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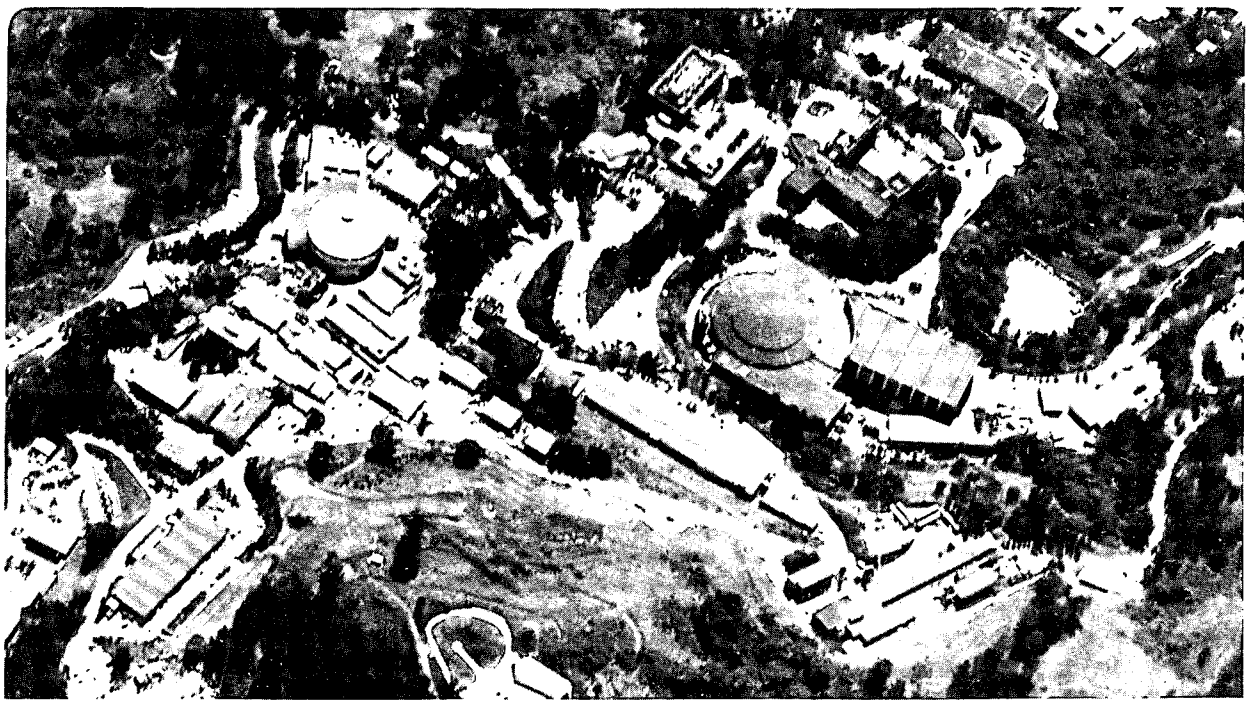

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Cosmions and Stars *

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Abstract

Hypothetical particles such as the heavy neutrino, the photino $\tilde{\gamma}$, or the sneutrino $\tilde{\nu}$ – generically called cosmions – may solve the so called missing mass problem. If they exist, the cosmions may close the Universe. In addition to their gravitational effect on cosmological scales, the cosmions may also be captured by stars and concentrate in their cores. Since cosmions are able to transport heat outside stellar cores much more efficiently than photons, they may seriously affect the thermodynamics of the inner layers of stars. We have done an exact calculation of the accretion rate of cosmions by main sequence stars and we have studied the suppression of their central convection. We concluded that central convection inside stars between 0.3 $M_\odot$ and 1 $M_\odot$ is broken in the presence of cosmions.

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1 Introduction

The dark matter puzzle is one of the most exciting issues of modern astrophysics. Solving this problem may require a close collaboration among various topics such as astrophysics and particle physics and it is mandatory that people from such different fields of research may gather and discuss as they did during this meeting.

