Atmospheric Radio Signals From Quark Nugget Dark Matter

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If the dark matter of our galaxy is composed of heavy nuggets of quarks or antiquarks in a colour superconducting phase there will be a small but non-zero flux of these objects through the Earth’s atmosphere. A nugget of quark matter will deposit only a small fraction of its kinetic energy in the atmosphere and is unlikely to be detectable. If however the impacting object is composed of antiquarks the energy deposited can be quite large and contain a significant charged particle content. These relativistic secondary particles will subsequently be deflected by the earth’s magnetic field resulting in the emission of synchrotron radiation. This work argues that this radiation, along with a thermal component emitted from the nugget’s surface, should be detectable at radio frequencies and that both present and proposed experiments are likely to prove capable of detecting such a signal.

I. INTRODUCTION

Several recent experiments have attempted to detect the radio emission associated with extensive air showers initiated by the impact of an ultrahigh energy cosmic ray on the earth’s atmosphere [1],[2], [3]. This radio wavelength emission is generated by the deflection of secondary particles by the earth’s magnetic field which produces synchrotron radiation. It is the purpose of this paper to demonstrate that experiments of this type will also capable of placing limits on dark matter in the form of heavy quark matter nuggets. In the following section I offer a brief overview of the quark nugget dark matter model and its observational consequences for both galactic observations and ground based detectors. Section II extends the previous analysis of the air shower induced by a quark nugget passing through the earth’s atmosphere [4] and estimates the synchrotron signal generated by such an event. Sections III and IV then determine specific observable properties of the radio emission. Finally, section V offers a brief description of future detection prospects.

A. dark matter as compact composite objects

The microscopic nature of the dark matter is not yet established. While the majority of dark matter models introduce a new particle which is fundamentally weak in its interactions with visible matter it is only the dark matter interaction cross section to mass ratio ($\sigma/M$) that is observationally constrained. As such, a sufficiently heavy dark matter candidate may avoid observational constraints despite having a relatively large interaction strength. This is possible due to the fact that only the dark matter mass density is directly measured, a heavier dark matter candidate will have a lower number density and thus smaller flux through any detector. In the model to be discussed here the dark matter takes the form of heavy compact composite objects with nuclear scale densities and composed of the standard light quarks [5],[6]. Several versions of this model have been proposed dating back to objects such as stranglets [7]. Current observational constraints on the dark matter $\sigma/M$ ratio require that these quark nuggets carry a mean baryonic charge of at least $10^{23}$. This lower bound is taken from a number of direct detection experiments as detailed in [8]. There is also a region of parameter space at $B \sim 10^{29} - 10^{31}$ likely excluded based on lunar seismic data [9].

Quark nuggets may be formed at the QCD phase transition and remain stable over the lifetime of the universe. Nugget formation allows for the creation of nuggets of both matter and antimatter and may explain both the dark matter and the matter-antimatter asymmetry of the universe. This is possible if the production of antinuggets is favoured by a factor of $\sim 1.5$ over the production of matter nuggets leading to dark matter which consists of two parts matter nuggets to three parts anti-matter nuggets. The excess matter (that not bound in the nuggets) then forms the visible matter of the universe in the observed five to one matter to dark matter ratio.

Originally proposed to explain the baryon asymmetry rather than any specific galactic observation this model has been found to have several observational consequences for the galactic spectrum.

- The quark nuggets are surrounded by an “electrosphere” of positrons the outer layers of which are bound with energies at typical atomic scales. The annihilation of these positrons with the electrons of the interstellar medium will result in a positronium decay line (and associated three photon continuum) in regions where both the visible and dark matter densities are large. In particular one should expect a $511 keV$ line from the galactic centre [10] [8]. Such a spectral feature is in fact observed and has been studied by the INTEGRAL observatory [11].

- Positrons closer to the quark matter surface can carry energies up to the nuclear scale. If a galactic electron is able to penetrate to a sufficiently large depth it will no longer produce the characteristic positronium decay spectrum but a direct $e^- e^+ \rightarrow 2\gamma$ emission spectrum [12]. Precisely modeling the transition between these two...
regimes allows for the determination of the strength of the MeV scale emissions relative to that of the 511keV line [13]. Observations by the COMPTEL satellite show an excess above the gamma ray background predicted from galactic sources at the energy and intensity predicted by this model [14].

