CMB Spectral Distortions from Cooling Macroscopic Dark Matter

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We propose a new mechanism by which dark matter (DM) can affect the early and late universe. The hot interior of a macroscopic DM, or macro, can behave as a heat reservoir so that energetic photons and neutrinos are emitted from its surface and interior respectively. In this paper we focus on the spectral distortions (SDs) of the cosmic microwave background before recombination. The SDs depend on the density and the cooling processes of the interior, and the surface composition of the Macros. We use neutron stars as a model for nuclear-density Macros and find that the spectral distortions are mass-independent for fixed density. In our work, we find that, for Macros of this type that constitute 100% of the dark matter, the μ and γ distortions can be near or above detection threshold for high proposed next-generation experiments such as PIXIE.

In the standard Λ-CDM model of cosmology, dark matter (DM) comprises ΩDM ≃ 0.27 of the total energy density of today’s universe. From observations of the cosmic microwave background (CMB) and cosmic structures, we know this DM must be “cold” (i.e. non-relativistic), and “dark” (i.e. interact rarely with ordinary matter and radiation) – hence Cold Dark Matter (CDM). It must also interact rarely with itself.

The microscopic nature of CDM is still unknown; however, the absence of a suitable Standard Model (SM) particle has driven the widespread belief that the DM is a Beyond the Standard Model (BSM) particle, and a comonstant decades-long search for such particles in purpose-built DM detectors and among the by-products of collisions at particle accelerators.

The ongoing infertility of such particle DM searches, whether for Weakly Interacting Massive Particles (WIMPs) or axions, suggests that other candidates return to serious consideration. Two such candidates have long histories: so-called “primordial” black holes (PBHs), and composite baryonic objects of approximate nuclear density and macroscopic size, which we will refer to as “Macros” [1], although that term properly includes macroscopic candidates of any density and composition.

This paper is focused on Macros, and specifically on observational consequences of the presence of nuclear-density Macros in the early universe. These have the particular virtue that they may be purely SM objects built of quarks or baryons. In this case they must have been formed before the freezeout of weak interactions at \( t \approx 1 \text{s} \) and the subsequent onset of big bang nucleosynthesis (BBN), if the success of the standard theory of BBN in predicting light-element abundances is to be preserved (although see [2]).

Witten first suggested [3] that DM could be composites of up, down and strange quarks assembled during the QCD phase transition. Subsequent proposals have included purely SM objects made of quarks [4] or baryons [5, 6] of substantial average strangeness. A variety of BSM variations also exist (e.g., [7]). Several authors have focused on the observational consequences ([1, 8, 9]).

Macros share with PBHs an important distinction from particle DM candidates: they achieve their low interaction rates by being massive, and therefore of much lower hypothetical number density. Non-observation of approximately nuclear-density Macros through the tracks they would have left in ancient mica [1] demands \( m_X \geq 55 \text{g} \). Limits on larger Macro masses have been obtained from gravitational micro-lensing (\( m_X \lesssim 2 \times 10^{20} \text{g} \)) [10, 12] and femto-lensing (excluding \( 10^{17} \lesssim m_X \lesssim 2 \times 10^{20} \text{g} \)). These limits as quoted assume that the DM consists of Macros of a single mass – an unlikely situation for a composite object, though the mass functions of Macros are model-dependent and difficult to predict [13].

Cosmological constraints on Macros, whether from the CMB or large scale structure, do not yet impose on generic nuclear-density objects.

The presence of dense assemblages of quarks or baryons from before BBN through today would undoubtedly have as-yet unexplored observational consequences, no matter the specific mechanism of their formation or stabilization. Novel physics peculiar to such Macros, with potential observational consequences include:

1) slow pre-recombination cooling of the Macro compared to the ambient plasma:
   a. distorting the spectra of the cosmic microwave and neutrino backgrounds (CMB and CNB),
   b. heating the post-recombination universe, or
c. contributing to the cosmic infrared background;

2) production of nuclei (including heavy nuclei) through:
   a. inefficiency in Macro assembly at formation,
   b. evaporation, sublimation or boiling, especially
soon after Macro formation,
c. Macro - Macro collisions;
3) formation of binary Macros, with potential
gravitational-wave and electromagnetic signals;
4) DM self-interactions, especially in high-density envi-
ronments such as galactic cores;
5) enhanced thermal and dynamical coupling of dark-
matter to baryons and photons.

