Probing the two temperature paradigm for advection dominated accretion flow: test for the component thermalization time-scale passed.

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ABSTRACT

We report here on a calculation of thermalization time-scale of the two temperature advection dominated accretion flow (ADAF) model. It is established that time required to equalize the electron and ion temperatures via electron-ion collisions in the ADAF with plausible physical parameters greatly exceeds age of the Universe, which corroborates validity one of the crucial assumptions of the ADAF model, namely the existence of a hot *two temperature plasma*. This work is motivated by the recent success (Mahadevan 1998a,b) of ADAF model in explaining the emitted spectrum of Sgr A*.

Subject headings: accretion, accretion discs — black hole physics — Galaxy: center

Identification of the nature of enigmatic radio source Sgr A* at the Galactic center has been source of debates since its discovery. Observations of stellar motions at the Galactic center (Eckart & Genzel, 1997; Genzel et al., 1996) and low proper motion ($\leq$ 20 km sec^{-1}; Backer, 1996) of Sgr A* indicate that, on the one hand, it is a massive $(2.5 \pm 0.4) \times 10^6 M_\odot$ object dominating the gravitational potential in the inner $\leq$ 0.5 pc region of the galaxy. On the other hand, observations of stellar winds and other gas flows in the vicinity of Sgr A* suggest that the mass accretion rate $\dot{M}$ is about $6 \times 10^{-6} M_\odot \mathrm{yr}^{-1}$ (Genzel et al., 1994). This implies that the luminosity of the central object should be more than 10^{40} erg sec^{-1}, provided the radiative efficiency is the usual 10%. However, observations indicate that the bolometric luminosity is actually less than 10^{37} erg sec^{-1}. This discrepancy has been a source of exhaustive debate in the recent past.

The broad-band emission spectrum of Sgr A* can be reproduced either in the quasi-spherical accretion model (Melia, 1992, 1994) with $\dot{M} \simeq 2 \times 10^{-4} M_\odot$ yr^{-1} or by a combination of disk plus radio-jet model (Falcke et al., 1993a, 1993b). As pointed out by Falcke and Melia (1997), quasi-spherical accretion seems unavoidable at large radii, but the low actual luminosity of Sgr A* points toward a much lower accretion rate in a starving disk. Therefore, Sgr A* can be described by a model of a fossil disk fed by quasi-spherical accretion. Recently, Tsiklauri & Viollier (1998) have proposed an alternative model for the mass distribution at the galactic center in which the customary supermassive black hole is replaced by a ball composed of self-gravitating, degenerate neutrinos. It has been shown that a neutrino ball with a mass $2.5 \times 10^6 M_\odot$, composed of neutrinos and antineutrinos with masses $m_\nu \geq 12.0$ keV/c^2 for $g = 2$ or $m_\nu \geq 14.3$ keV/c^2

for $g = 1$, where g is the spin degeneracy factor, is consistent with the current observational data. See also Munyaneza, Tsiklauri and Viollier 1998 for future tests of the model. Tsiklauri & Viollier 1999 have performed calculations of the spectrum emitted by Sgr A* in the framework of standard accretion disk theory, assuming that Sgr A* is a neutrino ball with the above mentioned physical properties, and established that at least part of the calculated spectrum, were the observational data is most reliable, is consistent with the observations.

Probably the most successful model which is consistent with the observed emission spectrum of Sgr A* has been developed by Narayan et al., 1995, 1998 (see also Manmoto et al., 1997). This model is based on the concept of advection dominated accretion flow (ADAF), in which most of the energy released by viscosity in the disk is carried along with the plasma and lost into the black hole, while only a small fraction is actually radiated off. Recent papers by Mahadevan 1998a,b have significantly advanced ADAF model. Inclusion of additional emission component, namely synchrotron radiation from $e^{\pm}$ created via decay of charged pions, which in turn are produced through proton-proton collisions in the ADAF, has significantly improved fitting of the Sgr A* spectrum in the low frequency band. After removing the latter discrepancy ADAF model of the Sgr A*, apart from the size versus frequency constraints (Lo et al. 1998 and references therein) which remain problematic for all current emission models of the radio source anyway, seems to be the most viable alternative. Thus, basic assumptions of the ADAF model should be carefully examined from the point of view physical consistency. As appropriately pointed out by Mahadevan (1998b), in order for the ADAF solutions to exist two basic assumptions in plasma physics must be satisfied: (a) existence of a hot *two temperature* plasma, and (b) the viscous energy generated primarily heats the protons. As to the assumption (b) its validity would be hard to verify as it is related to the yet unknown mechanism of viscosity in the accretion flow. The latter problem stands on its own in astrophysics. As concerns the assumption (a) it is from the field of plasma physics, a branch of physics which has been expensively studied in the laboratory, were we seem to have more comprehensive in comparison to astrophysics understanding of the underlying basic physical phenomena. Thus, motivated by the recent success (Mahadevan 1998a,b) of ADAF model in explaining the emitted spectrum of Sgr A*, we set out with the aim to check validity of the assumption (a).

