EARTH PRP-008

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1. Introduction.

This report presents the progress of the EARTH programme since the last report, published in July 2009. That report, EARTH PRP-007, gave a comprehensive overview of the project and the reader is referred to EARTH PRP-007 for background information and details.

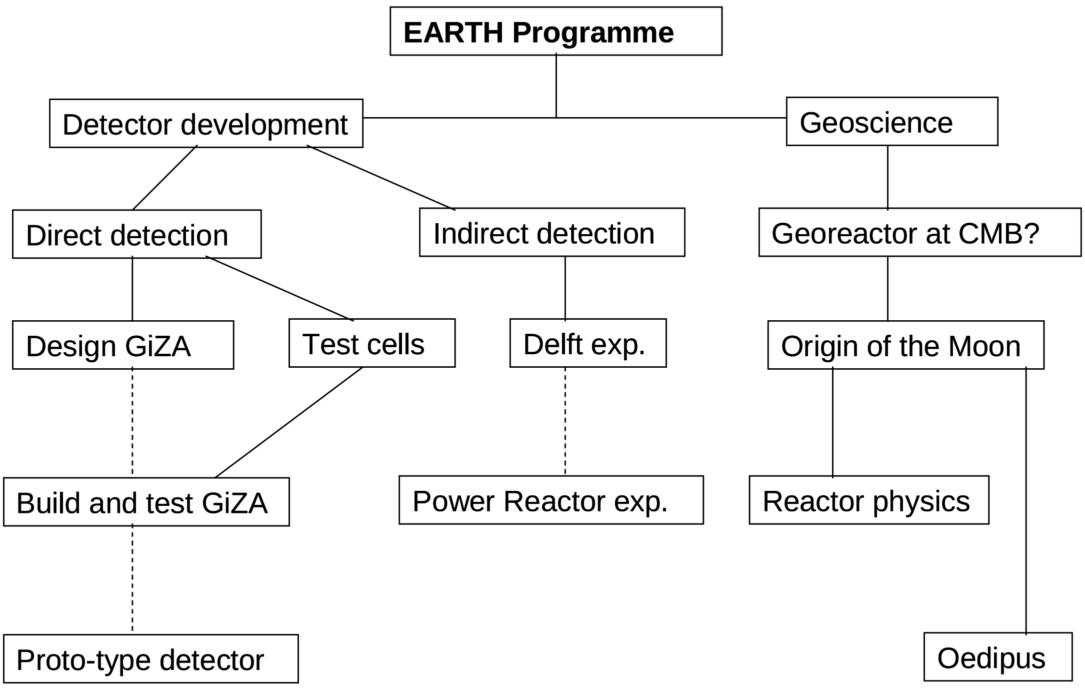

Figure 1. Schematic overview of various activities within the EARTH programme.

The present and planned activities within the EARTH programme have schematically been presented in Fig. 1. The programme has two main activities: Antineutrino detector development and Geoscience aspects that could result from the eventual data collection of antineutrinos emitted by various radiogenic processes in Earth. This update will be structured according to this scheme.

2. Detector development.

2.1 Direct detection of antineutrinos

This direct detection refers to the commonly used reaction in which an antineutrino is captured by a proton and the reaction products, a positron and a neutron, are measured.

In EARTH PRP-007 we reported the work of Stellenbosch MSc student Jaco Blanckenberg, who carried out laboratory experiments using a set-up with test cells filled with either EJ339 (loaded with 5% enriched ^{10}Boron) or EJ 309(loaded with natural Boron). Another difference between the two scintillator materials is the flash point (-1˚C and +144˚C, for EJ339 and EJ309, respectively), moreover EJ339 is on the list of dangerous goods, whereas EJ309 is not. Provided the other relevant properties for the neutron detection are not substantially different, EJ309 is clearly strongly favoured over EJ339 for application in detectors to be tested at a power reactor.

