Did Dark Matter Kill the Dinosaurs?

Michael Sarkis and Geoff Beck

School of Physics, University of the Witwatersrand, Private Bag 3, WITS-2050, Johannesburg, South Africa

E-mail: michael.sarkis@students.wits.ac.za; geoffrey.beck@wits.ac.za

Abstract. Potential links between astrophysical sources, such as gamma ray bursts and supernovae, and mass extinction events on Earth are of interest in the historical trajectory of life on our planet. There are strong arguments to suggest that these astrophysical sources can have several destructive effects, including depletion of atmospheric ozone and an increase in the radiation dose received by living organisms. Recently, the possibility of galactic dark matter clumps having an affect on life on Earth has been of some interest in the literature. In this work, it is shown that when the Earth passes through clumpy dark matter composed of WIMPs, there will be an increase to the internal heat flow of the Earth of as much as ∼3706 TW, leading to increased flood-basalt volcanism. There will also be an equivalent dose of ∼15.9 μSv imparted to organic tissue due to collisions between WIMPs and oxygen nuclei. If WIMPs are found to be a major constituent of dark matter, these effects could provide a supporting explanation for mass extinction events on Earth.

1. Introduction

Throughout the history of life on Earth, there have been periods in which a significant percentage of all living species become extinct. In the past these mass extinction events have been linked with several proposed causes - comet impacts with the Earth, flood-basalt volcanism, and rapid climate change. It has been suggested [1–4] that mass extinction events over the past 250 million years have been periodic, occurring at regular intervals of time. Periods of 26-62 million years have been found to match the extinction record with a high statistical significance, and an explanation for this periodicity could be provided by astrophysical sources, in particular galactic Dark Matter (DM) that resides in the solar system's galactic orbit.

Large scale numerical simulations based on the principles of structure formation in the universe have shown that DM tends to clump together in the form of halos [5–8]. Further, it is believed that substructure is present in these halos, with regions of comparatively high DM density or clumps, interspersed inside the surrounding halo. Several density profiles have been used to model these halos, with more sophisticated simulations leading to more complex profiles. Recently, a proposed halo profile dubbed the UltraCompact MiniHalo (UCMH) [9] has been of interest for its potential to account for microlensing observations of compact objects in the area around our solar system [10–13]. This profile has an extremely steep radial density dependence compared to other halos, and will be used as the model of choice in this work. The DM component of these halos will be considered to be composed of Weakly-Interacting Massive Particles (WIMPs), a generic candidate DM particle.

If the solar system were to interact with a clump of DM, there could be many unfavourable implications for life on our planet, and some of the hypothesised interactions between DM and the Earth lead to effects that are in agreement with the currently accepted causes of mass extinction events. There has been research conducted into the possibility of a galactic disk of DM gravitationally perturbing the Oort cloud of our solar system, leading to an increase in the number of comets that reach the Earth [14, 15]. This corresponds to one of the leading explanations for the extinction event at the Cretaceous-Paleogene boundary ∼65.5 My ago [16]. There has also been research conducted into the increase in volcanic activity of the Earth due to the heat generated from annihilating DM particles that have been captured in the core of the Earth [17, 18], which could correspond to a likely cause of the Permian-Triassic extinction event [19]. There has also been research into the carcinogenic effect of DM particle collisions with organic tissue [20, 21], which has obvious harmful implications for life, but could also provide a mechanism for the observed explosions in biodiversity shortly after several mass extinction events. Whether individually or combined, the potential of the above effects to disrupt life on Earth could support the hypothesis that mass extinction events on the Earth have an astrophysical origin.

The structure of this paper will be as follows: in section 2 we present the UCMH model used, in section 3 we discuss the hypothesis of DM capture and the generation of heat in the core of the Earth, and in section 4 we discuss the possibility of carcinogenesis resulting from WIMP collisions with tissue elements. These results are then summarised in section 5.

2. Ultracompact Dark Matter Minihalos

When the existence of UCMHs was proposed by [9], it was largely motivated by the potential for these objects to be observed using microlensing experiments. It is argued that UCMHs could provide a unique probe of the early universe, as they are believed to have formed in a similar way to primordial black holes - seeded by random density perturbations that underwent gravitational collapse and subsequent growth during the radiation and matter dominated epochs. However, the amplitude of the initial density perturbations needed to seed UCMHs would be weaker than those needed to form a black hole, which could make their existence more likely than primordial black holes.

