Infrasonic, acoustic and seismic waves produced by the Axion Quark Nuggets

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Abstract

We advocate an idea that the Axion Quark Nuggets (AQN) hitting the Earth can be detected by analysing the infrasound, acoustic and seismic waves which always accompany the AQN’s passage in the atmosphere and underground. Our estimates for the infrasonic frequency $\nu \simeq 5$ Hz and overpressure $\delta p \sim 0.3$ Pa for relatively large size dark matter (DM) nuggets suggest that sensitivity of presently available instruments is already sufficient to detect very intense (but very rare) events today with existing technology. A study of much more frequent but less intense events requires a new type of instruments. We propose a detection strategy for a systematic study to search for such relatively weak and frequent events by using Distributed Acoustic Sensing and briefly mention other possible detection methods.

Keywords: Axion, Dark Matter.

1. Introduction and Motivation

The main goal of the present work is to present a new possible detection methods of the axion quark nuggets (AQN) when they are propagating in the Earth’s atmosphere and underground. The AQN dark matter model \cite{1} was invented long ago with a motivation to explain the observed similarity between the dark matter and the visible densities in the Universe, i.e. $\Omega_{\text{DM}} \sim \Omega_{\text{visible}}$. The idea that dark matter may take the form of composite objects of standard-model quarks in a novel phase goes back to quark nuggets \cite{2}, strangelets \cite{3}, and nuclearities \cite{4}, see also the review \cite{5} with references to the original results. In the models \cite{2,3,4,5}, the presence of strange quark stabilizes the quark matter at sufficiently high densities allowing strangelets formed in

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the early universe to remain stable over cosmological timescales. This type of DM is “cosmologically dark” not because of the weakness of the AQN interactions, but due to their small cross-section-to-mass ratio, which scales down many observable consequences of an otherwise strongly-interacting DM candidate. We review the basics ideas, predictions and consequences of this model in Sec. 2 and mention the crucial ingredients here.

There are several additional elements in the AQN model in comparison with the older well-known and well-studied constructions [2, 3, 4, 5]. First, there is an additional stabilization factor for the nuggets provided by the axion domain walls which are copiously produced during the quantum chromodynamic (QCD) transition, which help to alleviate a number of problems with the original [2, 3, 4, 5] nugget model. Another feature of AQN which plays a crucial role in the present work is that nuggets can be made of matter as well as antimatter during the QCD transition. The direct consequence of this feature, given that the total baryon charge of the Universe is zero, is that DM density, $\Omega_{\text{DM}}$, and the baryonic matter density, $\Omega_{\text{visible}}$, will automatically assume the same order of magnitude $\Omega_{\text{DM}} \sim \Omega_{\text{visible}}$ without any fine tuning.

One should emphasize that AQNs are absolutely stable configurations on cosmological scales. The antimatter which is hidden in the form of the dense nuggets is unavailable for annihilation unless the AQNs hit stars or planets. There are also rare events of annihilation in the center of the galaxy, which, in fact, may explain some observed galactic excess emissions in different frequency bands, see Sec. 2. The AQNs composed of antimatter are capable of releasing a significant amount of energy when they enter the atmosphere and annihilation processes occur between antimatter in the AQNs and atmospheric material.

How can this enormous amount of energy manifest itself? What would be the best option (optimal path) to detect the corresponding effects due to the AQN-annihilation processes? The problem is that the weakly interacting particles (such as the axions and neutrinos) are hard to detect due to their weak interactions, while relatively strongly interacting photons and leptons have short mean free path such that it is hard to recover the origin of these particles.

Indeed, the corresponding emission of photons in dilute environments such as the galactic center and at the locations of high-altitude Earth orbits can be studied and properly analyzed because the mean free path in such dilute environments is long. The corresponding results are discussed in Sec. 2. This should be contrasted with the case of dense environments where the annihilation events occur in the Earth atmosphere when the energy is released in the form of the weakly coupled axions, neutrinos as well as $x$ and $\gamma$ rays and small number of low-energy electrons and positrons. It is hard to observe axions and neutrinos due to their feeble interactions, though the correspond-

\footnote{In particular, a first-order phase transition is not a required feature for nugget formation as the axion domain wall (with internal QCD substructure) plays the role of the squeezer. Another problem with [2, 3, 4, 5] is that nuggets likely evaporate on the Hubble time-scale. For the AQN model, this is not the case because the vacuum-ground-state energies inside (the color-superconducting phase) and outside the nugget (the hadronic phase) are drastically different. Therefore, these two systems can coexist only in the presence of an external pressure, provided by the axion domain wall. This should be contrasted with the original model [2, 3, 4, 5], which must provide stability at zero external pressure.}
ing computations have been carried out recently, see Sec. 2. At the same time, the x and γ rays emitted by AQNs are absorbed over short distances ∼ 10 m or so in the atmosphere, and therefore cannot be easily recovered for analysis due to the background radiation.

We propose in this work that the AQN-induced signal can be studied by analysing the acoustic waves which may propagate over large distances due to long absorption lengths for such waves. Furthermore, we shall argue that the corresponding signal can be discriminated from background noise. Therefore, in this work we describe a new detection strategy of the AQN based on their acoustic and seismic manifestations.

The presentation is organized as follows. In Sec. 2 we review the AQN model in the context of the present work, paying special attention to the size distribution, frequency of appearance, and the energy-emission pattern. In Sec. 3 we present our estimates for the AQNs propagating in the atmosphere and underground. The main lesson of this analysis is that the presently available instruments are capable to detect the signal produced by the large-size and intense AQNs which occur only once every 10 years or so. However, the presently available technical tools are not sufficiently sensitive to study typical and relatively small AQNs. Therefore, in Sec. 4 we present a proposal for a systematic study of acoustic and seismic events originating from AQNs with relatively small typical size which occur approximately once a day. We propose to employ Distributed Acoustic Sensing which uses optical-fiber cables. In Appendix A as a side note we describe the observed mysterious event which occurred on July 31st 2008 and was properly recorded by the dedicated Elginfield Infrasound Array (ELFO) [6], near London, Ontario, Canada. The infrasound detection was accompanied by non-observation of any meteors by an all-sky camera network. The signal was correlated with seismic signals in the area. It is tempting to identify the mysterious event recorded by ELFO with a very intense (and very rare) AQN annihilation event which has precisely the required features as described in Sec. 3.

2. AQN model: the basics

The main goal of this section is to review the basic ideas of the AQN model, its motivation, consequences, and (as of yet) indirect, rather than direct, supporting observations.

The original motivation for the model can be explained as follows. It is commonly assumed that the Universe began in a symmetric state with zero global baryonic charge and later (through some baryon-number-violating process, nonequilibrium dynamics, and CP-violation effects, realizing the three famous Sakharov criteria) evolved into a state with a net positive baryon number.

As an alternative to this scenario we advocate a model in which “baryogenesis” is actually a charge-separation (rather than charge-generation) process in which the global baryon number of the universe remains zero at all times. In this model, the unobserved antibaryons come to comprise the dark matter in the form of dense nuggets

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Footnote: The low-energy free electrons strongly interact with atmospheric material while the low energy positrons will be quickly annihilated such that it is hard to trace the origin of these particles emitted by AQNs.
of antiquarks and gluons in the color superconducting (CS) phase. The result of this “charge-separation process” is two populations of AQN carrying positive and negative baryon number. In other words, the AQN may be formed of either matter or antimatter. However, due to the global CP violating processes associated with the so-called initial misalignment angle \( \theta_0 \), which was present during the early formation stage, the number of nuggets and antinuggets will be different. This difference is always an order-of-one effect irrespective of the parameters of the theory, the axion mass \( m_a \) or the initial misalignment angle \( \theta_0 \). We refer to the original papers \[20, 21, 22, 23\] devoted to the specific questions related to the nugget formation, generation of the baryon asymmetry, and the survival pattern of the nuggets during the evolution in early Universe with its unfriendly environment.

It is known that the galactic spectrum contains several excesses of diffuse emission, the origin of which is not well established and remains to be debated. The best-known example is the strong galactic 511 keV line. If the nuggets have a baryon number in the \( \langle B \rangle \sim 10^{25} \) range they could offer a potential explanation for several of these diffuse components. It is a nontrivial consistency check that the \( \langle B \rangle \) required to explain these excesses of the galactic diffuse emission belongs to the same mass range as discussed below. For further details, see the original works \[24, 25, 26, 27, 28, 29\] with explicit computations of the galactic-radiation excesses for various frequencies, including the excesses of the diffuse x and \( \gamma \) rays. In all these cases, photon emission originates from the outer layer of the nuggets known as the electrosphere, and all intensities in different frequency bands are expressed in terms of a single parameter \( \langle B \rangle \) such that all relative intensities are unambiguously fixed because they are determined by the Standard-Model (SM) physics.

