, the quality of the plates, the letters "E," "G," "F," "P" and "vP" having their usual significance of "excellent," "good," "fair," "poor," and "very poor"; the remaining columns give the photographic magnitudes of the variables, which are designated by the numbers used on Plate XV. The exposures were usually from 60 to 75 minutes on Seed 30 plates.

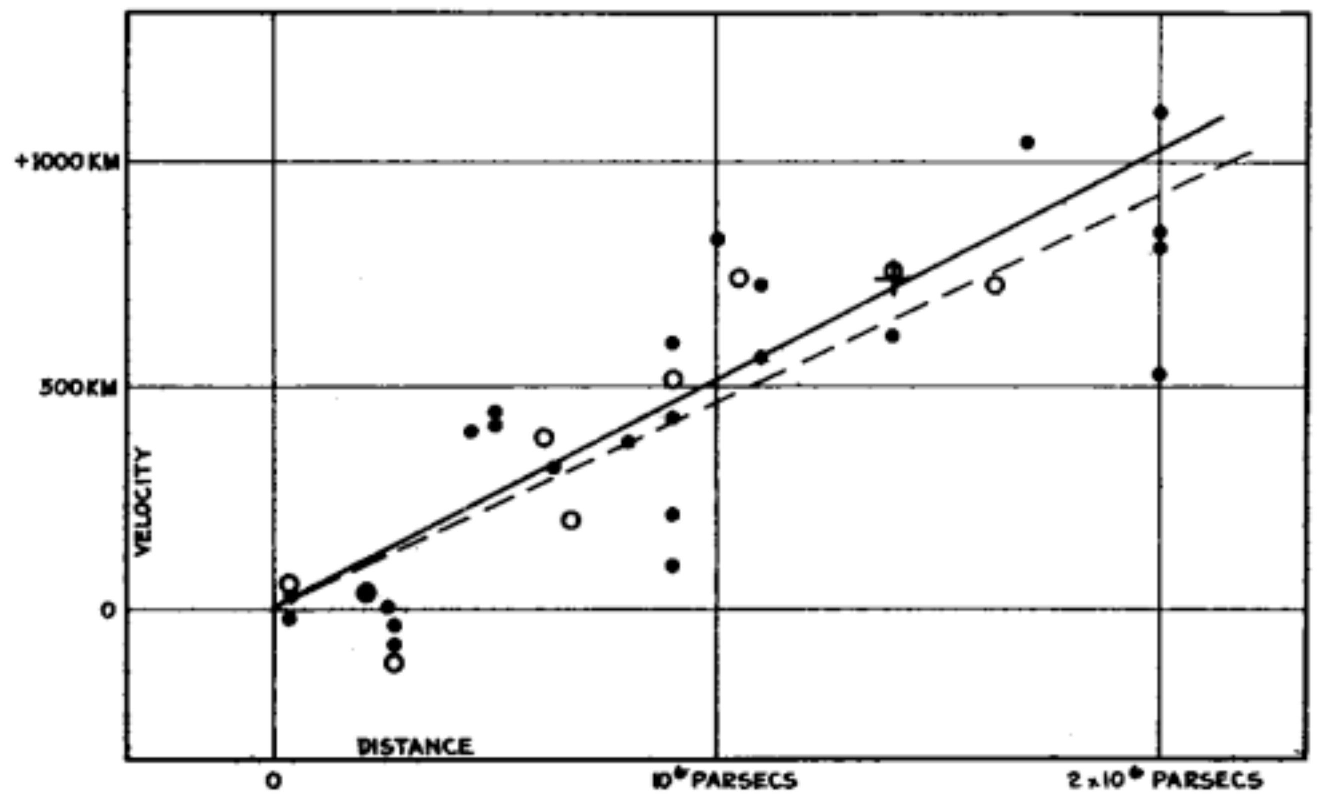
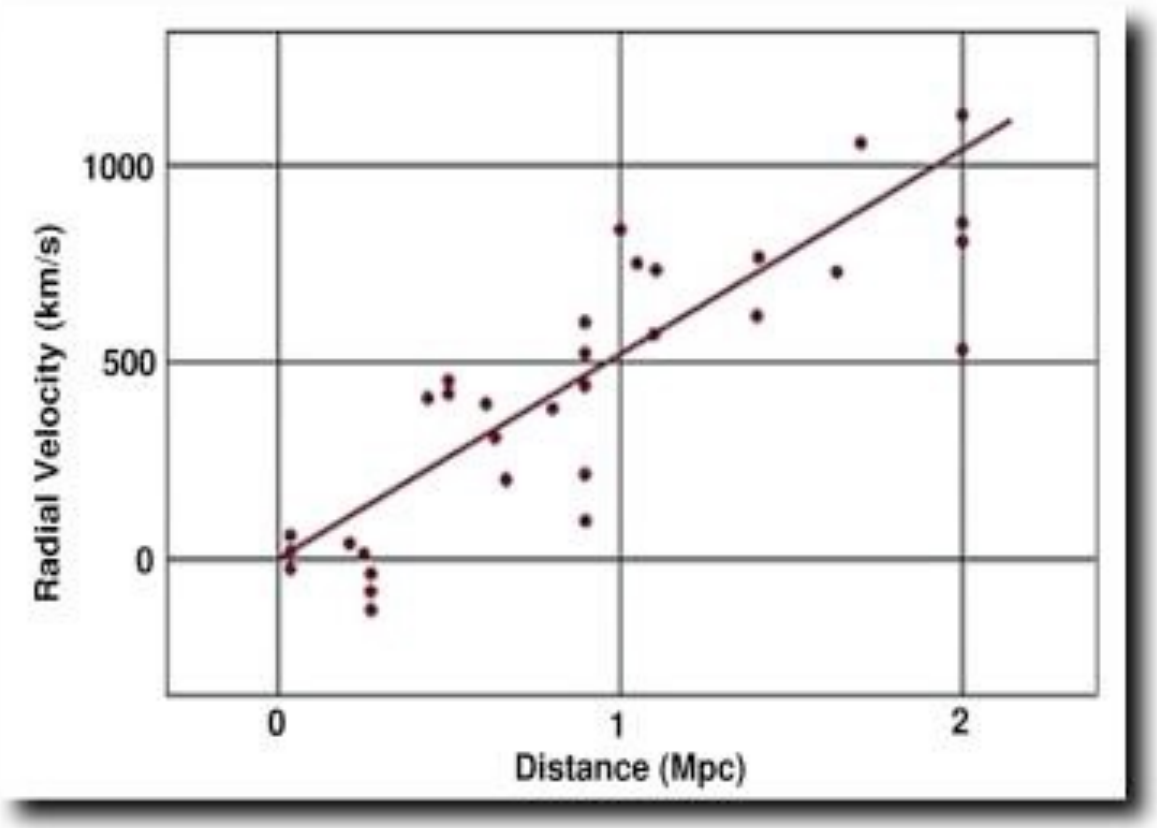