Many theoretical and observational reasons suggest the presence of dark matter on galactic as well as extragalactic scales :

- The density of matter in the galactic disk seems to be twice the observed in the form of stars in the solar neighborhood [1].
- The stability of spiral galaxies requires the existence of a large massive spherical halo, also needed to explain the flat rotation curves [2].
- The dynamics of galactic clusters also require a large amount of unvisible material.
- The scenarios of galaxy formation are in contradiction with observations (such as the limits on the anisotropy of the microwave background radiation) unless a large component of the mass of the universe is non baryonic [3].

The nature of dark matter is unknown, but among the many candidates for the missing mass, weak interacting massive particles are very attractive. These particles such as the heavy neutrino, the photino $\tilde{\gamma}$ or the sneutrino $\tilde{\nu}$, if they exist, have been processed during the Big-Bang in the appropriate amount to account for dark matter. These particles, generically called "cosmions", are mostly predicted by supersymmetric theories. They might be the unseen material of our galaxy and make up the galactic halo. If so, cosmions are steadily accreted by stars – our sun for instance – and concentrate in their cores. Press and Spergel [4] made an approximate calculation of the capture rate of cosmions by the sun and they showed that their concentration at the center of the star might be sufficient to solve the solar neutrino puzzle. Indeed, cosmions transport heat outside the solar core much more efficiently than photons do, leading to a reduction of the effective opacity of the central solar material and lowering the central temperature in the appropriate amount to make the solar neutrino flux compatible with the observations of Davis ($\Phi_\nu \leq 2.1$ SNU). Underground experiments are very active to try to detect cosmions either directly by their elastic scatterings upon ordinary nuclei, or indirectly through their annihilation products originating from the center of the sun.

Another interesting issue, on which we concentrate now on, is that cosmions trapped inside stars may affect their central thermal equilibrium in such a way that the inner stellar structure is changed. In order to study the thermal effects of cosmions on stars, we first must know how many of these particles can be captured by each star. That is why in section 2 we present an exact calculation [5] of the accretion rate of cosmions inside main sequence stars. Section 3 is a short overview of the consequences of energy transfer by cosmions from stellar cores. As we look for "first order" effects, we will concentrate on the suppression of central convection.

2 Capture rate of cosmions by main sequence stars

The most likely source of cosmions is the galactic halo. This last one may be roughly approximated by a nearly isothermal sphere, with a density falling as $1/r^2$ and an isotropic maxwellian distribution of velocity, with mean value $V_{halo} \simeq 300$ km/s :

$$n_x(\mathbf{r}, \mathbf{V}) = \frac{n_x(0)}{1 + \frac{r^2}{a^2}} \; e^{-\frac{3V^2}{2V_{halo}^2}} \tag{1}$$

where the scale length a ranges between 2 and 10 kpc. The density of cosmions in the solar neighbourghood is estimated to be around 0.01 $M_\odot/pc^3$.

The trajectories of the cosmions around some star of mass M and radius R are completely determined once the energy $E = \frac{1}{2}V^2$ and the angular momentum J with respect to the center of the star are known. Therefore, the incoming flux of cosmions (i.e. the number of cosmions which enter the star per second) is just given by :

$$Incoming\ Flux \;=\; 4\pi^2 n_x \left[\frac{3}{2\pi V_{halo}^2}\right]^{\frac{3}{2}} \int_{domain\ \mathcal{D}} e^{-\left(\frac{3V^2}{2V_{halo}^2}\right)} \, dE \, dJ^2 \, . \tag{2}$$

The domain $\mathcal{D}$ corresponds to the trajectories the perihelion of which is of course less than the radius R of the star and is defined by :

$$E \;\geq\; 0 \;\; and \;\; J^2 \;\leq\; 2R^2 \, (E + \frac{GM}{R}) \, . \tag{3}$$