It would be reasonable to believe that if the time required to equalize the electron and ion temperatures appears to be sufficiently large, then one might be confident that the assumption of the existence of the two temperature plasma in the ADAF is physically justified. The relevant time scale for the temperature equalization can be calculated using well formulated methods know in plasma physics. The rate at which temperature equilibrium between the electrons and ions is approached is determined by (see e.g. Melrose, 1986):

$$\frac{dT_e}{dt} = \nu_{eq}^{(e,i)}(T_i - T_e), \tag{1}$$

$$\frac{dT_i}{dt} = -\nu_{eq}^{(i,e)}(T_i - T_e), \tag{2}$$

with

$$\nu_{eq}^{(e,i)} = \frac{e^2 q_i^2 n \ln \Lambda^{(e,i)}}{3(2\pi)^{1/2} \pi m_e m_i \varepsilon_0^2 (V_e + V_i)^{3/2}}. \tag{3}$$

Here $\ln \Lambda^{(e,i)}$ is the Coulomb logarithm for electron-ion collisions given by $\ln \Lambda^{(e,i)} = 22.0 - 0.5 \ln n_e + \ln T_e$, ($T_e > 1.4 \times 10^5$ K), e and q_i are charges of electrons and ions respectively, m_e, m_i and T_e, T_i are their masses and temperatures (in Kelvin), V_e and V_i are thermal velocities of the electrons and ions, n is the number density of plasma (we have assumed the global charge neutrality of the ADAF, i.e. $n = n_e = n_i$) and finally as the SI system of units is used, $\varepsilon_0 = 8.8541878 \times 10^{-12}$ F/m.

Now, writing the thermal velocities $V_{e,i}$ as $V_{e,i} = \sqrt{T_{e,i}/m_{e,i}}$ in the Eqs.(1) – (3), these become closed set of ordinary differential equations for T_e and T_i. We set $q_i = e$ and m_i as a mass of proton. We solve numerically Eqs.(1) – (3) using `Numerical Recipes Software`, namely `odeint` driving routine with fifth order Cash-Karp Runge-Kutta method (tolerance error 10^{-15}). Calculations were performed for the values of the number densities ranging from 10^{16} to 10^{31} m^{-3}. The lower end of the number density's range is taken according to the actual value of the n in the ADAF around Sgr A* (Manmoto 1997, 1999). In the Fig.1 the number density (in cm^{-3}) profile is plotted. As established by Manmoto (1997, 1999) such ADAF number density profile corresponds to the case when best fit of the ADAF model to the observed emission spectrum is achieved. We gather form this plot that the maximal value of the n actually attained is somewhat less than 10^{10} cm^{-3} — the value we use in our calculations. Naturally, as more dilute plasma is as more time will be required to equilibrate electron and ion temperatures via electron-ion collisions. Therefore, actual time of the temperature equilibration is even larger than those values obtained here.

The results of our calculations are presented in the Fig. 2. For the initial values of the temperatures we have used $T_e = 10^{9.5}$ K and $T_i = 10^{12}$ K respectively (Mahadevan 1998a,b). We gather from the plot that the time required to equalize the temperatures of ions and electrons significantly exceeds the age of the Universe. Therefore we conclude that the assumption of the existence of a hot *two temperature* plasma is valid, or at least initial temperature difference will not be washed out by the electron-ion collisions within the age of the Universe.

The only concern one has bear in mind is that the formulas used in this paper, strictly speaking, are valid for non-relativistic plasma regime (Melrose, 1999) while the electron and ion temperatures concerned are relativistic (for the electrons $\gamma \simeq 200$). However, the temperature equalization time-scale obtained is so large, that even inclusion of the relativistic effects in our estimates would not change basic besults of this paper drastically.