The AQNs may also offer a resolution to the so-called “Primordial Lithium Puzzle” \[30\] and the “Solar Corona Mystery” where the corona heating is explained by the AQN annihilation events as argued in \[31, 32\]. Furthermore, the corresponding annihilation events are accompanied by the emission in radiofrequency bands which might already have been observed as advocated in \[33\]. Furthermore, the same model with the same set of parameters may resolve \[34\] the longstanding puzzle with the DAMA/LIBRA observation of the annual modulation at a 9.5\( \sigma \) confidence level, which is in direct conflict with other DM experiments if interpreted in terms of the WIMP interaction with nuclei. Finally, the annihilation events when an AQN traverses the Earth atmosphere under the thunderstorm (where strong electric fields are present) may mimic the ultrahigh-energy cosmic rays. The recent unusual events recorded by Telescope Array Experiment might be precisely those types of events as argued in \[35\].

The key parameter which essentially determines all the intensities for the effects mentioned above is the average baryon charge \( \langle B \rangle \) of the AQNs. There are a number of constraints on this parameter which are reviewed below. One should also mention that

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\[1\] The \( \theta_0 \neq 0 \) is the source of strong CP violation in QCD. It represents a fundamental coupling constant of the theory, which at the present epoch is experimentally observed to be very small, \( \theta_0 \lesssim 10^{-10} \). Explaining this smallness represents the celebrated strong CP problem. The most compelling resolution of the strong CP problem is formulated in terms of the dynamical axion, such that an arbitrary \( \theta_0 \neq 0 \) (at the QCD epoch during the evolution of the Universe) relaxes to zero at present time, see the original axion papers \[7, 8, 9\], and recent reviews \[10, 11, 12, 13, 14, 15, 16, 17, 18, 19\].
the AQN mass is related to its baryon charge by \( M_N \simeq m_p |B| \), where we ignore small differences between the energy per baryon charge in CS and hadronic confined phases. The AQNs are macroscopically large objects with a typical size of \( R \simeq 10^{-5}\text{cm} \) and roughly nuclear density of \( 10^{40}\text{cm}^{-3} \) resulting in masses of roughly 10 g.

An event where an AQN impinges on the Earth should be contrasted with conventional meteors. A conventional object with mass 10 g would have a typical size of order 1 cm occupying the volume which would be 15 orders of magnitude larger than the AQN volume. This is due to the fact that AQNs have nuclear density which is 15 orders of magnitude higher than the density of normal matter. One can view an AQN as a small neutron star (NS) with its nuclear density. The difference is that a NS is squeezed by gravity, while an AQN is squeezed by the axion-domain-wall pressure. The drastic density difference between AQNs and conventional small meteors leads to fundamentally different interaction patterns when they enter the Earth atmosphere.

We now turn to the observational constraints on such kind of dense objects. The strongest direct-detection limit is set by the IceCube Observatory, see Appendix A in [36]:

\[
\langle B \rangle > 3 \cdot 10^{24} \text{ [direct (non)detection constraint].} \tag{1}
\]

The authors of [37] used the Apollo data to constrain the abundance of quark nuggets in the range of 10 kg to one ton. They argued that the contribution of such heavy nuggets must be at least an order of magnitude less than would saturate the dark matter in the solar neighbourhood [37]. Assuming that the AQNs do saturate the dark matter, the constraint [37] can be reinterpreted as at least 90% of the AQNs having masses below 10 kg. This constraint can be expressed in terms of the baryon charge:

\[
\langle B \rangle \lesssim 10^{28} \text{ [Apollo constraint].} \tag{2}
\]

Therefore, indirect observational constraints (1) and (2) suggest that if the AQNs exist and saturate the dark matter density today, the dominant portion of them must reside in the window:

\[
3 \cdot 10^{24} \lesssim \langle B \rangle \lesssim 10^{28} \text{ [constraints from observations].} \tag{3}
\]

We emphasize that the AQN model with the limits (3) is consistent with all presently available cosmological, astrophysical, satellite and ground-based constraints. This model is rigid and predictive since there is little flexibility or freedom to modify any estimates mentioned above. In particular, the AQN flux (5) which plays a key role in the present studies cannot change by more than a factor of two, depending on the size distribution within the window (3).

It is important that the frequency of appearance of AQNs depends on the size distribution \( f(B) \) defined as follows: Let \( dN/dB \) be the number of AQNs which carry the baryon charge \([B, B + dB]\). The mean value of the baryon charge \( \langle B \rangle \) is given by

\[
\langle B \rangle = \int_{B_{\text{min}}}^{B_{\text{max}}} dB \ B f(B), \quad f(B) \propto B^{-\alpha}, \tag{4}
\]

where \( f(B) \) is a properly normalized distribution and \( \alpha \simeq (2 - 2.5) \) is the power-law index. One should emphasize that the parametrization (4) was suggested in solar
physics studies to fit the observed extreme UV radiation from the entire solar surface. We adopted this scaling in \[31, 32\], where it was proposed that the so-called nanoflares (conjectured by Parker many years ago to resolve the “Solar Corona Mystery”) can be identified with AQN-annihilation events in the solar corona. The main motivation for this identification is that the observed intensity of the extreme UV emission from the solar corona matches the total energy released as a result of the AQN-annihilation events in the transition region assuming the conventional value for the dark matter density around the Sun, \( \rho_{DM} \simeq 0.3 \, \text{GeV} \, \text{cm}^{-3} \). One should emphasize that this “numerical coincidence” is a highly nontrivial self-consistency check of the proposal \[31, 32\] connecting nanoflares with AQNs, since the nanoflare properties are constrained by solar corona-heating models, while the intensity of the extreme UV due to the AQN annihilation events is mostly determined by the dark matter density \[^4\]. One should note that the algebraic scaling (4) is a generic feature of the AQN-formation mechanism based on percolation theory \[23\], but \( \alpha \) cannot be theoretically computed in strongly coupled QCD.

We now estimate the rate at which AQNs hit the Earth assuming the local dark matter density of \( \rho_{DM} \simeq 0.3 \, \text{GeV} \, \text{cm}^{-3} \). Assuming the conventional halo model one arrives at \[36\]:

\[
\langle \dot{N} \rangle \simeq \frac{4 \cdot 10^{-2}}{\text{km}^2 \, \text{yr}} \left( \frac{\rho_{DM}}{0.3 \, \text{GeV} \, \text{cm}^{-3}} \right) \left( \frac{\langle v_{\text{AQN}} \rangle}{220 \, \text{km} \, \text{s}^{-1}} \right) \left( \frac{10^{25}}{\langle B \rangle} \right),
\]

\[
\langle \dot{N} \rangle \simeq 0.67 \, \text{s}^{-1} \left( \frac{10^{25}}{\langle B \rangle} \right) \simeq 2.1 \cdot 10^7 \, \text{yr}^{-1} \left( \frac{10^{25}}{\langle B \rangle} \right).
\]

(5)

Averaging over all types of AQN trajectories with different masses \( M_N \simeq m_p |B| \), different incident angles, different initial velocities and size distributions does not significantly modify this estimate. The result (5) suggests that the AQNs hit the Earth surface with a frequency approximately once a day per 100 \( \times \) 100 km\(^2\) area. This rate is suppressed for large AQNs according to the distribution function (4).

It is instructive to compare the rate (5) with the number of meteoroids which enter the Earth atmosphere. This rate is of order \( 10^8 \, \text{day}^{-1} \), see review \[38\]. It is more informative to represent this rate in terms of the total mass of the falling meteoroids, which is \( 10^5 \) tons/year and is much greater than the total mass of order \( 5 \cdot 10^2 \) tons/year associated with the dark matter AQN rate (5). The size distribution for meteoroids peaks at \( 2 \cdot 10^{-2} \) cm while the mass distribution peaks at around 10 \( \mu \)g, see \[38\]. This should be contrasted with a typical AQN size of \( R \simeq 10^{-5} \) cm and mass of roughly 10 g.

The final topic to be reviewed here is the spectral properties of the AQN emission. The most important feature of the AQN spectrum which distinguishes it from meteor emission is that the AQN spectrum is peaked in the (10-50) keV range, while

\[^4\]Furthermore, the required energy interval for the nanoflares must be in the range: \( E_{\text{nano}} \simeq (10^{21} - 10^{26}) \) erg. This allowed interval largely overlaps with the AQN baryonic charge window \( (3 \cdot 10^{-5} \, \text{erg}) \cdot B \) if the identification between nanoflares and AQN annihilation events is made. In this case, \( E_{\text{nano}} \simeq 2m_p c^2 B \simeq (3 \cdot 10^{-5} \, \text{erg}) \cdot B \), see \[31, 32\] for details.
the optically visible bands at $\sim (1-10) \text{eV}$ are strongly suppressed, see Fig. B.4 in Appendix B. Another crucial difference with meteor emission is that the AQN spectrum is not thermal black body radiation as it originates from the annihilation events. It should be contrasted with the black body radiation of conventional meteors and meteorites entering the Earth atmosphere with supersonic velocities and experiencing friction with the surrounding material resulting in heating of the meteoroids and surrounding material. We refer to Appendix B discussing the spectral features of the AQNs traversing the atmosphere, see in particular Fig. B.4.