The principles of structure formation and secondary infall predict that halos formed in this way would presently consist of a dense core of DM surrounded by a relatively sparse envelope of accreted dark and baryonic matter. The radial density profile of these objects is then given by

$$\rho_\chi(r) = \frac{3}{16\pi}\frac{\Omega_\chi}{\Omega_m}\frac{M_{\mathrm{UCMH}}}{R_{\mathrm{UCMH}}^{\frac{3}{4}}}\frac{1}{r^{\frac{9}{4}}}\,, \tag{1}$$

where Ω_χ/Ω_m are the usual density parameters for dark matter and the total matter content of the universe. R_{UCMH} is the radius of the UCMH at a given redshift, given by

$$R_{\mathrm{UCMH}}(z) = 0.019\left(\frac{1000}{1+z}\right)\left(\frac{M_{\mathrm{UCMH}}}{M_\odot}\right)^{\frac{1}{3}}\ \mathrm{pc}\,. \tag{2}$$

In this work the redshift is chosen to be $z = 10$, as this corresponds to the redshift at which accretion onto the UCMH ends - effectively setting the present radius of the UCMH. The masses of the UCMHs used follow the relatively conservative estimates adopted in [20]. The profile in (1) breaks down at radii close to the centre of the halo, when the approximation of radial infall is violated. This is remedied by considering the annihilation of WIMPs in the core, which provides an upper limit on the density at the center of the halo. As in [22, 23], this is estimated as

$$\rho_{\chi,\max} \equiv \rho_\chi(r_{\mathrm{cut}}) \approx \frac{m_\chi}{\langle\sigma v\rangle(t_0 - t_i)}\,, \tag{3}$$

where $\langle \sigma v \rangle$ is the WIMP self annihilation cross section, t_0 is the age of the universe and t_i is the time of halo collapse, estimated here as $t_i = t(z_{eq}) \approx 59$ Myr. The density inside the radius $r_{\rm cut}$ is then set to the value of $\rho_{\rm max}$.

3. Heat Generation and Volcanic Activity

The production of excess heat in the core of the Earth and the subsequent increase in volcanic activity due to DM capture was investigated by Ref. [17, 18], where it was found that DM clumps with high density could generate an extreme amount of heat through WIMP annihilation. According to Ref. [17], the energy produced by collisions between nuclei in the Earth's core and annihilation products of captured WIMPs would dissipate as heat from the core into the lower layers of the mantle, rendering them unstable. Plumes of molten mantle material formed by the breaking up of these layers would then carry the heat upwards through the Earth, creating volcanic rifts and flood basalts when they ultimately reach the surface.

The amount of heat (Q) generated by annihilating WIMPs that have been captured in the Earth's core is calculated as

$$Q = C \cdot m_\chi \cdot e \,, \tag{4}$$

where C is the capture rate of WIMPs and e represents the fraction of all WIMP annihilations that will lead to energy transfer in the core of the Earth, which is estimated as 0.5.

3.1. WIMP capture rate

The form of the capture rate used in [17, 18] does not consider resonant effects, identified by Ref. [24], which enhance the capture rate when the WIMP mass is similar to the mass of elements found in the Earth's core. A practical form of this improved capture rate equation, when applied to capture by the Earth, is

$$C = 4.0 \times 10^{16} {\rm s}^{-1} \left(\frac{\rho_\chi}{0.4\,{\rm GeV\,c^{-2}\,cm^{-3}}} \right) \left(\frac{\mu}{\mu_+^2} Q^2 f \right) \left\langle \hat{\phi} \left(1 - \frac{1 - e^{(-A^2)}}{A^2} \right) \xi_1(A) \right\rangle . \tag{5}$$

In this form, ρ_χ represents the density of WIMPs, the factor $(\mu/\mu_+^2 Q^2 f)$ sets the WIMP-nucleon scattering cross section and the final bracket is a calculation of the suppression/enhancement of capture resulting from differences in mass between WIMPs and nuclei in the Earth (for a detailed explanation of WIMP capture, the reader is referred to [24]). This "resonance" can be clearly seen in Figure 1 by the peaks which occur at WIMP masses that are similar to the most abundant elements in the Earth's core. Further, it should be noted that this equation only considers direct capture of WIMPs, and any WIMPs that don't lose enough energy to be captured but undergo subsequent interactions with the Earth could enhance this capture rate by as much as a factor of 100.

3.2. Updated cross sections from LUX experiment

The WIMP-nuclei cross sections used in [17], when used with the capture rate, lead to large amounts of produced heat when compared to the DM-independent internal heat flow of the Earth, which has been found using terrestrial borehole experiments to be ~ 44.2 TW [25]. The latest (2017) results from the Large Underground Xenon (LUX) experiment [26] suggest significantly lower cross-sections, which leads to a suppression of the overall heat generation. The total heat generated when the Earth passes through an UCMH using Equation 5 and the LUX cross-sections can be seen in Figure 1. Using the values for the heat capacity and mass of the core of the Earth used in [18], this temperature increase can be estimated, and it was found that for the relatively small UCMH mass used in [20], ΔT = 0.037 K. For a UCMH mass of 100 $M_\odot$, this value increases to ΔT = 3.9 K. These changes in temperature are much lower than the quoted values in [18], and small compared to the temperature of the Earth's core without DM effects, believed to be thousands of K [27].