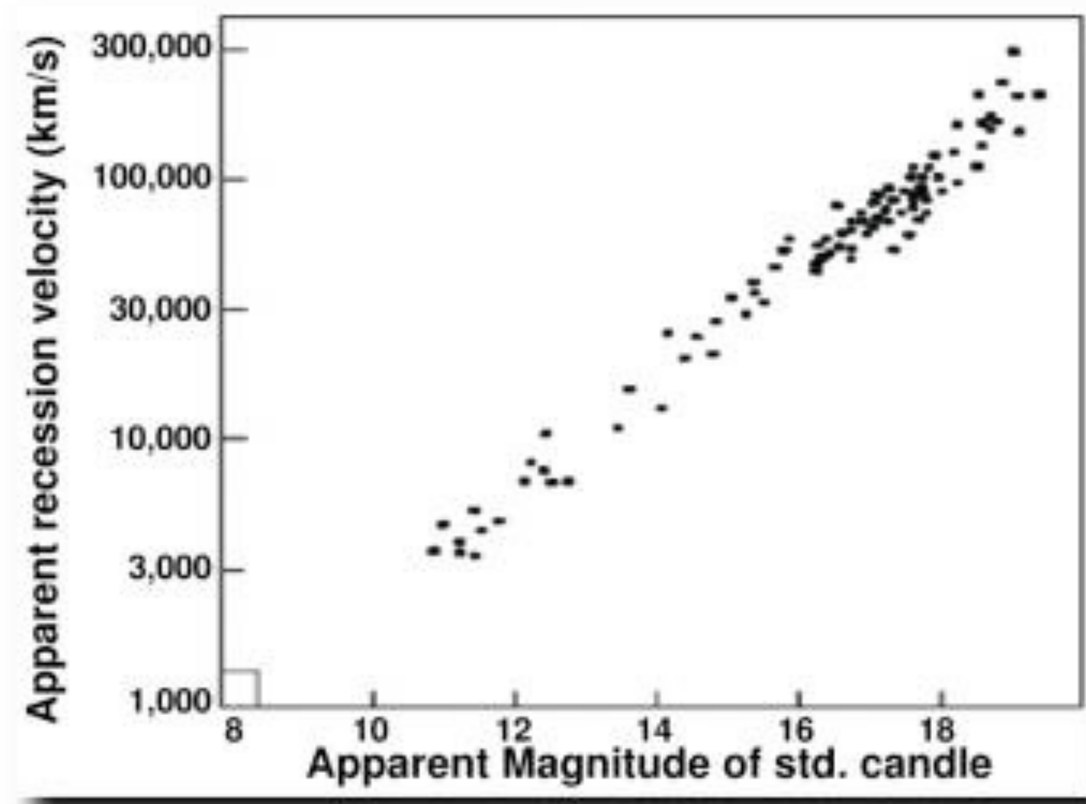
FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

