The Copernican Revolution: Observational Tests
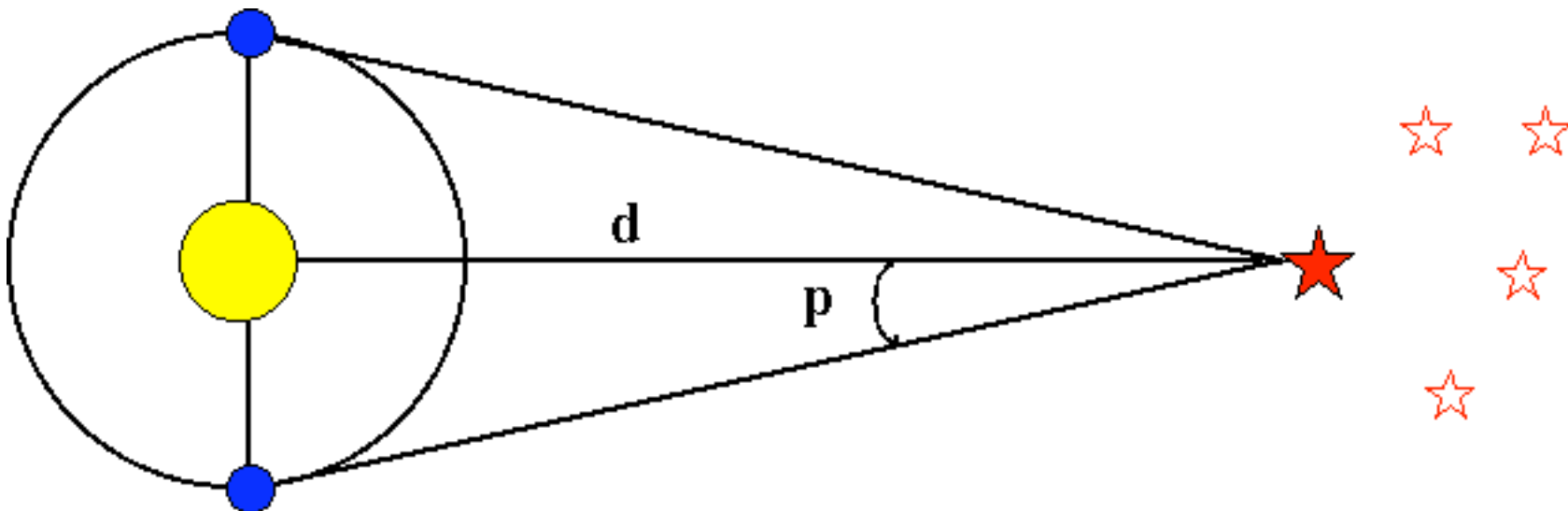
The Trigonometric (Geometric) Parallax

Aristotle's missing Stellar Parallax: The Earth has moved!

Parallactic ellipse has (angular) semi major axis **p = a/d** (radians)
... where **a** is the Earth's orbital "radius" and **d** is the distance to the star.

For **d** in parsecs (pc), and **p** in arc-seconds ("):
$$\text{(pc)} = 1/p(")$$
a_{Earth} = 1 au = 1.50 x 10^8 km and 1 pc = 206,265 au

First Measurement of a Stellar Parallax by Bessel (1838)

... 61 Cygni, also know as "Piazzi's Flying Star", with p = 0.287", d = 3.48 pc
(The largest stellar parallax is that of α Centauri with p = 0.75")
There are 206,265 arc-seconds (") in a radian: 180°= π radians; 1°= 60'= 3,600"
One astronomical unit is 23,455 Earth radii.

The Aberration of Starlight
The Earth is moving!

The Earth's <u>orbital</u> speed is $v = 30$ km s^{-1}

The speed of <u>light</u> is $c = 3 \times 10^5$ km s^{-1}

Therefore, the maximum aberration angle is $v/c = 10^{-4}$ radian $= 21"$

(Note that the semi major axes of <u>all</u> annual aberration ellipses are 21")

History
Roemer (1675) measures the velocity of light
Observations of eclipses of the satellites of Jupiter. (Io, P = 1.76d)

(His value for the speed of light was about 75% of the true value.)

