

Hubble, Dark Matter and Rhenium-187

or: How Old is the Universe?

Does the world have a beginning and an end? Has it always existed and will it exist for ever? These are questions that everyone has asked themselves at some point. Today, as in previous ages, we think that we can definitively answer the question of the beginning and end of the world—at least better than in the past. No doubt in 100 years people will shake their heads in affectionate disbelief at our current attempts to solve the cosmic cross-word puzzle. Despite this risk this article is about the “clocks” which astrophysicists have found to measure the age of the universe, how the “accuracy” of such clocks can be tested using a modern particle accelerator, the ESR experimental storage ring at GSI, and the surprising results this bring to light.

Hubble Discovers the First Cosmic “Clock”

Well into this century, a large majority of astronomers still favored a stationary, that is—viewed on a large scale—an unchanging universe. Edwin Hubble made the significant discovery which indicated a non-stationary, expanding universe in the 1920s at the Mount Wilson Observatory with the aid of what was at that time the largest reflector telescope on earth. He noticed that the spiral nebula move away from us more rapidly the further they are away. However, if the universe is “democratic”, that is no position or direction is different to any other, then we must be moving away from the distant spiral nebula just as they are from each other. This means that the universe as a whole is becoming larger, i.e. is expanding.

In a incompletely two-dimensional analogy, the universe can be pictured as the surface of an enormous balloon which is being steadily inflated: each point on its surface is moving away from every other point with a speed which is proportional to the distance between the points and to the rate of inflation of the balloon.

Hubble was first to quantitatively study this cosmic balloon, as he had found the right key, the recession velocity per distance (later called the Hubble constant, H_0 , in his honor). Hubble had determined “his” constant as roughly 500 km/s recession velocity for a galaxy 3.26 million light years (= one megaparsec) away. As this speed is approximately a six-hundredth of the speed of light, it must have taken six hundred multiplied by 3.26 million years, i.e. just about 2 billion years, for the galaxy to reach its current distance from us (constant expansion assumed). Therefore, according to Hubble’s first cosmic clock, the universe must have been created approximately two billion years ago in a singularity—the “Big Bang.”

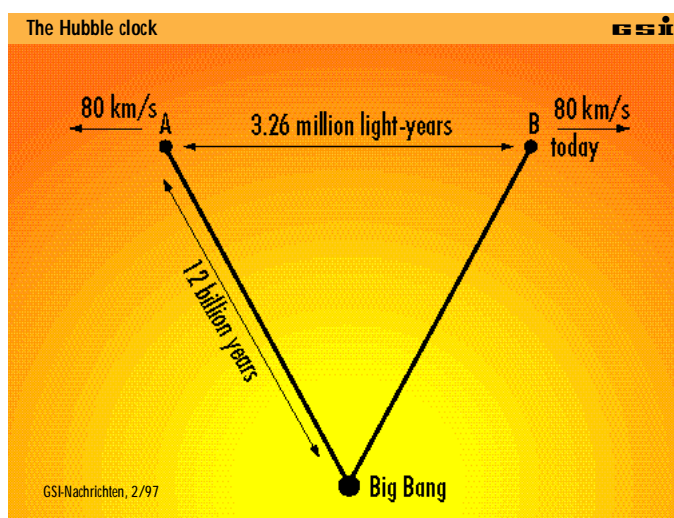
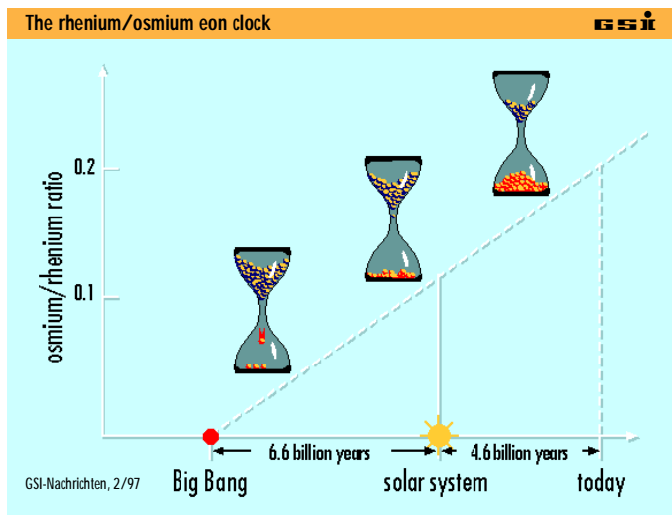


Figure 1: Following the discovery of Cepheids in the Virgo cluster in 1994 a new Hubble constant of $H_0 = (87 \pm 7)$ km/s recession velocity per megaparsec was obtained. Assuming a constant speed of expansion for the universe it therefore follows that the universe is 12 billion years old.