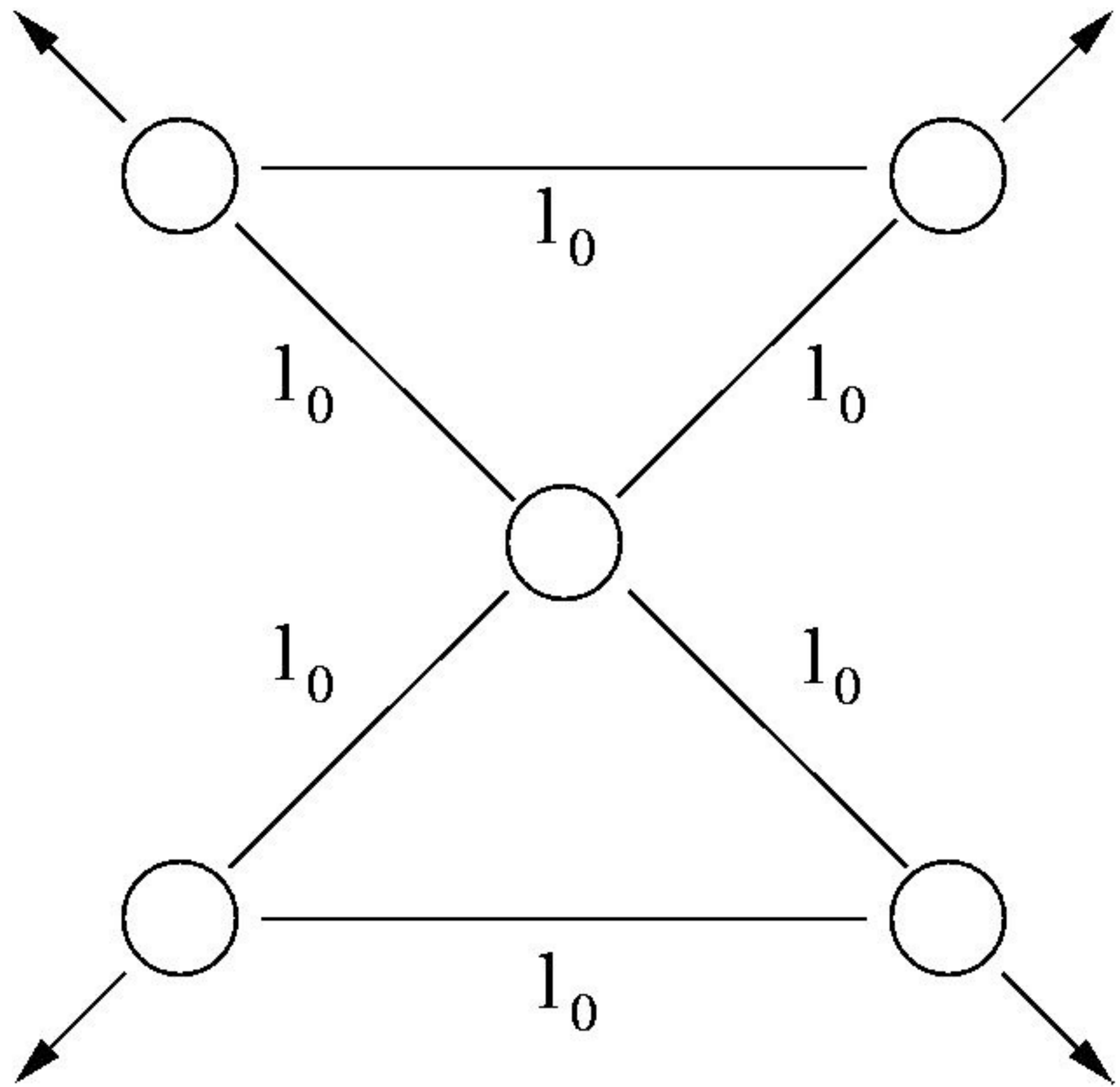
Radial velocities, corrected for solar motion, are plotted against distances estimated from involved stars and mean luminosities of nebulae in a cluster. The black discs and full line represent the solution for solar motion using the nebulae individually; the circles and broken line represent the solution combining the nebulae into groups; the cross represents the mean velocity corresponding to the mean distance of 22 nebulae whose distances could not be estimated individually.