Note: Light travels 1 astronomical unit in about 500 seconds.

Picard (1680) observes "puzzling parallax" of Polaris (~20")
$$d \text{ (parsecs)} = 1/p(")$$
.... but the motion was in the wrong direction for parallactic motion!

... and was seen with the same amplitude in all directions on the sky!

Bradley (1728) explains the phemomenon
(and provides observations of γ Draconis)

Note that this was over a century before Bessel successfully measured the trigonometric parallax of 61 Cygni in 1838.

The diurnal aberration due to the Earth's rotation about its axis is about 0.32"
- if observed from the equator where the rotational speed is 0.465 km s^{-1}.

(It's about 0.399 km s^{-1} = 892 mph at the latitude of Las Cruces, NM)

Distinguishing Parallactic Motion and Aberration

Parallax and Aberration
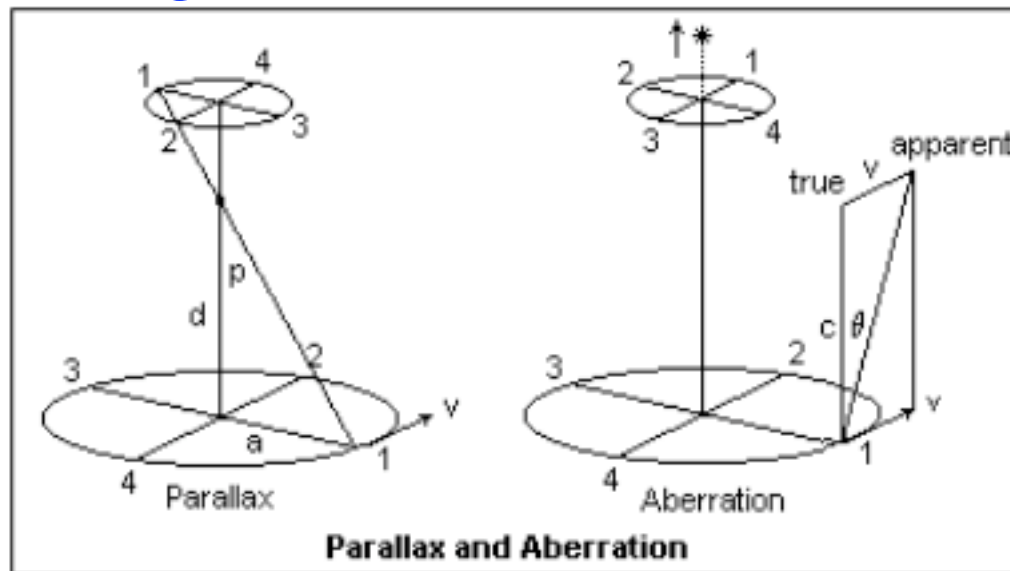
Note that the apparent displacement of the star due to the Earth's orbital **position** is, in this example, perpendicular to the apparent displacement due to the Earth's orbital **motion**. It will always be so.

In both cases the apparent annual motion will be an ellipse.
The **shape** of the ellipse will depend upon the ecliptic <u>latitude</u>, λ, of the object.
(The axial ratio will be b/a = cos λ, approaching zero near the ecliptic.)

The **size** (semimajor axis) of the <u>parallactic</u> ellipse will depend only on the star's distance:
$p = a/d$ (p in radians) $= 1/d$ (pc) (p in arc-seconds)

The **size** (semimajor axis) of the <u>aberration</u> ellipse will be essentially constant since the Earth's orbital speed is nearly constant:
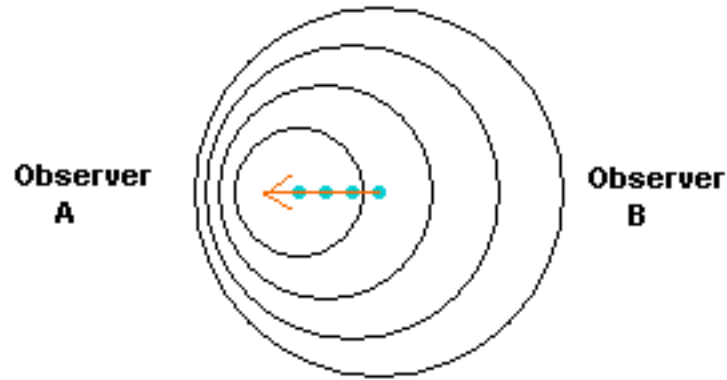$\theta = v/c = 10^{-4}$ (radian) $= 21$ (arc-seconds)

The Doppler Effect
The Earth is moving!

