

The Beginning of Cosmology

Development of General Relativity -1907

- ◊ In 1907 (2 years after Special Relativity publication, Einstein asked himself the question – how does Newtonian Gravity work to fit in with special relativity?
- ◊ In what he described as the *happiest thought of my life*, he realised that someone falling off the roof of a house experiences no gravitational field. Proposes the equivalence Principle:
 - ... we shall therefore assume the complete physical equivalence of a gravitational field and the corresponding acceleration of the reference frame. This assumption extends the principle of relativity to the case of uniformly accelerated motion of the reference frame

1911

- ◊ Einstein realised that the bending of light in a gravitational field – something he mentioned in 1907, could be tested by astronomical observations.
- ◊ Also realised that there should be gravitational redshift

1912

- ◊ Einstein proved that special relativity's Lorentz Transformations were invalid if Equivalence Principle held
- ◊ And that he could only make the equivalence principle hold locally, unless...

If all accelerated systems are equivalent, then Euclidean geometry cannot hold in all of them.

and started trying to incorporate the mathematics of surfaces and geometry into his theories.

... in all my life I have not laboured nearly so hard, and I have become imbued with great respect for mathematics, the subtler part of which I had in my simple-mindedness regarded as pure luxury until now.

1913

- ◇ Einstein and Grossman published a joint paper where the tensor calculus of Ricci and Levi-Civita is employed to make further advances.
- ◇ Gravitation was described for the first time by the metric tensor but still the theory was not consistent. When Planck visited Einstein in 1913 Planck said
 - *As an older friend I must advise you against it for in the first place you will not succeed, and even if you succeed no one will believe you.*

1914

- ◇ October 1914 Einstein publishes paper on GR including his ideas on tensor analysis and differential geometry.
- ◇ Levi-Civita pointed out technical errors in this work's use of tensors and helped Einstein fix them

1915

- ◇ Einstein lectures at Göttingen to Hilbert his October 1914 work, and this opens up correspondence with Hilbert.
- ◇ The final steps to the theory of general relativity were taken by Einstein and Hilbert at almost the same time. Both had recognised flaws in Einstein's October 1914 work and a correspondence between the two men took place in November 1915.

Five days before Einstein submitted his 25 November paper Hilbert had submitted a paper *The foundations of physics* which also contained the correct field equations for gravitation and.

Perihelion Advance of Mercury

- ◇ Le Verrier, in 1859, had noted that the perihelion (the point where the planet is closest to the sun) advanced by 38" per century more than could be accounted for from other causes.
- ◇ Many possible solutions were proposed,
 - Venus was 10% heavier than was thought
 - there was another planet inside Mercury's orbit
 - the sun was more oblate than observed,
 - Mercury had a moon and, really the only one not ruled out by experiment,
 - Newton's inverse square law was incorrect.
- ◇ By 1882 the advance was more accurately known, 43" per century.
- ◇ From 1911 Einstein had realised the importance of astronomical observations to his theories and he had worked with Freundlich to make measurements of Mercury's orbit required to confirm the general theory of relativity. Freundlich confirmed 43" per century in a paper of 1913.
- ◇ Einstein applied his theory of gravitation and discovered that the advance of 43" per century was exactly accounted for without any need to postulate invisible moons or any other special hypothesis. (Based on wrong Field Equations, but they gave the same answer in this instance)

Bending of Light

- ◇ Final paper of 25 November, 1915 found that bending of light was twice as large as Einstein's original predictions – $1.74''$ at the surface of the sun.
- ◇ Eddington thought Relativity must be right, and set out (after WWI) to prove it.



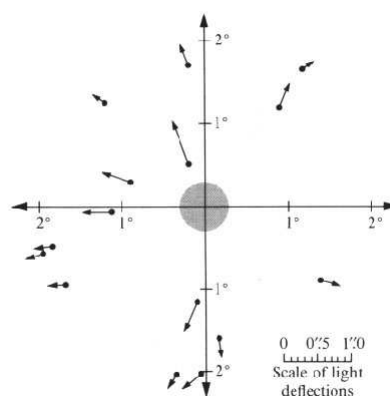
Eclipse of 1919

- ◇ Eddington leads expedition (complicated arrangement for him not be conscripted into WWI) to African Island Principe
- ◇ Brazil Expedition led by Crommelin of the RGO.
- ◇ Eddington had lots of clouds
- ◇ Crommelin had out-of-focus images.
- ◇ Eclipse first after WWI, passed in front of Hyades Cluster



- ♦ Britain's premier scientific body, the Royal Society, called a special meeting in London on 6 November. Dyson, as Astronomer Royal took the floor, and announced that Eddington's measurements did not support Newton's long-accepted theory of gravity. Instead, they agreed with the predictions of Einstein's new theory – and Einstein instantly was propelled into the limelight of the world
- ♦ It is widely believed now that Eddington's experiment was incapable of measuring the deflections of stars accurately enough. (much data removed, out-of-focus images, only 5 stars)
- ♦ Credit really should go to the eclipse of 1922, but alas, that is not how science always works!

