LECTURE 7 ASTB23

Early 20th century. Einstein and Eddington.

I hope the biographical details will be of interest to you.
However, they will not be required at exams.

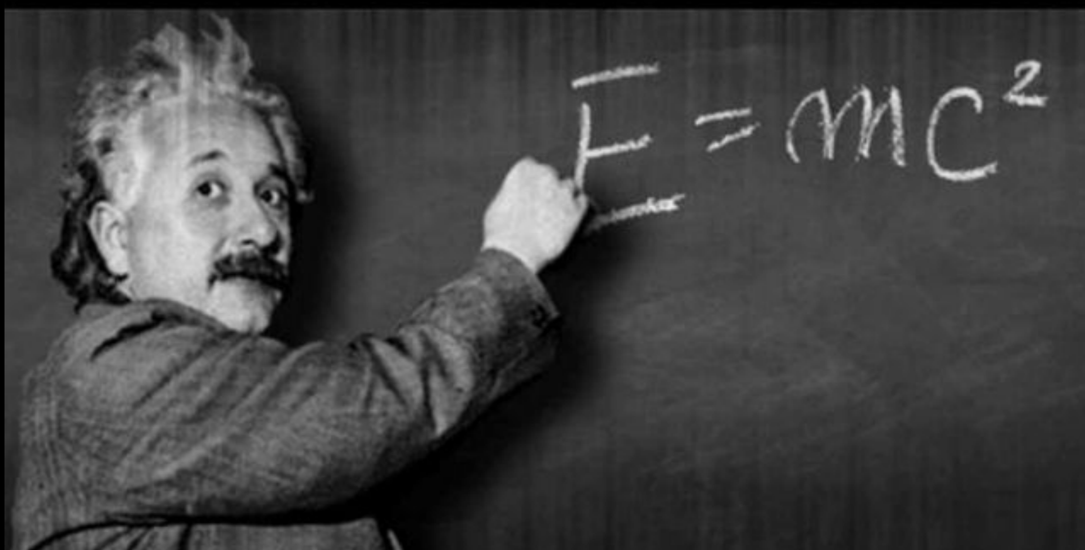
Interplay between physics and astronomy.

- Astronomical proofs of Einstein's General Theory of Relativity. Eddington's eclipse photos from 1919. Precession of Mercury's orbit.

- Why do stars shine?
- The problem of timescales and its 1920 resolution by Eddington, using Aston's experiments and Einstein's theory.
- [Gamow's solution to proton repulsion problem]

Einstein and Eddington: $E=mc^2$ and why the stars shine

(Fruitful interplay between physics and astrophysics in the 20th century)



Albert Einstein (1879-1955)

Arthur S. Eddington (1882-1944)

Young Albert was not seen as genius. On the contrary, he started speaking rather late as a child, and did not impress all school teachers.

But it is an urban myth that he had troubles with high school math.
On the contrary, math was his favorite subject and his tutors noticed the ease with which young Albert mastered geometry, algebra, and then calculus on his own, aged 12-14!

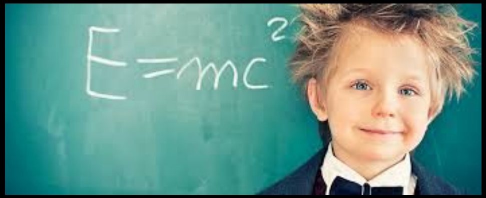
He did not shine in some other subjects. As a result, he was rejected for study at physics dept. by the polytechnic university now known as ETH in Zürich, Switzerland.
He enrolled in a 4-yr teaching program, where he met his future Serbian wife, Mileva Marić.

After studies, around 1900, Einstein failed in his search for assistantship in academia or a teaching job. He became patent office clerk in Bern, Switzerland.

Albert at 14

Albert Einstein was born in Ulm, Württemberg (Germany), to secular Ashkenazi Jewish family.
At the age of 17, Einstein renounced German citizenship to avoid military duty & moved to Switzerland.

In 1905 Albert Einstein published 4 papers, including his Special Theory of Relativity, drawing far-reaching conclusions from the constancy of the speed of light in vacuum & phenomena happening when objects move at comparable speeds. One of the conclusions was the famous formula



which turned out extremely important for astrophysics.

- How a joking question during habilitation examination “can you derive $E=mc^2$?” was briefly answered by Einstein

- What Einstein thought about Edison’s job interview questionnaire questions, such as ‘what is the value of the speed of sound?’

- Th. Edison, the great inventor of phonograph, lightbulb etc., a man of poor formal education himself, thought that higher education is useless. He tested job candidates on memory skills. Einstein hated such exercises while at school.

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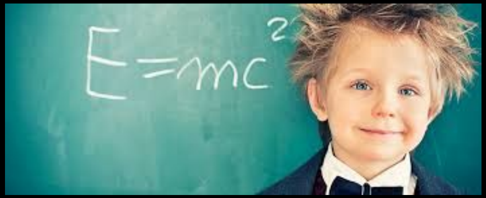


which turned out extremely important for astrophysics.

- Einstein said about his $E = mc^2$ formula:

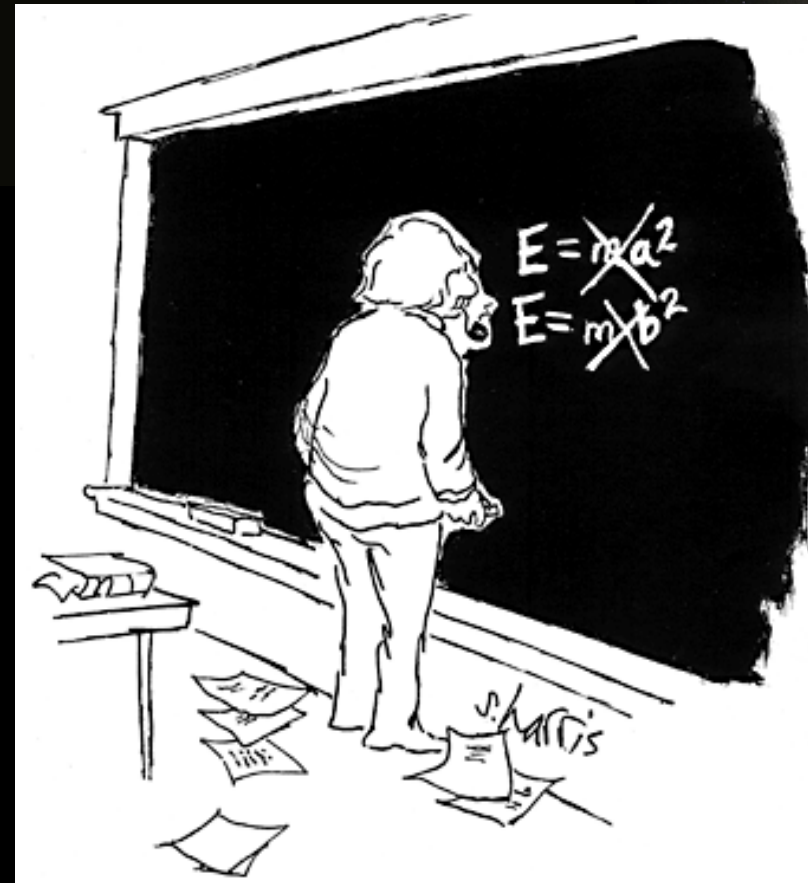
"I don't know the proof by heart but I know in which book, on which shelf in the library, I can find it". He actually did provide many elementary proofs of the energy-matter equivalence formula.