Christian Doppler (1803 -1852) and The Doppler Effect (1842)

$$(\lambda - \lambda_o)/\lambda_o = +v_{radial}/c \qquad \text{or} \qquad (\nu - \nu_o)/\nu_o = -v_{radial}/c$$

The variation of v_{radial} over the course of a year is measured.
The maximum possible amplitude* is $\Delta\lambda/\lambda_o$ or $\Delta\nu/\nu_o = \pm 10^{-4}$

Observer A   Observer B

Note: v_{radial} **is negative (approaching) for Observer A and positive (receding) for Observer B**

Optical Doppler Effect:
Stark (1905): Doppler Effect observed for "Canal Rays" in the Laboratory
Somebody (19??): Doppler Effect due to Earth motion observed for stars

*The Earth's orbital speed is 30 km s^{-1} = 10^{-4} c.
The observed shift be greatest for stars on the ecliptic.
The rotational speed at the Earth's equator is about 0.47 km s^{-1} or 1.6 x 10^{-6}c.

Resumé: The Copernican Revolution Completed

The Copernican Hypothesis explains:
• The apparent motions of the Sun, Moon, and Planets
• Observed diurnal and annual motions of the celestial sphere
... at least as well as do the Ptolemaic and Tychonic hypotheses*

and **correctly** predicts:
• The correlations among position, motion, and brightness variations
• Planetary phase and angular size variations (Galileo)
• The existence of stellar aberration (Bradley)
• The presence of a stellar parallax (Bessel)
• Stellar Doppler shifts (?)
... which the Ptolemaic and Tychonic hypotheses do not!

The Copernican Theory also:
• Has continued to accommodate newly discovered objects
• Has a fundamental theoretical foundation in Newtonian Mechanics and Gravity

* Also, it is relatively simple compared to alternative hypotheses with fewer planetary types, a more straightforward explanation of retrograde motions, etc. (Ockham's Razor, again)

..but the "Copernican Revolution", which displaced first the Earth (Copernicus) and then the Sun (Digges) from the center of the universe wasn't over yet ......

The Copernican Principle

History
Ptolemy (c. 140): A Geocentric and Geostatic Universe

Copernicus (1543): A Heliocentric and Geodynamic Universe

Digges (1576): A Non-Heliocentric Universe
The Sun as a star in an infinite space?

New Questions:

How are the stars distributed in space?
(Is the Universe of stars finite or infinite?)

What is the Sun's location in this "system" of stars?
(... assuming the system of stars is finite in extent.)