These primary processes could have important sec-
ondary consequences, including implications for early star
formation, assembly of supermassive black holes, and
21-cm emissions.\textsuperscript{14}

In this work, we focus our attention on the very first
of these: the effect on the CMB and CNB of macroscopic
objects that generically cool by volume emission of neu-
trinos and surface emission of photons. (BSM candidates
may have additional cooling mechanisms.)

By considering a specific example of a baryonic Macro – a neutron star (NS) – as a Macro, we demonstrate that
the weak coupling of neutrinos to baryons and the ineffi-
ciency of surface cooling by photons generically lead the
Macros to remain significantly hotter than the ambient
plasma through the epoch of recombination. Both en-
ergy and entropy are therefore injected into the plasma
in the form of photons and neutrinos well after the time
when thermal or statistical equilibrium can be restored.
The CMB and CNB spectra are thereby distorted.

In this first work, we characterize the distortion in
terms of the traditional $\mu$-type (photon-number excess)
and $y$-type (photon-energy excess) spectral distortions
(SD) of the CMB, and by $\Delta N_{\text{eff}}$, the increase in the
effective number of neutrino species. However, because the
temperature of the Macros can remain far above that
of the ambient plasma, and because the cooling is ongo-
ing through and after recombination, neither $\mu$ nor $y$
will fully capture the shape of the resulting distortion. This
will be considered in future work, as will the angular fluc-
tuations in the distortion, its correlation with other ob-
serverable, and other potential consequences of baryonic
Macro DM, as listed above.

The magnitude of SD caused by Macros is controlled
of course by their abundance, but also by their specific
internal physics. For NS material this includes: the
thickness and insulating properties of the non-degenerate
crust; the equation of state of the neutrino-emitting core,
in particular the presence/absence of a superconducting
phase and its detailed properties.

For a solar-mass NS, known or anticipated properties
result in $\mu$ and $y$-type distortions of the CMB that are
potentially above the threshold of detection by feasible
next-generation SD experiments, and $\Delta N_{\text{eff}}$ that are not.
These specific conclusions will change for other mi-
crophysical models of Macros, but may be instructive of
what to expect and why. To our knowledge, this is the
first study of the radiative cooling of DM and the CMB
spectral distortions it may cause.

The CMB has been measured\textsuperscript{15} to have a black
body (BB) spectrum with an average temperature of
$2.7255 \pm 0.0006\text{K}$. Some deviation from a BB is predicted
due to energy injection/absorption mechanisms\textsuperscript{16} –
\textsuperscript{21}, especially the damping of acoustic modes after they
have entered the horizon, a.k.a. Silk damping\textsuperscript{16} \textsuperscript{13} \textsuperscript{22} –
\textsuperscript{29}. At very high redshifts, $z \gg z_{\mu} \equiv 2 \times 10^6$, dis-

tortions would be wiped out by efficient photon number and
energy-changing interactions. For $5 \times 10^4 \lesssim z \lesssim 2 \times 10^6$, number-changing mechanisms are inefficient, and photon
injection results in a finite chemical potential in the Bose-
Einstein distribution of photons, a so-called $\mu$ distortion.
At lower redshifts, $z \lesssim 5 \times 10^5$, energy redistribution
by Compton scattering becomes inefficient, leading to $y$
-type distortions. The intermediate era, $z \approx 10^4 – 10^5$, is
also characterized by $i$-type distortions\textsuperscript{30}.

The only macroscopic objects of nuclear density known
to exist in nature are NS formed as endpoints of stellar
evolution. These appear to have masses below $2.2M_{\odot}$\textsuperscript{31}
\textsuperscript{32}, well below the total mass within the horizon at $z \approx
10^9$ (or even $10^{12}$, the epoch of quark confinement and
chiral symmetry breaking). We therefore use an ordinary
NS as a proxy for a Macro. We take the Macro’s central
density to be $\rho_{\text{X}} \approx \rho_{N} \approx 2.8 \times 10^{14} \text{g/cm}^3$, which we refer
as to nuclear density. Although microrelics limits preclude all the DM being NS, the Macro mass function
could include a sizable contribution from them.

