On the possible dark-matter content of QSO’s and of compact, very massive entities in the nuclei of galaxies: a metastable particle with mass of about $10^{10}$ GeV

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Abstract

We examine some general astrophysical results which can be related to the hypothesis that very heavy, metastable particles constitute compact, very massive central entities in QSO’s and the core of galaxies. The mass and lifetime have been calculated in detail previously: the mass is about $10^{10}$ GeV; the lifetime is $\gtrsim 10^{21}$ sec. The specific decay gives rise to a new source of very large amounts of energy in radiation. The essence of the ideas discussed in this paper is that very massive, metastable dark matter constitutes entities near to black-hole conditions, and that it is decay which provides a large primary energy source from such entities, as components of QSO’s, AGN, and possibly GRB’s.

1 Introduction

The purpose of this paper is to consider the hypothesis that very heavy, metastable particles[1], which can make up the main part of cold dark matter[1], are present in, and give rise to the principle sources of energy in compact, very massive astrophysical entities. The latter are observed as quasi-stellar objects (QSO’s) and as possibly related entities in the core of galaxies. Such entities can be considered to contain the mass equivalent of about $10^{10}$ solar masses[7] within a domain characterized by a linear dimension of the order $10^{16}$ cm (~ a light week)[8]. We have a specific motivation for examining some interrelated results which can follow naturally from the hypothesis. The motivation is provided by the results of detailed calculations[1, 3] using the renormalization group equations in a (chiral-like) dynamical, cosmological

[1] In this paper, we use the units of high-energy particle physics. A solar mass made up of about $10^{57}$ nucleons is about $10^{57}$ GeV.
model, involving only a neutral scalar inflaton field $F_2$, a neutral pseudoscalar field, and a neutral lepton. Two new ideas emerge from the results.

(1) A large part of the dark matter in the present universe can be composed of inflatons, whose mass is calculated to be near to $10^{10}$ GeV. The oft-repeated statement that the inflaton mass must be $\gtrsim 10^{13}$ GeV is based upon the assumption that rapid inflaton decay produces the radiation composed of ordinary matter. There is no empirical basis for this assumption. In our model [1], the inflaton is decoupled from ordinary matter (but for gravitational effects). The radiation is produced by decay processes involving other primary particles produced by the release of vacuum energy. The small CMB anisotropy can be related to the very small parameter in the inflaton potential, $\sqrt{\lambda} \sim 10^{-7}$. (The smallness of $\lambda$ can have a natural dynamical origin [1].)

(2) The inflatons are not absolutely stable; they can decay in a specific way, with a lifetime calculated to be several orders of magnitude greater than the present age of the universe, $t_0 \sim 4 \times 10^{17}$ sec.

In the next sections, we consider some qualitative consequences of the ideas taken together with the above hypothesis.

## 2 Degrees of freedom

In the astrophysical context, we consider as degrees of freedom the large numbers which are typical for the number of nucleons in the universe, the number of nucleons in a star $F_1$, the number of stars in a galaxy, the number of galaxies, and the large dimensions which characterize certain relevant scales of structure: $\sim 10^{16}$ cm for compact, massive central entities (to $\sim 10^6$ for neutron stars), $\sim 10^{23}$ cm for galaxies, $\sim \sqrt{2} \times 10^{28}$ cm for the universe accessible to observation $F_3$. Further, we consider the energy density in cold dark matter, and that in nucleons, as fractions of the critical density $\rho_c \approx 4 \times 10^{-47}$ GeV$^4 \approx 0.5 \times 10^{-5}$ GeV/cm$^3$. $F_3$ There are interesting possible relationships between these quantities which follow from the hypothesis, and the quantitative results (1) and (2), stated in the introduction.