The theological concern: Is there anything "special" about our location or motion with respect to the rest of the Universe?
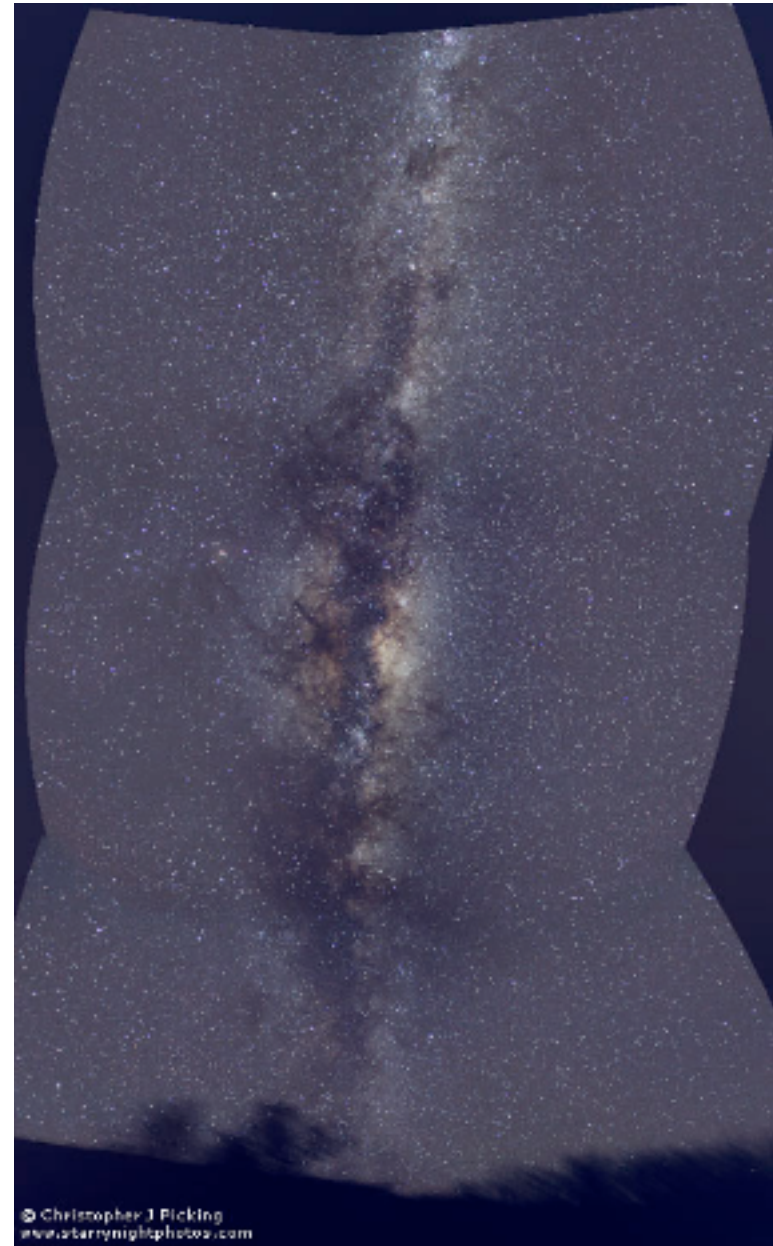
Answering the Questions: Mapping the Universe
• Surveying Stars: Distance and Direction
• Surveying Galaxies: Distance and Direction