Neutron stars theoretically are stable down to $(0.09 –
0.19)M_{\odot}$\textsuperscript{33} \textsuperscript{36}, but do not appear to arise as the end-
points of the evolution of main-sequence stars below
$\sim 1.2M_{\odot}$\textsuperscript{36}. If formed in the early universe, these would be
larger and of lower average density than post-stellar neu-
tron stars. This motivates us to consider NS-like Macros
of somewhat lower-than-nuclear density.

The discovery of a NS with $M_{NS} < 1.2M_{\odot}$\textsuperscript{36} would be
exciting evidence for early-universe Macro formation.

Smaller-still composite baryonic objects require
non-gravitational stabilization, whether within
the SM through the incorporation of strange
quarks/baryons\textsuperscript{3} \textsuperscript{5} \textsuperscript{6} or by more exotic BSM
mechanisms. Such SM or BSM baryonic composites may
also exist in the mass range that includes stable NS.

Except for the inner core, the composition of which is
still under debate, a NS is composed of neutrons, pro-
tons, electrons and heavy ions. After formation, it cools
down via neutrino emission from the interior and photon
emission from the surface.

Neutrino cooling occurs through three processes:
1) direct Urca (DUrca)

$$n \rightarrow p + e^- + \bar{\nu}_e, \ e^- + p \rightarrow n + \nu_e$$
takes place at high temperatures, when neutrons and
electrons are non-degenerate, but may also be important
below the degeneracy temperature;
2) modified Urca (MUrca) in the neutron and proton
branches

$$n + n \rightarrow n + p + e^- + \bar{\nu}_e, \ n + e^- + p \rightarrow n + n + \nu_e$$
$$n + p \rightarrow p + p + e^- + \bar{\nu}_e, \ p + e^- + p \rightarrow n + p + \nu_e$$
is dominant; at $T < 10^9 K$, when neutrons and electrons are degenerate;
3) nucleon Cooper pair (CP) cooling

$$\tilde{N} + \tilde{N} \to CP + \nu + \bar{\nu},$$

(where $\tilde{N}$ is a quasi-nucleon) is most efficient for $0.98 T_c \gtrsim T \gtrsim 0.2 T_c$, with neutrons in the NS interior become superconducting at $T_c$. [37]

The luminosity of these neutrino-cooling processes is

$$L_\nu^i = 10^{45} C_i \left( \frac{M_X}{M_\odot} \right) \left( \frac{\rho_X/\rho_N}{10^{9}} \right)^{-1/3} \text{erg/s} \quad (1)$$

for $i = DU, MU, CP$. $T$ dependence is encoded in

$$C_i = \begin{cases} 
5.2 \left( T_9^X \right)^6 R_D^i & i = DU \\
(3.0 R_m^N + 2.4 R_p^M) 10^{-6} \left( T_9^X \right)^{\alpha} & i = MU \\
7.1 \times 10^{-6} \left( \frac{\rho_X/\rho_N}{10^{9}} \right)^{-1/3} \left( T_9^X \right)^7 a F & i = CP
\end{cases}$$

$T^X$ is the Macro's internal temperature; the subscript 9 will be used for a temperature in units of $10^9 K$. $R_D^i, R_m^N$ and $R_p^M \leq 1$ are reduction factors due to superfluidity;

$$\alpha \approx 2 \left( 1 + m_e^2 / m_p^2 (n) \right)^{-2} - 0.3 \left( 1 + m_e^2 / m_p^2 (n) \right)^{-1} + 0.07$$

where $p_F (n) = 340 \left( \frac{\rho_X}{\rho_N} \right)^{1/3} \text{MeV/c}$ is the neutrons' Fermi momentum. The value of the dimensionless factor $a$ [38] and the temperature dependence of the control function $F$ [39] depend on the type of superfluidity.

The Macro photon luminosity is

$$L_\gamma = 10^{45} \left( \frac{M_X/\rho_X}{M_\odot/\rho_N} \right)^{2/3} \left( T_9^4 - T_9^{CMB4} \right) \text{erg/s} \quad (2)$$

where $T^*$ is the surface temperature of the Macro, and $T^{CMB}$ is the temperature of the ambient plasma.

We assume that the Macros have coalesced, and we can begin following their cooling from when the temperature of the ambient plasma is $10^9 K$, at $z = 3.7 \times 10^8$. (This is after any electroweak and QCD-associated phase transitions [13].) We take the Macro to be isothermal at that moment with temperature equal to that of the plasma. The interior electrons, neutrons and protons will be degenerate. The cooling of neutron stars below this temperature has been well explored, and we have verified that our conclusions are insensitive to the details of the Macro cooling before this epoch.