The data reported in EARTH PRP-007 were not satisfactory yet and in

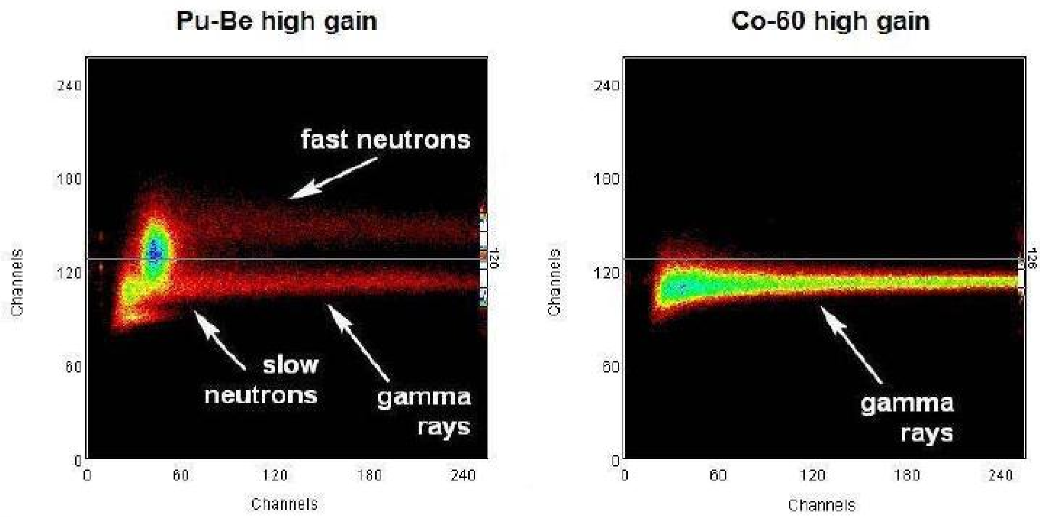

Fig.2. Differences in pulse shape between neutrons and gamma-radiation for a cell filled with EJ309-5% ^{nat}B. The figure the zero-crossing is plotted as function of energy, both in arbitrary units. (obtained from IPN. Warsaw)

consultation with the provider of the test cells they were send to dr. Lukasz Swiderksi and Prof. Marek Moszynki at IPN,Warsaw, Poland. At iThemba LABS the measurements were carried out with a digital scope, with in retrospect, insufficient bit resolution. The results in Warsaw, shown in fig. 2, were obtained by traditional analogue electronics.

The results of fig. 2 show that gamma-rays and neutrons may be distinguished based on their pulse shape. Based on these results EJ309 will be chosen for filling the large test detector and EJ309 will be a benchmark for further detector-material development.

Stichting EARTH and INCAS^3, Assen (NL) are entering an agreement in which the development of novel detection materials will be coordinated by INCAS^3 and includes a collaboration between INCAS^3 and a number of institutes of the University of Groningen, as well as industry. The cell filled with EJ309 will serve as the initial benchmark cell.

As pointed out in EARTH PRP-007 a larger test cell, named GiZA, will be constructed. In the meantime the construction design of the cell has been completed and we are awaiting sufficient funding to have the cell constructed, filled and prepared for testing. The main function of this detector will be the precise characterisation of an antineutrino event by measuring pulse-height properties of both the positron and neutron-capture signals, as well as their timing properties. With this detector, estimates of the background reduction achievable will also be tested. To obtain sufficient counting statistics in a reasonable time frame, a ~36 litre, tetrahedron-shaped detector with a PMT at each corner has been proposed. The optical properties of this detector have been optimised done by ASTRON using ray-tracing simulations. The testing is initially carried out under laboratory conditions and will be followed by tests at a power reactor. At present we are negotiating access to a reactor.

Lack of funding has stagnated our progress in detector development for quite some time. However, since the middle of 2010, we have been discussing the possibilities that private persons will contribute financially and allow us to develop a detector including a test of a proto-type detector. A final decision is expected in the beginning of 2011.