- ♦ In 1922, another observation was made at Wallal, Western Australia, and W. W. Campbell and R. J. Trumpler). Many stars and a much better measurement.



The Curtis Shapley Debate



Curtis



Shapley

26 April 1920
National Academy of Sciences,
Washington, D.C.

G. Abbot, Home secretary of the Academy in a letter to
George Ellery Hale

"You mentioned the possibility of a sort of debate, either on the subject of the island universe or of relativity. From the way the English are rushing relativity in Nature and elsewhere it looks as if the subject would be done to death long before the meeting of the Academy, and perhaps your first proposal to try to get Campbell and Shapley to discuss the island universe would be more interesting. I have a sort of fear, however, that the people care so little about island universes, notwithstanding their vast extent, that unless the speakers took pains to make the subject very engaging the thing would fall flat.... Are there not other subjects-the cause of glacial periods, or some zoological or biological subject-which might make an interesting debate?...As to relativity, I must confess that I would rather have a subject in which there would be a half dozen members of the Academy competent enough to understand at least a few words of what the speakers were saying if we had a symposium upon it. I pray to God that the progress of science will send relativity to some region of space beyond the fourth dimension, from whence it may never return to plague us."

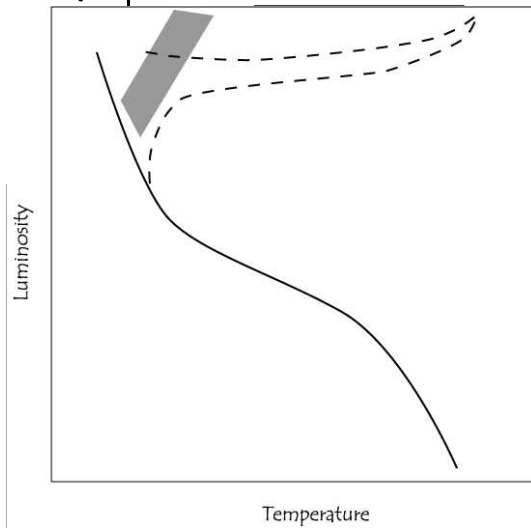
Harlow Shapley: Nebulae are part of our Own Galaxy

- ◊ Galaxy is large 100 kpc in diameter based on Globular Clusters, and we are removed from center
- ◊ If Nebulae (Galaxies) are like the Milky Way, then they are very distant. But the *novae* in these distant Galaxies are about the same brightness as those in our own Galaxy
- ◊ Rotation Measurement of M31 van Maanen
- ◊ Color of Spiral Arms of Galaxy are different – much bluer – than rest of Galaxy – so not composed of stars
- ◊ Nebulae avoid Milky Way
- ◊ Nebulae are all moving away from us (repulsed) – Vesto Slipher

Curtis: Milky Way and Nebulae are Galaxies of a Billion Stars

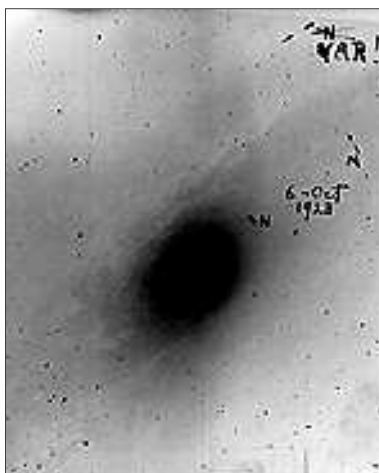
- ◊ Galaxy is 10 kpc across, and Sun Near center, so tough to see what is going on.
- ◊ Spectra of Nebulae look like the integrated spectra of many stars – if galactic they are completely unknown material
- ◊ Many nebulae have dark rings of occulting material, and if our own galaxy has this, this would obliterate the nebulae in the galactic plane.
- ◊ Most Novae in Andromeda are faint, and are much fainter than those in Milky Way
- ◊ Evidence that Milky Way may have spiral structure

New Technology, New Techniques



Cosmology Solved! 6 Oct 1923

Hubble
Discovers
Cepheids in M31
& NGC 6822 &
M33



Take Home Message

Astronomy is full of

- ◊ Red herrings
- ◊ Bad Observations
- ◊ Missing Information

Definitive Observations Provide a Way through
the Fog