In the numerical estimates in this paper, we use for the mass of the inflaton one of the specific values calculated in our recent work $F_4$, $m \approx 5 \times 10^{10}$ GeV. $F_3$ Assume that one compact, massive object composed of about $10^{57}$ inflatons exists in the core of a typical galaxy $F_5$. The central object is thus a compact entity with the equivalent...
of about 10\(^{10}\) solar masses. This is a mass equivalent near to that of some QSO and galactic-core entities. Assume that the galactic mass of all of the stars plus the mass of gaseous matter not in stars, a total mass essentially constituted from nucleons of mass \(\sim 1\) GeV, is approximately the same as the mass of the central entity. The number of nucleons typically present in a star is \(\sim 10^{57}\). The number of nucleons in gaseous material is of the order of five times that in all stars \([4]\). Denote a typical number of stars in a galaxy by \(s\). Then \(s\) is determined from

\[
(5 \times 10^{10} \text{ GeV}) \times (10^{57}) \approx (1 \text{ GeV}) \times (5s) \times (10^{57}) \rightarrow s \approx 10^{10}
\]

Denote a typical number for all galaxies by \(g\). The total number of nucleons is about

\[
n_b \approx 10^{-10} \times (10^{88}) \approx 10^{78}
\]

where \(10^{88}\) is approximately the total number of photons, and \(\sim 10^{-10}\) is the small empirical number which characterizes the baryon asymmetry. The galaxy number is determined from

\[
10^{78} \approx g(5s) \times (10^{57}) \approx g(5 \times 10^{67}) \rightarrow g \approx 2 \times 10^{10}, \ g \times s \approx 2 \times 10^{20}
\]

(We are not considering a possible large number of ill-formed, irregular dark entities.) The energy density of baryonic matter is

\[
\rho_b \approx \frac{10^{78}(1 \text{ GeV})}{4\pi \left(\sqrt{2} \times 10^{28} \text{ cm}\right)^3} \approx 0.85 \times 10^{-7} \text{ GeV/ cm}^3 \approx 1.7\% \times \rho_c
\]

This is essentially the same number as that produced by the recent, empirically informed, universal baryon budget-keeping\([4]\).

We can estimate an energy density in dark-matter inflatons. Paralleling the situation for nucleons, assume that the number of inflatons in less compact configurations is about ten times that in the core-entity, i.e. \(\sim 10 \times 10^{57}\). With \(g = 2 \times 10^{10}\) from eq. (3)\(^{F6}\), the cold dark-matter energy density from inflatons is

\[
\rho_{\text{CDM}} \approx \frac{(5 \times 10^{10} \text{ GeV}) \times (10^{58}) \times (2 \times 10^{10})}{4\pi \left(\sqrt{2} \times 10^{28} \text{ cm}\right)^3} \approx 0.85 \times 10^{-6} \text{ GeV/ cm}^3
\]

\[
\approx 17\% \times \rho_c
\]

This is about ten times the energy density of baryons; it remains however, a small fraction of the critical density\([4]\). We also estimate the dark-matter energy density on the scale of a single galaxy, using a galactic dimension of \(\sim 10^{23}\) cm.

\[
\rho_{\text{CDM}}^{\text{galaxy}} \approx \frac{(5 \times 10^{10} \text{ GeV}) \times (10^{58})}{4\pi \left(10^{23} \text{ cm}\right)^3} \approx 0.125 \text{ GeV/ cm}^3
\]

very high-energy neutrinos from inflaton decay, as discussed in section 3. An accretion region of decay neutrinos is possible; conversion to electrons would imply radiation from ejected, as well as infalling, charged matter.

\(^{F6}\)We do not believe in the, often repeated, popular mythology that inflation in the early universe necessarily implies that a critical density must be observed today. In particular, insistence upon trying to make results practically independent of initial conditions, appears to be a prejudice. (It does not acquire credibility in an empirical science through use of jargon, like “generic”.)
This is sufficient to meet the rotation-curve anomaly. Note that increasing $m$ by about 3 increases a typical star-number per galaxy to $s \sim 3 \times 10^{10}$ and increases $\rho_{\text{CDM}}^\text{galaxy}$ to $\sim 0.38 \text{ GeV/ cm}^3$. Thus, $m$ should lie within a relatively small interval around $10^{10} \text{ GeV}$.