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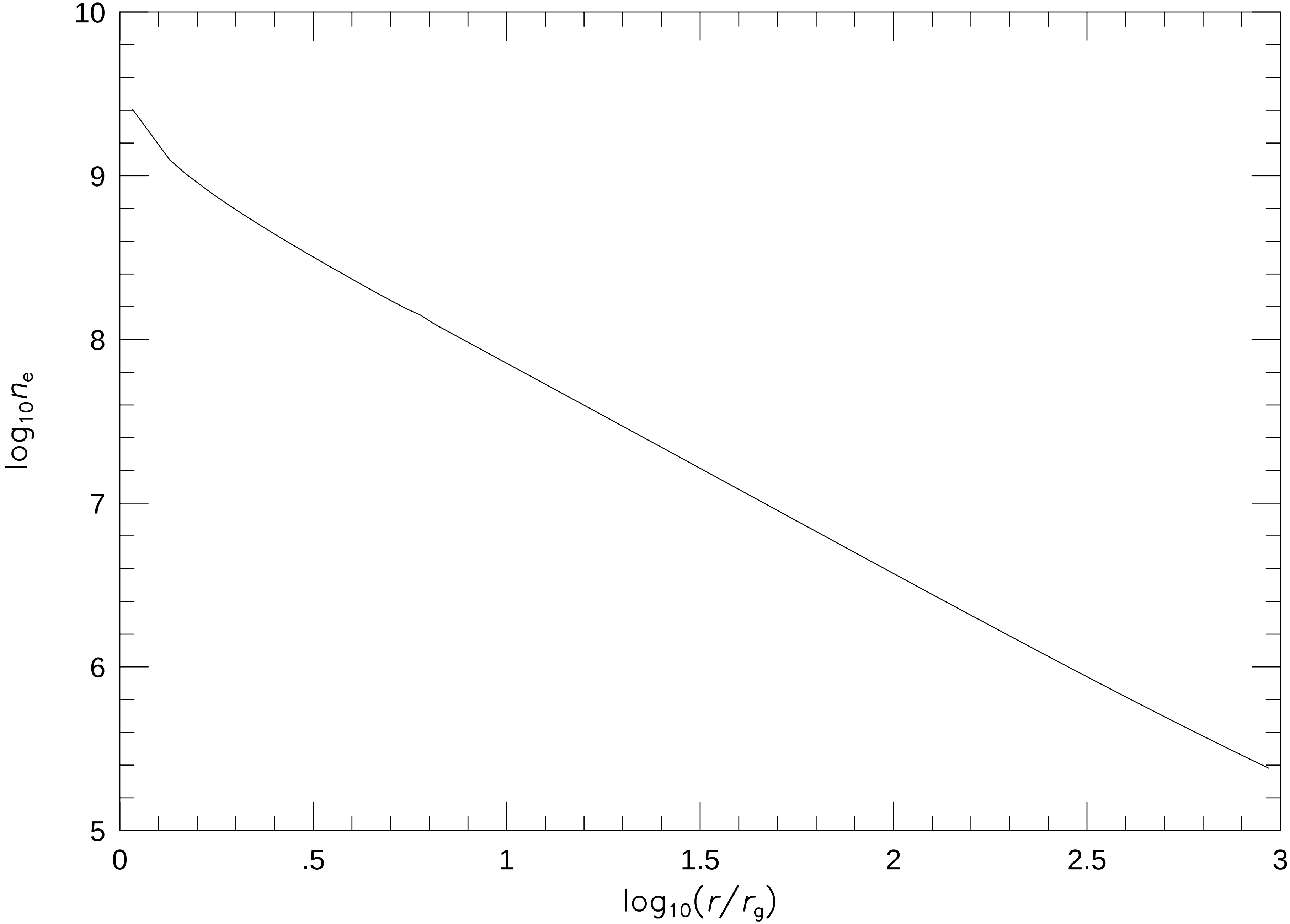
Fig. 1: The number density (n) profile which corresponds to the case when best fit of the ADAF model (Manmoto 1997, 1999) to the observed emission spectrum of the Sgr A* is achieved.