These features in the spectrum imply that the AQNs cannot be observed by conventional optical monitoring as AQNs are not accompanied by significant emission of the visible light and cannot be routinely observed by all-sky cameras. Therefore, the observation of a signal by infrasound instruments and non-observation by the optical synchronized cameras (which must continuously monitor the sky by recording the conventional meteors) would unambiguously identify the AQNs entering the atmosphere. This synchronization eliminates or dramatically reduces all possible spurious events from sky.

3. Acoustic signals from meteoroids and AQNs

3.1. Blast wave from meteoroids

We start by reviewing a model designed to study meteor-generated infrasound [39] (originally this model was introduced to describe a blast wave from a lightning discharge, so it has a general character). There were many recent advances in this framework including the comparison with observational data [40, 41]. Our goal here is to use this framework to estimate the intensity and frequency characteristics of the infrasound signal generated by AQNs propagating in the atmosphere. Our estimates cannot literally follow [39, 40, 41] as the nature of the released energy in the case of AQN is drastically different from the energy sources associated with conventional meteors in the Earth atmosphere. However, we think that the generic scaling features describing the sound waves at large distances hold in both cases. Furthermore, the Mach number $M = \frac{v}{c_s} \gg 1$ (here $v$ is the speed of the meteor and $c_s$ is the speed of sound) is very large for meteors as well as for AQNs such that cylindrical symmetry is assumed to hold for propagating sound and infrasound waves in both cases.

The basic parameter of the approach [39, 40, 41] is the so-called characteristic blast-wave relaxation radius defined as

$$R_0 \equiv \sqrt{\frac{E_l}{p_0}},$$

where $E_l$ is the energy deposited by the meteor per unit trail length, and $p_0$ is the hydrostatic atmospheric pressure. The physical meaning of this parameter $R_0$ is the distance at which the overpressure approximately equals the hydrostatic atmospheric pressure. In the case of a bomb-like explosion, the relevant parameter can be defined as

$$R_1 \equiv 3\sqrt{\frac{E_{\text{point source}}}{p_0}},$$
where $E_{\text{point source}}$ is the energy deposited to the air as a result of explosion. The parameter $R_1$ has the same physical meaning as $R_0$ and it determines the distance at which the overpressure approximately equals to the hydrostatic atmospheric pressure.

In simple cases for meteors, the parameter $R_0$ can be directly expressed in terms of the Mach number $M$ and the meteor diameter $d_m$ as $R_0 \sim M d_m$, see \[39, 40, 41\].

The significance of the parameter $R_0$ is that the overpressure $\delta p$ at larger distances can be expressed in terms of dimensionless parameter $x$ defined as follows \[39, 40, 41\]:

$$\frac{\delta p}{p_0} = \frac{2(\gamma + 1)}{\gamma} f(x), \quad x \equiv \frac{r}{R_0}, \quad f(x \gg 1) \simeq \frac{1}{x^{3/4}},$$

(8)

where $\gamma = c_p/c_v$. Note that the overpressure $\delta p$ decays faster than $r^{-1/2}$ as it would be for a cylindrical sound wave with a given frequency. This is due to increase of the width $l$ of the blast wave packet as follows: $l \sim R_0 x^{1/4}$. Correspondingly, the fundamental sound frequency $\nu$ decreases as $\nu \sim c_s/l \sim (c_s/R_0)x^{-1/4}$, where $c_s$ is the speed of sound.

The scaling (8) is justified when overpressure is relatively small. In case of conventional meteors, all parameters such as $R_0$ can be modelled and compared with observations \[40, 41\]. We do not have such luxury in the AQN studies. However, some theoretical estimates can be made, which is the topic of this section.

### 3.2. AQN in the atmosphere

We start with estimation of the parameter $E_l$ entering (6). In the AQN framework, the energy of annihilation events occurring per unit length while the nugget traverses the atmosphere is:

$$E_l \simeq \kappa \cdot (\pi R^2) \cdot (2 \text{ GeV}) \cdot n_{\text{air}}$$

(9)

$$\simeq 10^4 \cdot \kappa \left( \frac{B}{10^{25}} \right)^{2/3} \left( \frac{n_{\text{air}}}{10^{21} \text{ cm}^{-3}} \right) J/m,$$

where $n_{\text{air}}$ is the total number of nucleons in atoms such that $\rho = n_{\text{air}} m_p$. The parameter $\kappa$ as explained in Appendix B is introduced to account for the fact that not all matter striking the nugget will annihilate and not all of the energy released by an annihilation will be thermalized in the nuggets (for example, some portion of the energy will be released in the form of the axions and neutrinos), see the discussion after Eq. (B.3).

As such $\kappa$ encodes a large number of complex processes including the probability that not all atoms and molecules may be able to penetrate into the color superconducting phase of the nugget to get annihilated. It also includes complicated dynamics due to the very large Mach number $M = v_{\text{AQN}}/c_s \gg 10^2$ when shock waves are formed and the turbulence has developed. Both phenomena lead to efficient energy exchange between the nugget and surrounding material. Assuming a 10 km as a typical length scale where emission occurs one can estimate the total released energy in atmosphere on the level $10^8 J$, which of course represents a tiny portion $\sim 10^{-7}$ of the total energy hidden in the AQN. For simplicity we keep $\kappa \simeq 1$ in our order of magnitude estimates which follow.
Directly using the estimate (9), one arrives at the following approximate expression for the parameter $R_0$:

$$R_0^{\text{AQN}} \equiv \sqrt{\frac{E_l}{\rho_0}} \sim 0.3 \left( \frac{B}{10^{25}} \right)^\frac{1}{2} \left( \frac{n_{\text{air}}}{10^{21} \text{ cm}^{-3}} \right)^\frac{1}{2} \text{ m},$$

(10)

which has a physical meaning of a distance where overpressure due to the AQN annihilation events equals the hydrostatic atmospheric pressure.

Several comments are in order regarding this estimate. In the case of conventional or nuclear explosion the blast occurs as a result of the interaction of the radiation with surrounding material which rapidly heats the material. This causes vaporization of the material resulting in its rapid expansion, which eventually contributes to formation of the shock-wave. All these effects occurring in conventional explosions at very small scales, much smaller than a typical radius where over-pressure approximately equals to atmospheric pressure. In case of cylindrical symmetry the relevant parameter is determined by $R_0$ in Eq. (6). In case of a point-like explosion the corresponding distance $R_1$ is determined by (7) which plays the role of $R_0$ for point-like explosion.

Now we estimate the distances where the radiation is effectively converted to the shock-wave energy. In case of conventional or nuclear explosion the dominant portion of the radiation comes in the $20 \text{ eV}$ energy range and above. At this energy, the dominant process is the atomic photoelectric effect with cross section $\sigma_{\text{p.e.}} \sim 10^7 \text{ barn}$ and higher such that the photon attenuation length $\lambda \sim 10^{-6} \text{ g/cm}^2$, see e.g. Fig. 33.15 and Fig. 33.16 in [42] and references therein. In case of meteoroids the emission normally occurs in $(1 - 20) \text{ eV}$ energy range, which also includes the visible light emission. These spectrum features in air imply that the energy due to the heating will be completely absorbed on the scales which are much shorter than $R_0$ defined by (6), i.e.

$$\frac{\lambda}{\rho_{\text{air}}} \lesssim 10^{-3} \text{ cm} \ll R_0 \quad \text{[meteoroids]},$$

(11)

This should be contrasted with the AQN case with a drastically different radiation spectrum with typical energy in the $\sim 40 \text{ keV}$ range as reviewed in Appendix B. In this case the atomic photoelectric effect which is still the dominant process and the photon attenuation length is $\lambda \sim 0.5 \text{ g/cm}^2$ such that

$$L = \frac{\lambda}{\rho_{\text{air}}} \sim 5 \text{ m} \gg R_0^{\text{AQN}} \quad \text{[AQN events]},$$

(12)

These estimates suggest that only a small portion of the energy (9) will be released in the form of a blast, while the rest of the energy will simply heat the surrounding material. The attenuation length is even longer for higher-energy photons which saturate the total intensity for $T_{\text{AQN}} \simeq 40 \text{ keV}$, see Appendix B.