The incoming flux gives the upper bound on the capture rate. Performing the integration of equation (2) on domain $\mathcal{D}$ leads to :

$$Incoming\ Flux \;=\; 1.04\ 10^{30}\ s^{-1} \left[\frac{m_p}{m_x}\right] \left[\frac{M}{M_\odot}\right] \left[\frac{R}{R_\odot}\right] \left[\frac{300\ km/s}{V_{halo}}\right] \left[\frac{\rho_{halo}}{0.01\ M_\odot/pc^3}\right]$$

$$\left\{ 1 + 0.1573 \left[\frac{V_{halo}}{300\ km/s} \right]^2 \left[\frac{M_\odot}{M} \right] \left[\frac{R}{R_\odot} \right] \right\} \tag{4}$$

and gives a good order of magnitude of the capture fluxes which we are going to deal with. As an example, the sun may accrete as many as 10^{30} particles each second. Equation (4) may be understood as the sum of 2 terms. The geometrical incoming flux varies as R^2 and does not depend on the mass of the star. This contribution is dominant for low density objects such as gaseous planets or red giant stars. In addition, the trajectories may be bent and focused by gravitation, leading to an extra term in the incoming flux which varies as MR. This contribution turns out to be the dominant one for main sequence stars.

Of course, not every cosmion which enters the star is captured. The particle must undergo a collision with a nucleus inside the star and lose enough energy to be unable to escape back to infinity. This results in an additional factor in the integrand of equation (2) :

$$P(E, J^2) = 1 - e^{-\int_{Trajectory} S(r)\alpha_1(r)\sigma_s n_p(r)\, dl} \tag{5}$$

P(E,J^2) is just the probability of capture along the trajectory labelled by E and J^2. Obviously, n_p(r) is the number density of protons at distance r from the stellar center (the main component of stars is hydrogen). σ_s is the elastic scattering cross section of cosmions upon protons. α_1(r) describes the thermal enhancement of the cross section due to the thermal motions of protons and is given by :

$$\alpha_1(\omega) = erf(\sqrt{\omega}) \left[1 + \frac{1}{2\omega} \right] + \frac{e^{-\omega}}{\sqrt{\pi\omega}} \tag{6}$$

where ω is just the ratio of the kinetic energies (for unit masses) of the two colliding particles :

$$\omega = \frac{m_p V^2}{2\, kT_p(r)} \cdot \tag{7}$$

Finally, S(r) is a step function which takes the value 1 if the cosmion loses enough energy in its collision with a proton to be captured, and is set equal to zero if the cosmion escapes back to infinity after having scattered.

The final step of this calculation is the description of the stellar structure. We used for this purpose the n=3 polytropic model which fits fairly well stars on the main sequence (these stars are not completely convective and a substantial part of their interior is subject to radiative transport). In addition, the strong correlation between radii and masses along the main sequence was handled by enforcing the relation :

$$\frac{R}{R_\odot} = \left(\frac{M}{M_\odot} \right)^{0.8} \cdot \tag{8}$$

The results, displayed in fig.(1) as a function of the scattering cross section σ_s, may be summarized by the approximate relation :

$$F(M, m_x, \sigma_s) \approx 1.2\ 10^{30}\ s^{-1} \left[\frac{\rho_{halo}}{0.01\ M_\odot/pc^3}\right] \left[\frac{300\ km/s}{V_{halo}}\right] \left[\frac{m_p}{m_x}\right] \left[\frac{M}{M_\odot}\right]^{1.8} Min\left\{1, \frac{\sigma_s}{\sigma_c(M)}\right\} . \tag{9}$$

- The captured flux F scales as the inverse of the cosmion mass m_x.
- The gravitational focusing dominates over the simple geometrical capture. Therefore F varies with the mass of the star as $M^{1.8}$.
- Figure (1) clearly exhibits 2 regimes, depending on the scattering cross section :
  1. The "linear" regime occurs for low values of σ_s. The cross section factorizes out of relation (5) and therefore the captured flux F depends linearly on σ_s.
  2. On the contrary, if σ_s is large, every cosmion which enters the star is trapped and the captured flux F turns out to be equal, in this limiting case, to the incoming flux.