Hubbles' Original Data



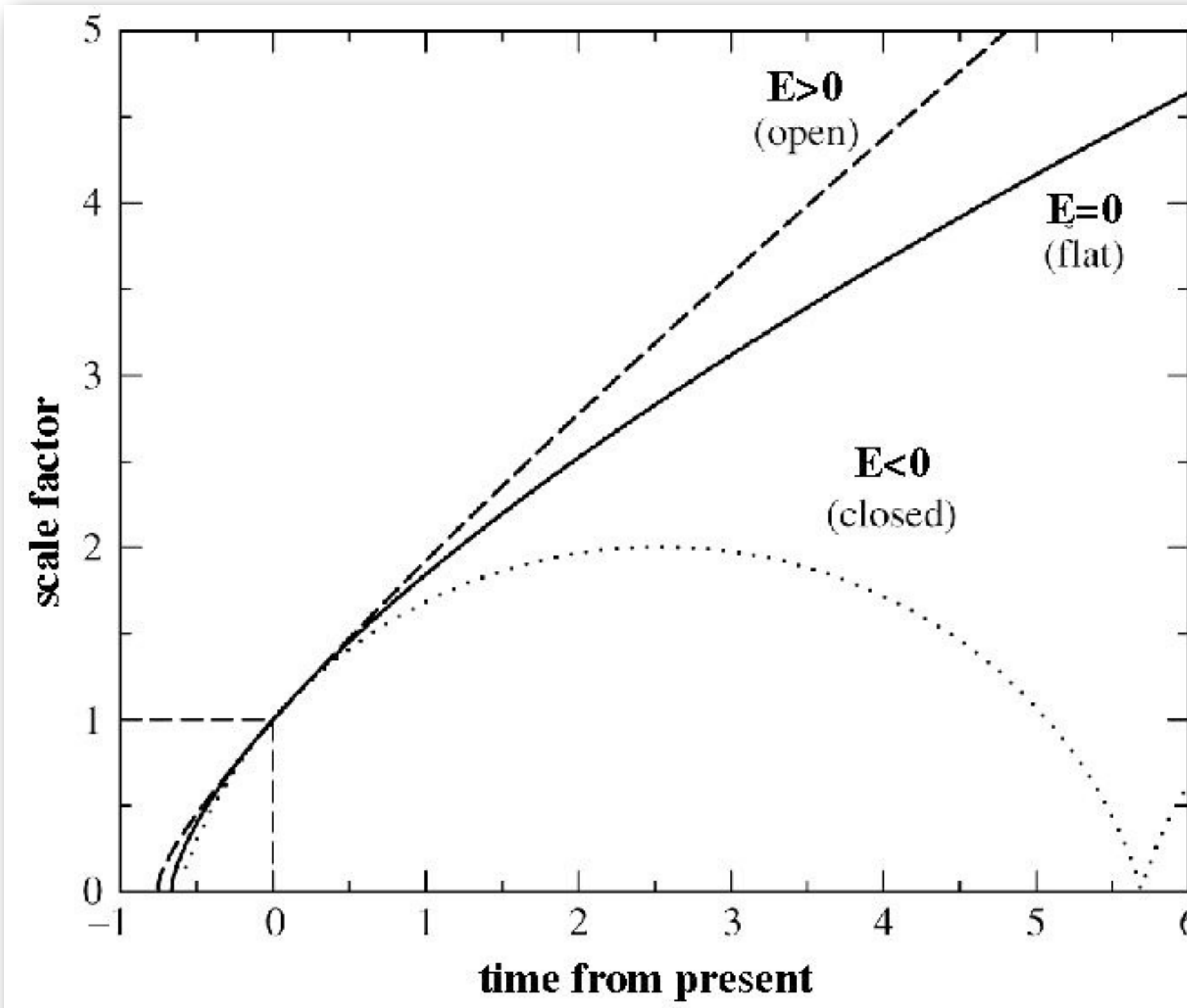
Modern Data



l_0
l_0
l_0
l_0
l_0
l_0