We can do an estimate of overpressure in this case as follows. The annihilation energy $E_l z$ released on the track of the length $z$ is absorbed in the volume of the cylinder $V = \pi L^2 z$. The internal energy of a diatomic ideal gas (air) is given by $U = (5/2)PV$. This gives an estimate of overpressure inside this volume $V$:

$$\delta p_0 \approx \frac{E_l}{2.5\pi L^2} \quad \text{[AQN events]},$$

(13)
As explained above, outside this volume, $\delta p$ decreases as $f(\bar{x}) \approx \bar{x}^{-3/4}$, where we introduced the dimensionless parameter $\bar{x} = r/L$, which plays the same role as $x$ in meteoroids formula (8):

$$\delta p(r) \approx \frac{\delta p_0}{\bar{x}^{3/4}} \approx \frac{E_l}{2.5\pi L^2} \left(\frac{1}{\bar{x}}\right)^{3/4} \quad [\text{AQN events}].$$  \tag{14}

To illustrate the significance of the estimate (14), we present an order of magnitude numerical estimate for the overpressure at a distance $r$, with the annihilation energy given by Eq. (9) and absorption of this energy within the radius $L = 5$ m as estimated by (12):

$$\delta p \approx 0.03 \text{Pa} \left(\frac{B}{10^{25}}\right)^{2/3} \left(\frac{100 \text{ km}}{r}\right)^{3/4} \quad [\text{AQN events}].$$  \tag{15}

This estimate shows that a typical AQN generates very small overpressure $\delta p/p \sim 10^{-3}$ even inside the absorption region $r \lesssim L$, which should be contrasted with the meteoroid case where $\delta p/p \approx 1$ at $r \approx R_0$. The difference is due to the large length $L \simeq 5$ m in comparison with the small absorption distance $\sim 10^{-3}$ cm for the meteoroids. The temperature increase in surrounding region $\delta T/T \sim \delta p/p \sim 10^{-3} \ll 1$ is too small to produce visible thermal radiation around the AQN path.

Another important characteristic of the acoustic waves produced by meteoroids is the scaling behaviour of the so-called line-source wave period $\tau(x)$ at large distances. The scaling behaviour can be expressed in terms of the same dimensionless parameter $x$ introduced above, and it is given by [39, 40, 41]:

$$\tau(x) \simeq 0.562 \tau_0 x^{1/4}, \quad \tau_0 = 2.81 \frac{R_0}{c_s} \quad [\text{meteoroids}],$$  \tag{16}

where $\tau_0$ is the so-called fundamental period where numerical factors 2.81 and 0.562 in Eq. (16) have been fitted from the observations [41]. Equation (16) determines the frequency of the sound (infrasound) wave at a distant point $x$:

$$\nu(x) \equiv \tau^{-1}(x) \sim \tau_0^{-1} x^{-1/4}, \quad x \gg 1 \quad [\text{meteoroids}].$$  \tag{17}

The same scaling behaviour is expected to hold for the AQN case. However, the parameters for AQNs are different:

$$\tau_0 \sim \frac{L}{c_s}, \quad \tau(\bar{x}) \sim \tau_0 \bar{x}^{1/4}, \quad \nu_0 \equiv \frac{1}{\tau_0} \sim 70 \text{ Hz},$$  \tag{18}

where we ignore all numerical factors which in the case of meteoroids were fixed by matching with observations, and obviously cannot be applied to our present studies.

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5 This temperature should not be confused with the much higher internal AQN temperature $T_{\text{AQN}} \sim 10$ keV.
of the AQNs. In this case we arrive at the following estimate for the frequency at a distance \( r \):

\[
\nu(\bar{x}) \sim \frac{\nu_0}{x^{1/4}} \sim 6 \text{Hz} \left( \frac{100 \text{ km}}{r} \right)^{1/4} \text{[AQN events]}. \tag{19}
\]

Thus, at a large distance from the AQN track in the air there will be emission of the infrasound waves of low frequency. We will see below that for the signal from an underground AQN track, the overpressure and the frequency are both several orders of magnitude higher.

### 3.3. AQN propagating underground

One should emphasize that the infrasound waves originating from AQNs as estimated in Sec. 3.2 will be always accompanied by sound waves emitted by the same AQNs when the nuggets hit the Earth surface and continue to propagate in the deep underground. The corresponding estimates of intensity and frequency of the sound emitted as a result of the annihilation events occurring underground are presented in this subsection.

The starting point is similar to (9) which for underground rocks assumes the form:

\[
E_{\downarrow} \approx \kappa \cdot (\pi R^2) \cdot (2 \text{ GeV}) \cdot n_{\text{rock}} \tag{20}
\]

where we use the notation \( E_{\downarrow} \) for the energy produced by annihilation (some of which may remain in the AQN) to avoid confusion with the similar equation (9) applied to the atmosphere, \( n_{\text{rock}} \) is the total number of nucleons in atoms such that \( \rho = n_{\text{rock}} m_0 \).

We introduce an unknown parameter \( \xi_{\downarrow} \) which applies to the underground case (at sufficiently high density of the surrounding material) to account for the complicated physics which describes the transfer of the AQN energy into the surrounding material energy denoted as \( E_{\downarrow}^{\text{blast}} \):

\[
E_{\downarrow}^{\text{blast}} = 10^7 \cdot \xi_{\downarrow} \left( \frac{B}{10^{25}} \right)^{2/3} \left( \frac{n_{\text{rock}}}{10^{24} \text{ cm}^{-3}} \right) \frac{J}{m}. \tag{21}
\]

There are several important new elements in comparison with the atmospheric case discussed in Sec. 3.2. First of all, the increase of the density of the surrounding material naively drastically increases the released annihilation energy as Eq. (20) suggests assuming that the coefficient \( \kappa \) remains the same as in the atmospheric case, Eq. (9). However, it is expected that this assumption is strongly violated.\(^6\) If one re-

\(^6\)The main reason for that is due to increase of the internal temperature \( T_{\text{AQN}} \) which consequently leads to strong ionization of the positrons from electrosphere. As a result of this ionization the positron density of the electrosphere (which is responsible for the emissivity) drastically decreases. It suppress the emissivity from the electrosphere as Eq. (B.1) states. It should be contrasted with the BB radiation where emissivity scales as \( \sim T^4 \). In our case, the source of emission are the positrons from electrosphere, not BB radiation.
moves the low-energy positrons from the electrosphere, the suppression factor could be $\xi_↓ \sim 10^{-2}$ and even much smaller.

The second important effect which was ignored in the atmosphere in Sec. 3.2 is that $\delta p$ could be much larger underground in comparison with the estimate of Eq. (15). It results in pushing material from the AQN path which effectively decreases the geometrical cross section $\pi R^2$ assumed in (20). This effect further suppresses the parameter $\xi_↓$ entering (21).

We cannot at the moment compute $\xi_↓$ from first principles as mentioned in footnotes 6 and 7. Therefore, we keep it as a phenomenological unknown parameter which strongly depends on the environment, temperature $T_{AQN}$ and many complex processes as mentioned above.

Another important parameter is the absorption length $L_↓(T_{AQN})$ for the energy emitted by AQN in underground (hence the $↓$ label), which also indirectly depends on the AQN internal temperature $T_{AQN}$. This is because the length $L_↓$ strongly depends on the energy of the photons emitted by the AQNs, which is determined by the internal temperature $T_{AQN}$. For the photon energy $\sim 100$ keV, an absorption length in silicon is about $L_↓ \approx 2$ cm. However, it is an order of magnitude larger for 1 MeV photons. We account for this uncertainty by introducing another unknown dimensionless parameter $\eta$ defined as follows: $L_↓(T_{AQN}) = (2\text{ cm}) \cdot \eta$. In terms of these unknown parameters the deposited energy per unit volume $\epsilon_\text{blast}$ surrounding the AQN can be estimated as follows:

$$\epsilon_\text{blast} \simeq 10^2 \frac{J}{\text{cm}^3} \cdot \left(\frac{\xi_↓}{10^{-2}}\right) \cdot \left(\frac{1}{\eta^2}\right),$$

which leads to an instantaneous increase of temperature $\Delta T$ of the surrounding material:

$$\Delta T \simeq 30 \text{ K} \cdot \left(\frac{\xi_↓}{10^{-2}}\right) \cdot \left(\frac{1}{\eta^2}\right).$$

We now in position to estimate the overpressure for the blast wave in two different approximations. First, we may estimate the overpressure as deposited energy per unit volume. This yields

$$\delta p \simeq 10^7 \text{ Pa} \cdot \left(\frac{\xi_↓}{10^{-2}}\right) \cdot \left(\frac{1}{\eta^2}\right) \text{ at } r \simeq L_↓.$$  

(23)