The turn over between these two regimes occurs for the special value $\sigma_c(M)$ of the scattering cross section that corresponds to a mean free path of the cosmion inside the star precisely of the order of the stellar radius R :

$$\sigma_c(M) \approx \frac{m_p R^2}{M} \approx 4\ 10^{-36}\ cm^2 \left(\frac{M}{M_\odot}\right)^{0.6} . \tag{10}$$

3 Cosmions and central convection

Cosmions are continuously captured by stars and accumulate in their cores. If cosmions annihilate, their density inside stars is of course suppressed, but it still may be possible to detect their presence through the annihilation products originating from the center of the sun. However, in this paper, we concentrate on the other issue : cosmions are stable against annihilation and their density in stellar cores steadily increases with time. As cosmions are weakly interacting particles, they transport energy more efficiently than baryons do, and therefore may compete with the other heat transport mechanisms such as radiative transport or convection. Therefore, cosmions can flatten the temperature profile at the center of stars and may induce an isothermal core. In order to understand the possible

influence of cosmions on stellar structure, we are looking for the sites where the effects of these particles are potentially large. Stars the center of which are degenerate are not affected by the presence of cosmions. Indeed, electronic conduction is so large that the core of these stars is already isothermal. Therefore, we will disregard in this analysis neutron stars, white dwarfs and red giants. Stars with a radiative core are more sensitive to dark matter. The presence of cosmions leads to a decrease of their temperature gradient. This effect has been invoked to explain the solar neutrino problem. However, in this case, neither the internal structure of the star is changed, nor its lifetime. The largest effect cosmions may induce on stars is the suppression of their central convection. Not only the temperature gradient is lowered, but the structure of the core is severely changed when the star flips from convection to radiation. Moreover, convection continuously mixes matter from the outer layers with the central regions where nuclear burning takes place. As convection provides the core with fresh fuel, nuclear burning can actually take place for a much longer time than in the pure radiative case. The most important effect dark matter might have on stars is to suppress central convection – whenever it exists – and, consequently, to induce their premature death through starvation.

The rate of energy production by nuclear reactions is given by :

$$\epsilon_{nuc} = 0.562\,\rho X_H^2 \left(\frac{T}{1.5\,10^7\,K}\right)^4 + 2.59\,\rho X_H X_{CNO} \left(\frac{T}{1.5\,10^7\,K}\right)^{20} \quad erg.g^{-1}.s^{-1} \qquad (11)$$

where the first term refers to the PP chain and the second one describes the CNO cycle. ϵ_{nuc} is nearly constant inside the core of radius $r_{Wimps} = 0.14\ R_\odot \sqrt{m_p/m_x}$ where cosmions accumulate.

The nuclear energy may be radiated outside the stellar core with a luminosity L_{rad} which, at distance r from the center, is given by :

$$L_{rad} = -\frac{16\pi}{3}\frac{acT(r)^3}{\kappa\rho(r)}\,r^2\,\frac{dT}{dr}\,. \qquad (12)$$

ρ is the density of matter and κ is its opacity. The product $\kappa\rho$ is just the inverse of the photon mean free path λ_γ. The convective core of a star is well described by a n = 1.5 polytrope and in this case, the radiative losses from the center may be accounted for by introducing the negative energy " production " term :

$$\epsilon_{rad} = -\frac{32\pi}{15}\frac{acG\mu T(0)^3}{\kappa\rho(0)R_{Boltzmann}} \quad erg.g^{-1}.s^{-1} \qquad (13)$$

where a is the energy constant of the photon gas, c is the speed of light, G is the Newton's constant of gravitation and μ is the mean molecular weight.

The cosmion heat transport takes place in two different regimes depending on the value of the Knudsen number :

$$K_n = \frac{1}{n_b \sigma_s R} = \frac{\lambda_x}{R} \cdot \tag{14}$$

1) Large Knudsen numbers correspond to small values of the scattering cross section σ_s. Therefore, the mean free path λ_x of cosmions inside the stellar interior is much larger than the stellar radius R. Cosmions tend to have throughout the star the same mean velocity and they will be assumed here to behave as an isothermal gas with temperature T_x. T_x is just an average of the temperatures of the regions which the particles sample. The heat transferred from cosmions to baryons, due to the collisions among the two species, may also be expressed in terms of an energy production term [6] :

$$\epsilon_x = 8\sqrt{\frac{2}{\pi}} n_x n_p \frac{\sigma_s}{\rho} \frac{m_x m_p}{(m_x + m_p)^2} \sqrt{\frac{m_p k T_x + m_x k T}{m_x m_p}}\, k\,(T - T_x) \quad erg.g^{-1}.s^{-1} \cdot \tag{15}$$