• Answering the theological concern: The Copernican Principle

Mapping The Distribution of Stars in Space

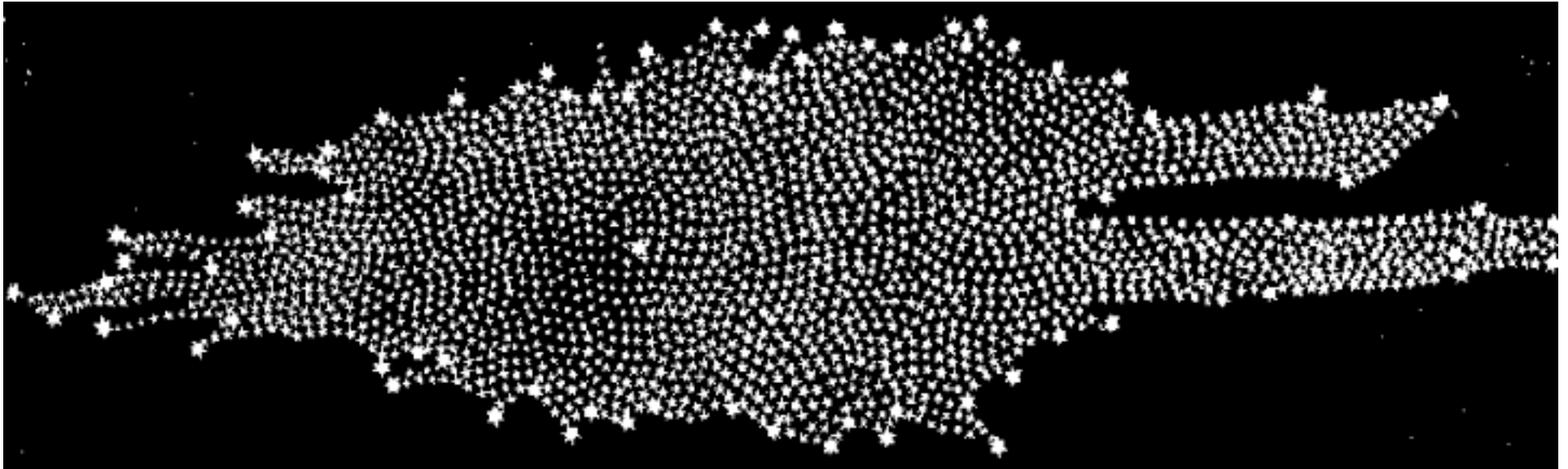## The Northern Milky Way

The Southern Milky Way

© Christopher J Picking
www.starrynightphotos.com
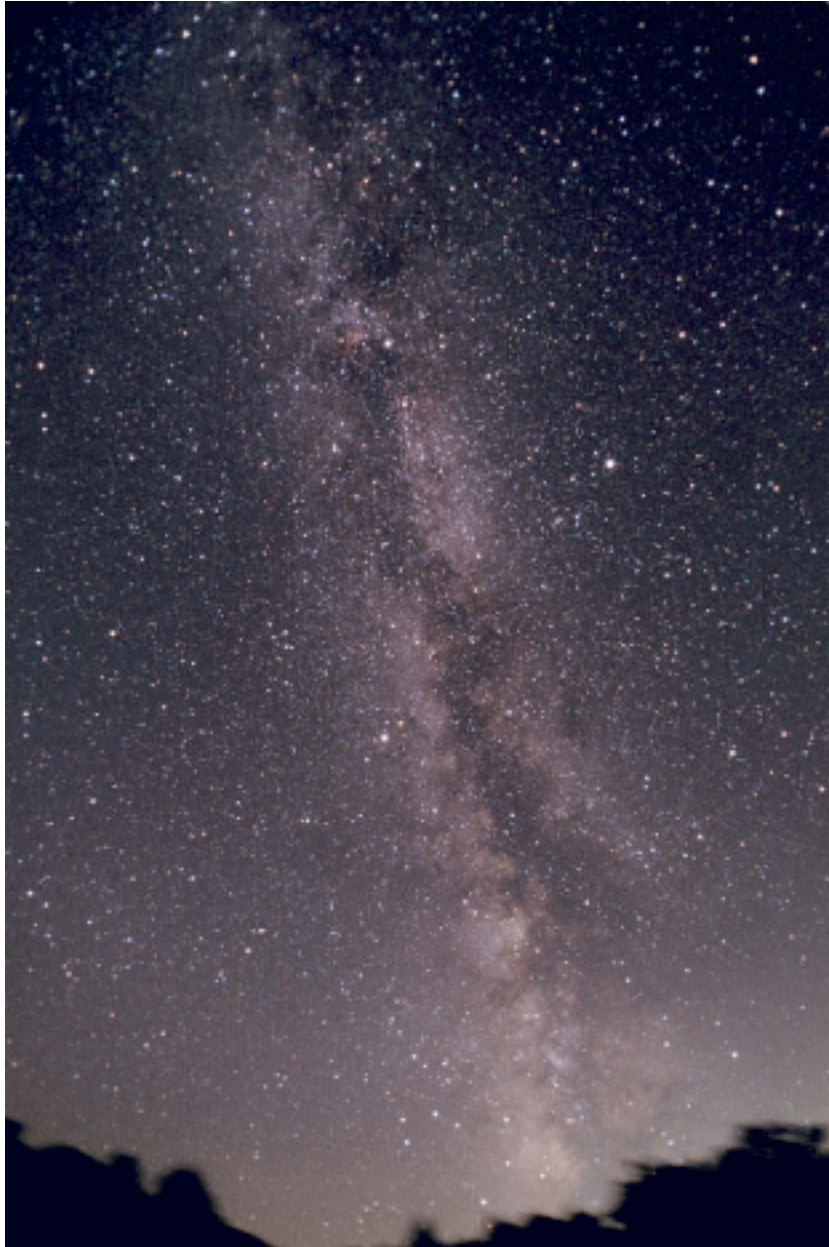
Digression: The Difficulty of Measuring Stellar Distances

Mapping the Galaxy (the "Milky Way") *via* Star Counts
Sir Fredrick William Herschel (1738 - 1822)
Caroline Lucretia Herschel (1750 - 1848)

A Copernican Puzzlement: "Herschel's "Grindstone"

Possible Implications:

