A New Signature of Dark Matter

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ABSTRACT

Dark matter capture and annihilation in planets and their satellites, in addition to producing neutrinos (already the basis of several ongoing experiments), is shown to lead to more significant heat generation in these bodies for a uniform dark matter halo. This thermal output becomes more prominent when clumped dark matter passes through the solar system. The dark matter annihilations should be treated as a new source of heat in the solar system which in some special cases may lead to unique imprints. Such new signatures of the dark matter are found in the generation of the puzzling magnetic field of Ganymede. This new source of heat perhaps cannot explain the formation and segregation of Ganymedean structure (which are probably due to conventional gravitational and radioactive heating), but provides a possible explanation of the origin of the Ganymedean magnetic field.

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1 Introduction

Investigations have revealed that clumping \[1\] may be a generic characteristic of dark matter \[2, 3\]. The weakly interacting massive particles (WIMPs), an especially favoured group of dark matter candidates \[4\] that are thought to comprise the galactic halo may be detected by direct methods or indirect techniques \[4\]. Nuclear recoil from elastic WIMP-nucleus collisions is used in the direct technique. The indirect detection procedures utilize solar \[5\] and terrestrial \[6, 7\] capture of these WIMPs. After crossing a critical threshold density \[8\] these particles start annihilating with one another \[10\]. The neutrinos escaping from the centre of the Earth and Sun through this process have been the subject of intensive investigation \[4, 11, 12, 13\]. So far the searches as reported by Kamiokande, IMB, Frejus and MACRO have yielded null results \[4\]. In this paper it shall be pointed out that in addition to neutrinos the above dark matter annihilations produce large amounts of heat as well. This effect should be treated as a new source of heat in the solar system. In some special situations where the conventional heat sources fail to explain a particular phenomenon dark matter heat generation may leave a singular imprint. We shall discuss one such possible signature from recent puzzling and unexpected observations in the solar system.

The conventional accretional and radiogenic heat sources are known to be important during the early phases of a planet’s history. Thus, whenever new empirical information arises indicating more recent heat sources (eg. the presence of Ganymede’s magnetic field), the tendency of planetary scientists is to seek refuge in the only other known source of heat, ie. tidal heating. Even when the orbital parameters constrain the present tidal heating to insignificant proportions, sometimes contrived and artificial models are propagated to explain mysterious empirical information. In this paper it is asserted that, in addition to the conventional sources of heat mentioned above, dark matter annihilation in planetary interiors may be a new heat source, in addition to explaining several mysteries in planetary science.

2 Requirement of New Sources of Heat

The first such mystery is the absolutely unexpected discovery during the recent Galileo mission of the magnetic field of Ganymede, the largest satellite of Jupiter \[14\] which necessitates a reevaluation of the structure of Ganymede \[15\]. This mission uncovered the existence of a surface equatorial magnetic field of $\sim 750 \text{nT}$, strong enough to carve out a magnetosphere with clearly defined boundaries within Jupiter’s. Since magnetic fields generally arise via a dynamo action \[16\] this observation implies a partly molten iron or iron-iron sulphide core. Accretional heating is probably inadequate for early formation of the Ganymedean metallic core, though it may be sufficient to segregate the ice from the rock and metal \[16\]. Radiogenic heating during the course of Ganymede’s evolution however could provide enough heat to separate an Fe-FeS core if the eutectic melting temperature of 1250K is all that is required.
Thus formation of a metallic core in Ganymede may not be energetically difficult, but there is a more serious problem involved in explaining how the core has remained convective throughout Ganymede’s history as small cores tend to evolve toward an isothermal state \[16\]. Speculative solutions within the tidal heating framework involve a jolt of tidal heating in the past, but these are at best contrived and rather artificial \[17\]. It may be reasonable to conclude that a consistent physical explanation of the origin of the Ganymedean magnetic field does not exist. This may be an indication of ‘new physics’. It will be shown below that this new physics may be provided by dark matter.