Requiring that cosmions are in a steady situation of thermal equilibrium with the surrounding matter :

$$\int_{star} 4\pi r^2 \epsilon_x \rho \, dr = 0 \tag{16}$$

leads to the relation between the cosmion temperature T_x and the baryonic central temperature T_C :

$$\frac{T_x}{T_C} = 1 - \frac{3}{5}\frac{m_p}{m_x}\frac{\mu}{1\,g} \cdot \tag{17}$$

2) Small Knudsen numbers, on the contrary, correspond to a small mean free path λ_x with respect to R. This situation is more simple to treat since cosmions are locally in thermal equilibrium with baryons (ie $T_x = T$) and the heat transport is just due to the conduction by dark matter :

$$L_x = -4\pi r^2 n_x(r) \sqrt{\frac{kT(r)}{m_x}} \frac{k}{n_p(r)\sigma_s \sqrt{\frac{3m_x + m_p}{m_x + m_p}}} \frac{dT}{dr} \cdot \tag{18}$$

In the case of a convective core, this expression leads to :

$$\epsilon_x = \frac{8\pi}{5}\frac{G\mu}{\mathcal{N}_a} \frac{n_x(0)}{n_p(0)\sigma_s \sqrt{\frac{3m_x + m_p}{m_x + m_p}}} \sqrt{\frac{kT(0)}{m_x}} \cdot \tag{19}$$

Our analysis simply consists in comparing the energy production or absorption terms : ϵ_{nuc} (energy produced by nuclear reactions) versus ϵ_{rad} and ϵ_x (energy absorbed by radiation and by dark matter inside a convective core). In the absence of dark matter, a convective core develops whenever radiation alone is unable to drag away all the energy generated by nuclear reactions. The star tries to radiate the central energy in increasing its temperature gradient. Whenever this last one overcomes the adiabatic gradient, which indeed corresponds to the n = 1.5 polytropic case, the center becomes unstable against convection. Relation (13) gives therefore the upper limit on the energy which may be dragged away from the stellar center through radiation losses. The condition for the existence of a convective core in the absence of dark matter is :

$$\epsilon_{nuc} \geq \epsilon_{rad} \cdot \tag{20}$$

When dark matter comes into play, it provides the stellar core with an additional cooling mechanism, and may be sufficiently large to supplement the radiation mechanism without any need for convection. This translates into :

$$\epsilon_{nuc} \leq \epsilon_{rad} + \epsilon_x \cdot \tag{21}$$

Therefore, dark matter suppresses convection in stellar cores whenever both relations (20) and (21) hold. In this case, the mixing of matter between the external layers and the very center of the star stops in the presence of cosmions, leading to a shortage of nuclear fuel inside the energy producing region. The star is starved and therefore, driven to extinction more rapidly than in the standard case.

To illustrate this effect, we deal now with main sequence stars. Recall that conditions (20) and (21) may be expressed just in terms of the central temperature T(0) and the central mass density $\rho(0)$. These quantities only depend on the mass M of the star through the somewhat phenomenological relations :

$$\begin{aligned} \rho(0) &= 89.1\ g.cm^{-3} \left(\frac{M}{M_\odot}\right)^{-1.2} \\ T(0) &= 14.6\ 10^6\ Kelvins \left(\frac{M}{M_\odot}\right)^{0.35} \\ \kappa &\approx 1\ cm^2.g^{-1}\ (\ approximate\ relation\ ) \\ \mu &\simeq 0.62\ g\ (\ for\ Pop\ I\ stars\ ) \cdot \end{aligned} \tag{22}$$

In addition we have set $X_H \approx 0.7$, $X_{He} \approx 0.3$ and $X_{CNO} \approx 2\%.X_H \approx 0.014$. The final expressions for ϵ_{nuc} and ϵ_{rad}, on the main sequence are fairly simple :

$$\epsilon_{nuc} = 22. \left(\frac{M}{M_\odot}\right)^{0.2} + 1.32 \left(\frac{M}{M_\odot}\right)^{5.8} \quad erg.g^{-1}.s^{-1}$$

and

$$\epsilon_{rad} = 26.2 \left(\frac{M}{M_\odot}\right)^{2.25} \quad erg.g^{-1}.s^{-1} \cdot \tag{23}$$