Another approximation is based on an increase of pressure due to the thermal expansion of solids. Relative thermal expansion of silicon is $\delta x/x = 2.6 \cdot 10^{-6}/\text{K}$, the Young

---

7Such simplified procedure for the estimate of $\xi_↓$ by complete removing the low energy states is not a proper way of computation because the positron’s density will be adjusting when $T_{AQN}$ varies. The consistent procedure would be a mean-field computation of the positron density by imposing the proper boundary conditions relevant for nonzero temperature and non-zero charge, similar to $T_{AQN} \approx 0$ computations carried out in [23][29]. The corresponding computations have not been done yet, and we keep the parameter $\xi_↓(T_{AQN})$ as a phenomenological free parameter.
Our next task is to estimate the amplitude of the wave at large distance \( r \). Using the conventional scaling arguments when \( \delta p(r) \sim 1/(\bar{x}^4)^{3/4} \) with dimensionless parameter \( \bar{x}^4 \) defined as \( \bar{x}^4 = r/L^4 \) we arrive to the following estimate for overpressure at a distance \( r \):

\[
\delta p(r) \sim 10^2 \cdot \left( \frac{\xi^4}{10^{-2}} \right) \cdot \left( \frac{1}{\eta} \right)^{\frac{3}{4}} \cdot \left( \frac{100 \text{ km}}{r} \right)^{\frac{3}{4}} \text{ Pa.} \tag{24}
\]

Following the same logic as for Eq. (19) we obtain a numerical estimate for the frequency of sound emitted by an AQN propagating underground:

\[
\nu_0 \sim \frac{L^4}{c_s}, \quad \tau(\bar{x}^4) \sim \tau_0 \cdot \sqrt{\bar{x}^4}, \quad \nu_0 \equiv \frac{1}{\tau_0} \simeq 170 \left( \frac{1}{\eta} \right) \text{ kHz,}
\]

where we use \( c_s \approx 3 \text{ km/s} \) for speed of sound in rocks. For large distances \( r \) our estimate for the frequency becomes

\[
\nu(\bar{x}^4) \sim \frac{\nu_0}{\sqrt{\bar{x}^4}} \sim 3.5 \left( \frac{1}{\eta} \right)^{\frac{3}{4}} \cdot \left( \frac{100 \text{ km}}{r} \right)^{\frac{1}{4}} \text{ kHz,} \tag{25}
\]

which is almost three orders of magnitude higher than the frequency of the infrasound emitted by AQNs in atmosphere (19).

In the estimate (24) above we assumed that the absorption can be neglected. We now estimate the corresponding attenuation effects to support our assumption. To proceed with estimates we note that the sound absorption length scales as \( \propto \nu^{-2} \). A proper estimation of the absorption effects must include the integration over distance where sound wave propagates since the frequency depends on the distance according to (25) as \( \nu \propto r^{-1/4} \) and the absorption length \( l \propto \nu^{-2} \propto r^{1/2} \). As a result, formula (24) will receive an additional exponential factor which describes the suppression of the sound intensity (intensity \( \propto \delta p^2 \)) due to the absorption of the sound wave:

\[
\exp(-X), \quad \text{where} \quad X \approx 2 \left( \frac{L^4 + r^4}{l_0 \eta^2} \right)^{\frac{1}{4}}, \tag{26}
\]

where \( l_0 \) is the absorption length for the initial frequency \( \nu_0 \). For a numerical estimate of the blast wave absorption we may use detailed data on the sound absorption in sea water [43]. The absorption length for sound with \( \nu_0 \simeq 170 \text{ kHz} \) is \( l_0 \simeq 0.1 \text{ km} \), and we arrive at an estimate for \( X \simeq \eta^{-3/2} \) for \( r = 100 \text{ km} \). Since \( \eta \) is probably larger than 1, this gives us an indication that a significant part of the blast wave may reach a detector on the distance up to 100 km.

The absorption of the blast wave is even smaller in water where the sound frequency is expected to be significantly smaller. For the photon energy \( \sim 100 \text{ keV} \) the absorption
length in water is 4.15 cm, so we assume \( L = 4.15 \eta \) cm. The speed of sound in water is \( c_s = 1.5 \text{ km/s} \), so we have our estimate for frequency in water \( \nu_0 \simeq 36 \text{ KHz} \) and

\[
\nu(\bar{x}^{\perp}) \sim \frac{\nu_0}{\sqrt{\bar{x}^{\perp}}} \sim \left( \frac{1}{\eta} \right)^{\frac{3}{4}} \left( \frac{100 \text{ km}}{r} \right)^{\frac{1}{4}} \text{kHz}. \tag{27}
\]

The sound absorption length in water is \( l_0 \simeq 0.45 \text{ km} \) and \( X \simeq 0.2 \eta^{-3/2} \) for \( r = 100 \text{ km} \). Thus, the absorption of the blast wave in water is insignificant.

We conclude this section with the following comment. In case of conventional meteoroids all numerical factors entering the scaling relations such as (8) and (16) have been fitted to match with numerous observations. Therefore, we introduce into our AQN estimates empirical parameters \( \xi^{\perp} \) and \( \eta \) which are very hard to compute from the first principles, but could be fixed by observations. Further studies are needed to collect more statistics of mysterious events when sound signatures are recorded without any traces in the synchronized optical monitoring systems.

- We conclude this section with few important comments. Our prediction for the overpressure (15) for a typical AQN event with \( B \simeq 10^{25} \) at the infrasound frequency (19) suggests that the existing instruments such as ELFO are not sufficiently sensitive to detect such small signals on the level of \( \delta p \simeq 0.03 \text{ Pa} \). Nevertheless, some strong and rare events still can be recorded with existing technology. In particular, it is tempting to identify a single mysterious event recorded by ELFO [6] as the AQN event with very large baryon charge \( B \simeq 10^{27} \), see Appendix A with detail arguments. Here we just highlight this reasoning.

The radius of the nugget goes as \( R \sim B^{1/3} \) which effectively leads to an increase in the number of annihilation events for larger nuggets, which eventually releases higher energy output per unit length as Eq. (9) states. Therefore, the intensity of the event scales correspondingly. The recorded by ELFO a powerful explosion with overpressure on the level \( \delta p \simeq 0.3 \text{ Pa} \) is consistent with the AQN annihilation event with large \( B \simeq 10^{27} \). Such intense events are relatively rare ones according to (4) and (5) as the frequency of appearance is proportional to \( f(B) \sim B^{-\alpha} \) with \( \alpha \simeq (2 - 2.5) \). It might be a part of an explanation of why this area has observed a single event in 10 years rather than observing similar events much more often.

It is obvious that we need much more statistics for systematic studies of relatively small but frequent typical events with \( B \simeq 10^{25} \). In the next section we present a possible design of an instrument which could be sufficiently sensitive to infrasound and seismic signals to fulfill this goal. If our proposal turns out to be successful, one can routinely record a large number of such events which manifest themselves in the form of the infrasonic and seismic signals, while the optical synchronized cameras may not see any light from these events. Infrasonic signals must be always accompanied by sound and seismic waves as discussed above, and which can be routinely recorded by conventional seismic stations. These events should demonstrate the daily and annual modulations as the source for these events is the dark matter galactic wind.

4. Detection strategy and possible instruments

As we mentioned in previous section, the sensitivity of the instruments similar to ELFO is not sufficient to record relatively small events in the atmosphere which occur
approximately once a day in an area of \((100 \text{ km})^2\) with \(\delta p \simeq 0.01 \text{ Pa}\) and frequency \(\nu \simeq 5 \text{ Hz}\). In this section we suggest several possible designs of instruments which we think are capable of fulfilling this role as sufficiently sensitive devices to detect the dark matter signals from small and common AQNs with \(B \sim 10^{25}\).

We start the overview with a promising recent development, Distributed Acoustic Sensing (DAS), which is becoming a conventional tool for seismic and other applications, see, for example, \([44, 45, 46, 47]\) and references therein. The basic idea of these activities can be explained as follows. It has been known for quite sometime that distributed optical fiber sensors are capable of measuring the signals at thousands of points simultaneously using an unmodified optical fiber as the sensing element. The recent development is that the DAS is capable of measuring strain changes at all points along the optical fiber at \textit{acoustic frequencies}, which is crucial for our studies of the acoustic waves emitted due to the AQN passage.