- Asked one of Edison's job interview questions, Einstein said: 'I do not burden my memory with such facts, which can be found in textbooks'.

- Einstein also said that university is great not because it teaches facts but, more importantly, how to think.

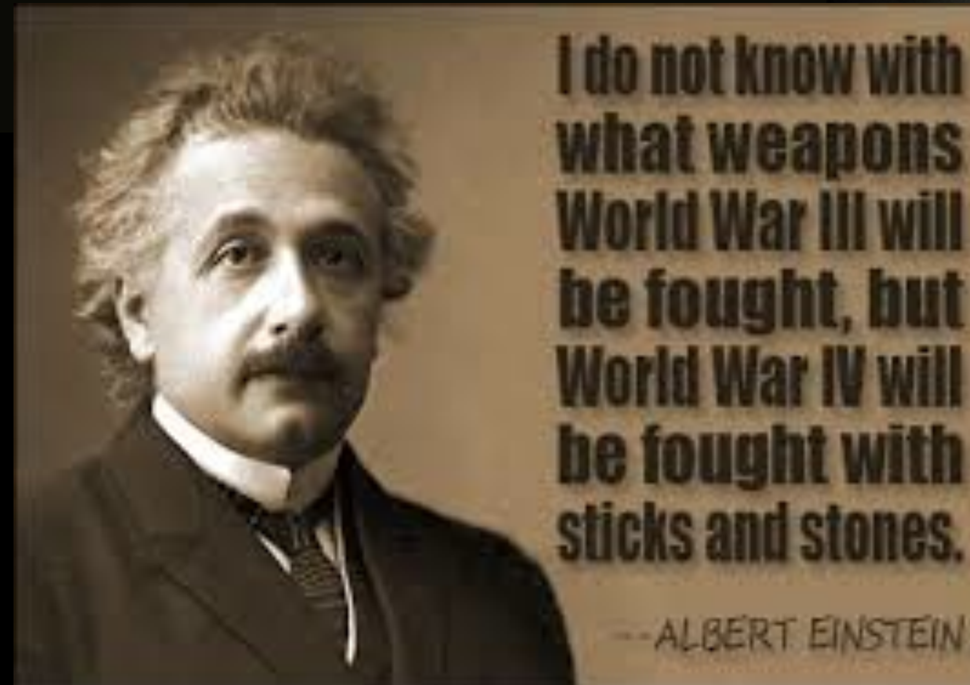
Einstein once jokingly consoled someone complaining about the difficulty with mathematics:

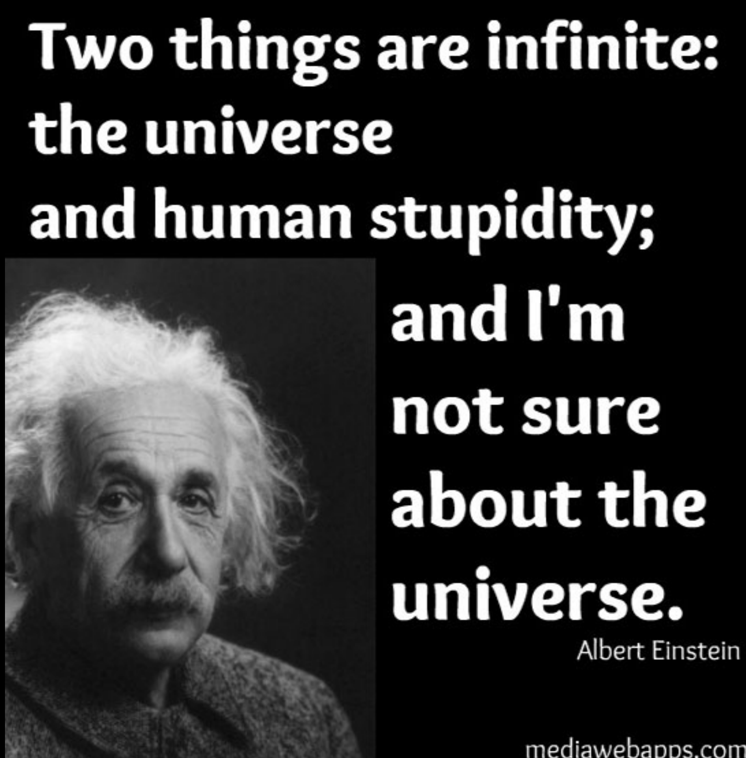
If you think that *you* have problems with math, mine are larger still.



(c) New Yorker magazine

He may have meant his struggle to cast General Relativity (GR) equations into the mathematical form of Riemannian geometry.


I do not know with what weapons World War III will be fought, but World War IV will be fought with sticks and stones.
--ALBERT EINSTEIN


Two things are infinite: the universe and human stupidity; and I'm not sure about the universe.
Albert Einstein
mediawebapps.com

"In theory, theory and practice are the same.
In practice, they are not."

"Theory is when you know everything but nothing works.
Practice is when everything works but no one knows why.

In our laboratory, theory and practice are united:
Nothing works and no one knows why."

Einstein’s career took off exponentially after 1905:

Lecturer at Bern University in 1908,
Assoc. professor of Zürich in 1909,
Full professor at Carl-Ferdinand university in Prague in 1911,
Professor of theoretical physics at ETH Zürich in 1912, and a
Member of the Prussian Academy of Sciences in Berlin,1913.