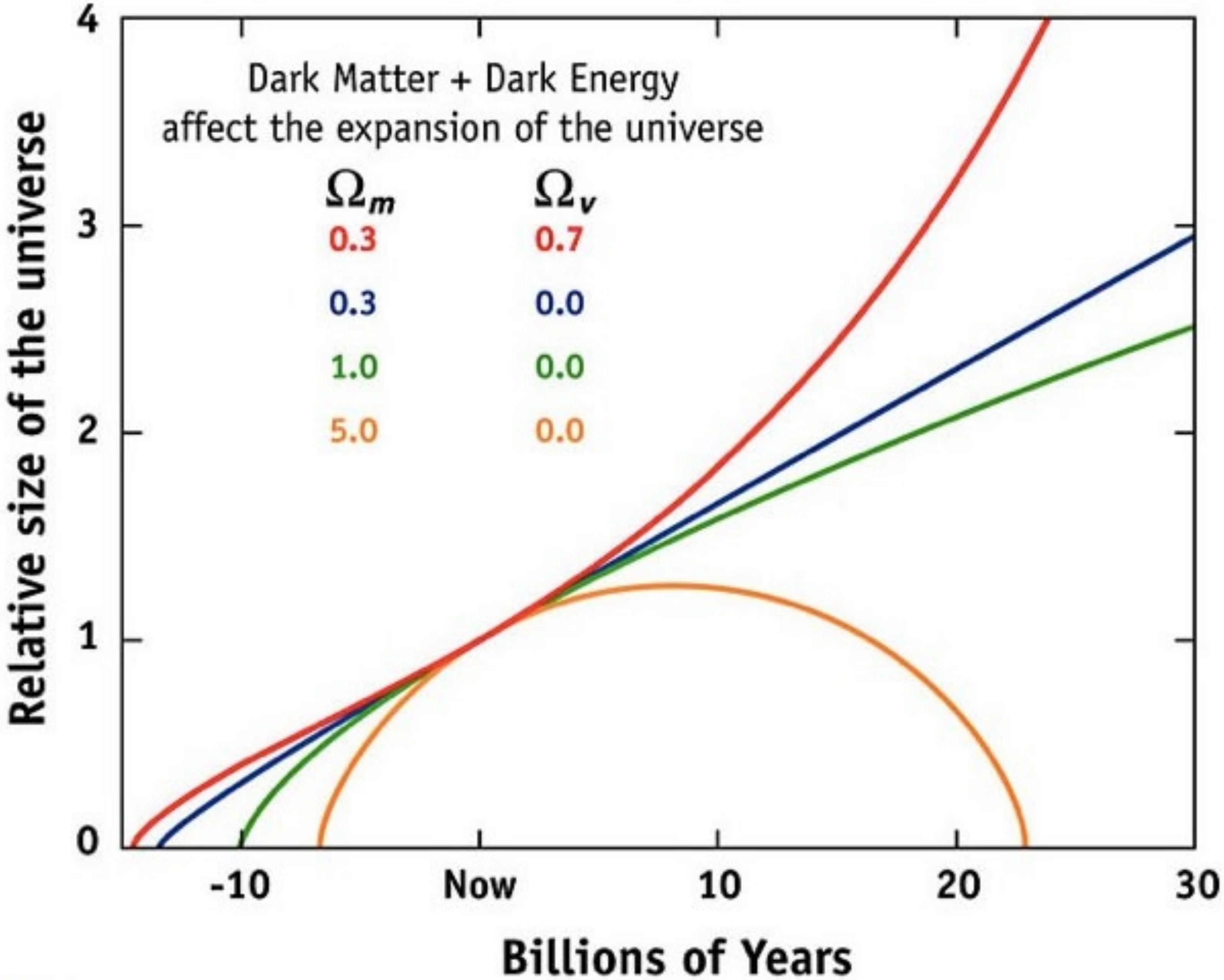
The anatomy of a scientific revolution: At any time there exists

