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# Planet-bound dark matter and the internal heat of Uranus, Neptune, and hot-Jupiter exoplanets

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A B S T R A C T

We suggest that accretion of planet-bound dark matter by the Jovian planets, and by hot-Jupiter exoplanets, could be a significant source of their internal heat. The anomalously low internal heat of Uranus would then be explained if the collision believed to have tilted the axis of Uranus also knocked it free of most of its associated dark matter cloud. Our considerations focus on the efficient capture of non-self-annihilating dark matter, but could also apply to self-annihilating dark matter, provided the capture efficiency is small enough that the earth heat balance constraint is obeyed.

The galactic halo dark matter mass density in the vicinity of the solar system is currently believed to be about 0.3 $(\mathrm{GeV}/c^2)\mathrm{cm}^{-3}$, and corresponds to dark matter that is gravitationally bound to the galactic center of mass, around which it orbits along with our solar system. Whether there is additional dark matter in the solar system, either gravitationally bound to the sun, or to the individual planets, is currently an open question. Frère et al. [1] have pointed out that local dark matter concentrations in the galaxy may have played a role in formation of the solar system, and this could give a rationale for considering the possibility of both sun-bound and planet-bound dark matter. This suggestion is reinforced by recent simulations [2] finding "very concentrated dark matter clumps surviving near the solar circle"; such clumps could be natural nuclei for the formation of stars and planets.

Purely gravitational limits on the density of possible sun-bound or planet-bound dark matter allow densities much larger than the galactic halo density. Arguments based on planetary orbits in Frère et al. [1] and the papers of Sereno and Jetzer [3], Iorio [4], and Khriplovich and Pitjeva [5] place a limit on the mass density of sun-bound dark matter of $\sim 10^5$ $(\mathrm{GeV}/c^2)\mathrm{cm}^{-3}$. A comparison of lunar ranging and geodetic satellite tracking observations [6] places a bound on the mass of earth-bound dark matter lying between the $\sim 384\,000$ km radius of the moon's orbit and the 12 300 km radius of the LAGEOS satellite orbit of $4 \times 10^{-9}$ of the earth's mass; if such earth-bound dark matter were uniformly distributed, this translates into a mass density limit of $\sim 6 \times 10^{10}$ $(\mathrm{GeV}/c^2)\mathrm{cm}^{-3}$.

Another source of limits on sun-bound and planet-bound dark matter comes from considering the effect of dark matter accretion on solar evolution and earth and planetary heat flows. Here assumptions about the nature of dark matter non-gravitational interactions come into play, and the assumption generally made is that dark matter is self-annihilating. From solar evolution, Fairbairn et al. [7] find that stellar evolution starts to be altered by self-annihilating dark matter when the product of the spin-dependent WIMP-nucleon cross section times mass density exceeds $10^{-30}$ to $10^{-29}$ $(\mathrm{GeV}/c^2)\mathrm{cm}^{-1}$. From considering the earth's heat flow, Mack et al. [8] concluded that efficient capture in the earth of self-annihilating dark matter with the galactic halo density would lead to a rate of energy deposition that exceeds the earth's well-measured heat flow by a factor of about 100. This analysis, by filling the gap between astrophysical constraints and underground detector constraints, shows that galactic halo dark matter, under the standard assumption that it is self-annihilating, cannot have interaction cross sections with ordinary matter larger than the usually assumed weak interaction cross sections. Constraints on galactic halo dark matter arising from considering annihilation in Uranus were discussed by Mitra [9], and heating of Jovian planets by galactic halo dark matter annihilation has also been discussed in [10]. A possible role for galactic halo dark matter in the heating of exoplanets was considered briefly in [8], again under the assumption that dark matter is self-annihilating, but was dismissed as unlikely because of the earth heat flow constraint. Planetary heat production and volcanism that may result from the passage of the solar system through clumps of galactic dark matter have been discussed in papers of Abbas et al. [11].