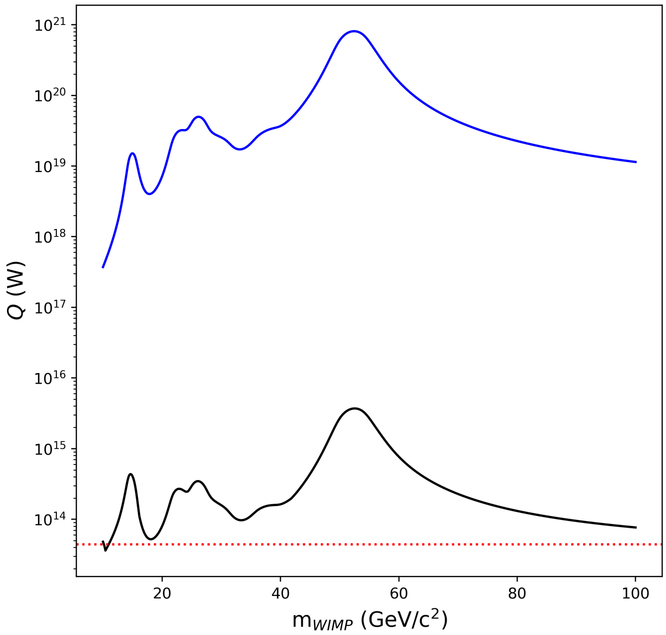

Figure 1. The total amount of heat generated by annihilating WIMPs captured in the core of the Earth during traversal of an UCMH. The blue curve represents the heat generated using previous estimates of the WIMP-nuclei scattering cross sections, and the black curve shows heat generated using the 2017 data on cross-sections from the LUX experiment. The dotted red line at 44.2 TW shows the DM-independent heat flow of the Earth. The largest peak occurs at $m_\chi = m_{^{56}Fe}$, with a maximum value of $Q = 3706$ TW.

4. Carcinogenesis from WIMPs

There is evidence that suggests ionising radiation is a "universal carcinogen", able to form cancers in most of the tissue types of most species, at any age [28]. This could help support claims that mass extinction events have been partly or fully caused by large increases in the radiation levels received by living organisms on Earth. A hypothesis proposed in Ref. [20] tries to estimate the efficacy of carcinogenesis for WIMPs inside a DM clump that pass directly through the Earth. By investigating the deposition of energy into tissue, from direct collisions of WIMPs and secondary recoiled oxygen nuclei, it was proposed that these effects would have a non-negligible impact on life on the planet. This hypothesis was later revisited by Ref. [21], where it was found that this effect would have a much weaker impact than estimated before.

4.1. Estimating the efficacy of carcinogenesis from WIMPs

A measure of the health risk associated with exposure to different radiation types, called the equivalent dose, is defined as

$$\text{equivalent dose}\,(Sv) \;=\; RBE \cdot \text{absorbed dose}\,(Gy)\,, \tag{6}$$

where RBE stands for the Relative Biological Effectiveness value, and the absorbed dose represents the amount of energy deposited into a target material by the radiation. The absorbed dose is measured in units of J/kg or Gy (gray) and is independent of the radiation type. The RBE is a number used to scale the effectiveness of different radiation types, and is conventionally defined relative to a specific type, usually X-rays.

The equivalent dose, having units of J/kg but measured specifically in Sv (sievert), represents the stochastic health risk associated with exposure to different radiation types. To find this value, the absorbed dose and RBE values for WIMPs and recoiled nuclei need to be estimated. Since oxygen nuclei constitute the majority of all recoiled tissue nuclei [20, 21], this work only considers the effects of recoiled oxygen nuclei. This approximation produces accurate results for simple tissue compositions, but more detailed tissue compositions would require an analysis involving all recoiled nuclei. The approximate absorbed dose was calculated by multiplying a scattering rate S by the average recoil energy $\langle T \rangle$ and the duration of a typical clump crossing, for a range of WIMP masses. The scattering rate was calculated as

$$S = \left(\sum_i \frac{f_i(\sigma_N, m_\chi, m_i)}{m_i} \right) \left(\frac{\rho_\chi}{m_\chi} \right) v_{\rm disp} \,, \qquad (7)$$

where the index i represents each element found in the tissue, f is a total scattering cross section, σ_N is the spin-independent (SI) WIMP-nucleon cross section, and ρ_χ, $v_{\rm disp}$ are the WIMP density and velocity dispersion. The LUX results [26] were used for the WIMP-nucleon cross section.