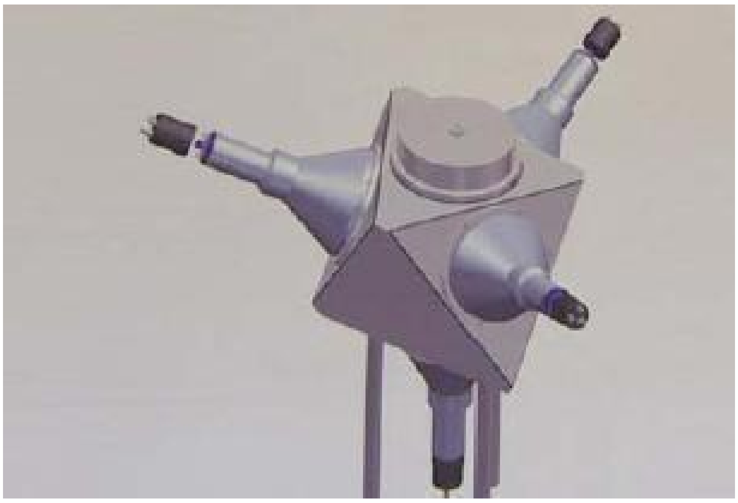

Fig. 3. The GiZA detector according to one of the latest design studies.

2.2. New scintillation materials.

The technology of scintillation liquids for neutron detection dates from the middle of the last century and there has been very little development since then. It is therefore quite reasonable to expect that there have been material developments which could assist us in removing some of the disadvantages of the traditional liquid scintillation materials. These disadvantages include a low-flash point, toxicity, and of the most importance to our work, a strong quenching of the neutron-induced α-particle signal. This signal reduction brings the α-pulse height from about 2.5 MeV to a 60-100 keV signal in the energy spectrum. As a consequence it is much harder to distinguish the signal in the more intense continuum part of the spectrum. The difference in the effective energy of the α-pulse height between EJ339 (60 keVee) and 110 keVee for EJ309, suggests that there is room for further improvement. To search for solutions, the University of Groningen spin-off company Polyvation B.V., in collaboration with Stichting EARTH, has made a feasibility study on developing new scintillation materials in a project sponsored by Stichting Sensor Universe. They conclude that they have identified a number of potential alternatives for the scintillation material as well as compounds of materials with suitable properties.

Based on this report $INCAS^3$ has taken the initiative to bring a number of researchers and industry together to develop new scintillation materials. At this time a Letter of Intent between $INCAS^3$ and Stichting EARTH is being finalised in which $INCAS^3$ will coordinate the new scintillation materials and Stichting EARTH the detector housing to test promising materials initially in the laboratory and later at a power reactor.

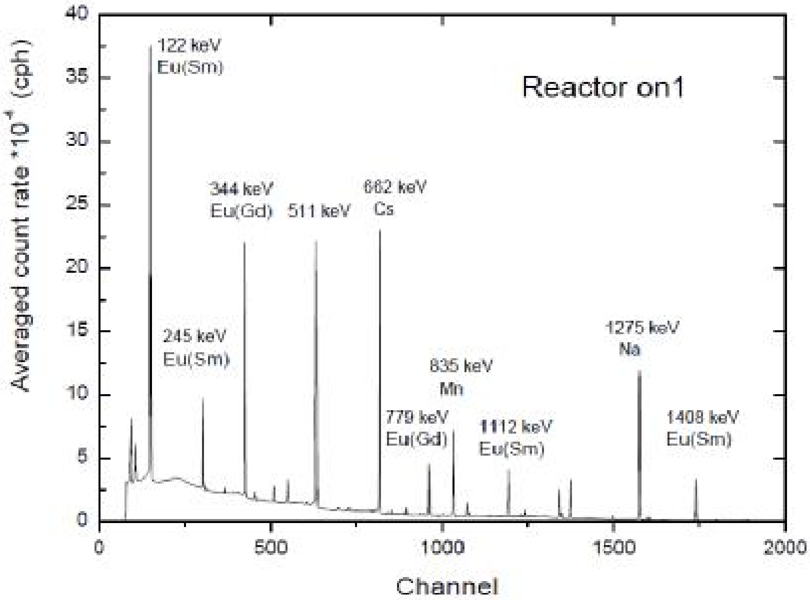

Fig. 4: Hourly gamma-ray spectrum averaged over reactor-on1 period.