We assume that the Macro, like a NS, has a degenerate isothermal interior containing neutrons, protons and electrons, and a non-degenerate “atmosphere” of electrons and heavy ions. This acts as an insulating layer, keeping the interior warm as the ambient plasma cools. For a constant atmospheric photon luminosity $L_\gamma$, the atmospheric density and temperature are related by

$$\rho_{\text{atm}} = 1.2 \times 10^{10} \rho_N \left( \frac{\mu (M_X/\rho_X) \text{erg/s}}{Z (1 + W) L_\gamma} \right)^{1/2} T_9^{3.25} \quad (3)$$

where $\mu, Z$ and $W$ are the mean molecular weight, mass fraction of elements heavier than hydrogen and helium, and mass fraction of hydrogen.

Where the atmosphere meets the interior, the relation between density $\rho_*$ and temperature $T^*$ can be found ([10] Chapter 4) by equating the electron pressure of the degenerate interior and the non-degenerate atmosphere

$$\rho_* = 7.6 \times 10^9 \mu_e T_9^{3/2} \text{g/cm}^3 \quad (4)$$

where $\mu_e$ is the mean molecular weight per electron. Equating (4) and (1),

$$L_\gamma = 8.9 \times 10^{36} \left( \frac{M_X}{M_\odot} \right) T_9^{3.5} \text{erg/s} \quad (5)$$

where $\lambda = \left( \frac{\mu_e}{\mu} \right) \frac{2.0}{\lambda + 1}$ [40]. In the case of a NS, $\lambda \approx 1$ (see [40], Chapter 11). We take $\lambda$ to be a free parameter.

The Macro interior is nearly isothermal, due to the thermal conductivity of the degenerate electrons. Since $T^X \approx T^*$, equating the photon luminosity (2) at the surface to yields the Macro's surface temperature $T_9 (t)$.

Starting from its assumed initial isothermal condition at $10^9 K$, the Macro cools according to

$$\frac{dU_X}{dt} = -(L_\nu^\text{DU} + L_\nu^\text{MU} + L_\nu^\text{CP} + L_\gamma). \quad (6)$$

where the internal energy is ([10] Eq.(11.8.2))

$$U_X = 6.1 \times 10^{47} \left( \frac{M_X}{M_\odot} \right) \left( \frac{\rho_X/\rho_N}{10^{9}} \right)^{-2/3} T_9^{X-1} \sum C_i \quad (7)$$

The interior temperature of the Macro therefore obeys

$$\frac{dT_9}{dt} = -8.3 \times 10^{-4} s^{-1} \left( \frac{\rho_X/\rho_N}{10^{9}} \right)^{1/3} T_9^{X-1} \sum C_i \quad (8)$$

where the sum over $i$ now includes photons, and

$$C_\gamma = 8.9 \times 10^{-9} \left( \frac{\rho_X/\rho_N}{10^{9}} \right)^{1/3} \lambda \left( T_9^X \right)^{7/2}$$

Neutrino emission via MUrca occurs from the onset, since we take the initial temperature to be $10^9 K$. For simplicity, we consider only singlet-state neutron superfluidity of Type-A. The associated reduction factors $R_m^N$ and $R_p^M$ are given by Eq.(32) and (37) in [41] respectively.

Emission via CP begins below $T_c$. We select the control function $F$ to be $F_A$ given by Eq.(34) in [39]. The factor $a$ has the maximum value of 4.17 and 3.18 for triplet states of neutrons and protons respectively.

We explore two possibilities: first, no DUrca cooling $R^D = 0$; second, a proton fraction sufficient to support DUrca, with $R^D$ given by Eq.(31) in [37].

In practice, SDs are relatively insensitive to the exact values of these various numerical factors.

In the case where there is negligible DUrca emission, cooling proceeds in three stages:

Stage 1: MUrca-dominated cooling from $T_9^X = T_9^\text{MU} = 1$, at time $t_0$, to $T_9^\text{CP} = 0.98 T_{9}, t_c < t_0$; Stage 2: CP-dominated cooling from $T_9^\text{CP}$ to $T_9^\gamma < 0.2 T_{9}$ at $t_\gamma$;

Stage 3: photon cooling below $T_9^\gamma$, i.e. after $t_\gamma$.