Fig.(2) is a plot of the various energy production or absorption rates as a function of the stellar mass M for main sequence stars. ϵ_{nuc} overcomes ϵ_{rad} on nearly the entire range of masses, except around 1 $M_\odot$ where radiation is sufficient to drag alone the nuclear energy produced in the core. The curve of the nuclear energy production rate exhibits two different regimes : below $\approx 1.6 M_\odot$ the PP chain is dominant but above, the CNO cycle overcomes the PP chain and ϵ_{nuc} steeply increases with M. This analysis breaks down for low mass stars – $M \leq 0.3$ $M_\odot$ – where matter starts to be partly degenerate and where electronic conduction is a powerfull energy loss mechanism.

Finally, we have expressed ϵ_x in term of M. The additional feature of this calculation is that n_x depends on the capture rate F and on the lifetime τ which the star has spent on the main sequence.

$$\tau = Min\left(10^{10}\,,\, 10^{10}\left(\frac{M}{M_\odot}\right)^{-3.6\,+\,\log\left(\frac{M}{M_\odot}\right)}\right) \quad years \cdot \tag{24}$$

This leads to the relations :

$$\epsilon_x \approx 21350\, erg.g^{-1}.s^{-1}\, Min\left(\left(\frac{M}{M_\odot}\right)^{-0.6}, \left(\frac{M}{M_\odot}\right)^{-4.2+\log\left(\frac{M}{M_\odot}\right)}\right) \frac{\sigma_s^2}{\sigma_c^2(M_\odot)}\left[1 + \frac{m_x}{m_p}\right]^{-\frac{3}{2}}$$

for large Knudsen number

and (25)

$$\epsilon_x \approx 6070\, erg.g^{-1}.s^{-1}\, Min\left(\left(\frac{M}{M_\odot}\right)^{0.85}, \left(\frac{M}{M_\odot}\right)^{-2.75+\log\left(\frac{M}{M_\odot}\right)}\right) \frac{\sigma_c(M_\odot)}{\sigma_s}\sqrt{\frac{m_x + m_p}{3m_x + m_p}}$$

for small Knudsen number ·

In fig.(2), ϵ_x is compared with ϵ_{rad} and ϵ_{nuc}. For both low and large Knudsen numbers, dark matter is definitely unable to suppress core convection inside massive stars. The limiting effect comes from the mere fact that, despite a large capture rate F, massive stars spend too few time on the main sequence to accrete the appropriate amount of cosmions. We therefore concluded that non-annihilating cosmions may affect low mass stars ($0.3\, M_\odot \leq M \leq 0.9$ $M_\odot$) by breaking their central convection, provided the scattering cross section lies in the range

[7. 10^{-38} , 7. 10^{-34}] cm^2. The largest thermal effect occurs for 7. 10^{-36} cm^2 and may be enhanced if the density of cosmions in the galactic disk is larger than the " canonical " value of 0.01 $M_\odot$ /pc^3. Finally, dark matter might also affect horizontal branch stars for the same reasons, but a carefull analysis is still needed.