2.3. Indirect detection of antineutrinos.

In an article of the New Scientist of June 2009 (*J. Mullins, 2009)* it was mentioned that Ephraim Fischbach and Jere Jenkins had interpreted annual oscillations of 0.3% in the decay rate of ^{32}Si as found by Alburger as an effect of neutrinos on nuclear beta-minus decay. The Earth-Sun distance varies 3% over the year and the oscillations found by Alburger fit precisely with a corresponding 6% change of solar neutrino flux of $6*10^{10}$ $cm^{-2}{\cdot}s^{-1}$ of which 1/3 are electron-neutrinos, due to the averaged exchange with other neutrino flavours.

If we assume that antineutrinos and neutrinos behave in the same way an estimate on the change in the exponential decay rate of beta-plus decay due to a change in antineutrino flux can be estimated. The background flux of antineutrinos due to processes in Earth is of the order of 10^6 $cm^{-2}{\cdot}s^{-1}$. At a 1 GW_{th} power reactor the flux of electron-antineutrinos is $4*10^{12}$ $cm^{-2}{\cdot}s^{-1}$ at 20m from the core, which means that at a distance of about 300m from such a reactor, the electron-antineutrino flux would be similar to the solar-neutrino flux, if flavour effects are ignored for the antineutrinos, or, if the effect were to be linear with the relative change in flux. In this case we should notice a reduction in the decay rate of 5% between reactor-on and reactor-off. Such an effect would allow us to monitor the state of the reactor and probably even its fissile content at distance as far as 300m or more.

To investigate this possibility an experiment was carried out at the 2 MW_{th} research reactor at the Delft University of Technology. This reactor is on during week days and off during the weekend. A measurement over 200h was carried out at a distance of 8m from this swimming-pool reactor with a HPGe detector and calibration sources of ^{22}Na, ^{54}Mn, ^{137}Cs and ^{152}Eu. A gamma-ray spectrum, measured during the reactor-on1 period is shown in fig.4. It shows how clearly the lines belonging to the decay of the various sources stand out over the continuum and indicates the statistical precision that can be obtained.

Fig.5 schematically depicts the changes in count rate if an effect of antineutrinos on the decay rate were to be present. Based on this approach the measured changes in count rate were analysed. From this analysis we conclude that if the interpretation of Jenkins et al. (2009) were to be correct our result limits any possible effect to $<3*10^{-4}$. This is a factor of about 400 lower than would be expected, under the assumptions that the influence of electron antineutrinos on β^+-decay is the same as for electron neutrinos on β^--decay and the effect being proportional to the flux. This limit also holds if we assume that the influence of antineutrinos on β^+-decay and β^--decay is the same. Hence either the hypothesis of Jenkins et al. is not true or the effect of neutrinos on β^--decay differs considerably from the effect of antineutrinos on β^+-decay.

