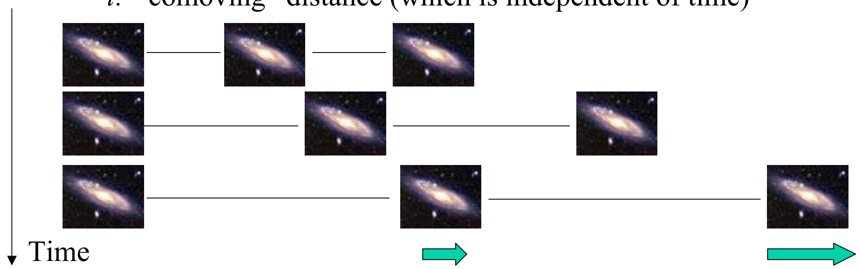
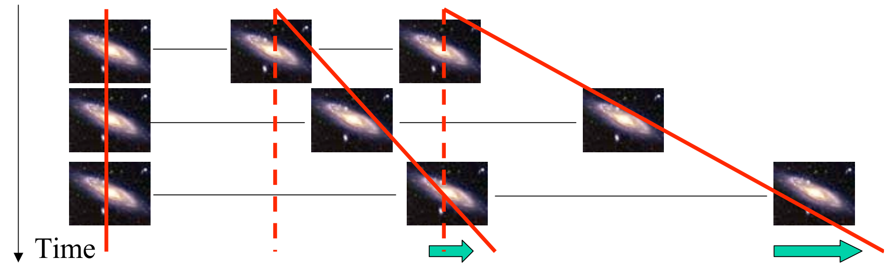
Expansion of the Universe

- The universe is expanding.
  - General relativity: space is dynamical and expanding.
  - Distance between galaxies increases with time
    - But there is important exception.
- $L = R\, l$
  - L: actual distance (which increases with time)
  - ***R*: scale factor** (which represents the size of the universe and increases with time)
  - l: "comoving" distance (which is independent of time)



Comoving Coordinate

- Galaxies are **not** moving!
  - It is space between galaxies that is expanding.
  - (But there is peculiar motion which we have ignored so far)
- "Comoving coordinate" is the coordinate which expands in the same way as space.
  - Therefore, galaxies always remain at the same position in comoving coordinates.



Velocity-distance Law

- Galaxies appear to be moving away from us.
  - Recession velocity of galaxies represents expansion velocity of space
- $L = R\, l$
  - Recession velocity V

    = rate of increase of L

    = (rate of increase of R) x l

    = (rate of increase of R)/R x L

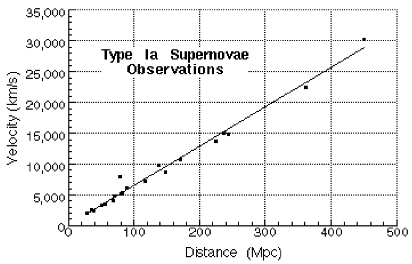
    = ***H*** L
  - More distant galaxies recede faster.
  - But, this does not mean that we are at the center of the universe.

Discovery: Expansion of the Universe

- How do we confirm the velocity-distance law?
  - We need recession velocities of galaxies: V
  - We need distances to galaxies: L
- How do we measure V?
  - Use Cosmological Redshifts: $V = c\, z$
  - *This relation must be used with caution.*
- How do we measure L?
  - There are various ways to estimate distances --- this is the most difficult part.
- Edwin Hubble (1889-1953) has done this and discovered expansion of the universe in 1929!

Expansion Rate

- ***V = H L***
  - *H* is the expansion rate, and is called "Hubble's parameter"
  - *H* has to be determined observationally.
  - The latest determination:
    - *H* = 70 km/s/megaparsec, or
    - *H* = 21.5 km/s/million light years
    - Therefore, a galaxy at 100 million light-years away appears to move away from us at 2150 km/s.
    - A galaxy at 1 billion light-years away appears to move away from us at 21500 km/s (about 7% of the speed of light)



- Galaxies at 14 billion light-years away appear to move away from us at the speed of light!

Faster Than the Speed of Light

- Galaxies at 14 billion light-years away recede at the speed of light.
  - Even more distant galaxies recede faster than the speed of light.
- Is this in accord with relativity?
  - The answer is yes.
  - If galaxies were moving faster than the speed of light, it would be in conflict with relativity; however, *galaxies are **not** moving!* It is space that is expanding.
  - Besides, we don't see galaxies receding faster than the speed of light because light does not reach us: **Horizon**

The age of the universe

- The age of the universe
  - Time elapsed from the birth of the universe (R=0) to the present epoch ($R=R_{present}$).
  - Therefore, it depends on how R changes with time.
- The latest determination = **13.7 billion years**
  - This estimate was made possible by knowing the expansion of the universe accurately.

Deceleration and Acceleration

- Time evolution of R is classified as follows.
  - Constant speed expansion
  - Decelerating expansion
  - Accelerating expansion
- The latest observations suggest that the expansion was
  - accelerating in the very early universe,
  - then decelerating until recently, and
  - accelerating again at present.