In 1913 he was visited by Max Planck and Walter Nernst, who offered him to move from Zürich to Berlin, to work at the Prussian Academy as a Director of the new Keiser Wilhelm Institute for Physics.
Einstein accepted the invitation and moved to Berlin.

- In 1914, as the Great War broke out (WW I), practically all German intellectuals and scientists actively supported the war.
- 93 of them signed a manifesto of patriotism justifying militarism.
- Being a pacifist, Einstein signed a declaration opposing the war.
- Due to his anti-militarism he became isolated in Berlin.

Einstein's Special and General Theories of Relativity were initially met with controversy and skepticism by scientists.
Thus when A. Einstein finally received the long overdue 1921 Nobel Prize, it was for... work on photoelectric effect, not relativity!
General Relativity (GR) is a classical field theory of gravity, much different from Newtonian mechanics. It rejects Newton's notion of force-at-a-distance and explains gravitation as a result of a curvature of space-time.
GR reduces to Newtonian mechanics in case of weak gravity fields, but surprisingly predicts this:

Rays of massless light (as well as massive particles moving at speed $v \approx c$, the speed of light) are bent by gravity of a massive body **twice** as much as Newtonian mechanics predicts, using the classical $1/r^2$ gravity force and the mass=energy/c^2 formula.

This is very important for astronomy as the physics of cosmos, with almost *all* information carried by light rays arriving on Earth!

Astronomy helped Physics by discovering:
(i) the GR-predicted effects of light bending and
(ii) the precession of Mercury's orbit, the former an especially easy-to-grasp proof of GR!

To measure the predicted bending of light was easier said than done. The problem was that the amount of deflection due to Earth or Jupiter is unmeasurable, and due to the Sun marginally detectable with the technology of early 20th century.

Today every student of classical mechanics can calculate how much the Newtonian force deflects objects moving at the speed of light next to the sun's surface. The angle equals 0.”86 (less than one arcsecond = 1” = 1^{o} / 3600). That's very small.

General Relativity in its quasi-Newtonian limit adds enough modification to the $1/r^2$ force that we expect 1”.73, but even that 2x larger amount was very hard to measure 100 yrs ago.

Many attempts to observe total eclipses of the sun were undertaken in 1901-1918 period, mainly by Erwin Freundlich from Berlin Obs. and Charles Perrin, then at Lick Observatory.

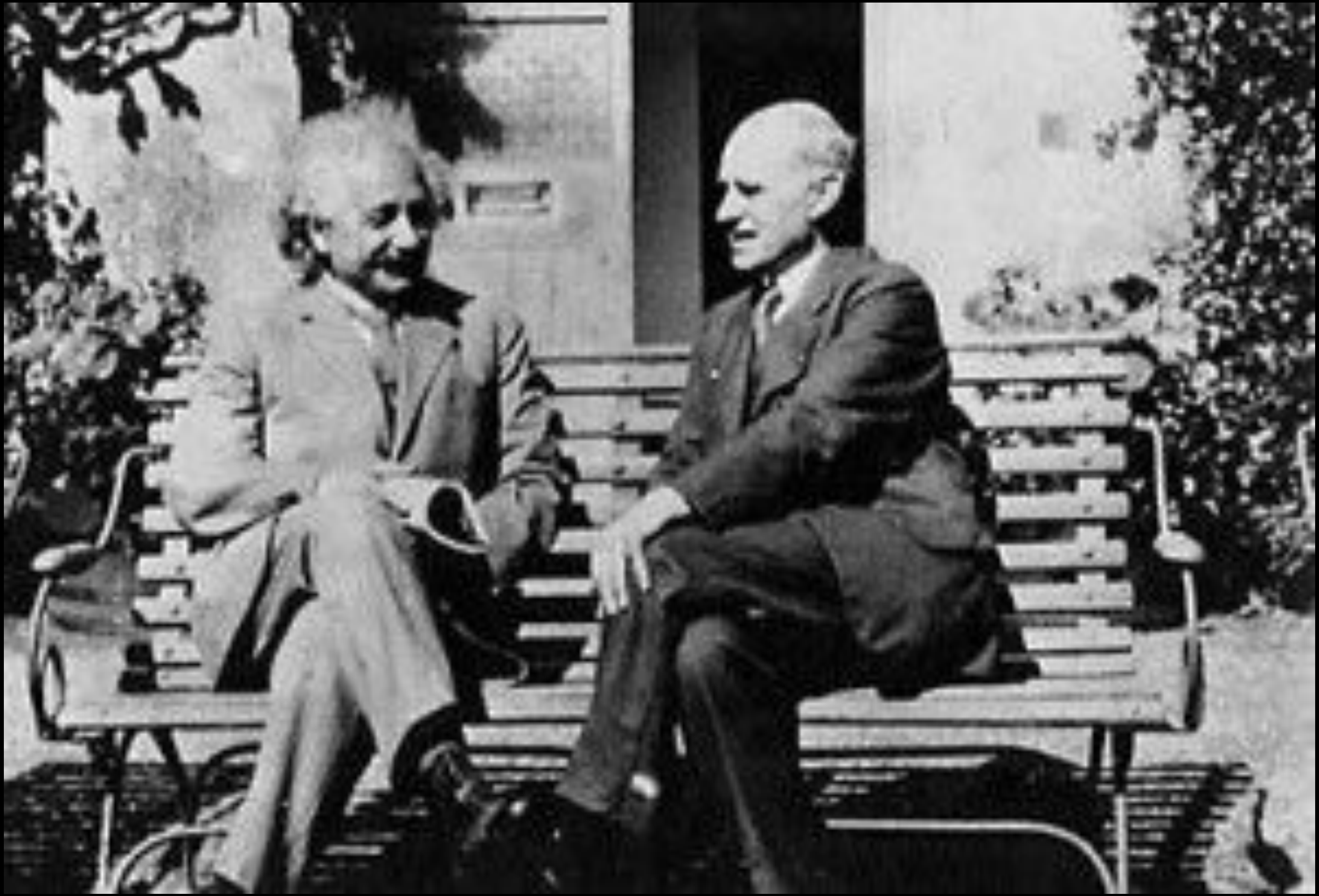
As it happens in observational astronomy, special instruments were built but could never be used. In 1912 on the day of total eclipse there were torrential rains at observing stations.

Three teams went to observe a total eclipse in 1914 to Crimea, Russia, only to have again been thwarted. The war broke out, and Freundich’s team was detained by Czar’s soldiers as enemy citizens. Others were clouded out.

The same bad luck pursued American astronomers in 1918, clouds or equipment problems prevented observations...