(If $T_9^\text{CP}$ is high enough, the first stage may be omitted.) The Macro cooling can be followed numerically, but by
Recombination
eras when $\mu$ distortions occur are indicated.

assuming that the dominant cooling mechanism in each stage is the only one (and taking $R^M_n, R^M_p = 1$), we find

$$T^X_9(t) \simeq \begin{cases} 
T^\text{MU}_9 \left[1 + 2.7 \times 10^{-8} a T^\text{MU}_9^6 \left(\frac{\rho\text{X}}{\rho\text{N}}\right)^{1/3} \frac{t - t_9}{s}\right]^{-1/6} & 
\text{for } 1 \equiv T^\text{MU}_9 \geq T^X_9 \geq T^\text{CP}_9 \simeq 0.98 T_{9\gamma}, \\
T^\text{CP}_9 \left[1 + 1.8 \times 10^{-2} a F T^\text{CP}_9^5 \frac{t - t_9}{s}\right]^{-1/5} & 
\text{for } 0.98 T_{9\gamma} \simeq T^\text{CP}_9 \geq T^X_9 \geq T^Y_9 \simeq 0.2 T_{9\gamma}, \\
T^\gamma_9 \left[1 + 1.1 \times 10^{-11} \lambda T^\gamma_9^{3/2} \left(\frac{\rho\text{X}/\rho\text{N}}{\rho\text{N}}\right)^{2/3} \frac{t - t_9}{s}\right]^{-2/3} & 
\text{for } 0.2 T_{9\gamma} \simeq T^\gamma_9 \geq T^X_9.
\end{cases}$$

The above relations can also be expressed in terms of redshift, $z$, using the time-redshift relation $z = 4.9 \times 10^9 (t/s)^{-1/2}$. The times (and thus redshifts) at which the interior temperature $T_X$ falls to $T_9$ depend on detailed properties of the Macro, such as its central density $\rho_X$, and the composition parameter $\lambda$. In Figure 1 we plot the central and surface temperatures of the Macro, as well as the temperature of the ambient plasma as a function of time for a representative value of these parameters.

In the presence of DURca cooling, Stage 1 is DURca dominated until $T^X_9$ becomes $T^X_9 = 0.1 T_{9\gamma}$ at $t_\gamma$. In this case, during Stage 1 (now $T^X_9 = 1$)

$$T^X_9(t) = T^\text{DU}_9 \left[1 + 0.017 \left(T^\text{DU}_9\right)^{4} R^D \left(\frac{\rho\text{X}}{\rho\text{N}}\right)^{1/3} \frac{t - t_9}{s}\right]^{-1/4}.$$

The pre-recombination contributions to $\mu$ and $y$ distortions of the CMB can be approximated by

$$\begin{cases} 
\mu & = \int dt J_{\text{bb}} \left\{ \frac{1.4}{4} \frac{J_\mu}{J_\sigma} \right\} \frac{1}{c^2 \rho_\gamma} \dot{Q}, \\
y & = \int dt J_{\text{bb}} \left\{ \frac{1}{4} \frac{J_\mu}{J_\sigma} \right\} \frac{1}{c^2 \rho_\gamma} \dot{Q}.
\end{cases}$$

The window functions are

$$J_\mu(z) = 1 - J_\mu(z) \simeq \left[1 + 4.7 \times 10^{-13} z^2 2.58\right]^{-1},$$
$$J_{bb}(z) \approx \exp \left[-(z/\rho_\gamma)^{5/2}\right].$$

The CMB energy density $\rho_\gamma \approx 7.0 \times 10^{-34} z(t)^4$ g/cm$^3$, while the rate at which energy density is injected into the photon distribution by Macros of density $n_X$ is

$$\dot{Q} = n_X L_\gamma.$$
FIG. 2. Top panel: μ distortion as a function of Macro surface composition factor λ for three different cooling scenarios. On the left, no DUrca, no CP; in the middle no DUrca, with CP; on the right; with DUrca, with CP. Green lines denote ρX = ρN, red lines 0.1ρN; blue lines 10ρN. The panels with CP show results for Tc = 10^9K (dashed) and Tc = 4 x 10^9K (solid). Bottom panel: as for top panel but for y distortion.

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