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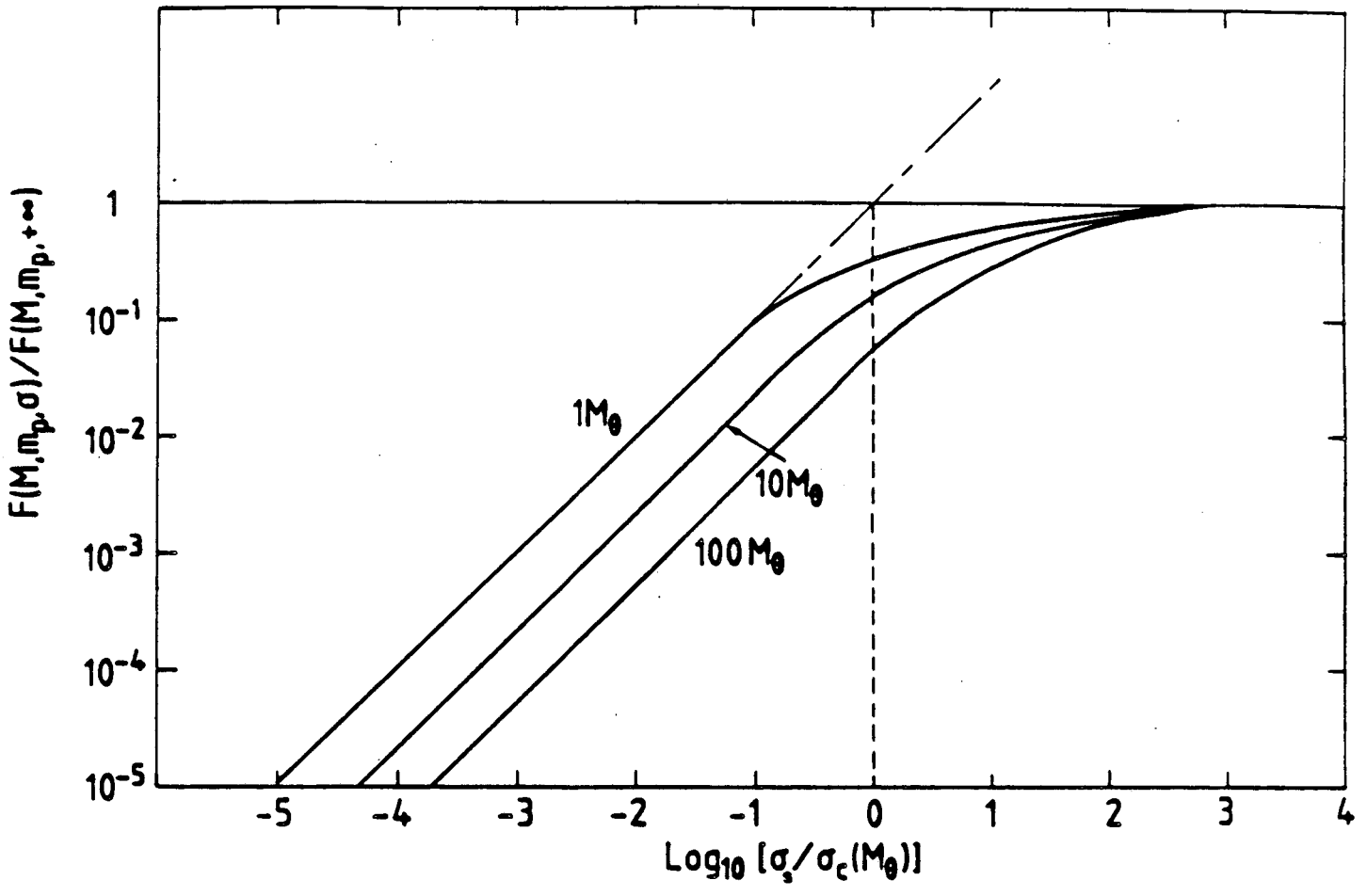

Figure 1:

The ratio of the captured flux F(M,m_x,σ_s) to the incoming flux F(M,m_x,$\sigma_s = \infty$) is plotted as a function of the cosmion-proton scattering cross section σ_s. $\sigma_c(M_\odot)$ is equal to 4. 10^{-36} cm^2 and corresponds to a mean free path of a cosmion inside the sun of the order of the solar radius. Three main sequence stars, with masses 1 $M_\odot$, 10 $M_\odot$ and 100 $M_\odot$ are analyzed : when the mass M of the star increases, the curve is just shifted to the right of the plot, while its shape is preserved. The cosmion mass m_x has been set equal to the proton mass m_p.