Years ago, in his textbook, Hoyle noted a numerical relationship, with the remark: “Here is something odd to think about”. Hoyle observed that the ratio of the total number of nucleons to the dimension characteristic of the universe is nearly the same large number as the ratio of the number of neutrons to the dimension characteristic of a compact neutron star, $\sim 10^6$. That is, we have

$$\frac{10^{78}}{(\sqrt{2} \times 10^{28}) \text{ cm}} = 0.7 \times 10^{50} \text{ cm}^{-1} \sim \frac{10^{57}}{10^6 \text{ cm}} = 10^{51} \text{ cm}^{-1}$$

(7)

Although neutron stars could exist with appreciably less than $10^{57}$ neutrons, this near equality “specifies the magic $10^{57}$” [5]. Since the mass of the nucleon is $\sim 1 \text{ GeV}$, this relationship is equivalent to a kind of “column energy” (denote this by $\epsilon$) characterized by a quantity of the order of $\epsilon_b \sim 10^{51} \text{ GeV/ cm} \approx (2 \times 10^{37}) \text{ GeV}^2$. This quantity is almost the square of the Planck mass, $M^2_P \approx 1.5 \times 10^{38} \text{ GeV}^2$. The near-equality can be viewed as relating a particle-physics scale ($\sim 1 \text{ GeV}$) to a cosmological scale. Now consider such a quantity for the inflaton dark matter. On the dimension scale of the universe, with $\sim (10 \times 10^{57}) = 10^{58}$ inflatons in the core entity and gas of approximately each of $\sim 2 \times 10^{10}$ galaxies, we have for the inflaton

$$\epsilon_i \approx \frac{(5 \times 10^{10} \text{ GeV}) \times (10^{58}) \times (2 \times 10^{10})}{(\sqrt{2} \times 10^{28}) \text{ cm}} = 7 \times 10^{50} \text{ GeV/ cm}$$

(8)

Consider that a single compact, massive dark-matter central object is characterized by a dimension of the order of light-week, $\sim 2 \times 10^{16} \text{ cm}$. Then, on the scale of this dimension for a QSO or for a galactic-core entity, we have

$$\epsilon^\text{core}_i \approx \frac{(5 \times 10^{10} \text{ GeV}) \times (10^{57})}{(2 \times 10^{16}) \text{ cm}} = 2.5 \times 10^{51} \text{ GeV/ cm}$$

(9)

So $\epsilon^\text{core}_i \approx \epsilon_i \approx M^2_P$, or turning the argument around, requiring the near-equality specifies the dimension of about a light-week. This is just above the Schwarzschild radius. With consideration given to the numbers resulting from eqs. (1,3,5,6,8,9), we conclude this section by remarking that the repeated presence of the number $\sim 10^{10}$ among basic astrophysical quantities - the approximate star number per galaxy, the approximate galaxy number, and the possible (maximal) solar mass equivalent in QSO’s and galactic-core entities - points to the possible effects of a metastable particle with mass near to $10^{10} \text{ GeV}$, i.e. about $10^{10}$ times the nucleon mass. Aggregates of this particle have primarily gravitational interactions.

### 3 Energy considerations

The first observation concerning energy is simply the correct order of magnitude of the very large gravitational potential energy associated with the compact, massive

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F7 There is a repulsion between inflaton quanta originating in the very small self-coupling [1]. The internal energy might be sufficient to balance gravity only beyond galactic dimension.
dark-matter core. The (classical) order of magnitude of the self-energy is

\[
- V_{\text{gravity}}^{\text{inflaton}} \sim \frac{3}{5} \left( \frac{5 \times 10^{10} \text{ GeV} \times 10^{57}}{10^{19} \text{ GeV}} \right)^2 \approx 3 \times 10^{67} \text{ GeV} \approx 4.8 \times 10^{64} \text{ ergs} \quad (10)
\]

This is somewhat greater than an empirical energy equivalent in emission from a very strong radio source. Such entities would have a tendency to form at an earlier stage than usual structure formation. (This could be about 10^6 sec.) They could give a kind of impulse for later galaxy formation\[4].