3 Critical Threshold and Capture Rates

In the cosmic string, texture and inflationary models dark matter in a clumped form is a natural outcome. The concentration of dark matter inside these clumps can reach \(10^{10} - 10^{14}\) times the background for WIMPs \[1, 2\]. The dark matter particles continue to accumulate inside the planet until their number density becomes so high that they start to annihilate with one another. Let this critical number be \(N_{\odot}^{\text{crit}}\). Equilibrium is achieved when the capture rate equals the annihilation rate. The critical number density of sneutrinos for any planet is \[8\]

\[
N_{\odot}^{\text{crit}} = \left( \frac{4\pi}{3} \right) \left( \frac{\bar{r}_\nu}{\bar{c}} \right)^{3/2} \left[ \sqrt{\hat{N}_\odot} \left( \frac{1}{(\sigma v)_{\text{ann}}} \right) \right]^{1/2}
\]

where \(\hat{N}_\odot\) is the capture rate for the planet in question, \(r_\nu\) is the scale radius of sneutrinos inside the core, \(v\) the dispersion velocity of the dark matter and \((\sigma v)_{\text{ann}}\) the annihilation cross-section. The critical number for Ganymede in the case of an iron core is therefore

\[
N_{G}^{\text{crit}} = 9.1 \times 10^{33} \sqrt{\Omega_\odot} h_{50} \left( \frac{m_{\bar{\nu}}}{10^{9} \text{eV}} \right)^{-3/4} \sqrt{\frac{\hat{N}_G}{10^{17} \text{sec}^{-1}}} \]

which compares to a critical value for the Earth of \[8\]

\[
N_{\oplus}^{\text{crit}} = 1.7 \times 10^{34} \sqrt{\Omega_\odot} h_{50} \left( \frac{m_{\bar{\nu}}}{10^{9} \text{eV}} \right)^{-3/4} \sqrt{\frac{\hat{N}_\oplus}{10^{17} \text{sec}^{-1}}}
\]

where \(h_{50}\) is the normalized Hubble constant and \(\Omega_\bar{\nu}\) is the ratio of the sneutrino density to the closure density. These and the following formulas hold for sneutrinos but similar results hold for most WIMPs.

The time period between successive core passings is \(\tau = (yF\sigma)^{-1}\) where \(F\) is the flux of the DM particles, \(\sigma\) the cross-section and \(y\) the fraction of dark matter still in clump cores. Hence \(\tau = y^{-1} (n\sigma v)^{-1}\) i.e., \(\tau = M_C (y p_H v \sigma)^{-1}\). Since the core mass \(M_C \sim \rho_C R_C^3\), and \(\sigma \sim R_C^2\), one obtains \(\tau = (\rho_C R_C)(\rho_H v)^{-1}\).

Since \(M_C = 0.02M_\odot \left( \frac{m_X^{3/2}}{\Omega_0} h^2 \right)^{-1}\), \(\sigma = \pi R^2\) with \(R = m_X^{-1/2}\Omega_0^{-1} h^{-2} \times 10^{-3} \text{pc}\) and
taking \( v \) to be 300 km/sec the relation between the mass of the dark matter and the
time period of crossing is

\[
\tau = 2.1 \times 10^9 m_X^{-1/2} y^{-1} \Omega_0 h^2 \text{years} \quad (4)
\]

where \( m_X \) is the mass number of the dark matter particle in GeV.

We thus find [9] that a time scale of \( \sim 10 – 100 \text{My} \) results. Hence, as explained
below, Ganymede may have experienced a jolt of rejuvenation approximately 10 –
100 My ago, perhaps leading to the melting of a part of Ganymede’s core with the
consequent rebirth or reinvigoration of a magnetic field.

Improving upon the previous work, Gould [7] obtained greatly enhanced capture
rates for the Earth ( 10-300 times that previously believed ) when the WIMP mass
roughly equals the nuclear mass of an element present in the Earth in large quantities,
thereby constituting a resonant enhancement. Gould’s formula gives the capture rate
for each element in any planet as [7] :

\[
\dot{N} = \left[ \frac{8}{3\pi} \sigma n_x \bar{v} \right] \frac{M}{m_N} \left[ \frac{3v_{esc}^2}{2\bar{v}^2} \right] < \phi > [\xi(\infty)] \left( \frac{1 - e^{-A^2}}{A^2} \right) \frac{\xi(\infty)}{\xi(\infty)} \quad (5)
\]

where the third term is the escape velocity term. \( v_{esc} \) is the escape velocity, Dirac
brackets indicate averaging over the mass of the body, \( M \) is the mass of the body and
\( \xi(\infty) \) is a correction factor, and \( \phi \) is the dimensionless gravitational potential.