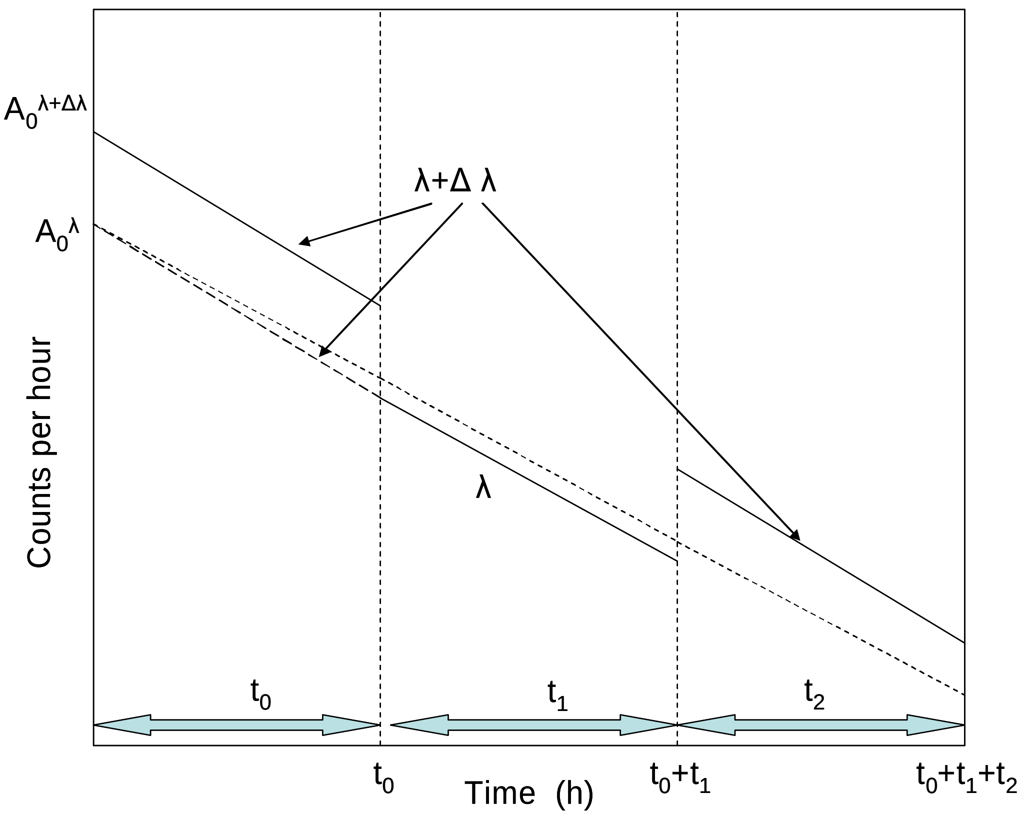

Fig. 5. Schematic diagram showing the count rates for decay constants λ and $\lambda+\Delta\lambda$ during the three reactor periods (on-off-on) if there were to be an effect.

As the present result provides only an upper limit for the effect, and this upper limit would still allow changes in the decay rate of beta-plus emitters to be detected at a distance of about 30 m from the core of a 1 GW_{th} reactor, we are preparing an experiment at such a distance at a power reactor. At the time of writing this report, we are in contact with a number of potential reactor sites. Although we do not expect that this method will allow reactor monitoring, the present perspective can not be ruled out and hence should be investigated. A paper on the Delft experiment has been accepted for publication in Applied Radiation and Isotopes (de Meijer et al, 2011) and is available online.

2.4. Reactor Monitoring.

As a follow-up of the Focused Workshop on Antineutrino Detection for Safeguards Applications held at the IAEA Headquarters, Vienna, from 28-30 October 2008, antineutrino monitoring has become a part of the Safeguards programmes of ESARDA (European SAfeguards Research and Development Association: www. ESARDA.eu) and IAEA. ESARDA called a meeting of a new Working Group on Novel Approaches/Novel Technologies held in Vienna on 28 and 29 October 2010. At this meeting various methods and approaches novel to ESARDA, meaning that they have not been applied for safeguarding, were discussed. The Working Group will act as a group of researchers that, together with the safeguarding specialists of IAEA and EURATOM, will search for technologies and approaches that may help to make safeguarding more efficient.

Following the ESARDA Working Group meeting there was the 11th Symposium on Safeguards, organised by IAEA. Also at the Symposium antineutrino monitoring of nuclear power reactors was presented as a potential Safeguard by Design. At the Symposium a small ad-hoc meeting was organised between IAEA Safeguards employees and antineutrino researchers attending the Symposium. The group decided to form an ad-hoc Working Group that could eventually evolve into a task group and could work on the Umbrella agreement with the Member State Support programme (MSSP). The short term goal is put together a set of requirements which detectors must meet. Moreover the detectors should have a positive impact on the Safeguards needs of IAEA. From the EARTH side Ricky Smit and I will be members of the Working Group. The next meetings of the groups will be in Budapest on 21 May and Vienna on 21 September, for ESARDA NA/NT and the ad-hoc working group of IAEA, respectively.