Figure 2: A minimum period of 6.6 billion years for nucleon synthesis follows from the osmium-187/rhenium-187 ratio of occurrence of 0.11—calculated back to the origin of the solar system 4.6 billion years ago—and a mean lifetime of 60 billion years for neutral rhenium. This corresponds to a minimum age for the universe of approximately 11 billion years.



1994: Pierce Recalibrates Hubble's Clock

It was immediately realized, by Hubble too, that this first clock ran noticeably "slow": in the 1920s it was already clear from "radioactive clocks" (which will be discussed later) that the earth and our solar system have existed for 4.6 billion years. So where is the "error in the works" of Hubble's clock?

Certainly it wasn't Hubble's assumption that the rate of expansion is constant. Actually the rate of expansion (and with it Hubble's constant) decreases over time: the gravitational attraction of the masses retards the expansion of the universe, and this more strongly the larger the average mass density. However, it can be shown that the derived age becomes shorter with increasing density. In the limiting case of the "critical" density, for which the rate of expansion is retarded to zero over an infinitely long period of time, the time elapsed since the beginning of the universe is exactly two thirds of the time calculated for constant expansion, i.e. 1.3 billion years in the case of Hubble's first clock. So in this case the clock would run even slower.

The main problem lay and still lies in the determination of the true distance to objects which are unimaginably many millions of light years away from us. It is necessary to look so far away as there is little point in trying to

determine cosmic relative movements using nearby objects such as the moon, the sun, or the stars of our own galaxy. They are, so to speak, in the same boat as ourselves and perform only local movements relative to us. We can only learn something about cosmic expansion from galaxies receding at speeds which are large compared to these local speeds. To do this however, we must look millions of light years deep into the universe.

The only available "calibration points" at such distances are Cepheids, variable nonstable stars, for which the relationship between their periodic changes in brightness and their absolute luminosity is known. It is only three years ago that the astrophysicist Pierce and his colleagues [1], discovered such Cepheids in an extremely distant group of spiral nebulae, the Virgo cluster, and from them were able to determine its distance as roughly 50 million light years (15 megaparsecs). From the known recession velocity for the Virgo cluster of 1300 km/s a newly calibrated Hubble constant of 87 ± 7 km/s recession velocity per megaparsec was obtained. However, the "new" Hubble constant is still highly controversial as it depends on exactly where the Cepheids are situated in the million light year deep Virgo cluster. Maximum ages for the universe, T_U , of 12 billion years for a constant expansion and 8 billion years for the critical density (Fig-

ure 1) respectively, are derived from Pierce's new value exactly as demonstrated before.

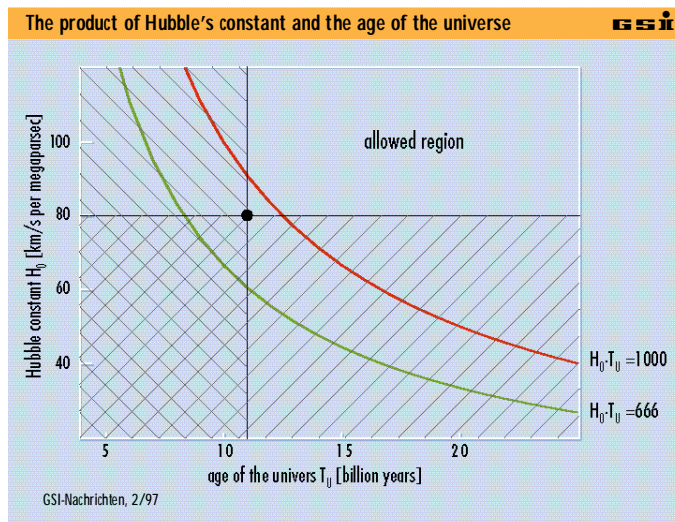
For many important reasons, most astrophysicists involved in research on the cosmos believe that the universe must have exactly the critical density (the "inflationary" universe model). However, in this case, four times the amount of directly or indirectly observed matter must be present as puzzling "dark matter," whose nature and form are unknown. Do enormous numbers of dead stars or other non-luminous objects make up this mass deficit? Do the innumerable neutrinos have a mass? Or do completely different exotic particles exist? Whatever, in the last few years feverish experimentation has broken out world wide to find this dark matter—if it is there.