To apply the Gould formula to Ganymede, we note that

- The mass of Ganymede as determined by the Galileo mission is \( 1.482 \times 10^{23} \text{kg} \) [15].
- \( v_{esc} = 2.75 \text{km/sec} \), \( \bar{v} = 300 \text{km/sec} \)
- \( n_x = (1/m_x) \rho_{0.4} 0.4 \text{ Gev/cm}^2 \)
- \( \sigma = \frac{\mu^2}{\mu^2_+} Q^2 m_{mx}^2 (5.2 \times 10^{-40} \text{cm}^{-2}) \)

This yields the Ganymedean capture rate as :

\[
\dot{N}_G = (6 \times 10^{13} \text{sec}^{-1}) \left[ \frac{\mu}{\mu^2_+} Q^2 f_{\rho_{0.4}} \right] \left( \hat{\phi}(1 - \frac{1 - e^{-A^2}}{A^2}) \xi_1(A) \right) \quad (6)
\]

Then, noting that

- \( Q = N - (1 - 4\sin^2 \theta_W) Z = 30 - 0.124 \times 26 = 26.8 \),
- The mass of Ganymede’s core ranges from 2% – 33% of the planetary mass in
case of Fe-FeS core and from 1.4% – 26% in the case of an Fe core [15].
For $A >> 1$, the last term in the Dirac brackets is one.

This yields a capture rate of

$$N_G^{Fe} = 4.33f \times 10^{16}s^{-1}$$

where $f =$ fraction of Fe in the Fe-FeS core and varies from 2% to 33% for an Fe-FeS core.

One obtains capture rates of $\sim 10^{14} - 10^{16}s^{-1}$ particles per sec, depending on the quantity of iron. For dark matter masses other than 52 GeV, but lying in the range of 10-100 GeV, the capture rates are generally 1/10 - 1/100 of those obtained above, so we here take the capture rate of dark matter particles in the range of 10-100 GeV to be in the range of $\sim 10^{14} - 10^{16}s^{-1}$ in case of a 33% Fe-FeS core, and from $\sim 10^{12} - 10^{14}$ in case of a 2% Fe-FeS core for particles in the range of 10-100 GeV.

During clump core passage, lasting of the order of a year, the capture rate will rise by a maximum factor of $10^8$, i.e. $\sim 10^{22} - 10^{24}s^{-1}$. In a single year the number of particles captured is thus $\sim 10^{29} - 10^{31} y^{-1}$ (33 % Fe-FeS core). Thus the critical number (of order $10^{33}$) would be crossed in $10^{2-4}$ core passages. Given a rate of one passage every 30 my, this translates into a time scale of 3 billion to 30 billion years. For the case of a 2% Fe-FeS core, the time required to cross the critical number will be longer than the lifetime of the Solar System ($\sim 4 \times 10^9 yr$) since the capture rate is only $\sim 10^{27} - 10^{29} y^{-1}$ (2 % Fe core). Thus, in case of a heavier core with greater iron content the critical number of dark matter particles can be crossed within the lifetime of the Solar System. This is the capture rate for iron. That due to other elements will be much less, however, being off-resonance, and we take the approximation that the entire capture rate as being that of iron.

4 Thermal Output

Depending on the nature of the dark matter (neutralino, photino, gravitino, sneutrino, Majorana neutrino, etc.), different annihilation channels are possible [10, 11]. Generally the most significant channels are $\chi\bar{\chi} \rightarrow q\bar{q}$ (quark-antiquark), $\chi\bar{\chi} \rightarrow \gamma\gamma$ (photons) and $\chi\bar{\chi} \rightarrow ll$ (lepton-antilepton). In the quark channel hadronization will take place through jets and subsequent radiative decay will lead to mesons which in turn will decay through their available channels. Hence [11]:

$$\chi\bar{\chi} \rightarrow q\bar{q} \rightarrow (\pi^0, \eta, ...) \rightarrow \gamma + Y$$

All annihilation processes which directly or indirectly create photons and where energy is delivered to the core through inelastic collisions would lead to the generation of heat in the core. Note that the study of the neutrinos is the basis for several ongoing dark matter detection experiments mentioned above. Here we wish to study this heat generation in Ganymede’s core through annihilation. This heat is:

$$\dot{Q}_G = e\dot{N}_G m_X$$

\number{5}
where $e$ is the fraction of annihilations which lead to the generation of heat in the core of Ganymede. Note that $e$ may be as large as unity for the ideal case where the WIMPs annihilate predominantly through photons only. We shall however take it to be $\sim 0.5 \text{ [10, 11]}$ for an order of magnitude estimate.