We wish in this note to reexamine the possible role of dark matter in planetary heating, initially under the assumption that dark matter is *not* self-annihilating, just as ordinary baryonic/leptonic matter is not self-annihilating. This could happen, for example, if dark matter is fermionic and consists of fermions but not the corresponding antifermions. It could also happen if dark matter is bosonic and carries one sign of an additive conserved quantum number, but not the opposite sign. Non-self-annihilating

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dark matter would permit a large dark matter interaction cross section with ordinary matter, making possible efficient capture without violating the earth heat flow constraint. Specifically, the analysis of the flyby anomaly in [12] shows that if the reported results are not an artifact, a dark matter explanation would require dark matter masses well below a GeV and a dark matter inelastic scattering cross section from ordinary matter in the range between around $10^{-33}\ \mathrm{cm}^2$ and $10^{-27}\ \mathrm{cm}^2$. Parameter values in this range are allowed by existing constraints on dark matter masses and cross sections, which are summarized in Section 2 of Mack et al. [8]. In Section 2.1, these authors review the astrophysical constraints, which require (for dark matter mass $m_d$ smaller than a GeV) that the dark matter scattering cross section from ordinary matter should be smaller than about $3 \times 10^{-25}\ (m_d c^2/\mathrm{GeV})\mathrm{cm}^2$. Direct detection constraints are summarized in Section 2.2 and Fig. 1 of [8], as well as in Fig. 3 of Gelmini [13], and show that for dark matter masses below a GeV, the entire cross section range between $10^{-33}\ \mathrm{cm}^2$ and $10^{-27}\ \mathrm{cm}^2$ is allowed. For conventional self-annihilating dark matter, this cross section range is almost entirely excluded by the earth heat budget constraint, as shown in Fig. 2 of [8]. However, for non-self-annihilating dark matter, as noted by [8], the earth heat budget constraint is weakened by a factor of order $10^6$, and parameter values of interest for our present discussion are allowed.

The reason that the direct detection constraints reviewed in [8] and [13] are not effective in placing limits on dark matter masses much below 1 GeV, is that these experiments rely on detecting the recoil of a nucleon from which a dark matter particle has scattered. The smaller the mass of the incident dark matter particle, the lower the kinetic energy of nucleon recoil, and the harder it is to pick up this signature. Hence experiments of this type have a characteristic low mass cutoff in their sensitivity to dark matter particles. The same problem applies to the time of flight beam dump experiment of Gallas et al. [14], in which one looks for events produced by particles that have detectable time of flight differences from neutrinos, because for light, energetic, dark matter particles, the time of flight difference that might serve to distinguish them from neutrinos is not large enough. The experiment of [14] has a lower mass limit of 0.5 GeV, and for dark matter particles lighter than this places no constraints. For dark matter particles in the mass range between 0.5 and 1 GeV, interaction cross sections with nucleons between $10^{-29}$ and $10^{-31}\ \mathrm{cm}^2$ are excluded if one assumes a production cross times branching ratio $\sigma \times \mathrm{br} = 1000$ picobarn per nucleon, whereas if one assumes $\sigma \times \mathrm{br} = 100$ picobarns per nucleon, there is no excluded region for interaction cross sections (see their Fig. 10).

The only type of accelerator search experiment that we have found that does not have a low mass exclusion is the missing energy beam dump experiment reported by Åkesson et al. [15]. In their Fig. 6, they use a theoretical model to extrapolate their experimental results to give bounds on the production cross section for stable neutral particles of masses 1–5 GeV. For masses below 1 GeV, their bound is in the range $1\text{–}4 \times 10^{-31}\ \mathrm{cm}^2$. However, such a production cross section does not translate directly into an interaction cross section for dark matter scattering on nucleons. For example, in QCD production of particles by multiple gluon exchange, the phenomenological Okubo–Zweig–Iizuka rule [16] states that production processes involving "hairpin" quark lines, in which the exiting quark is not also an entering quark, are suppressed. Thus, in QCD large classes of production processes are suppressed relative to the cross sections expected from the corresponding scattering processes. If analogous considerations apply to dark matter particles, then the elastic scattering cross sections corresponding to the allowed range of the experiment of [15] could be several orders of magnitude larger, and would then encompass the whole range on which we are focusing our discussion here. There are of course many other accelerator experiments searching for new particles, but they either assume that the new particles are unstable, and so decay within a tracking device, or are charged, so that they leave tracks themselves. Finding neutral stable (or very long lived) particles, such as putative dark matter particles, is much more difficult, which is why there are relatively few accelerator experiments placing bounds.