However, the problem can also be considered from a different angle: calculation of the product of Hubble's constant H_0 (in km/s per megaparsec) and the age of the universe, T_U (measured in billions of years) gives a value of 1000 for a small density and $2/3 \cdot 1000$ for the critical density. Now if it were possible to derive a minimum value for T_U by some other, independent method, then a minimum value for the product of the two values ($H_0 \cdot T_U$) could be determined and then one could directly measure how large the highest density can be, in other words, how much dark matter must be postulated. (However this is only correct, if the "cosmological constant" is equal to zero).

Clayton Discovers the "Eon Clock" Rhenium/Osmium

The history of the universe stretches back over billions of years. Where might there be other "clocks"—apart from the Hubble constant—for such an unimaginably long time span? The only direct chronometers with the endurance of cosmic marathon runners and the precision of Swiss watches

Figure 3: The product of Hubble's constant H_0 (in km/s per megaparsec) and the age of the universe T_U (in billions of years) is ≈ 1000 for a very small density and $\approx 2/3 \cdot 1000$ for the critical density. With a lower limit for T_U of 11 billion years from the "neutral" rhenium clock and 80 km/s per megaparsec for H_0 a value would be obtained of about 880, which corresponds to a density considerably less than the critical density.



which have been found by geologists and astrophysicists are "Eon clocks," long lived radioactive atomic nuclei ("parents") and their decay products ("daughters"). Incredibly the "clockwork" of these clocks is not much more complicated than sand running through an hour-glass: in this example if the rate of flow of the sand through the narrow glass waist is known then a time scale can be assigned to the pile of sand below. Correspondingly, if the half-life of a radioactive nuclide and the relative occurrences of parent and daughter nuclei at a particular point in time are known, then by measuring their ratio at an arbitrary time later the time elapsed can be determined.

Nowadays we know that our solar system was formed almost exactly 4.6 billion years ago from intergalactic gas. But what about the time before that, when the matter which would later become the sun, earth, sea and living beings, was still scattered and lost in the stars and the interstellar space of our galaxy? For a long time the relative occurrence of uranium-238 and thorium-232 (half-life 14.5 billion years) was regarded as the best clock for this "pre-solar" era. From the ratio of these nuclide types as measured today, the corresponding ratio at the dawn of the solar system can be calculated. However, prior to that, both nuclides were being continuously produced and the total duration of this nucleosynthesis

can only be estimated if the relative probabilities of formation of uranium-238 and thorium-232 are known. This is exactly the problem, since they are not part of a common decay chain and so have "nothing to do with each other."

Therefore, in 1964, the astrophysicist Clayton suggested that the rhenium-187/osmium-187 pair would provide a better clock for the period of nucleosynthesis [2]. Rhenium-187 decays to osmium-187 via beta decay (a neutron decays into a proton, an electron, and a neutrino) with a half-life of 42 billion years. The main point here is that the relative occurrence of parent and daughter nuclei is independent of the rate of formation of the parent nucleus (rhenium-187). At about the same time the astrophysicists Schramm and Wasserburg were able to show that the minimum period of nucleosynthesis could simply be obtained as the product of the osmium/rhenium ratio at the end of nucleosynthesis (i.e. at the beginning of the solar system) and the average life of rhenium (= half-life \cdot 1.44 = 60 billion years), independent of details of the nucleon synthesis process itself.

This left *just* one problem to be solved: apart from the decay of rhenium-187, osmium-187 can be formed by a second process, so-called slow neutron capture (s-process). This contribution should of course not be included in the ratio and so, in previous decades, all the efforts of rhenium-cosmo-

nologists have concentrated on determining the fraction of osmium-187 arising from s-processes as reliably as possible.

Today, after enormous effort and extremely difficult measurements, it is believed that the s-contribution can be estimated with an accuracy of better than 10%. The mean life-time of rhenium-187 (60 billion years) has been measured to an accuracy of a few percent—not an easy task. The ratio of osmium-187 to rhenium-187 was calculated back to the beginning of the solar system and, after subtraction of the s-contribution, was determined, to the best of all geochemical experimental ability and experience, to be at least 0.11.

This results in a minimum period for nucleosynthesis of 6.6 billion years (Figure 2). Together with the well known figure of 4.6 billion years for the age of the solar system this leads to a minimum age for our galaxy—and therefore for the universe—of approximately 11 billion years. The product of the newly determined Hubble constant (87 ± 7) and the age of the universe results in a value of at least 880 (Figure 3). This number is considerably higher than 666, the value for the critical density. So does this mean that it has already been proven that the universe does not have the critical density?

How Long Does Highly-Ionized Rhenium-187 Live?