Here we are concerned with a completely new source of a comparably large quantity of energy in radiation, which results from the specific decay of the inflaton, with a very long lifetime. The inflaton decays only into a neutrino-antineutrino pair, with a lifetime which we have estimated to be of the order of 10^{21} sec \sim (2.5 \times 10^3) t_0, or greater\[5]. (This occurs because of the very small mixing of the massive neutral lepton, to which the inflaton couples, with the heaviest of the known neutrinos.) The decay neutrino and antineutrino have energy of the order of 10^{10} GeV. In a gas of these neutrinos, interactions occur which give rise to lepton-antilepton pairs and quark-antiquark pairs. In addition, if there is an existing gas of electrons and nucleons in or nearby the system, then the pressure of the very high-energy neutrinos can accelerate these electrons. Prior to decays, the total energy in inflaton mass associated with the compact, central entity is \sim (5 \times 10^{10} \text{ GeV}) \times (10^{57}) \sim 8 \times 10^{64} \text{ ergs}. If one considers less dense configurations, of about (10 \times 10^{57}) inflatons (as in eqs. (5,6)) from a dimension of the order of 10^{17} cm (beyond the central entity with dimension of \sim 10^{16} cm), then the number density is

\[
n_i \sim \frac{10^{58}}{4\pi (10^{17} \text{ cm})^3} \approx 2.5 \times 10^6 / \text{ cm}^3 \quad (11)
\]

This number is not unusual; it is a particle density characteristic of ordinary matter in some gaseous layer away from the center of a QSO. A small fraction of the inflatons have decayed, of the order of \((t_0/\tau) \approx 0.4 \times 10^{-3}\). (In the following numerical estimates we use a little smaller fraction, \sim 1/5 \times 10^{-3}.\[6\]) The energy in neutrinos is then about 10^{62} \text{ ergs}, with a pair number-density of \sim 3 \times 10^2 / \text{ cm}^3. These very high-energy neutrino-antineutrino pairs will interact and produce very energetic charged leptons and antileptons, via \(\nu + \bar{\nu} \rightarrow \ell^-, \ell^+\). (Also, quark-antiquark pairs.) If we assume relevant cross sections of roughly \(\sigma_\nu \sim 10^{-32} \text{ cm}^2\), then a mean-free path of \sim \frac{1}{3} \times 10^{30} \text{ cm} results in a fraction \sim 1.5 \times 10^{-13} \text{ of the number of neutrino pairs converting to } \ell\bar{\ell} \text{ (and } W\bar{W}, ZZ) \text{ over an interaction-path length of } \sim 10^{17} \text{ cm}. The energy in promptly-produced\[7] \(e^-, e^+\) (via \(Z\)'s, \(W\)'s), is then \(\sim 10^{-13})(10^{62} \text{ ergs}) \approx 10^{49} \text{ ergs}. Distributing this over a galactic dimension gives an energy density contained in the very high-energy \(e^−\) and \(e^+\) of the order of

\[
\rho_{e^+e^-} \sim \frac{10^{49} \text{ ergs}}{4\pi (10^{23} \text{ cm})^3} \approx (0.25 \times 10^{-6})(10^{-14} \text{ ergs} / \text{ cm}^3) \quad (12)
\]

This estimate is interesting for the following reason. The number \(10^{-14} \text{ ergs}/ \text{ cm}^3\) is similar to a (total) energy density characteristic of our galactic cosmic-ray particles.