The next good opportunity was to come in 1919. The path of total eclipse ran from Brazil to equatorial Africa across Atlantic.

Einstein and Eddington. Two scientists with different lives, ethnicities, national allegiances, on different sides of the WW I divide. United by the belief in one humanity, aversion of wars, and interest in cosmos and its physics.



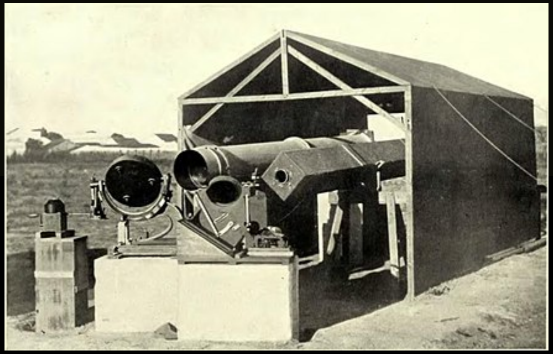
Arthur Stanley Eddington (1882-1944)

Educated in Manchester U., then Cambridge U.,
he became professor & Director of Astronom. Observatory in Cambridge, UK. Eddington was:

- an avid biker
- one of the 1st who understood both the formalism and the great importance of Einstein's GR (General Relativity) already in 1915.
- understood what powers the stars (we'll cover that soon)
- Member of a Quaker family (Christian denomination), thus
- rejecting military duty on religious grounds. A pacifist.
- Being conscientious objector was socially unacceptable and officially punishable by detention in internment camp in England.
- In the patriotic fervor of the Great War of 1914-1918 (WW I) this nearly resulted in Eddington's prosecution, but other scientists managed to obtain his deferral*. Still, to diffuse potential trouble Eddington was asked to leave England to go observe the eclipse. He agreed willingly, although he never had doubt in GR.

*) – cf. book "Eddington –the most distinguished astrophysicist" by S. Chandrasekhar

Eddington's expedition

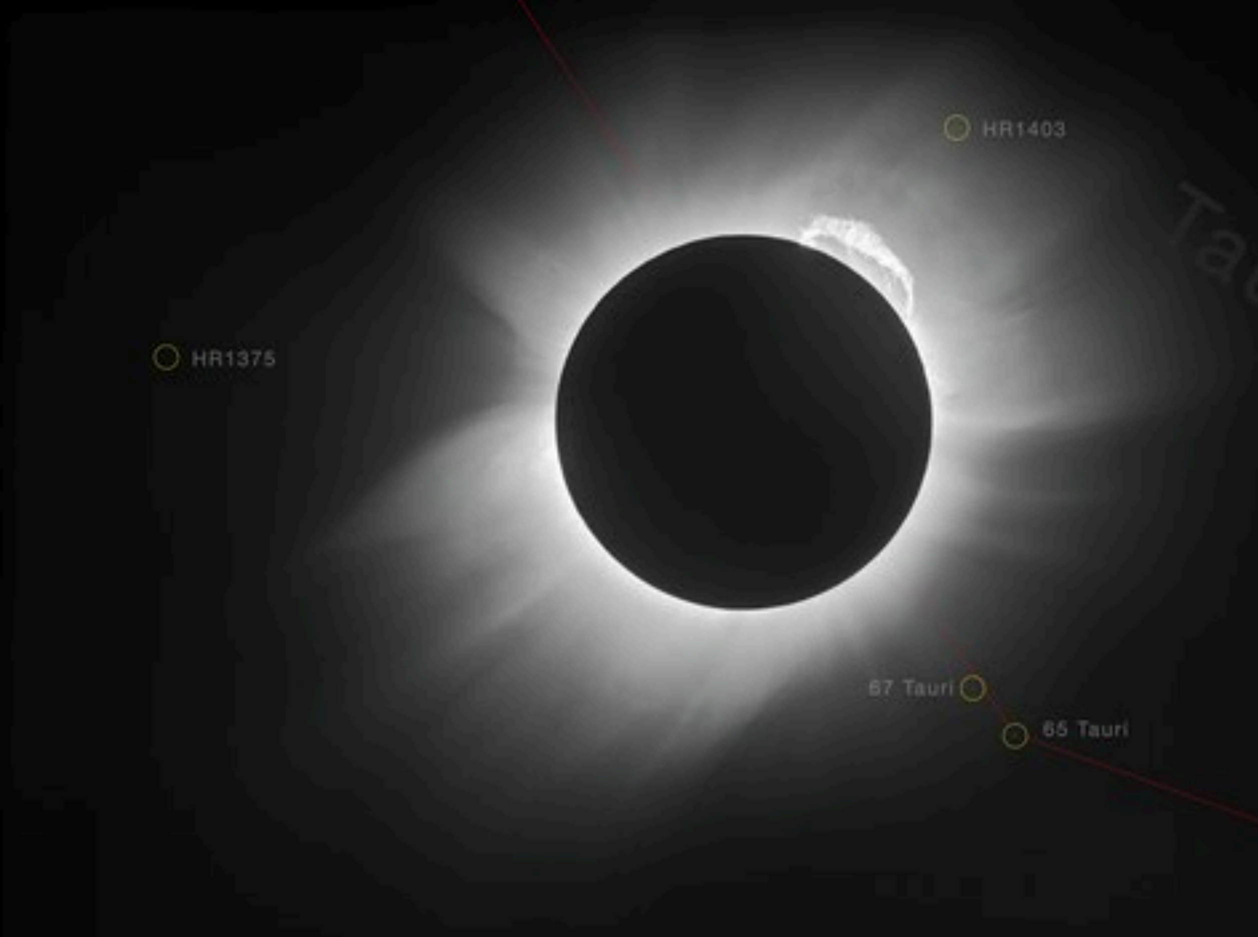


Eddington organized two long expeditions to record the total eclipse in 1919, to:

(i) Sobral in Brazil

(ii) the equatorial island Ilho do Principe (Prince's Island) in the Sao Tome and Principe archipelago off the west coast of Africa.

An article on the centennary of the expedition: https://www.smithsonianmag.com/science-nature/total-solar-eclipse-100-years-ago-proved-einsteins-general-relativity-180972278/



Ironically, photographic plates from Sobral were a bit *too well* exposed, making star images larger than necessary for position measurements. This robbed them of the much needed accuracy ☹ The plates from Principe island were exposed, even though just before the total eclipse clouds were still present after the morning heavy rain. Two plates of Eddington’s group turned out useful. ☺

IX. *A Determination of the Deflection of Light by the Sun's Gravitational Field, from Observations made at the Total Eclipse of May* 29, 1919.