The main element of the DAS technology is that a pulse of light is sent into optical fiber and, through scattering in the glass, a small amount of the incident light is scattered back towards the sensing unit. The key point is that the DAS is capable of determining from this scattered light, a component which indicates changes in the local axial strain along the fibre. It has been shown that this technology is capable of detecting signals at frequencies as low as 8 mHz and as high as 49.5 kHz with sensitivity at the level of \(\delta p \sim 0.1 \text{ mBar} \approx 10 \text{ Pa}\) [44] which is more than sufficient for our purposes for \(\delta p\) as estimated in (24) and typical frequencies in kHz band as estimated in (25). Furthermore, it has been shown that using an amplifier chain one can extend the range of DAS unit to 82 km, while maintaining high signal quality [44]. Such a long range on the scale of 100 km matches well with what is needed for AQN-passage detection. Indeed, we anticipate approximately one event per day per an area of \((100 \text{ km})^2\) according to (5) reviewed in Section 2. An important point is that such studies can in principle detect not only the intensity and the frequency of the sound wave, but also the direction of the source. We note that networks of optical-fiber telecommunication cables cover a significant part of the Earth’s surface.

We anticipate that the main problem with DAS will be separation of the AQN signal from the seismic noise and numerous spurious events. We discuss one of the possibilities to separate the signal from a much larger noise below. The main point is that the AQN signal must show the annual (28) and daily (29) modulations characteristic of the dark matter galactic wind, in contrast with much more numerous and much more intense random events. One of possibilities to separate the signal from a much larger noise was suggested in [48].

The basic idea of [48] can be explained as follows. The AQN flux is given by (5) if averaged over very long period of time, longer than a year. However, due to the relative motion and orientation of the Sun, Earth and the galaxy, the AQN flux, as that of any other dark matter particle, receives the time-dependent factor \(A_{(a)}(t)\) representing the annual modulation which is defined as follows:

\[
A_{(a)}(t) \equiv [1 + \kappa_{(a)} \cos \Omega_a (t - t_0)], \quad (28)
\]

where \(\Omega_a = 2\pi \text{ yr}^{-1} \approx 2\pi \cdot 32 \text{ nHz}\) is the angular frequency of the annual modulation and label ‘\(a\)’ in \(\Omega_a\) stands for annual. The \(\Omega_a t_0\) is the phase shift corresponding to
the maximum on June 1 and minimum on December 1 for the standard galactic DM
distribution, see \[49, 50\]. Similar daily modulations are also known to occur \[51\] and
can be represented as follows:

\[
A_{(d)}(t) \equiv [1 + \kappa_{(d)} \cos(\Omega_{d}t - \phi_{0})],
\]

(29)

where \(\Omega_{d} = 2\pi \text{ day}^{-1} \approx 2\pi \cdot 11.6 \mu\text{Hz}\) is the angular frequency of the daily modula-
tion, while \(\phi_{0}\) is the phase shift similar to \(\Omega_{a}t_0\) in (28). It can be assumed to be constant
on the scale of days. However, it actually slowly changes with time due to the variation
of the direction of DM wind with respect to the Earth. The modulation coefficients \(\kappa_{(a)}\)
and \(\kappa_{(d)}\) have been computed in the AQN model in \[51\], see also application of these
results to analysis of the seasonal variation observed by XMM-Newton collaboration
in X-ray bands \[52\].

The idea advocated in \[48\] is to fit the data to the modulation formulae (28) and
(29) even if the noise is large and exceeds the expected signal. The key point here is the
statistics factor and accumulation of the signal for a long period of time assuming that
the noise can be treated as being random in contrast with signal being characterized by
well defined frequencies \(\Omega_{a}\) and \(\Omega_{d}\). A hope is to discover the annual (28) and daily
(29) modulations by recording a large number of AQN events which represent the dark
matter galactic wind in this specific model.

A specific signal from AQN tracks is very different from the ordinary seismic noise
and Earthquakes. Therefore, AQN signals may, in principle, be detected by an existing
network of seismic stations. In addition to optical-fiber based methods, it may be
possible to search for the AQN-passage signatures also in the large volumes of existing
historical data from networks of seismometers \[53\].

We would like to briefly mention other possibilities for the AQN detection, see
also relevant references in Section 2 leading to the constraints (3). The AQN produce
only a small amount of visible light as we already mentioned. However, the emitted
x-rays will be absorbed and heat the atmosphere along the track on scales of order
\(L\) as Eq. (12) suggests. It may produce vapor tracks along the AQN path. Therefore,
one may try to observe infrared radiation from AQN tracks using infrared telescopes
being synchronized with infrasonic detectors and all-sky cameras. Similarly, the AQN
tracks also produce microwave and radio wave radiation which may be detected by
radio telescopes which can be also synchronized with infrasonic and all sky cameras.

Furthermore, while an AQN itself is only \(R \approx 10^{-5}\) cm in size, nevertheless, it
may leave larger and noticeable cracks along its path in solids as instantaneous defect
creation and temperature increase occur on a cm scale according to (22). The cracks
could be sufficiently large to be observed. A search for AQN annihilation tracks could
also be performed in old rocks and Antarctic ice.

Finally, one more possibility to study the long ranged signals which could be pro-
duced by the AQN traversing the Earth atmosphere is to search for signals similar to the
ones which are normally attributed to the ultra high energy cosmic rays. One should
consider specifically the area under the thunderstorm condition\[9\] which could generate

\[9\text{ such condition occur on average for } 1\% \text{ of the time. The estimation is based on compilation of the annual thunderstorm duration from 450 air weather system in USA, see } 35 \text{ for references.} \]
enormous enhancement factor in the intensity of the signal as argued in [35]. In fact, the recent unusual events recorded by Telescope Array Experiment might be precisely those types of events, see [35] for the details.

5. Conclusion

The main results of the present work can be summarized as follows:

1. We argue that an AQN propagating in the Earth atmosphere generates infrasonic waves. We estimated the intensity (15) and spectral features (19) of these waves for a typical AQN event with $B \approx 10^{25}$;
2. We also performed similar estimates for an AQN propagating inside the Earth;
3. We propose a detection strategy to search for a signal generated by a typical relatively small AQN event with $B \approx 10^{25}$ by using Distributed Acoustic Sensing as existing instruments are not sufficiently sensitive to detect such signals;
4. Specific signals from AQN passage may also be detected with a variety of alternative techniques, for instance, with an existing network of seismic stations (or even by analyzing the already existing data) or by analyzing specific correlations under the thunderstorm conditions which may mimic the Ultrahigh Energy Cosmic Ray events, as mentioned at the end of Sec. 4;
5. We further speculate that the mysterious explosion which occurred on July 31st 2008 and which was properly recorded by the dedicated Elginfield Infrasound Array [6] might be a good candidate for an AQN-annihilation event with very large $B \approx 10^{27}$ as our basic estimates for the overpressure (A.1) and the frequency (A.2) are amazingly close to the signal recorded by ELFO.

One should emphasize that our estimates are based on the parameters of the AQN model which were fixed long ago for completely different reasons, namely, to explain various different phenomena occurring in drastically different environments, as reviewed in Sec. 2.

Why should one take this (AQN) model seriously? A simple answer is as follows. Originally, this model was invented to explain the observed relation $\Omega_{\text{DM}} \sim \Omega_{\text{visible}}$ where the “baryogenesis” framework is replaced with a “charge-separation” paradigm, as reviewed in the Introduction and in Sec. 2. This model is shown to be consistent with all available cosmological, astrophysical, satellite and ground-based constraints, where AQNs could leave a detectable electromagnetic signature as discussed in the Introduction and Sec. 2, with one and the same set of parameters. Furthermore, it has been also shown that the AQNs could be formed and could survive the unfriendly environment of the early Universe. Therefore, the AQNs deserve to be considered a viable DM candidate. Finally, the same AQN framework may also explain a number of other (naively unrelated) observed phenomena as mentioned in Sec. 2.

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Appendix A. Theory confronts observations

As we mentioned in the main text of the paper our prediction for the overpressure \( \delta p \) for a typical AQN event with \( B \approx 10^{25} \) at the infrasound frequency \( \nu_{\text{inf}} \) suggests that the predicted signal is too weak to detect by existing instruments such as ELFO. We also mentioned that some strong and intense events may still occur and can be recorded with existing technology. However, the frequency of appearance for such intense events should be very low.

In particular, it is tempting to identify a single mysterious event recorded by ELFO \( \text{[6]} \) as the AQN event with very large baryon charge \( B \approx 10^{27} \).

The goal of this Appendix is to present the arguments suggesting that the mysterious explosion which occurred on July 31st 2008 and which was properly recorded by dedicated Elginfield Infrasound Array \( \text{[6]} \) is consistent with the AQN annihilation events. Localization of the source position, Elginfield Infrasound Array (ELFO) and seismic stations are shown on Fig.A.1 adopted from \( \text{[6]} \).

