Did Dark Matter Kill the Dinosaurs?

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Overview

Extreme changes to the Earth's biosphere and ecosystem have often been attributed to astrophysical phenomena, and recent atmospheric simulations have shown that a nearby gamma-ray burst or supernova could deplete a large amount of ozone in the Earth's atmosphere [1]. Such an event would be disastrous for all living organisms, as ozone molecules effectively shield the Earth's surface from solar ultraviolet radiation that is harmful to DNA. This work investigates the possibility and extent of ozone depletion from gamma rays that have been produced in the cores of dense dark matter (DM) minihalos residing within the Milky Way, and estimates the rate at which this type of event might occur.

Method

We initially calculate, using a range of realistic DM parameters, the gamma ray fluxes produced by WIMP annihilations occuring within a set of DM minihalos. These fluxes are then used as input data for the Goddard Space Flight Center 2D Atmospheric Model, which computes chemical reactions between a host of atmospheric species. The most important atmospheric effect, the change in the abundance of ozone molecules, is calculated over a period of several years. We finally compute the rate at which different thresholds of ozone depletion would occur by using estimates on the mass distribution of DM minihalos in the Milky Way.

Models and parameters

The DM minihalos we consider are exotic, extremely compact objects with density profiles of $\rho \propto r^{-9/4}$ and $\rho \propto r^{-3/2}$ (the latter is referred to as Moore-like in this work). The particle DM model we consider is of generic WIMPs with a variety of possible masses, that self-annihilate through the light quark-antiquark channel with the standard thermal relic cross-section. The calculated gamma-ray flux is input to the atmospheric model over the Earth's equator for a total period of ten days. The input fluxes are also scaled to a total fluence of $\mathcal{F} = 100\,\mathrm{kJ/m^2}$, which is a common reference value in the literature for these types of effects.

Atmospheric effects

The most notable effect of an incident gamma-ray flux on the Earth's atmosphere is the depletion of ozone (O_3) molecules, which are found predominantly in the stratosphere [2]. An incident gamma-ray flux leads to the formation of several molecules, including NO and OH, which can then participate in a series of catalytic chemical reactions that remove ozone from the atmosphere. An example of such a reaction can be seen with the NO molecule:

$$\mathrm{NO} + \mathrm{O_3} \rightarrow \mathrm{NO_2} + \mathrm{O_2}. \quad (1)$$