By Sir F. W. Dyson, *F.R.S., Astronomer Royal, Prof.* A. S. Eddington, *F.R.S., and Mr.* C. Davidson.

(*Communicated by the Joint Permanent Eclipse Committee.*)

Received October 30,—Read November 6, 1919.

[Plate 1.]

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I. Purpose of the Expeditions.

1. The purpose of the expeditions was to determine what effect, if any, is produced by a gravitational field on the path of a ray of light traversing it. Apart from possible surprises, there appeared to be three alternatives, which it was especially desired to discriminate between—

(1) The path is uninfluenced by gravitation.

(2) The energy or mass of light is subject to gravitation in the same way as ordinary matter. If the law of gravitation is strictly the Newtonian law, this leads to an apparent displacement of a star close to the sun's limb amounting to $0''\cdot 87$ outwards.

(3) The course of a ray of light is in accordance with Einstein's generalised relativity theory. This leads to an apparent displacement of a star at the limb amounting to $1''\cdot 75$ outwards.

Outward deflection of star's position is extrapolated to sun's limb. Deflection is inversely proportional to the angular distance from sun's center. Different star 'moved' by 1.67", 1.44" and so on..

Hence deflection at the limb is

$$1''\cdot 75 - 0''\cdot 08 = 1''\cdot 67.$$

The corresponding deflection at the limb is

$$1''\cdot 75 - 0''\cdot 31 = 1''\cdot 44.$$

Hence deflection at the limb is

$$1''\cdot 75 - 0''\cdot 20 = 1''\cdot 55.$$

This gives the deflection

$$2''\cdot 90.$$

The probable error is, however, $\pm 0''\cdot 87$, so that the result is practically worthless. Further, it is much more likely to be affected by systematic error than the previous results.

As the four determinations involve only two eclipse plates and are not wholly independent, and further small accidental errors may arise through inaccurate determination of the orientation, the probable error of our mean result will be about $\pm 0''\cdot 25$. There is further the error of $\pm 0''\cdot 14$ affecting all four results equally, arising from the determination of scale. Taking this into account, and including the small correction $-0''\cdot 04$ previously mentioned, our result may be written

combined result from Eddington's Principe expedition:

$$1''\cdot 61 \pm 0''\cdot 30.$$

vs. predicted 1".75

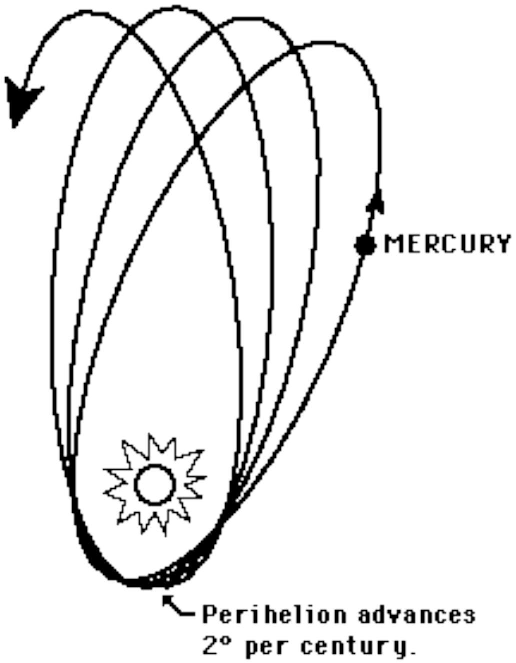
It will be seen that the error deduced in this way from the residuals is considerably larger than at first seemed likely from the accordance of the four results. Nevertheless the accuracy seems sufficient to give a fairly trustworthy confirmation of EINSTEIN's theory, and to render the half-deflection at least very improbable.

3. The only opportunity of observing these possible deflections is afforded by a ray of light from a star passing near the sun. (The maximum deflection by Jupiter is only $0''\cdot017$.) Evidently, the observation must be made during a total eclipse of the sun.

Immediately after EINSTEIN's first suggestion, the matter was taken up by Dr. E. FREUNDLICH, who attempted to collect information from eclipse plates already taken; but he did not secure sufficient material. At ensuing eclipses plans were made by various observers for testing the effect, but they failed through cloud or other causes. After EINSTEIN's second suggestion had appeared, the Lick Observatory expedition attempted to observe the effect at the eclipse of 1918. The final results are not yet published. Some account of a preliminary discussion has been given,† but the eclipse was an unfavourable one, and from the information published the probable accidental error is large, so that the accuracy is insufficient to discriminate between the three alternatives.

4. The results of the observations here described appear to point quite definitely to the third alternative, and confirm EINSTEIN's generalised relativity theory. As is well-known the theory is also confirmed by the motion of the perihelion of Mercury, which exceeds the Newtonian value by 43″ per century—an amount practically identical with that deduced from EINSTEIN's theory. On the other hand, his theory predicts a displacement to the red of the Fraunhofer lines on the sun amounting to about 0·008 Å in the violet. According to Dr. ST. JOHN‡ this displacement is not confirmed. If this disagreement is to be taken as final it necessitates considerable modifications of EINSTEIN's theory, which it is outside our province to discuss. But, whether or not changes are needed in other parts of the theory, it appears now to be established that EINSTEIN's law of gravitation gives the true deviations from the Newtonian law both for the relatively slow-moving planet Mercury and for the fast-moving waves of light.

A very solid proof of General Relativity (GR) by astronomy was also: Relativistic precession of orbit of Mercury



(drawing is not to scale; elongation of orbit and its precession are exaggerated!)

Gravitational perturbations by planets cause the 5600”/century precession of Mercury, while the 19th century astronomical observations showed a slightly **larger** precession. Where is the extra precession coming from?

The answer was presciently suggested already by Isaac Newton! Remember his remarks in *Principia Mathematica Phil. Naturalis (1687)* about the line of apses being *very* sensitive to any deviation of force from the $1/r^2$ law? Well, the General Relativity predicts a tiny deviation of the type $\sim 1/r^4$. Nicely enhanced by the sensitivity of the precession to such small deviations, it causes the extra precession.

Astronomical observations show unexplained (41”.4 ± 0”.9)/century precession, while the GR theory predicts 42”.98/century, within 2 standard deviations of observation. Bingo! However, this proof (which in fact preceded Eddington’s expedition) was not easy to grasp by non-specialists. Thanks to Eddington, Albert Einstein became a world-wide idol after the 1919 eclipse.