Using the capture rates obtained above, the heat output due to resonant capture by iron

$$Q_G = 3.63 \times 10^8 e f W \quad (10)$$

Taking specific model results of $e = 0.5$, and $f = 0.02 - 0.33$ for an Fe - FeS core and $f = 0.014 - 0.26$ for an Fe core, the heat output becomes

$$Q_G^{Fe} = 3.63 \times 10^6 - 6.0 \times 10^7 W \quad Fe - FeS \text{ core}$$

$$= 2.54 \times 10^6 - 4.7 \times 10^7 W \quad Fe \text{ core} \quad (11)$$

Thus the heat output is in the range of $10^6-7W$ for a uniform dark matter distribution and on iron resonance. For masses other than 52 GeV which are non-resonant, the heat output is still 1/10 - 1/100 of that due to iron.

### 4.1 Current Heat Output

The current heat output of Ganymede was measured to be $\sim 10mW/m^2$ at the rock - ice interface (corresponding to a radius of 1800 km) during the Galileo mission [16], i.e. $\sim 4 \times 10^{11}W$. Thus the heat production even due to a uniform background of dark matter yields a non-negligible fraction, in the range $0.001 - 0.01\%$ of current Ganymedean heat output. This heat output of $10^6-7W$ rises to $10^{14-15}W$ in case of clumping by a $10^8$ factor. It is to be noted that the product of period and clumping factor must be unity, ie. $\rho_x \times \tau = 1$. The current heat output of Ganymede is $4 \times 10^{11} W$. So, if Ganymede is passing through a dark matter concentration of $10^5$, the current level of Ganymedean heat output can be explained. Conversely we can say that the current level of clumping is less than $10^5$.

Clump passage lasts for a time of the order of 1 year, hence the heat produced due to the passage of a clump core in 1 year is $\sim 10^{6-7}W \times 10^7s/\text{year} \sim 10^{13-14}J$. Thus, once every $\sim 100my$, Ganymede would experience a jolt of $10^{13-14}W$, 100 -1000 times larger than its current heat output.

### 4.2 Formation and Segregation

The latent heat of fusion of the Earth’s mantle is $L_{\text{mantle}}^{\oplus} = 420kJ/kg$ while that of the Earth’s core is $L_{\text{core}}^{\oplus} = 580kJ/kg$. Hence a value of $500kJ/kg$ for the latent heat of fusion of the Ganymedean core may not be unreasonable. For the range of the masses of the Fe and Fe-FeS core used above, we find that the latent heat of fusion of the Ganymedean core is $\sim 10^{27} - 10^{28}J$ The specific heat of the Earth’s core is

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\( c_{p,\text{core}} = 500 - 700 \text{J/kg/K} \), while that for alpha iron at 25K is 451 J/kg/K \cite{20}. Hence it would not be too unreasonable for the Ganymedean core to have a specific heat of \( \sim 500 \text{J/kg/K} \). Thus the heat required to raise the temperature of the Ganymedean core by one degree is \( \sim 10^{24} - 10^{25} \text{J} \). Thus the heat required for core segregation is \( \sim 10^{27} - 10^{28} \text{J} \).

We already found that the heat generation per year due to a dark matter clump core passage through Ganymede yields \( \sim 10^{13} - 10^{14} \text{J} \). This is hence not sufficient to explain the formation of the Ganymedean core. Indeed, the results from the Galileo mission indicated that accretional and radiogenic heating would be sufficient to explain the formation of Ganymede. The greater problem is that there is no heat source for the magnetic field.

The heat evolved is not very large, but still non-negligible. Thus, at the peak of the iron resonance, the total mass of WIMPs captured per iron nucleus during the lifetime of the solar system is:

\[
0.72 \xi(\infty) \sqrt{\frac{6}{\pi}} \sigma \bar{\rho} \frac{v_{\text{esc}}^2}{\bar{v}^2} \langle \phi \rangle \tag{12}
\]

where \( \bar{\rho} \) is the mean ambient wimp density in the universe, \( v_{\text{esc}} \) is the escape velocity of Ganymede and \( \bar{v} \) is the velocity dispersion of the dark matter particles. Thus, if all the wimp mass is converted to heat energy, the thermal energy per iron nucleus is

\[
E = \sigma \bar{\rho} \frac{v_{\text{esc}}^2}{\bar{v}^2} \langle \phi \rangle \tag{13}
\]

which yields \( 1.4 \times 10^{-4} \text{eV} \). This may appear small, but it is in fact equivalent to the heat produced above. In fact, only 6 eV would be sufficient to explain the melting of the core. However, the process of formation and segregation is not explainable by dark matter (the other sources gravitational and radioactive, were much more important), but perhaps the magnetic field and a fraction of present heat output (considered anomalously high) may be due to dark matter annihilations.