The ability of the rhenium clock, to indicate the minimum age of the universe, relies on the assumption that there is only one half-life, namely the half-life determined for neutral rhenium-187 with a full shell of 75 electrons. However in 1983, K. Takahashi, K. Yokoi, and M. Arnould aired well founded reservations [3] that this assumption is not correct. They postulated that rhenium-187 can be partially or completely ionized in the course of

galactic history (just like any other nuclide) and that in the case of rhenium-187 this well known process might lead to drastic changes in the lifetime.

Like all atomic nuclei created by “fast” nucleon synthesis (r-process), rhenium-187 is formed within a matter of seconds, probably during the explosive phase of supernovae, and is immediately flung into interstellar space. At a later stage this galactic gas probably compresses again, with rhenium a small part of it, and becomes part of a new star. Some of the atoms created by nucleon synthesis go through this process of “astration” several times. Depending on the location of the star and the temperatures prevailing there the atoms are more or less strongly ionized, that is they lose some (or all) of their electrons.

In this state, a special type of beta decay, which does not play a role for neutral atoms, becomes important. It is the so-called bound beta decay, whereby the electron created is not free but remains in an unoccupied inner electron shell. In this way the electron “saves” energy, as no work is required to escape the attractive region of the

positively charged atomic nucleus. A bound beta decay is also possible for rhenium-187, depending on the degree of ionization, and causes a considerable decrease in its average lifetime of 60 billion years.

In principle, this acceleration of the decay for highly-ionized rhenium-187 had already been known about for a long time. However, what K. Takahashi and his colleagues realized for the first time was that a bound beta decay is possible from rhenium-187 to the first excited state of the daughter nucleus osmium-187, which is only 10 keV above the ground state (Figure 4). By extrapolation from similar transitions in neighboring nuclei, Takahashi and colleagues now estimated a half-life of just 14 years for the bound beta decay of completely-ionized rhenium-187 into the first excited state of osmium-187. This prediction of a lifetime for “naked” rhenium shortened by more than nine orders of magnitude has of course dramatic consequences for the rhenium clock, even if highly-ionized rhenium-187 only occurs with a small probability and for a short period of time in the various astration processes. As this

prediction was obtained through extrapolations, which are very unreliable, it was imperative for the “calibration” of the rhenium clock that it be experimentally tested.

Naked Rhenium-187 Decays a Billion Times Faster

The determination of the half-life of naked, i.e. completely-ionized rhenium-187, is almost tailor-made for the ESR storage ring at GSI. Rhenium-187 can be introduced in an ion source, ionized there and subsequently be accelerated to several hundred MeV per nucleon in UNILAC and SIS. On leaving the synchrotron the remaining electrons are stripped off in a foil; the naked rhenium is transported to the ESR where it is cooled to a sharp energy with the aid of the electron cooler. After that it can be stored for many hours in the ESR.

During the storage period, some of the naked rhenium-187 ions decay through a bound beta decay to osmium-187 with one electron. The number of osmium nuclei increases proportional to the storage time. At first, the daughter atoms follow the same trajectory as the parent nuclei, with the same revolution frequency, since both have almost exactly the same ratio of mass to charge. This is also why they do not leave a “fingerprint” in the Schottky spectrum [4], from which each type of stored ion can be identified by its revolution frequency (see *GSI-Nachrichten-4/96*). However, if after the storage period, the osmium-187 electron is removed, e.g. by switching in a gas jet, then naked osmium-187 appears as a clearly separated signal.

It is possible to determine the number of osmium nuclei produced from the signal area. This number increases in proportion to the storage time—in contrast to all reaction products, whose numbers depend only on the strength (intensity multiplied by duration) of the gas jet. Thus, a plot of the number of