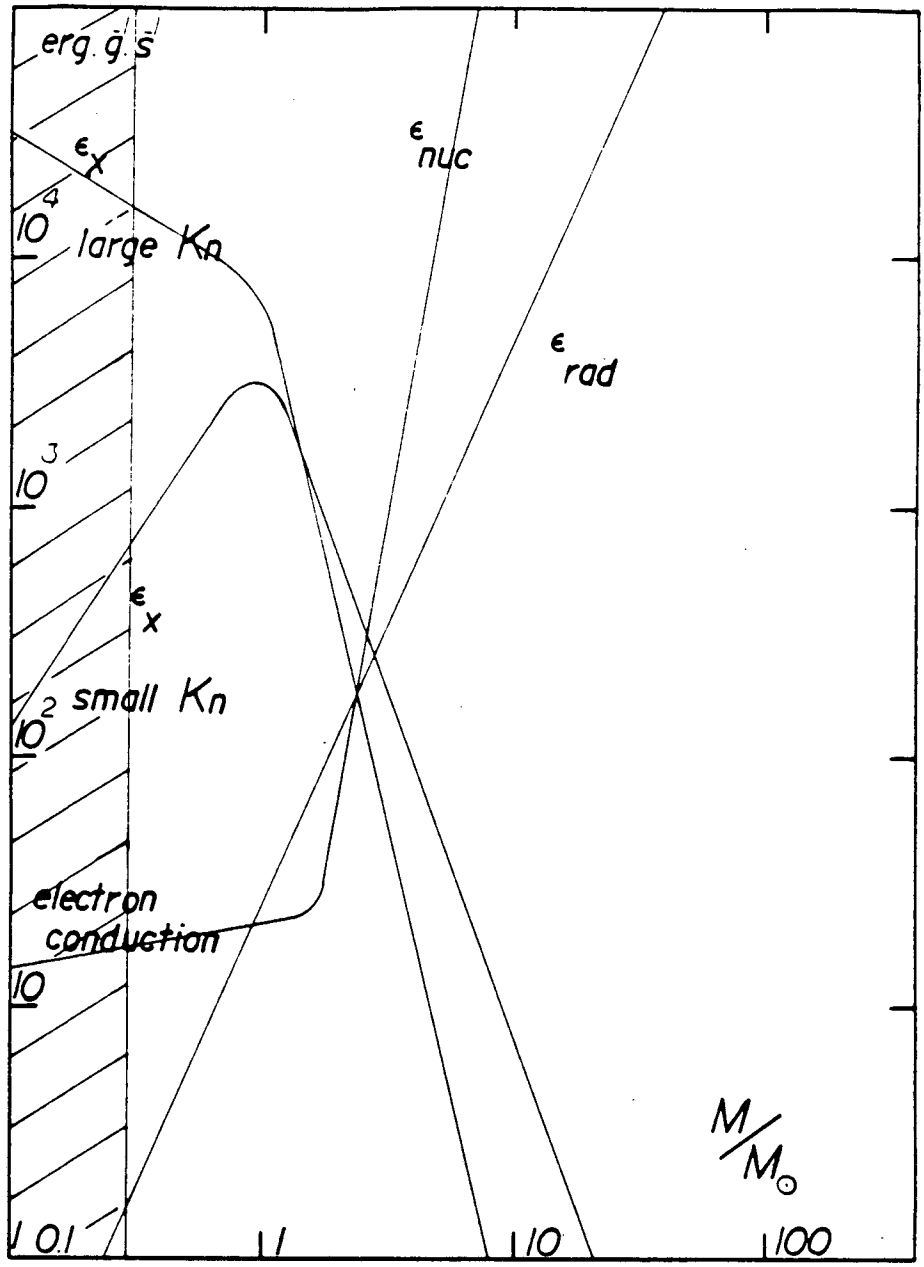

Figure 2:

The nuclear energy production rate ϵ_{nuc} and the heat absorption rates ϵ_{rad} (radiative losses) and ϵ_x (energy transported by cosmions) are plotted as a function of the mass M for main sequence stars. ϵ_x is shown in the two limiting situations of small and large Knudsen numbers. In addition, $m_x = m_p$ and $\sigma_s = 4.\ 10^{-36}$ cm^2. For massive stars, dark matter is unable to supplement the radiation mechanism sufficiently enough to break convection.

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