A report on the meetings is available as EARTH Report-028.

3. Neutrino Geoscience.

3.1. Georeactors.

The goal of the Stichting EARTH is to work towards a 3D-image of the radiogenic heat source of Earth by means of antineutrino tomography. Although the present detector development focuses in the short term on reactor monitoring, the long-term goal remains unchanged. On the basis of the rapidly growing geoscience literature on these topics and in the absence of any data, we are exploring the nature of the radiogenic heat sources being either natural radioactive decay, or possibly a natural georeactor.

A first step in this direction was our work to investigate the feasibility and implications of georeactors at the Earth Core-Mantel Boundary (CMB). We investigated the geoscience evidence of a hidden reservoir near the CMB and used the published data on the concentration of fissile elements in calcium perovskite to conclude that for a homogenous CMB, the concentration of U and Th would be an order of magnitude to low for igniting a georeactor and that an additional concentration by an order of magnitude would be needed for ignition. Such concentration factors are rather common in geoscience. It is therefore concluded that, based on our present knowledge of geoscience, georeactors in the CMB cannot be ruled out. Indicators for georeactors are gases coming out of Earth such as the $^{3}He/^{4}He$ ratio and the isotopic abundances of ^{129}Xe and ^{136}Xe. (de Meijer and van Westrenen, 2008)

3.2. Moon formation.

The commonly accepted hypothesis on the formation of Moon is at present that a rather gentle collision of Earth with a Mars-sized celestial object leads to its formation. According to numerical calculations, as a result of this collision Moon should be to 80% composed of the material of the impactor. In recent years the evidence deduced from elemental and isotopic analysis of lunar surface rocks increasingly stress the similarities between Moon and and the mantle of Earth. The composition information of Moon therefore strongly suggests that Moon originates from Earth.

One of the earliest hypothesis of the origin of Moon is by George Darwin who suggested that Moon was pulled out of Earth by Sun. Even later modifications to this model by Ringwood and Wise did not resolve the counter argument that the Earth-Moon system had insufficient energy and angular momentum.

Since the missing energy should be supplied in a relatively short time, the only process that could supply the missing energy is a nuclear “explosion”. In our hypothesis this explosion is an excursion of a georeactor. Such an excursion leads to a very rapid increase in temperature in the reactor environment, resulting in some the mantle material being pushed out and eventually forming Moon. Details on the model and ways to check the hypothesis can be found in de Meijer and van Westrenen, 2010a.

3.3 Reactor physics.

Wim van Westrenen and I have been approached by prof. Seifritz, a retired reactor physicist from Würlingen, Switzerland, to investigate the reactor-physics aspects of the Moon-formation hypothesis. After initial calculations based on simplified calculations indicated that an excursion of a georeactor leading to the formation of Moon, could not be ruled out, Monte Carlo simulations were started.

3.4 Oedipus.

One of the objections made after we placed a preprint of our Moon-formation manuscript on the internet site ArXiv (ArXiv 1001.4243), was that we proposed a more general model for moon formation which, if true, would mean that such nuclear moons should be present at other planets in the solar system. The statement was followed by a challenge to explain why Venus, which is more or less the sister planet of Earth, does not have a moon.

We took up the challenge and started from a point in time where Venus and Earth had gone through core-mantel differentiation and assumed that Venus had a moon at that stage. We placed that moon at a distance from Venus, comparable to the Earth-Moon distance, gave it a mass comparable to the Moon, and let Venus rotate around its axis in 25 hour in a normal mode. The question posed was if the evolution of that system can explain why Venus rotates retrograde (in the opposite direction), has a surface temperature of 740 K, has no moon, has an atmosphere two orders of magnitude denser than the Earth's atmosphere and consisting mainly of CO_2, as well as why the surface of Venus was formed about 0.5 Ga ago?