An (almost) Sun - Centered System of Stars?
"Holes in the Heavens"?
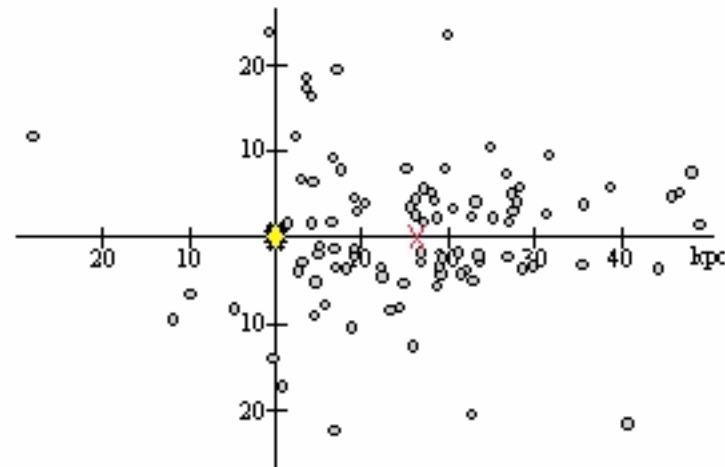**"The Finger of God Effect"?**

Complication: Extinction by Interstellar Dust
(also Interstellar Reddening)

An Island Universe?

Harlow Shapley (1885 - 1972)

**Getting around the interstellar dust problem:
Globular clusters and the Galactic center (1918)**

Shapley's Globular Cluster Distribution

Conclusions
The Sun resides ~17 kiloparsecs from the Galactic center.
The stellar system we call the Galaxy extends ~40 kpc from its center

and, tentatively
Our galaxy is an island of stars in an otherwise empty universe.
But:
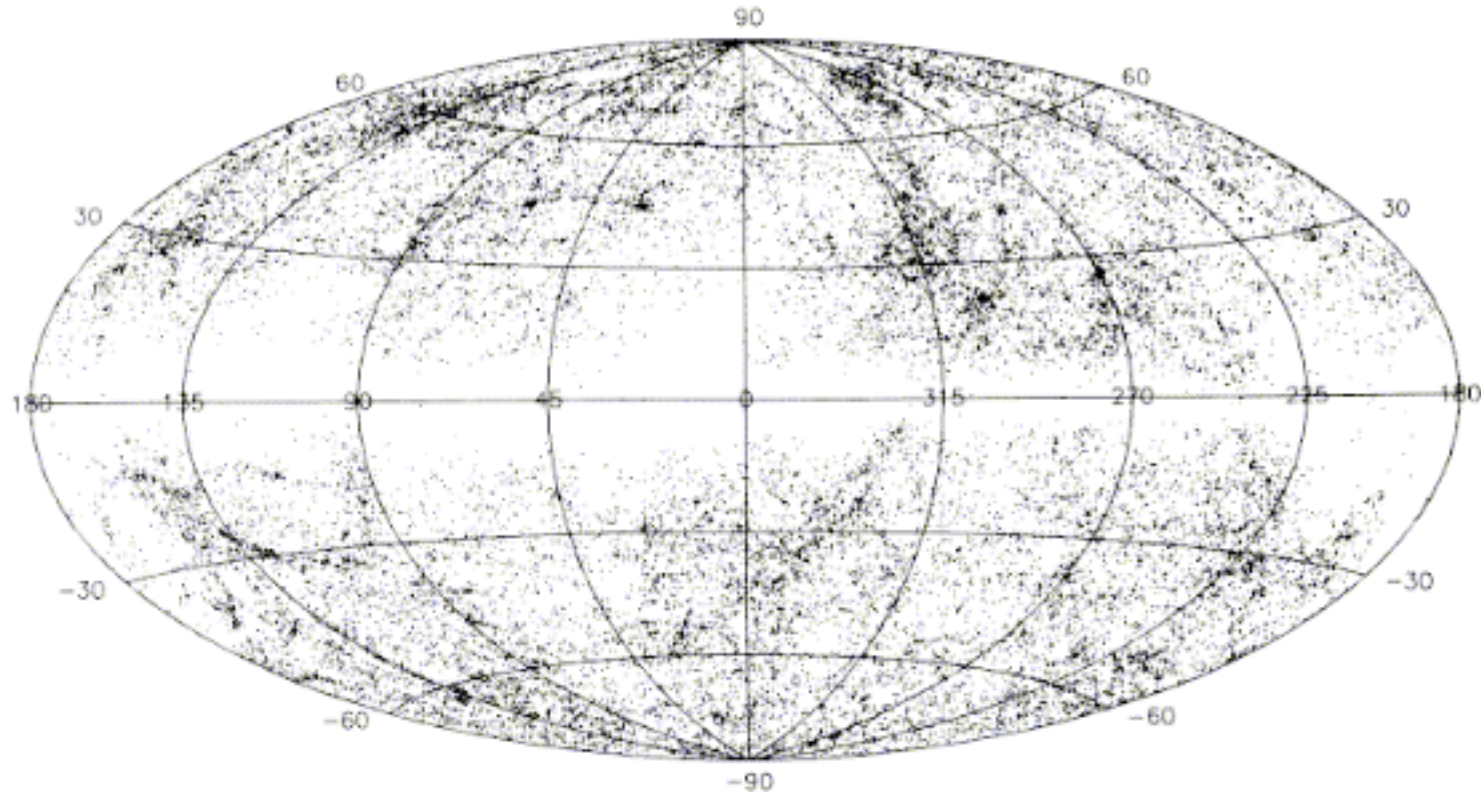## What was the nature of the "spiral nebulae"?
... and why should it matter?