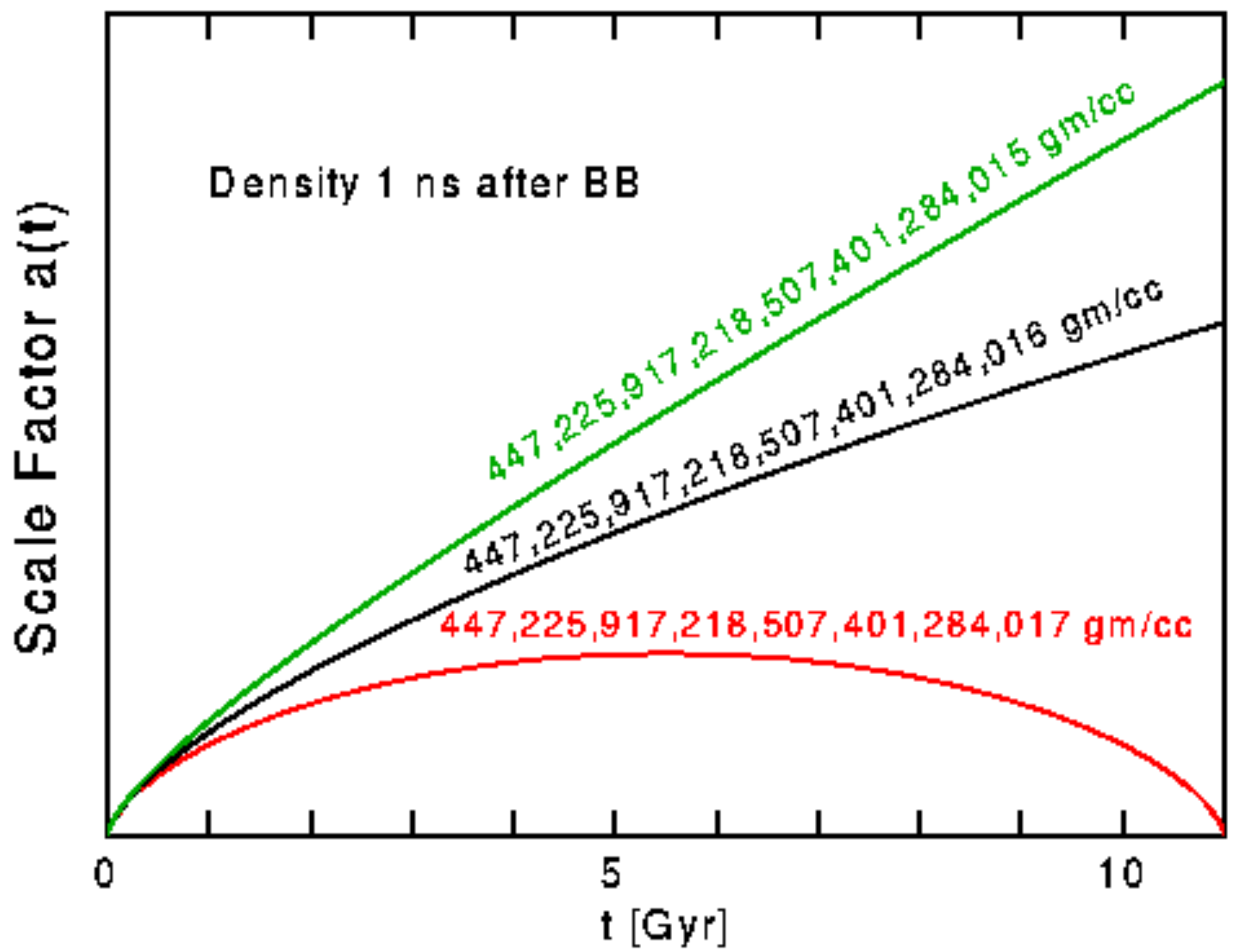
- Observations that are wrong.
- Observations that are correct and can be explained by existing theories.
- Observations that are correct but that are too complex to be explained by existing theories.
- Observations that are correct but for which there are no theories to describe them.