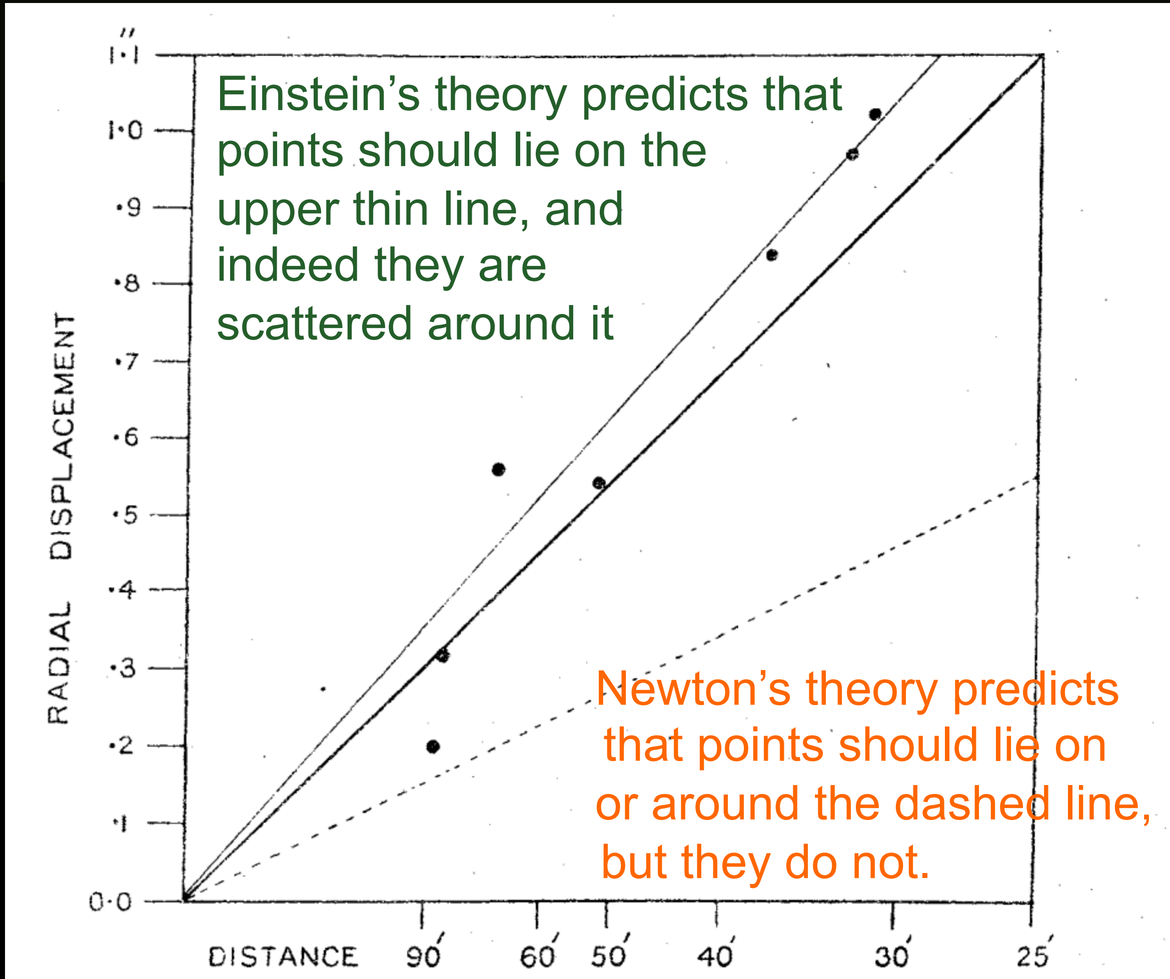


Diagram 2.

LIGHTS ALL ASKEW IN THE HEAVENS

New York Times, 10 Nov 1919

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

Turning to the portrait of Newton at Royal Society meeting in 1919, Arthur Eddington said:

"Sorry Sir Isaac! We have a new theory of gravity."

After that meeting...

In reality, many expeditions and many decades had to pass until radio telescopes confirmed light-bending angles to be as expected from GR theory with high accuracy.

There are two, 99%-true, anecdotes about:

- Silberstein and Eddington (“Don’t be so modest Eddington...”)
- E. Rutherford, M. Amos and A. Eddington (“Ask Eddington. He is responsible for this.”)

★ Physicist Ernest Rutherford explained:

“The war has ended. The people felt that all their values and all their ideals had lost their bearings. Now, suddenly, they learnt that an astronomical prediction by a German scientist had been confirmed by expeditions to Brazil and West Africa and, indeed, prepared for already during the war, by British astronomers. Astronomical discovery, transcending worldly strife, struck a responsive chord. The meeting of the Royal Society, at which the results of expeditions were reported, was headlined in all the British papers, and the typhoon of publicity crossed the Atlantic. From that point on, the American press played Einstein to the maximum.”

(E. Rutherford quoted by S. Chandrasekhar in his book about Eddington)

Stellar riddles

- Why do stars shine?
  & Why do they shine for so long?

- The proposed answers and their biggest problem: timescales
- 1920 resolution of the problem by Eddington using Einstein’s theory: the thermonuclear reactions

- Gamow’s solution to proton repulsion problem

Astronomy helped Physics with the proofs of relativity theory. Now came a chance for Physics to reciprocate.

The main problem in Astrophysics of 19th and 20th century:

What are stars and why do they shine?

Incomplete answer to this question was provided in late 1800s by the theory of hydrostatic equilibrium. Subject to the pull of own gravitation, a gas sphere obeys the so-called Lane-Emden equation. From it, astronomers knew how to estimate the central temperature in the sun in equilibrium. It was enormous: many millions K (or ^{o}C).

From the flux of energy illuminating the Earth (1360 W/m^2) it was also known that the sun emits large power (luminosity): $L = 3.86 * 10^{26}$ W.

But neither the internal composition nor the mechanism of sun's energy production were easy to figure out.

What powers stars? Chemical reactions?

- Chemical reactions of solar material were excluded as a source of its energy release.

If 1kg of burning or otherwise chemically reacting material gives off heat amounting to, say, ~10^7 J, then to produce L~10^{27} J/s, the sun would have to burn
~10^{20} kg/s of fuel (since $10^{20}\ 10^7=10^{27}$).

The mass of the sun is ~10^{30} kg, therefore the burning would stop before ~10^{10} s, or only a thousand years – way too short!