Spiral & Elliptical Galaxies: M31 and its Companions

An Island Universe or Island Universes?

The Nature of the Spiral Nebulae
Are They Milky Way Objects or or External Galaxies?
The Shapley-Curtis Debate (1921)

Galaxies on the Sky: The Zone of Avoidance
Spiral nebulae seem to avoid the galactic plane and do not appear centered on or concentrated toward the galactic center like the globular clusters.

The Shapley-Curtis Debate (1921)

What are the Spiral Nebulae?

They are

Other Galaxies (Curtis)   **Milky Way Objects (Shapley)**

Zone of Avoidance   "Observed" rotation (van Maanen)

Emission line (gaseous) spectra

The Matter is Finally Resolved

Edwin P. Hubble (1889 - 1953)

1923: Hubble resolves individual stars (including Cepheid Variables) in the spiral nebulae M31 and M33 - and in the Irregular Galaxy NGC 6822.

Distance to M31 determined to be about 300 kiloparsecs* (about 900,000 light years) via the (wrong) Cepheid Period-Luminosity Relation.

(The actual distance to M31 is 773 kiloparsecs (kpc) based upon the correct P - L relations, binary star observations, and observations of other luminous classes of stars.)

* A kiloparsec is 1,000 parsecs = 3,262 light-years = 3.0856×10^{19} meters

So the "Copernican" question now concerns the relationship of our Galaxy to the other galaxies in the universe - and the distribution of galaxies in space.

But now things get more interesting ......

More from Edwin Hubble:

**The external universe of galaxies looks the same in all directions.
(Numbers of galaxies, types of galaxies, brightness of galaxies,...)
i.e., The universe appears <u>isotropic</u> from our location.**

**External galaxies all seem to be receding from us with speeds which
increase in direct proportion to their distances**

$$v_{radial} = H_O d$$

**This <u>linear</u> relation (and the value of the "Hubble Constant" H_O) is the
same in all directions; this relation is also <u>isotropic</u>.**

Hubble has discovered that the Universe is expanding!

**Important: The fact that the observed "expansion" is both <u>linear</u> and
<u>isotropic</u> implies that this universe of galaxies is <u>homogeneous</u>.**

**Translation: The external universe would look the same from any
location within it.**

An present-day observer on some distant galaxy would see the same
isotropic distribution of galaxies, the same isotropic expansion about its
location, and obtain the same value for the Hubble Constant.