To our own surprise the answer is yes it can and is in remarkable good agreement with the present prevailing conditions. The basic calculation that leads to this result is the assumption that, similar to the case of Moon, the distance between a moon and a planet increases due to a torque created by the tidal friction. This torque transfers angular momentum from Venus to its moon we are naming Oedipus, within the condition of conservation of angular momentum of the moon-planet system. Due to the increasing planet-moon distance, the rotation of the planet slows down and decreases the total energy of the system. Fig. 6 shows the changes in the rotational energy of Venus and the total energy of the Venus-Oedipus system as function of the distance between Venus and its moon.

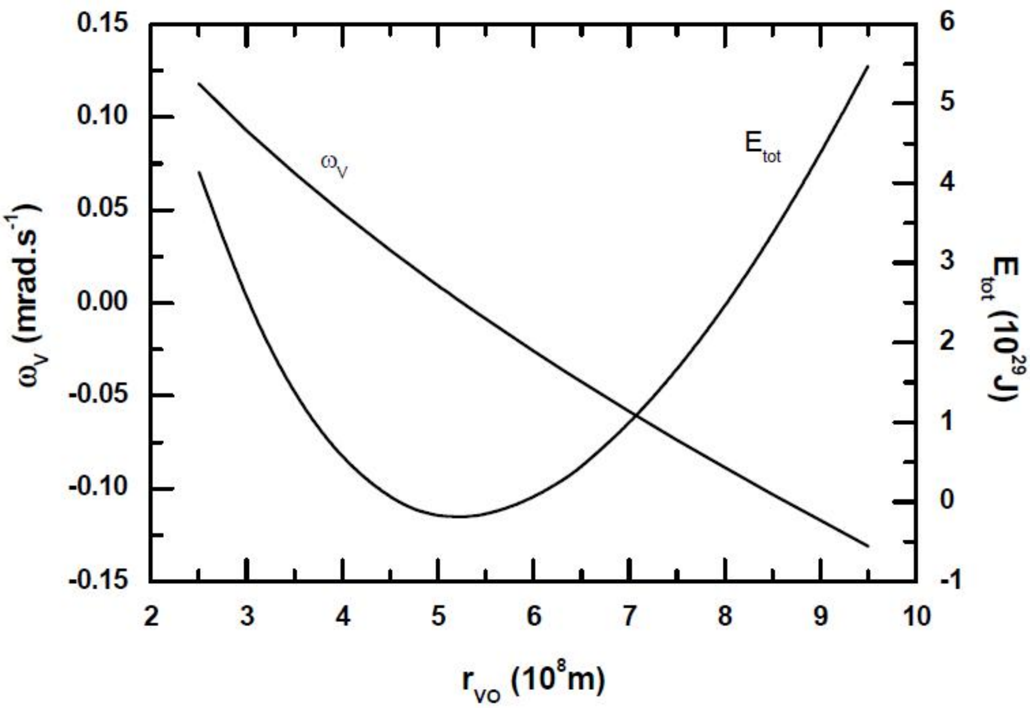

Fig.6 The total energy of the Venus-Oedipus system, E_{tot} and the rotation rate of Venus, ω_V, as function of the distance, r_{VO}, between Venus and Oedipus.

At a distance apart where the total energy of the system reaches a minimum, Venus has started to rotate in the opposite direction. The Venus-Oedipus distance cannot increase any further, as this would require an input of energy. At this distance the gravitational pull of the Sun on Oedipus is an order of magnitude larger than that from Venus. Hence the orbit becomes unstable and we assume that Oedipus impacts on Venus. The conversion of its energy into heat causes the release of volatile elements, and melting of a considerable part of the Venus mantle. Subsequent atmospheric chemistry leads to almost its present atmosphere and the diffusion of heat to the rise in surface temperature. So similar to Greek mythology, Oedipus returned to its mother and their marriage resulted in quite a disaster. A manuscript on this topic has been submitted to Icarus for possible inclusion in a special issue on Venus (de Meijer and van Westrenen, 2010b).

4. References.

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