The sounds, as reported by residents of Kincardine, Ontario, Canada were apparently loud enough to rattle windows and objects on walls. An important point here is that the infrasound detection associated with this sound shock was recorded by ELFO as presented in Fig.A.2 with a typical overpressure \( \delta p \approx 0.3 \) Pa. These observations (along with non-observations in the all-sky camera network) ruled out a meteor source, as well as operations at the Bruce Nuclear Power Plant, while Goderich salt mine logs eliminated it as a source \( \text{[6]} \). Furthermore, a local airport radar reported no aircraft in the area at the time. The impulses were also observed seismically as ground coupled acoustic waves around South Western Ontario and Northern Michigan as shown on Fig. A.3. One should emphasize that the seismic stations which record ground coupled acoustic waves may detect signals before ELFO because the speed of sound in a solid is much higher than in the atmosphere. Furthermore, the propagation of seismic waves is complicated and depends on the geological structure, which is specific to the local area. There are also different propagation speeds for transverse and longitudinal waves. The analysis of the seismic stations \( \text{[6]} \) suggests that two blasts (if interpreted as quarry-type explosions) are localized in the area denoted with the red symbols with error bars on Fig.A.1. It should be contrasted with the infrasound signal detected by ELFO which arrives from the atmosphere from a different location and propagates with a much lower speed.

Now we are in a position to apply the scaling behaviour (15) to see if the mysterious event recorded by ELFO might have resulted from the AQN annihilation events along its trajectory when it crosses the atmosphere in this area. Our estimate (15) suggests
Figure A.1: Location of ELFO and seismic stations in the area, adopted from [6]. One degree along the latitude corresponds to 112 km, i.e. $1^\circ \approx 112$ km, while along the longitude $1^\circ \approx 82$ km. It explains our benchmark 300 km in eqs. (A.1) and (A.2) which covers the relevant area shown on the map. The green triangles represent the seismic stations in the area. Red symbols with error bars represent the position of the blasts (with errors) assuming quarry-type explosions, other red symbols with blue lines directed to them show the directions from ELFO to these potential sources of the explosions (they have been considered but ruled out as the sources).

Figure A.2: Infrasound impulses as recorded by ELFO, adopted from [6].
that the overpressure $\delta p$ assumes the following numerical value at $r \approx 300$ km:

$$\delta p \approx 0.3 \text{ Pa} \left( \frac{B}{10^{27}} \right)^{2/3} \left( \frac{300 \text{ km}}{r} \right)^{3/4},$$  \hspace{1cm} (A.1)

where we choose the benchmark for $r = 300$ km corresponding to a typical distance in the area shown on Fig. A.1 and $B = 10^{27}$ to bring the numerical coefficient close to the measured value $\delta p \approx 0.3$ Pa as recorded by ELFO, see Fig. A.2. Estimation for the intensity (A.1) is consistent with observation $\delta p \approx 0.3$ Pa if one assumes that the mysterious explosion had resulted from the AQN annihilation event of a relatively large size with the baryon charge $B \approx 10^{27}$. We shall support this interpretation at the end of this Appendix by analysing the frequency of appearance of such large sized nuggets.

Another parameter which characterizes the acoustic shock is the frequency determined by the scaling formula (19). Assuming the same numerical parameters as before we arrive at the following numerical estimate:

$$\nu(\bar{x}) \sim \frac{\nu_0}{\bar{x}^{1/4}} \sim 5 \text{ Hz} \left( \frac{300 \text{ km}}{r} \right)^{1/4},$$  \hspace{1cm} (A.2)

which is precisely in the range of the highest sensitivity of ELFO where the noise levels are: $10^{-4}$Pa$^2$/Hz for the 10 Hz frequency band and $10^{-3}$Pa$^2$/Hz in the 1 Hz frequency band [6].

Now our task is to estimate the relevant frequency for the sound emitted in the underground rocks. The corresponding expression for the frequency at $r \approx 300$ km is determined by the scaling relation (25) and it is given by:

$$\nu(\bar{x}) \sim \frac{\nu_0}{\sqrt{\bar{x}}} \sim 2.5 \left( \frac{1}{\eta} \right)^{3/4} \left( \frac{300 \text{ km}}{r} \right)^{1/4} \text{ kHz.}$$  \hspace{1cm} (A.3)
The estimate for the underground frequency of Eq. (A.3) should be contrasted with the estimate of Eq. (A.2) for the atmosphere. The basic observation is that the acoustic waves in the atmosphere are in the infrasonic frequency range, while underground, they are in the sound frequency band, as already mentioned.

Several comments are in order. First of all, our proposal demonstrates a qualitative consistency with the mysterious event recorded by ELFO on July 31st 2008. Indeed, as we mentioned above the AQNs do not emit directly the visible light, see Appendix B. It should be contrasted with conventional meteors which directly emit the visible light being consistent with black body radiation spectrum. This observation implies that the AQNs cannot be observed by conventional optical monitoring. The mysterious event recorded by ELFO on July 31st falls into this category because it was observed by infrasound instruments and not observed by the optical synchronized cameras.

Another qualitative comment goes as follows. The frequency (A.3) of the sound from the underground blast falls in human hearing range. Therefore, it is also consistent with the fact that residents of nearby Kincardine could hear the sound (rather than infrasound) signal which originates from the underground with frequency (A.3). It is also consistent with seismic observations which are correlated\(^\text{10}\) with infrasound impulses recorded by ELFO. As discussed above, the atmospheric and underground acoustic waves emitted by the same AQN are always accompanied by each other as they originate from one and the same AQN propagating from outer space through the atmosphere and the Earth.

How we should interpret two blasts recorded in the acoustic and infrasonic frequency bands? The answer depends on the theory of formation of the acoustic waves as a result of ultrasonic motion with very large Mach number which of course is not developed yet. The complicated structure of the signal may, in principle, be explained by the fact that there are actually four waves moving with different speed and originating from different points, which arrive at a different time: atmospheric wave (slow), longitudinal and transverse waves coming from underground, and surface wave. In addition, there are reflected waves (echo). The answering all these hard questions obviously requires an analysis of large number of events, and obviously cannot be accomplished at the present time with a single recorded event. However, the basic characteristics such as the frequency and over-pressure for infrasonic signal are consistent with ELFO record.

Furthermore, our estimations are also consistent on the quantitative level with the mysterious event recorded by ELFO on July 31st 2008. Indeed, our estimates for over-pressure (A.1) and the frequency estimate (A.2) are consistent with description [6] represented on Fig. A.2. This obviously should be considered as a strong support of our identification between a rare intense AQN event and the mysterious explosion recorded by ELFO.

Our final comment is related to the energetics and frequency of appearance of such mysterious events interpreted in terms of the AQNs. As we already mentioned at the end of Section 3 we interpret a relatively high overpressure (A.1) at the level of \(\delta p \simeq 0.3\) Pa as a result of hitting of a sufficiently large AQN with \(B \simeq 10^{27}\) which represents\(^\text{10}\) the corresponding bangs are classified as seismically coupled “Audible Bangs”.

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\(^{10}\)The corresponding bangs are classified as seismically coupled “Audible Bangs”.
our explanation of why this area has observed a single event in 10 years rather than observing similar events much more often.

Appendix B. AQN emission spectrum

The goal of this Appendix is to overview the spectral characteristics of the AQNs as a result of annihilation events when the nugget enters the Earth atmosphere. The corresponding computations have been carried out in [28] in application to the galactic environment with a typical density of surrounding visible baryons of order \( n_{\text{galaxy}} \sim 300 \text{ cm}^{-3} \) in the galactic center. We review these computations with few additional elements which must be implemented for Earth’s atmosphere when typical density of surrounding baryons is much higher \( n_{\text{air}} \sim 10^{21} \text{ cm}^{-3} \).

The spectrum of nuggets at low temperatures was analyzed in [28] and was found to be,

\[
\frac{dE}{d\omega}(\omega) = \frac{dE}{dt \, dA \, d\omega} \simeq \frac{1}{2} \int_0^\infty dz \frac{dQ}{d\omega}(\omega, z) \sim \frac{4}{45} \frac{T^3 \alpha^{5/2}}{\pi} \sqrt{\frac{T}{m}} \left(1 + \frac{\omega}{T}\right) e^{-\omega/T} h\left(\frac{\omega}{T}\right),
\]

where \( Q(\omega, z) \sim n^2(z, T) \) describes the emissivity per unit volume from the electrosphere characterized by the density \( n(z, T) \), where \( z \) measures the distance from the quark core of the nugget. In Eq. (B.1) a complicated function \( h(x) \) can be well approximated as

\[
h(x) = \begin{cases} 
17 - 12 \ln(x/2) & x < 1, \\
17 + 12 \ln(2) & x \geq 1.
\end{cases}
\]

Integrating over \( \omega \) contributes a factor of \( T \int dx \, (1 + x) \exp(-x)h(x) \approx 60T \), giving the total surface emissivity:

\[
F_{\text{tot}} = \frac{dE}{dt \, dA} = \int_0^\infty d\omega \frac{dE}{d\omega}(\omega) \sim \frac{16}{3} \frac{T^4 \alpha^{5/2}}{\pi} \sqrt{\frac{T}{m}}.
\]