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\[\text{Footnotes:}\]

1. The numerator is generally a time less than \(t_0\). This reflects the subtraction from \(t_0\) of the “look-back” time to the entity.

2. Electrons are also produced in (time dilated) decays following \(\tau^- \tau^+\) production.
(\sim 10^{-12} \text{ ergs/cm}^3), \text{times the approximate 1\% of this in electrons. The number of order } 10^{-6} \text{ is roughly indicative of the fraction in electrons with energies a few times } 10^{10} \text{ GeV. This number is at most the small fraction } \sim (10^6/10^{11}) = 10^{-5} \text{ which arises from the empirical[7], approximate effective (1/E^2) fall-off of the cosmic-ray particle flux between } \sim 10^6 \text{ GeV and } \sim 10^{11} \text{ GeV.}

Similar numbers to those above, hold for the transfer of energy from very high-energy neutrinos to electrons via scattering (and to nucleons, via deep-inelastic scattering), if there is a nearby gas of electrons and nucleons with number density at least as large as that of the neutrinos from inflaton decay. The important physical difference is of course that, whereas neutrino annihilation produces positrons as well as electrons, and quark-antiquark pairs, the neutrino “pressure” accelerates “fuel” (and does not transfer all of the neutrino energy). If some of these particles can “escape” the influence of the inner core, then very energetic electrons and nucleons, as well as the neutrinos themselves from inflaton decay[8], can occur throughout the galaxy. (There would also be \gamma-rays from quark fragmentation.)

For the purpose of orientation, we give estimates for the flux of these very high-energy neutrinos, and electrons, upon the earth’s atmosphere, assuming no large losses within the galaxy. An approximate flux formula gives[9]

\[ I_{\nu,\tau} \simeq \frac{\rho_{\text{CDM}}}{4\pi m} \frac{L}{\tau} \simeq 2 \times 10^{-13} \left( \frac{\text{cm}^2}{\text{sec} \cdot \text{sterad}} \right)^{-1} \]  \hspace{1cm} (13)

We have used \[ \rho_{\text{CDM}} \simeq 0.125 \text{ GeV/cm}^3 \] from eq. (6), \[ L \simeq 10^{23} \text{ cm}, \] and for \[ m \sim 5 \times 10^{10} \text{ GeV} \] \[ \tau \simeq 10^{24} \text{ sec}. \] Neutrinos (\(\nu_\tau\)) with energies of about \(10^{10} \text{ GeV}\) can have a cross section in air greater than \(10^{-33} \text{ cm}^2\). With an interaction probability in the atmosphere[12] of about \(10^{-7}\), the effective flux becomes of the order of \(10^{-20} \left( \text{cm}^2 \cdot \text{sec} \cdot \text{sterad} \right)^{-1}\). It is worth noting that cosmic-ray experiments have recently reached exposures[13] of \(2.6 \times 10^{20} \left( \text{cm}^2 \cdot \text{sec} \cdot \text{sterad} \right)^{-1}\), and will eventually go much further. There are a few unusual events near to \(10^{11} \text{ GeV}\)\[8, 9\].

Quasars may have a maximum occurrence near to red-shift \(z \sim 2\). Their decline at later times may be related to a diminution of atmospheric “fuel” \[8, 9\]. However, their decline at very early times may be related to the decreasing amount of energetic neutrinos (and of conversion electrons\[5\]) from inflaton decay.