RBE values for specific types of radiation are usually quantified through experiment. It was found in Ref. [29] that the RBE of several heavy-ions depends both on the absorbed dose and on the Linear Energy Transfer (LET) value, which is a measure of the length scale in which the radiation deposits its energy into the tissue. This dependence showed a peak in the RBE when the LET value was in the range 100-200 keV/μm, with higher RBE when the dose rate was low. SRIM [30] was used to estimate the LET of oxygen nuclei recoiled from collisions with WIMPs, having an average energy of 25 keV and incident on a representative tissue composition [20]. The results, which show energy deposition via ionisation and the generation of phonons, are shown in Figure 2. Because the LET of WIMP collisions with tissue elements at this time have not be estimated, and under the naive assumption that the RBE of WIMPs is also dependent on the LET value, the RBE and any further effect of direct WIMP collisions has to be neglected.

4.2. Results

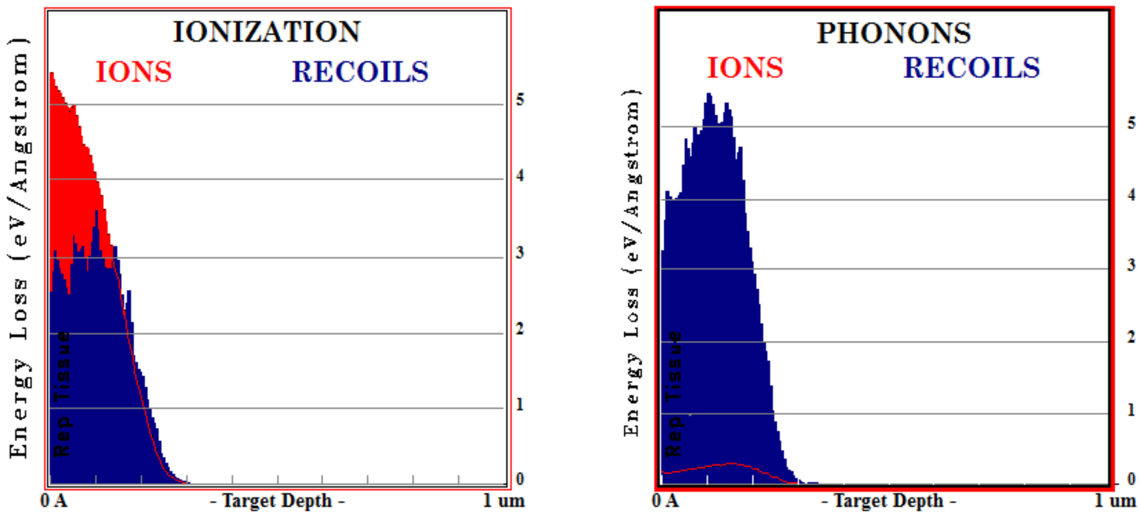

Figure 2. Energy deposition into representative tissue $C_4H_{40}O_{17}N$ used by Ref. [20] from an oxygen ion of 25 keV, by ionisation of target material and by phonons produced by incident ion. The maximum total LET for oxygen in this tissue type is $\sim 138\,\mathrm{keV}/\mu\mathrm{m}$.

The total LET of recoiled oxygen nuclei in a representative tissue composition was found to be approximately $138\,\mathrm{keV}/\mu\mathrm{m}$. An estimate of the RBE corresponding to this LET value is taken from [31], which set a range of 1.9-3.1 for the RBE of oxygen nuclei incident on human HCC cell lines at an LET of $146\,\mathrm{keV}/\mu\mathrm{m}$. These values, when used together with the typical duration of a clump crossing in the calculation of the equivalent dose for oxygen recoils, yield a maximum dose of 1.5935×10^{-5} Sv. When compared to the average natural radiation dose rate of 0.4-44 mSv/year [21] protracted over the same period, the risk of this effect having a significant effect on large populations seems unlikely.

5. Conclusion

The possibility of Earth interacting with a dense clump of DM could bring with it disruption to life on Earth. The generation of heat from annihilating WIMPs in the core of the Earth can lead to temperature increases of up to 3.9 K for large UCMHs. Although the instantaneous heat generation is large, the global and long-term effects from the small temperature changes are uncertain. Also, the onset of cancers from recoiled oxygen collisions with tissue elements leads to an equivalent dose of $\sim 15.9\,\mu$Sv, the effect of which could be enhanced if direct WIMP collisions have an LET value that is conducive to DNA damage.

The results from both of these hypotheses are lower than previous estimates, which can be attributed to the new WIMP cross section limits obtained by the LUX experiment. However, when these effects are considered with other potential mechanisms for extinction from DM like gravitational perturbations of the Oort cloud, they could still provide a supporting explanation for mass extinction events on Earth.

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