It may appear that the quantity of heat produced in the Earth would also be very small. However, in this case the larger mass of the body is much larger, leading to greater quantities of heat that are sufficient to lead to volcanism. Such drastic effects would not occur in case of Ganymede, but dark matter could still re-invigourate the magnetic field.

### 4.3 Ganymedean Magnetic Field

During the last clump core passage the planet is likely to have received a jolt of heat which would have led to re-melting of part of the core. Convection may have restarted if it had stopped since the previous core passage. Planetary magnetic fields are thought to result from vigorous convection in the interior. Thus this jolt may
have led to the re-starting/envigoration of the planet’s magnetic properties. If the heat could escape quickly, then the field may die down before the next clump core passage after $\sim O(10 My)$. If not, then the magnetic field would continue throughout, becoming stronger during core passages. Sustained core convection and maintenance of the liquid state may have been powered by dark matter.

Gravitational and radiogenic heating are significant only during the initial phases of a planet’s history, gradually declining in importance as the remnant accretional heat dissipates or the highly active radionuclides decay. In case of small planets, and especially in case of Ganymede, the gravitational heat dissipates away much faster than for larger planets. The only other source of heat that can be significant in later phases of a planet’s history so far has been tidal heating. Thus, whenever experimental data indicate excess heat production during the later phases of a planet’s history, tidal heating is the refuge. Even when the present orbital parameters preclude any tidal heating in the known past, sometimes artificial models are set forth.

5 Comparison with Other Heat Sources

Whereas the other heat sources like gravitational heating and radioactive heating were active during the early part of Ganymede’s history and were much stronger then, dark matter heating is larger now. Moreover, dark matter provides periodic pulses of heat that cannot be provided by other heat sources. Tidal heating, although large in the case of Io, is thought to be small in the case of Ganymede. Models involving jolts of tidal heating in the past are speculative. Thus, although dark matter heating is small, yet it may explain the survival of the magnetic field. Thus heat through dark matter annihilations appears to be a viable explanation for the survival of the Ganymedean magnetic field.

6 Earth Volcanism

It has been shown that the heat produced in Ganymede is not sufficient to produce the core and represents only less than 1 % of current heat output. The question naturally arises as to whether this invalidates the idea of Earth volcanism set forth in [21]? The answer is that Earth volcanism is still viable for the following reasons:

- The capture rate for large bodies is much larger than just a simple scaling of masses would suggest. Thus, although the capture rate is linear in the mass of the body, the term consisting of the square of the escape velocity is dominant and leads to a much decreased capture rate for smaller bodies.

- Iron represents one-third of the Earth’s mass, while current experimental limits for Ganymede’s iron fraction range from 2 % to 33 %. The heat output is linear in this term.
Ganymede lies in the potential well of Jupiter, so incident WIMPs move faster and hence become more difficult to capture. This will decrease the capture somewhat in case of Ganymede. For the Earth, however, Gould showed that this decrease in capture is almost fully compensated by enhanced capture of WIMPs bound in solar orbits [22].

The passage of a clump core through the Solar System would be expected to have consequences not limited to Ganymede alone. It has been demonstrated by S. Abbas & A. Abbas [21] that the passage of the Earth through dark matter clumps leads to the heating of the core and the core-mantle boundary (CMB). After a critical stage, this layer breaks up, ejecting enormous superplumes that rise through the mantle. On arrival at the surface, these plumes cause volcanism and attendant mass extinctions recorded in the history of the Earth. The authors found that the periodicity of clump passages approximately agrees with that of major flood basalt volcanic episodes as well as that observed for mass extinctions. Once again, the model of dark matter annihilations in planets can explain another puzzle, viz. why the Earth should experience periodic episodes of massive volcanism when this planet has in fact been cooling ever since its birth.

Hence the heat generation in the planets and their satellites due to dark matter annihilations should be treated as a new source of heat in addition to accretional heating, gravitational heating, radiogenic heating and tidal heating. The limit of the evaporation mass of the dark matter [4, 13] indicates that in addition to Mercury and Ganymede, Venus, Mars, Europa, Callisto, Io and Titan should also have observable heat generation through the above process. One may even ask whether the dark matter heating mechanism has anything to say regarding cryovolcanism [23]? More data would be needed to sort things out. This work is in progress [24].

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