4 Summary

In one of the concluding paragraphs of his book[10], Hoyle made the comment: “There could be a connection here with the outbursts of radio galaxies and QSO’s... I have had for some years the lurking suspicion that the cascades of highly energetic particles responsible for our observations might be generated by the decays of some superparticle.” The considerations in this paper suggest that this may be part of

\[ \text{F10For } \tau \gg t_0, \text{ and } E_{\nu_\tau} \lesssim \frac{m}{\tau}. \text{ A similar estimate is made in ref. 8, using possible distant, diffuse sources. Then } L \simeq 10^{28} \text{ cm}; \text{ this is nearly compensated by a decrease in the diffuse } \rho_{\text{CDM}} \text{ by about } 10^{-5} \text{[10]. There is a small diminution in neutrino energy here, due to red-shift } z < 1. \text{ Diminished inflaton decay at very early times tends to reduce contributions (at lower energies here) from very large } z. \]

\[ \text{F11If the mass of } \nu_\tau \text{ is only } \sim 0.05 \text{ eV (instead of } \sim 1.8 \text{ eV as used in [1]), then the lifetime is lengthened by } \sim 10^{3}, \text{ and the flux in eq. (13) is reduced to } \sim 2 \times 10^{-16} \left( \text{cm} \cdot \text{sec} \cdot \text{sterad} \right)^{-1}. \text{ However, some compensation could occur from a possible neutrino interaction probability in air as large as } \sim 10^{-5}. \]
the truth. The other more traditional part, the very large energy source from gravitational attraction is here also closely linked to the hypothetical massive particle.

Definite observational tests of these ideas are possible. In particular, through determination of the amount of cold dark matter that is actually present, and through the detection of very high-energy neutrinos. There is accumulating evidence for the presence of massive dark objects in the centers of galaxies. This is also relevant for the very high-energy cosmic rays, because if neutrinos from decay of massive dark matter are emanating from these objects, then scattering in a dilute atmosphere can produce energetic protons and gamma-rays. These could constitute a very energetic component of hadron-like cosmic rays, from sources in the sky which are not very distant.

It is possible that a gamma-ray burst is powered by a very compact source ($\sim 10^8$ cm) of the very high-energy neutrinos from inflaton decays. An energy of about $10^{52}$ ergs in relativistic motion would be produced by a source containing the equivalent of about $10^2$ solar masses (only about $10^{49}$ inflatons). The process $\nu + \overline{\nu} \rightarrow \ell^- + \ell^+$ could result in a comparable energy being ejected in highly relativistic, charged particles. It is noteworthy that both the two-body decay to $\nu \overline{\nu}$, and the above two-body reaction, can produce highly correlated (through coherence) streams of energy in opposite directions, in effect a coherent entity moving outward from the source. Interactions of the electrons with an existing, moderate atmosphere of ordinary matter (say, of the order of $10^{13}$ particles/cm$^3$), over a dimension considerably greater ($> 10^{10}$ cm) than that of the very compact source, could produce the initial gamma-ray burst within a short time interval $O$(secs). Subsequent interactions would produce lower-energy photons in regions approaching the boundary with space, over longer time intervals. The “visibility” (i.e. via gamma-rays and photons) of the burst, and the later emission, ceases if the atmosphere is effectively dispersed by the high-energy collisions. However, the “dark” primary source is still producing very high-energy neutrinos. There are clumps of dark matter which are not associated with luminous centers or halos. Relative to the QSO’s as discussed in this paper, the source mass is less by a factor of about $10^{-8}$ and the source dimension is also less by $\sim 10^{-8}$, being again just above the Schwarzschild radius relevant to this mass. The hypothetical decay of very massive dark matter provides a specific connection between the energy sources of gamma-ray bursts and of QSO’s; this can produce a frequency for the former of $\gtrsim 10^{-6}$ per galaxy per year, and also some possible anisotropy in the bursts at cosmological distances. The anisotropy would be mainly evident in the GRB’s which are nearer to us; this should be correlated with these bursts being at higher energy, on the average. This is natural consequence of the greater accretion of the decay neutrinos around older systems, and of their more effective conversion into the relativistic electrons which are essential for bringing about a GRB.

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Our estimates for the inflaton mass suggest a restricted range, from $\sim 10 \times \rho_b$ to $\sim \frac{1}{3} \times \rho_c$. For the converse reason, an exception could be a lower-energy GRB which is correlated with an unusually massive supernova event.
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