To proceed, then, let us consider the collision of a dark matter particle of mass $m_d$ and velocity $v_d$ with a medium containing nucleons of mass $m_N$, and of sufficient optical depth that the dark matter particle is certain to interact. If the collision is elastic, a non-self-annihilating dark matter particle will multiply scatter until it comes to rest, with an energy release in the medium of $\frac{1}{2} m_d v_d^2$, which is smaller than the annihilation energy $m_d c^2$ by the factor [17]

$$f_{\mathrm{el}} = \frac{1}{2} \frac{v_d^2}{c^2}. \tag{1}$$

Consider next the case examined in [12], in which a dark matter primary particle of mass $m_d$ scatters inelastically on a nucleon into a secondary particle of mass $m'_d$, with $\delta m_d = m_d - m'_d > 0$, so that the reaction is exothermic. There are then two limiting cases. If the secondary scatters from nucleons strongly enough it will be trapped in the medium, and the kinetic energy $\delta m_d c^2$ will be dissipated, giving an energy release which is smaller than the annihilation energy $m_d c^2$ by the factor

$$f_{\mathrm{inel}\,1} = \frac{\delta m_d}{m_d}. \tag{2}$$

On the other hand, if the secondary scatters from nucleons only very weakly, so that it escapes from the medium without energy loss, then the energy release is given by the nucleon recoil energy $(1/2) m_N v_{\mathrm{recoil}}^2$. As shown in [12], if $m'_d$ and $\delta m$ are of similar order of magnitude, then $v_{\mathrm{recoil}} \sim (m_d/m_N)c$, and so the nucleon recoil energy is $(1/2)(m_d^2/m_N)c^2$, giving an energy release which is smaller than the annihilation energy $m_d c^2$ by the factor

$$f_{\mathrm{inel}\,2} = \frac{1}{2} \frac{m_d}{m_N}. \tag{3}$$

Clearly, other cases are possible, but we see already from the examples considered that the factors $f_{\mathrm{el}}$, $f_{\mathrm{inel}\,1}$ and $f_{\mathrm{inel}\,2}$ can all be much smaller than unity. For example, for a velocity $v_d$ in the range $10\ \mathrm{km\,s^{-1}}$ to $50\ \mathrm{km\,s^{-1}}$, characteristic of matter orbitally bound to a solar system planet, $f_{\mathrm{el}}$ ranges from $5.6 \times 10^{-10}$ to $1.4 \times 10^{-8}$. If $\delta m_d \ll m_d$, then $f_{\mathrm{inel}\,1}$ is very small, while if $m_d \ll m_N$, then $f_{\mathrm{inel}\,2}$ is very small. So for non-self-annihilating dark matter, there are many possibilities for achieving a much smaller energy release in the nucleon medium than the dark matter annihilation energy.

Consider now a planet with outward energy flow per unit area at its surface $H$. Suppose that the planet is immersed in a dark matter cloud, with mass density $\rho_m$ and mean velocity $v_d$ at the planet's surface. We will assume that the velocity $v_d$ is of the same order of magnitude as the orbital velocity around the planetary surface $(G M_{\mathrm{planet}}/R_{\mathrm{planet}})^{1/2}$. Continuing to denote by $f$ the fraction of the dark matter annihilation energy that is deposited in the planet when a dark matter particle is accreted, and including a solid angle factor of $1/2$, the condition for all of $H$ to be supplied by dark matter capture is

$$\frac{1}{2} \rho_m c^2 v_d f = H, \tag{4}$$

which gives for the dark matter density at energy flux equilibrium

$$\rho_m = \frac{1}{f} \frac{2H}{c^2 v_d} = \frac{K_{\mathrm{planet}}}{f}, \tag{5}$$

with

$$K_{\text{planet}} = \frac{2H}{c^2 v_d} \sim \frac{2H}{c^2}\left(\frac{R_{\text{planet}}}{GM_{\text{planet}}}\right)^{1/2}. \tag{6}$$

Using the planetary heat flow data given in de Pater and Lissauer [18], we get the following values for $K_{\text{planet}}$ for Earth, Jupiter, Saturn, Uranus, and Neptune,

$$\begin{aligned} &K_{\text{Earth}} = 0.12\ \left(\text{GeV}/c^2\right)\text{cm}^{-3}, \\ &K_{\text{Jupiter}} = 1.6\ \left(\text{GeV}/c^2\right)\text{cm}^{-3}, \\ &K_{\text{Saturn}} = 1.0\ \left(\text{GeV}/c^2\right)\text{cm}^{-3}, \\ &K_{\text{Uranus}} < 0.04\ \left(\text{GeV}/c^2\right)\text{cm}^{-3}, \\ &K_{\text{Neptune}} = 0.3\ \left(\text{GeV}/c^2\right)\text{cm}^{-3}. \end{aligned} \tag{7}$$