Digression: The Hubble Constant and the Age of the Universe

Hubble's Data (1929)

Type Ia Supernovae Observations
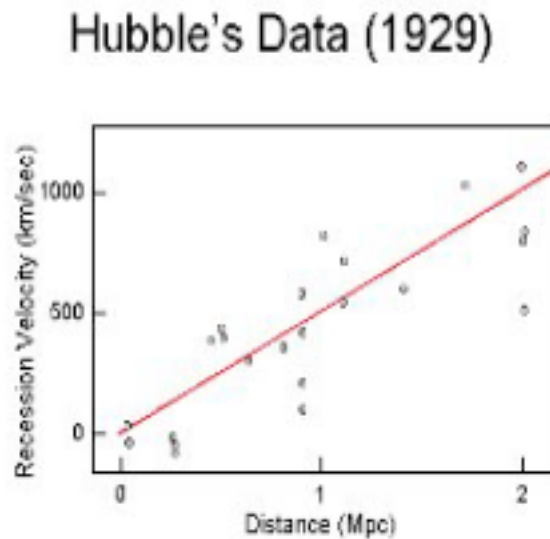
$H_O = 500$ km/s/Mpc
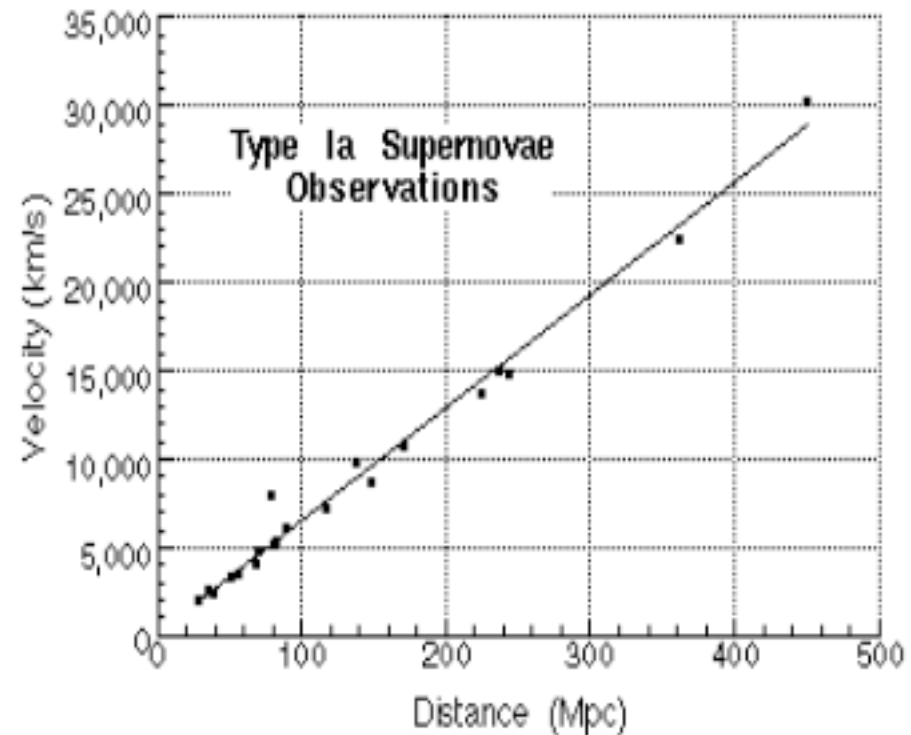
$H_O = 65$ km/s/Mpc

The Age of the Universe

If the universe expands at a constant rate (it doesn't) so H_o always has had the same value then the age of the universe is simply the "Hubble Time" $T_o = 1/H_o$

Example: **T = 15 Gyr if H_o = 65** km/s/Mpc

The Copernican Principle in Cosmology

The Cosmological Principle

**The Universe on large scales is spatially <u>homogeneous</u> and <u>isotropic</u>.
"At any given time, the universe looks the same from all locations."**

There is no "special place" in the Universe
... not the Earth, not the Sun, not our galaxy - nor any other location.
The Universe does not have a "center"

This Cosmological Principle constitutes a testable hypothesis: It has been tested again and again as the universe is observed to greater distances - and at earlier times*.

*The **"Perfect Cosmological Principle"** (Hoyle, Gold, & Bondi, 1948) considered an expanding universe that was, nonetheless, unchanging in time - as well as being spatially homogeneous and isotropic. This was a well-motivated hypothesis which was testable ("falsifiable"). It was, in fact, falsified through observations of the early universe. See "Steady State Cosmology"

...but more on all of this later.