- Could the energy be gravitational instead?

Matter of mass dm falling into grav. potential well –GM/r may turn the energy difference |-GM dm/r| into heat or radiation. So at first, suspicion fell on meteoritic or gaseous matter falling onto sun's surface. To satisfy L_{sun} = GM/R dm/dt, however, implausible rate of infall dm/dt was needed. [Do the calculation & judge for yourself!]

What powers stars? Gravitational contraction?

A better idea is that a slow shrinking of a star would push it deeper into its own gravitational potential well (the smaller the star of a constant mass, the more negative its potential energy).
The positive energy difference, energy of contraction, can be released as heat.

This is the Kelvin-Helmholtz contraction hypothesis
(William Thomson, 1st baron of Kelvin; and Hermann von Helmholtz).

Today, you are able to work out the shrinking rate needed to reproduce the solar L, and from this, also max lifetime of the sun.

What powers stars? Gravitational contraction?

The result is that the characteristic time, so-called Kelvin-Helmholtz contraction time, equals 20 to 30 million years.

That's a 10000x improvement w.r.t. the chemical reactions. But... the Kelvin-Helmholz contraction, of order 10^7 yr, is still too brief!
Natural sciences (geology of Lyell, paleontology, biology of Darwin) provided ever growing estimates of the age of Earth (and the sun), reaching $> 10^9$ yr.
Astronomy itself immediately cast doubt on contraction hypothesis too. The massive stars called Cepheids would change their color 100x faster than observational limits allowed.

Then, after Maria Skłodowska (later Marie Curie) started extracting radio-isotopes from minerals and ores, a new technique for dating the oldest rocks sprung up: radio-isotope dating. It works as follows.

Radio-isotope dating shows an old age of Sun and Earth

We know that some minerals (e.g. zircon $ZrSiO_4$) when they form avoid at all cost the inclusion of certain atoms (e.g., Pb), which don't fit their crystal structure well. However, if the spontaneous decay of radionuclides (unstable, radioactive isotopes, e.g. ^{238}U) produces such 'misfit' nuclei inside a crystal, their atoms have to stay there, accumulating in time. That provides a way to find out how much time passed since the formation of the crystal.

It's like an isotope-pair clock. To increase accuracy, several such clocks can be used to study the same piece of rock.

For instance, if ½ of ^{238}U has already decayed through a chain of nuclear transformations into ^{206}Pb, we know that the mineral is 4.47 Gyr old (the U-Pb dating). Some meteorites are that old, and older. We now know that the sun and planets started forming 4.567±1 Gyr ago.

What powers the stars? Radioactivity? Other reactions?

Thus in the beginning of 1900s we have learned that the Solar System, including the Earth, is > 4 billion years old, and a much different explanation for sun's energy production than K-H contraction was needed.

Radioactivity of the substance of the sun was **not** a sufficient source. Some scientists therefore speculated that another subatomic energy release mechanism is at work, but the ideas were not specific enough.

In 1920, Arthur S. Eddington provided the first concrete proposal.

He based it on Einstein's relativity theory, namely the $E = mc^2$ formula, and the idea that hydrogen (^{1}H), common gas, at least in stellar atmospheres, exothermally converts into helium (^{4}He). We call such reactions thermonuclear reactions, or fusion of hydrogen.
A crucial role in understanding where "m" in Einstein's formula comes from was played by careful and imaginative work by a colleague of Eddington working at Cavendish Laboratory in Cambridge, UK.

Table of Elements and Isotopes

Element.	Atomic number.	Atomic weight.	Minimum number of isotopes.	Masses of isotopes in order of intensity.
H . .	1	1·008	1	1·008
He . .	2	4·00	1	4
Li . .	3	6·94	2	7, 6
Be . .	4	9·1	1	9
B . .	5	10·9	2	11, 10
C . .	6	12·00	1	12
N . .	7	14·01	1	14
O . .	8	16·00	1	16
F . .	9	19·00	1	19
Ne . .	10	20·20	2	20, 22, (21)
Na . .	11	23·00	1	23
Mg . .	12	24·32	3	24, 25, 26
Si . .	14	28·3	2	28, 29, (30)
P . .	15	31·04	1	31
S. . .	16	32·06	1	32
Cl . .	17	35·46	2	35, 37, (39)
A . .	18	39·88	2	40, 36
K . .	19	39·10	2	39, 41
Ni . .	28	58·68	2	58, 60
As . .	33	74·96	1	75
Br . .	35	79·92	2	79, 81
Kr . .	36	82·92	6	84, 86, 82, 83, 80, 78
Rb . .	37	85·45	2	85, 87
I . .	53	126·92	1	127
X . .	54	130·2	5, (7)	129, 132, 131, 134, 136, (128, 130 ?)
Cs . .	55	132·81	1	133
Hg . .	80	200·6	(6)	(197–200), 202, 204

Dempster's later results (V. p. 148)

Ca . .	20	40·07	(2)	(40, 44 ?)
Zn . .	30	65·37	(4)	(64, 66, 68, 70)

Using his mass spectrometer F. Aston in 1919 measured masses of atoms of different elements (unit of mass based on carbon C = 12.000,

and He = 4.000). Aston received Nobel Prize in chemistry in 1922

Francis W. Aston (1877-1945)
measured atomic mass of H = 1.008 > 1.000

In 1920 Eddington proposed that four hydrogen nuclei become one helium, nucleus, and the mass difference is converted to radiation.

mass of 4 times (^1H) = 4 * 1.008 = 4.032 u.
mass of helium (^4He) = 4.000 u.

---

mass *m* which disappears = 0.032 u.;
it corresponds to the energy of the released radiation:
MASS is convertible to ENERGY $E = m c^2$
➔ 0.032/4.000 = 0.8% is the part of participating hydrogen mass that 'disappears' in a thermonuclear reaction. In fact it does not disappear but converts into high-energy radiation, heating the interior of the sun.
Today we find a more exact value 0.71% for the conversion factor.

Let us see if there is enough energy in the sun's hydrogen to carry on for giga-years. Only of order 1/5 of the mass of the sun is in the core, at a temperature allowing fusion reactions.
That's 0.4e30 kg, but only ~75% of that is hydrogen, the rest is mostly helium.
So we have 0.3e30 kg of hydrogen available to 'burn' in the beginning.

(incidentally, astrophysicists actually do say 'burn' about thermonuclear reactions!)