E>0
(open)
E=0
(flat)
E<0
(closed)
scale factor
time from present
0
1
2
3
4
5
−1
0
1
2
3
4
5
6

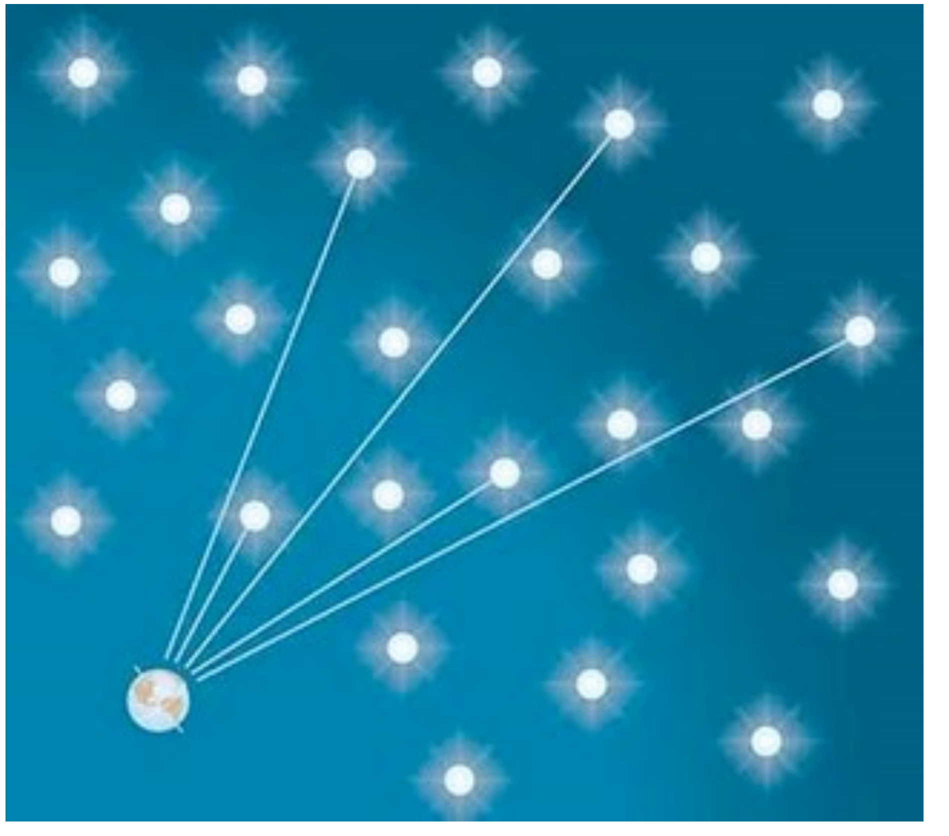
History of Cosmic Expansion for General Ω_M & Ω_Λ





Density 1 ns after BB
447,225,917,218,507,401,284,015 gm/cc
447,225,917,218,507,401,284,016 gm/cc
447,225,917,218,507,401,284,017 gm/cc
Scale Factor a(t)
0
5
10
t [Gyr]

Olbers' paradox



The horizon problem