Fig. 2: Solutions of the Eqs.(1) – (3) for the three values of the number density (log-log plot). Thin lines correspond to $n = n_e = n_i = 10^{31}$ m^{-3}, thick lines correspond to $n = n_e = n_i = 10^{26}$ m^{-3}, while the thickest lines correspond to $n = n_e = n_i = 10^{16}$ m^{-3}. Solid lines correspond to the $T_e(t)$'s whereas dashed lines correspond to the $T_i(t)$'s. Note that equalization of the temperatures occurs at times greatly exceeding age of the Universe ($\simeq 10^{10}$ yr) and decreasing of the number density postpones the temperature equalization which is, of course, in accordance to the general physical expectations.



10
9
8
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1.5
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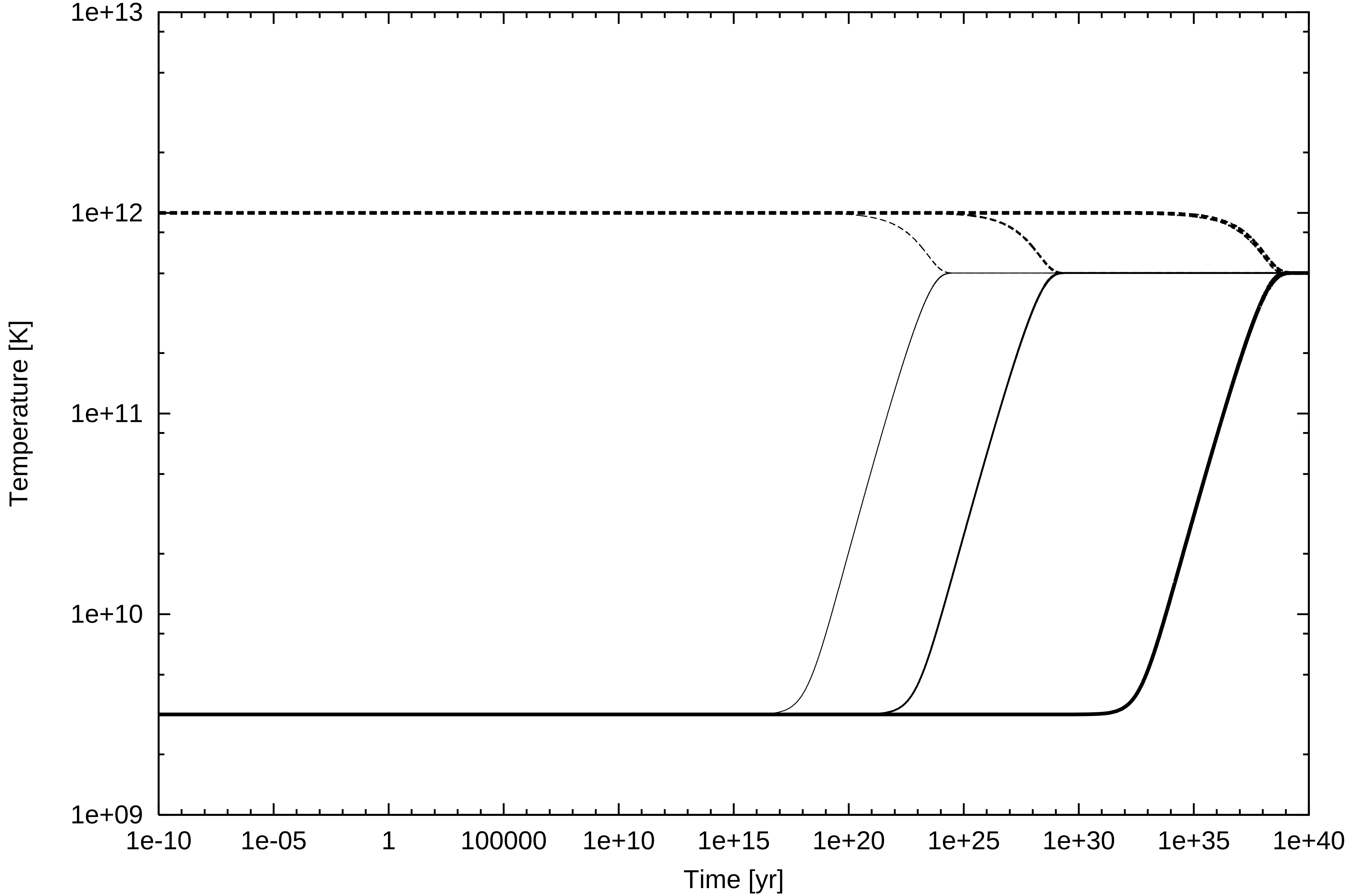
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1e+25
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1e+35
1e+40
Time [yr]