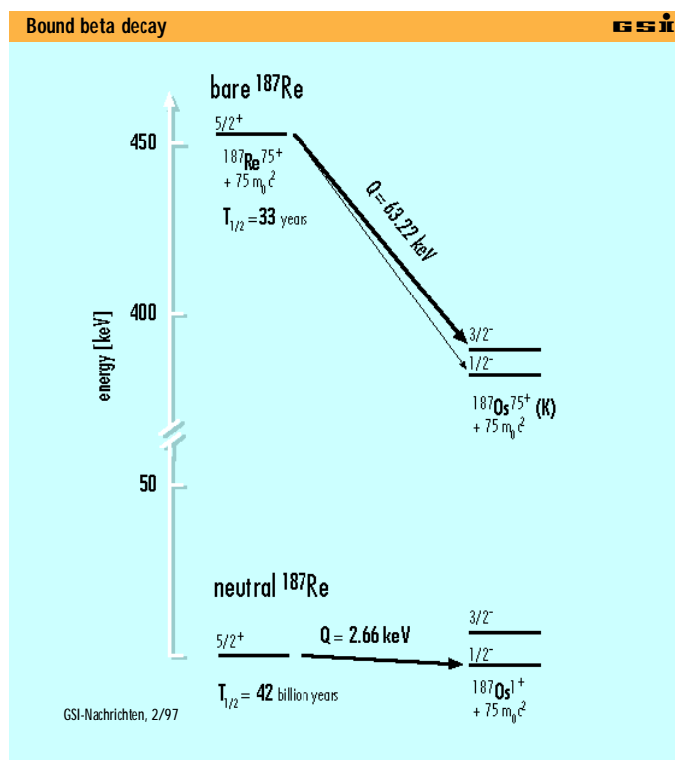
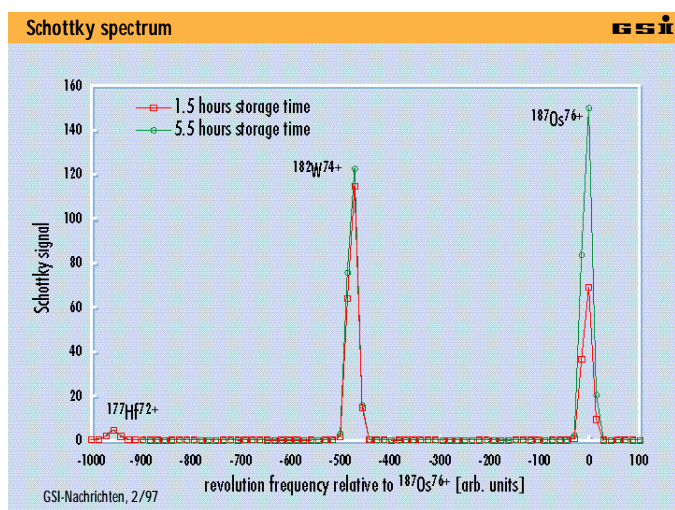


Figure 4: While neutral rhenium-187 (below) has a half-life of 42 billion years, it decays significantly faster if is completely ionized. In this case the created electron can occupy a bound state in the K-shell of the daughter atom osmium-187. Moreover decay to the first excited state of osmium-187 is possible. Together this results in a dramatic reduction of the half-life which was measured at ESR to be only 33 years.

Figure 5: The Schottky spectrum of the circulation frequency for different types of ions in the ESR for two different storage times of naked rhenium-187 ions after the gas jet has been switched on. In addition to the nuclear reaction products tungsten (W) and hafnium (Hf) the daughter atom osmium-187 from the bound beta decay of rhenium-187 is visible. Only the number of osmium-187 ions depends significantly of the storage time.



osmium nuclei created (relative to the number of rhenium parent nuclei) against the storage time directly provides the decay constant and hence the half-life of rhenium-187 (Figure 5).

Alternatively the number of osmium nuclei can be determined using a detector introduced into the ring aperture. From these two independent experiments, which were carried out as a collaboration between GSI and the Technical University of Munich, a half-life of 33 years was obtained for naked rhenium-187 [5].

Can the Rhenium Clock Be Recalibrated?

The lifetime of every other ionized state of rhenium-187 can be reliably calculated from this result. Nevertheless, one automatically suspects that this dramatic change in lifetime ren-

ders the rhenium clock rather useless. How can we possibly know all the details of the history of rhenium-187, namely the location, duration of stay and temperature after each astration? However, the situation is not completely hopeless.

K. Takahashi had already thought about the possible consequences with respect to his lifetime estimates of 14 years. For example, the dramatic change in the lifetime only applies to naked or hydrogen-like rhenium-187, since only these ions can decay into the first excited state of osmium-187. This degree of ionization corresponds to temperatures of 600 million degrees which are only present for very short periods in the innermost zones of stars. In this extremely hot and dense stellar plasma osmium-187 can also “decay back” to rhenium-187, through the capture of a free electron. The half lives of

all other charge states are many orders of magnitude greater than 33 years.

Nevertheless, within the framework of a model of the chemical evolution of the galaxy, it is not clear how well and with what margin of error corrections can be determined for the rhenium clock. K. Takahashi, who took part in the experiment described above, is currently undertaking this mammoth task. The result is sure to be very interesting.

It is almost certain that in the next few years the discovery of even more distant Cepheid variables will result in more exact limits for Hubble’s constant. Perhaps we will also very soon know whether both the Hubble constant and the “Eon clocks” point to the conclusion that the universe has less than critical density and so will continue expanding for ever. In that case the end of our universe will be a lot less dramatic than its singular beginning. ■

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