Eddington explains the energy budget of the stars in 1920:

Energy that can be released by H→He fusion of 0.3e30 kg of hydrogen into helium equals $E \sim 0.0071 * 0.3e30\ kg * c^2 = 1.9e44\ J$.

At the current rate of energy release, L = 3.9e26 J/s, our sun will last for

t = E/L ~ 15 Gyr (billions years) ~ 3 times the age of the sun.

Physics has thus reciprocated and served Eddington well.
He has found the correct solution to the riddle of the long lives of stars.

More detailed calculations nowadays show that the sun has another 5 Gyr to go, until it bloats to become a red giant star for a short while. Soon thereafter it will stop producing energy in thermonuclear reactions. Its bloated envelope will be ejected and the core become the white dwarf, a star which over time simply cools down.

Nuclear energy research raised two problems,
#1 of human nature (unsolved)
#2 of physics (solved in 1920s)

In 1920, in his address to the British Association in Cardiff, Arthur Eddington stated problem #1:

"The reservoir [of Sun's energy] can scarcely be other than the subatomic energy; we sometimes dream that man will one day learn how to release it and use it for his service. The store is well-nigh inexhaustible, if only it could be tapped. There is sufficient in the Sun to maintain its output for 15 billion years...
Aston has shown conclusively that the mass of the helium atom is less than the sum of the masses of the fours hydrogen atoms which enter into it (...)
the deficit can only represent the mass of the electric energy set free in the transmutation.
(...)
It seems to bring a little nearer to fulfillment our dream of controlling this latent power for the well-being of the human race – or its suicide."

Indeed, humanity almost committed nuclear suicide 42 year later during the Cuban missile crisis. That was prescient!

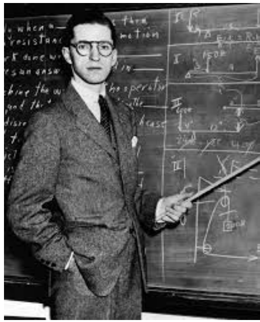
Are we much safer today? Yes, but not much safer.

Problem #2 of forcing the positively-charged protons together and its 1928 solution by young quantum physicist George Gamow

While nuclear fusion eventually releases a lot of energy, it has a problem. Imagine that you have to force 4 positively charged protons (hydrogen nuclei) together to collide and somehow merge against their will. They want to be separate, and repel each other (all of them carry positive charge!)

Neither classical physics nor Einstein's relativity explain how protons can overcome the electrostatic repulsion barrier. True, some protons in a gas have more energy than others, but the electrostatic barrier is so high that too few would have enough energy to merge either 4 at a time, or 2 at a time (which is easier and actually happens in a chain of reactions).
The barrier is 100 times higher than the mean energies of particles.

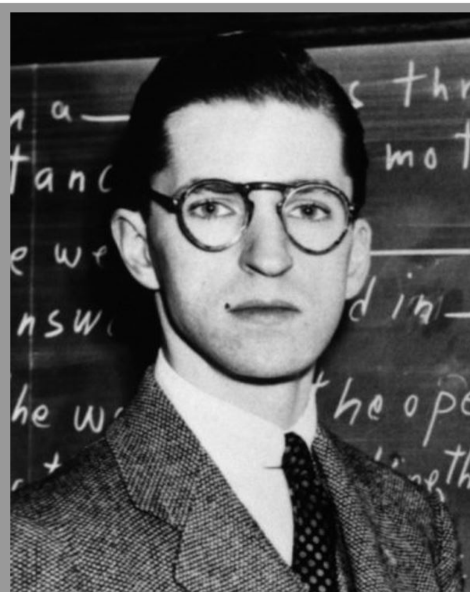
This next conundrum was solved by George Gamow using new physics that emerged in the decade after Eddington's solution of the basic question about stars, physics that Einstein did not particularly like – quantum mechanics.



In 1928 Gamow proposed that the so-called *quantum tunneling* effect allows the classically forbidden fusion reactions H → He.

“It is well known that theoretical physicists cannot handle experimental equipment; it breaks whenever they touch it”

George Gamow
Russian Cosmologist
1904-1968



..this does not seem to be true in his case. With Kurchatov, Gamow designed the first cyclotrone (particle accelerator)

George Gamow was born Георгий Антонович Гамов in Odessa, Russian Empire, in 1904. He graduated from Leningrad University in 1926. He was a student of cosmologist Alexander Friedman, but his sudden death a year before graduation forced him to change the topic of research. He computed the alpha decay of nuclei and the probability of nuclear fusion of hydrogen into helium. (In fact the two processes are mutually inverse.)
Later he wrote a book on red stars, and papers about hot Big Bang. He predicted Cosmic Microwave Background Radiation, for which others unfairly got full credit, and even estimated its temperature as 7 K (correct value: 3 K).

He and his wife emigrated from Soviet Union to America in 1934, after previously plannig twice to escape by kayak.

How the problem of forcing the positively-charged protons together was solved by George Gamow in 1928.

The effect happens in accordance with Werner Heisenberg's principle of uncertainty, stating that the minimum product of uncertainties of position & momentum of a quantum particle is a constant (called Planck constant).

Uncertainty of position and momentum are thus inversely proportional. When protons decelerate and almost stop under their mutual electric repulsion force, the uncertainty of their momentum drops, and the uncertainty of position grows considerably.

Particles in quantum mechanics are not localized. If their positional uncertainty becomes large, there is a non-negligible probability of finding them within a large spatial region. This makes it possible if not very probable that two protons will overlap (and merge), disregarding the classical electrical energy barrier. The effect is likened to a quantum tunnel bored by p^+ through a classical energy barrier. A better analogy might be p^+ becoming a ghost.

It's good for us that the probability of quantum tunneling (so-called Gamov factor) is very small. Otherwise, where we are, we'd be evaporated, and even at safer distances there would not be enough time for bio-evolution.

Stellar evolution studies after 1928

Understanding stars was a wonderful moment for Astronomy...
But it took astrophysicists of the whole world two more decades after 1928 to fully figure out the complicated nuclear reaction chains in stars, which power their emission of radiation.

Stars initially much more massive than the sun do not stop at the H → He conversion, and after exhausting hydrogen will ignite ‘helium burning’, that is energy-releasing synthesis of carbon from helium, and so on, up to iron – an element having the most closely packed nucleus, not able to spontaneously undergo further fusion.

★ ★ ★

We and our Earth’s rocks consist mostly of oxygen atoms (by mass). We are the product of stellar energy cycles, our atoms literally were inside many stars in the past. *That’s were we come from, we are from the stars!*