As noted, these numbers have been computed using a dark matter velocity $v_d$ appropriate to planet-bound dark matter, which is much smaller than the corresponding velocity associated with galactic halo dark matter. As a check on our rather crude estimates, let us compare with the corresponding estimate of Mack et al. [8] for the case of galactic halo dark matter. In their "maximum capture rate" estimate, these authors take for $v_d$ the galactic halo dark matter average velocity 270 $\text{km}\,\text{s}^{-1}$, which is a factor of 34 larger than the earth surface orbital velocity of 7.9 $\text{km}\,\text{s}^{-1}$ used to compute the first number in (7). Dividing the figure for the earth by 34 gives $K_{\text{Earth: halo dark matter}} = 0.0035\ (\text{GeV}/c^2)\text{cm}^{-3}$, which in agreement with [8], is two orders of magnitude smaller than the estimated galactic halo dark matter density. Hence, as concluded in [8], for self-annihilating dark matter (corresponding to $f = 1$), accretion of galactic halo dark matter with perfect efficiency (corresponding to cross sections greater than $10^{-33}$ cm$^2$, for which the optical depth of the earth is smaller than the earth's radius) would give too large an internal energy generation for the earth, by two orders of magnitude.

However, let us now suppose that dark matter is not self-annihilating, so that this constraint on dark matter scattering cross sections is no longer present, and that planets are typically surrounded by a bound dark matter cloud. The dark matter mass density $K_{\text{planet}}/f$ at the planetary surface that gives energy equilibrium is then, according to (7), considerably larger than the galactic halo density, and not outside the range determined by the gravitational bounds on sun-bound and earth-bound dark matter. So it then becomes reasonable to hypothesize that some substantial fraction of the planetary internal energy generation comes from the accretion of dark matter. This fraction of the heat production coming from dark matter could account for unexplained residual heat production in the earth [8], the Jovian planets [19], and in "hot-Jupiter" exoplanets [20]. This proposal assumes, and this is a topic for further study, that the surface depletion of the planet-bound dark matter cloud can be balanced by accretion of planet-bound dark matter from the galactic halo dark matter, or from dark matter bound to the sun or star around which the exoplanet orbits.

The hypothesis that planetary heat flows receive a significant contribution from efficient accretion of planet-bound, non-self-annihilating dark matter, also can give a plausible explanation of the mystery of the anomalously low heat production from Uranus. Uranus and Neptune are structurally very similar [21], so one at first hand would expect the internal heat flows to be similar. However, in addition to the difference in their heat flows, there is a second well-known difference between Uranus and Neptune: the axis of rotation of Uranus is tilted 98 degrees with respect to the plane of the solar system, whereas the rotational axes of Neptune and the other Jovian planets have much smaller tilt angles ($< 30$ degrees) with respect to this plane. The large axial tilt of Uranus is generally believed to be the result of a collision of Uranus with a supermassive impactor. Suppose now that the heat flux of Neptune and the other Jovian planets is primarily associated with accretion from a planet bound-dark matter cloud. Before its axis was tilted by a collision, Uranus would also have been expected to have had an associated bound dark matter cloud, and a heat flux similar that of the other Jovian planets. But a collision at small impact parameter would have occurred within the bulk of the Uranus-bound dark matter cloud, and plausibly could have knocked Uranus out of the cloud, in analogy to what is observed in the colliding "bullet" galactic cluster merger [22]. Once freed from its associated dark matter cloud, Uranus would then be left with a much lower internal heat production than Neptune and the other Jovian planets.

Finally, let us return to the case of self-annihilating dark matter, where the energy release factor $f$ defined above is unity. The suggestions we make concerning planetary heating could still apply if the dark matter interaction cross section with ordinary matter is small enough so that the capture efficiency is small, corresponding to parameter values below the heavily-shaded region in Fig. 2 of [8]. Then the earth heat balance constraints of [8] can be satisfied by galactic halo dark matter, but an excess of planet-bound dark matter above the galactic halo density could lead to significant heating. The formulas (4), (5), and (6) would still apply, now with $f \ll 1$ the capture efficiency rather than the ratio of the energy release to the annihilation energy. In the most general application of these formulas, $f$ should be taken as the product of the capture efficiency times the ratio of the energy release to the annihilation energy, since both of these factors can be smaller than unity in the generic case.

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