Although a discussion of black-body radiation is inappropriate for these nuggets (for one thing, they are too small to establish thermal equilibrium with low-energy photons), it is still instructive to compare the form of this surface emissivity with that of black-body radiation \( F_{BB} = \sigma T^4 \):

\[
\frac{F_{\text{tot}}}{F_{BB}} \simeq \frac{320}{\pi^3 \alpha^{5/2}} \sqrt{\frac{T}{m}}.
\]

At \( T = 1\text{eV} \) which was an appropriate internal nugget’s temperature for the galactic environment, the emissivity \( F_{\text{tot}} \sim 10^{-6} F_{BB} \) is much smaller than that for black-body radiation. As we discuss below a typical internal nugget’s temperature when AQN enters the atmosphere is of order of \( T = 10 \text{ keV} \) which results in the emissivity \( F_{\text{tot}} \sim 10^{-5} F_{BB} \) for such high temperatures.
A typical internal temperature of the nuggets can be estimated from the condition the radiative output of equation (B.3) must balanced the flux of energy onto the nugget due to the annihilation events. In this case we may write,

\[(4\pi R^2)^{16/3} \frac{T^4}{\pi} \frac{3}{4} \sqrt{\frac{T}{m}} \simeq \kappa (\pi R^2)^2 \text{GeV} n_{\text{air}} v_{\text{AQN}},\]  

(B.5)

where the left hand side accounts for the total energy radiation from the nuggets’ surface per unit time, while the right hand side accounts for the rate of annihilation events when each successful annihilation event of a single baryon charge produces \( \sim 2m_p c^2 \simeq 2 \text{ GeV} \) energy. In Eq. (B.5) we assume that the nugget is characterized by the geometrical cross section \( \pi R^2 \) when it propagates in environment with local density \( n_{\text{air}} \) with velocity \( v_{\text{AQN}} \sim 10^{-3} c \).

The factor \( \kappa \) is introduced to account for the fact that not all matter striking the nugget will annihilate and not all of the energy released by an annihilation will be thermalized in the nuggets (e.g. some portion of the energy will be released in form of the axions and neutrinos). As such \( \kappa \) encodes a large number of complex processes including the probability that not all atoms and molecules are capable to penetrate into the color superconducting phase of the nugget to get annihilated. In a neutral environment when no long range interactions exist the value of \( \kappa \) cannot exceed \( \kappa \sim 1 \) which would correspond to the total annihilation of all impacting matter into thermal photons. The high probability of reflection at the sharp quark matter surface lowers the value of \( \kappa \). The propagation of an ionized (negatively charged) nugget in a highly ionized plasma will increases the effective cross section, and therefore value of \( \kappa \) as discussed in [32] in application to the solar corona heating problem.

For the neutral environment (such as Earth’s atmosphere) and relatively low temperature when the most positrons from electrosphere remain in the system the parameter \( \kappa \) should assume values close to unity, i.e. \( 0.1 \lesssim \kappa \lesssim 1 \). In this case, assuming that \( 0.1 \lesssim \kappa \lesssim 1 \) one can estimate a typical internal nugget’s temperature in the Earth atmosphere:

\[ T \sim 40 \text{ keV} \cdot \left( \frac{n_{\text{air}}}{10^{21} \text{ cm}^{-3}} \right)^{4/17} \kappa^{4/17}. \]  

(B.6)

Thus, in the air \( T \simeq (20-40) \text{ keV} \), depending on parameter \( \kappa \). In case of solids the temperature must be higher because of higher density. This leads to a stronger AQN-ionization. This attracts more positively charged ions from surrounding material, which consequently may increase the rate of annihilation (effectively increasing \( \kappa \)). All these effects are very complicated at large \( T \) and deserve a separate study. In the present work for the order of magnitude estimates we adopt the previous value of \( 0.1 \lesssim \kappa \lesssim 1 \) for the case of solids as well, which would correspond to \( T \simeq (100-200) \text{ keV} \). All the uncertainties related to \( \kappa \) do not modify our qualitative discussions in this work. There is much more important element of the spectrum which drastically affects the observational consequences of the emission. It is a relatively large magnitude of plasma frequency \( \omega_p \) of the electrosphere at \( T \neq 0 \) when the temperature reaches \( T \simeq (20-40) \text{ keV} \) in atmosphere as estimated above.

Indeed, there are few additional elements which should be taken into account for Earth’s atmosphere in comparison with original computations [28][29] applied to very
dilute galactic environment with much lower temperatures $T \simeq 1 \text{ eV}$. These effects do not modify the basic scale (B.6). However, these additional elements strongly affect the spectrum at the lower frequency bands. In particular the visible portion of the spectrum at $\omega \sim 1 \text{ eV}$ demonstrates a dramatic suppression. It has some profound consequences for the present work as discussed in the main body of the text. In particular, it implies that the AQNs do not emit the visible light with $\omega \sim 1 \text{ eV}$, in huge contrast with conventional meteors and meteorites which are normally characterized by strong emission in the visible frequency bands through sputtering and ablation [38, 40, 41].

We start our analysis on additional elements to be implemented with the plasma frequency $\omega_p$ which characterizes the propagation of photons in the ionized plasma, which represents the electrosphere for our AQN system. The $\omega_p$ can be thought as an effective mass for photon: only photons with the energy larger than this mass can propagate outside of the system, while photons with $\omega < \omega_p$ can only propagate for a short time/distance $\sim \omega_p^{-1}$ before they get absorbed by the plasma. For our estimates we shall use a conventional non-relativistic expression for $\omega_p$:

$$\omega_p^2(z, T) = \frac{4\pi \alpha n(z, T)}{m}, \quad (B.7)$$

where the positron density $n(z, T)$ in electrosphere in the nonrelativistic mean-field approximation has been computed in [28, 29].

$$n(z, T) \simeq \frac{T}{2\pi \alpha} \cdot \frac{1}{(z + \bar{z})^2} \cdot \frac{1}{\bar{z}} \simeq \sqrt{2\pi \alpha m} \sqrt{\frac{T}{m}}, \quad (B.8)$$

where $\bar{z}$ is a constant of integration being determined by appropriate boundary condition deep inside the nugget’s core. Important implication of the plasma frequency $\omega_p(z, T)$ is that the very dense regions in electrosphere essentially do not emit the photons with $\omega \lesssim \omega_p(z, T)$.

There is another effect which further suppresses the emission of low energy photons. It is related to the ionization processes when the AQN assumes a sufficiently large negative charge due to the $T \neq 0$ as estimated above (B.6). Essentially it affects all loosely bound positrons which will be completely stripped off by high temperature, while more strongly bound positrons will be less affected by the same temperature. The corresponding effect leads to very strong suppression of low energy photons with $\omega \ll T$ as loosely bound positrons represent the main source of low frequency photons.

Both these effects have been implemented in Eq. (B.1) by performing numerical computation of the integral $\int dz$ over electrosphere region with corresponding modifications of the positron density $n(z, T)$ and inserting $\omega_p(z, T)$ as discussed above. We present the corresponding results for these numerical studies on Fig. B.4 for $T = 10$ keV and $T = 50$ keV. These values for the temperature essentially cover the most relevant window (B.6) for the present analysis which dealt with AQN emission in atmosphere.

Few comments are in order. First of all, as one can see from Fig.B.4 the spectrum is almost flat in the region $\omega \lesssim T$ which is the direct manifestation of the well known soft photon theorem when the emission of the photon with frequency $\omega$ is proportional to $d\omega/\omega$. For large $\omega \gg T$ the exponential suppression $\exp(-\omega/T)$ becomes the most
Figure B.4: The spectral surface emissivity of a nugget with the suppression effects at $\omega \ll T$ as discussed in this Appendix. The top plot corresponds to $T = 10$ keV while the bottom plot corresponds to $T = 50$ keV.
important element of the spectrum. The emission is strongly suppressed at very small \( \omega \simeq \omega_p \ll T \). The strong suppression of the spectrum with \( \omega \ll T \) has profound phenomenologically consequences: drastic intensity drop at small \( \omega \ll T \) implies that the luminosity of the visible light from AQN with \( \omega \sim (1 - 10) \text{ eV} \) is strongly suppressed in comparison with X-ray emission. This strong suppression is entirely due to the two effects mentioned above: the presence of the plasma frequency in the electrosphere \( [B.7] \) and complete stripped off of the loosely bound positrons. It implies that the AQNs cannot be observed by conventional optical monitoring as AQNs are not accompanied by emission of the visible light. It should be contrasted with meteors and meteorites which are normally characterized by strong emission in the visible frequency bands through sputtering and ablation \[38, 40, 41\] and routinely observed by all-sky cameras.

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