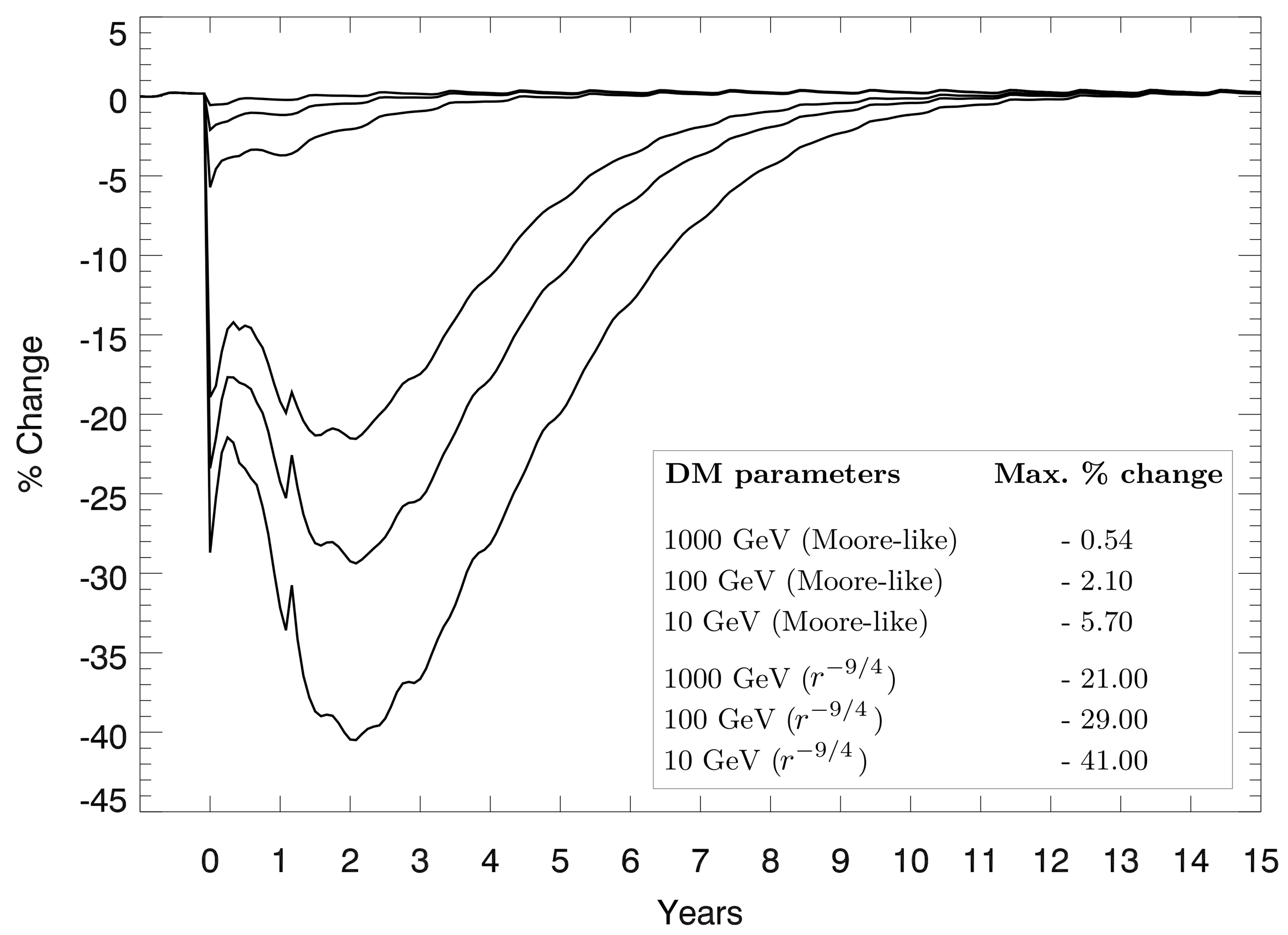
Since another reaction preserves the NO molecules:

$$\mathrm{NO_2} + \mathrm{O} \rightarrow \mathrm{NO} + \mathrm{O_2}, \quad (2)$$

the reaction cycle in Equations 1 and 2 can occur hundreds of times before the NO interacts with other atmospheric species. This catalytic depletion of O_3 molecules is the primary mechanism we investigate in this work.

Results

Amount of ozone depletion



This figure shows the percentage change in the global amount of atmospheric ozone after an encounter with various DM minihalos.

Note that the total fluence values from $r^{-9/4}$ minihalos are numerically scaled to $\mathcal{F} = 100\,\mathrm{kJ/m^2}$, and Moore-like minihalos of equal WIMP mass are then set to the corresponding $r^{-9/4}$ distances. We infer from these calculations that $r^{-9/4}$ minihalos with less massive WIMPs produce more extreme atmospheric effects, the magnitude of which are also comparable to nearby GRBs of equal fluence [1].

Rate of encounters

σ	μ ($M_\odot$)	Γ_{100}
0.25	10^{-6}	0
	10^{-4}	1.675×10^{-36}
	10^{-2}	4.760×10^{-4}
	1	1.173×10^{-3}
	10^{2}	1.427×10^{-3}
	10^{4}	1.507×10^{-3}
0.5	10^{-6}	3.311×10^{-56}
	10^{-4}	7.509×10^{-14}
	10^{-2}	4.709×10^{-4}
	1	1.171×10^{-3}
	10^{2}	1.427×10^{-3}
	10^{4}	1.508×10^{-3}

This table shows a subset of the results from calculating the rate of encounters with minihalos that produce a fluence of $\mathcal{F} = 100\,\mathrm{kJ/m^2}$. Here, the factors σ and μ are the statistical parameters in the minihalo mass distribution, given by a log-normal form:

$$\Psi(M, \sigma, \mu) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{\log^2(M/\mu)}{2\sigma^2}\right)$$

The values of Γ_{100} represent the total probable number of encounters with a minihalo over the Earth's entire history of ~ 4.5 Gyr. From these values, we note that the rate of encounters with minihalos is markedly lower than GRBs with equal fluence (see [3]), making GRBs much more likely sources of the effect studied here.

References

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[3] T. Piran & R. Giminez, *Physical Review Letters*, **113**, 2014