- Galactic protons may also annihilate with the antimatter comprising the quark nuggets. The annihilation of a proton within a quark nugget will produce hadronic jets which cascade down into lighter modes of the quark matter. If the energy in one of these jets reaches the quark surface it will excite the most weakly bound positron states near the surface. These excited positrons rapidly lose energy to the strong electric field near the quark surface. This process results in the emission of Bremsstrahlung photons at x-ray energies [15]. Observations by the CHANDRA observatory indicate an excess in x-ray emissions from the galactic centre in precisely the energy range predicted [16].

- The annihilation of visible matter within the nuggets heats them above the background temperature. The thermal spectrum from the nuggets may be predicted based on the emission properties of the electrosphere along with the annihilation rate at various positions within the galaxy [17]. The majority of this thermal energy is emitted at the eV scale where it is very difficult to observe against the galactic background. However the emission spectrum will extend down to the microwave scale where it may be responsible for the “WMAP haze” [18].

- The same thermal emission that may contribute to the WMAP haze associated with the galactic plane must also have been produced in the high density early universe when the isotropic matter density was comparable to that presently seen in high density regions such as the galactic centre. Taking the nugget temperature scale from the galactic centre and scaling it with the cosmological expansion one predicts an excess in the isotropic radio background beginning a few decades in frequency below the CMB peak [19]. The ARCADE2 experiment show just such a low frequency isotropic radio excess [20] which does not currently have an obvious astrophysical source.

The emission mechanisms involved in describing the full nugget spectrum span a very large energy range from the modified thermal spectrum in the microwave up to energies associated with nuclear annihilations observable as gamma rays. However, they make no significant contribution to the galactic spectrum at the GeV scale or above, an energy range across which the FERMI telescope has placed significant constraints on a possible dark matter contribution [21], [22], [23].

While the uncertainties in the astrophysical backgrounds involved make an exact determination impossible a best fit to the galactic spectrum favours quark nuggets with a mean baryon number of roughly \( B \sim 10^{25} \).

B. quark matter in the atmosphere

While the low number density of quark nuggets required to explain the observed dark matter mass density implies a flux many orders of magnitude below conventional dark matter models they may still have observational consequences. Assuming the nuggets to have roughly nuclear scale densities the observational constraints on baryon number cited above imply a minimum mass of a gram and a radius of \( \sim 10^{-7} \text{m} \). Assuming the local dark matter mass density near the galactic plane average (\( \rho \sim 1 \text{GeV/cm}^3 \)) and a mean velocity at the galactic scale \( v_g \sim 200 \text{km/s} \) one may make an order of magnitude estimate the yearly flux of nuggets through the atmosphere as,

\[
\frac{dn}{dt dA} = n_N v_g = \frac{\rho_{DM}}{M_N} v_g = \left( \frac{B}{10^{25}} \right) \text{km}^{-2} \text{yr}^{-1}
\]

this flux is at a level comparable to that of ultra high energy cosmic rays near the GZK cutoff [24]. Consequently the current generation of large scale cosmic ray observatories have a sufficient collection area to conduct a meaningful search for these objects provided their mass is near the lower end of the allowed range. Unlike standard cosmic rays the flux of quark nuggets will experience an annual variation as the earth moves through the background of galactic matter. This annual variation has been used in dark matter detection experiments such as DAMA [25].

In the case of nuggets of quark matter all energy deposited in the atmosphere comes through collisional momentum transfer. Relatively little energy is deposited and the nugget continues through the atmosphere with virtually no change in velocity. The observational prospect for such an event are very low. If however the nugget is composed of antiquarks (as the majority will be in the model under consideration) atmospheric molecules will annihilate on contact with the quark matter surface resulting in the release of substantial amounts of energy into the surrounding atmosphere. While the total annihilation of a quark nugget with \( B = 10^{25} \) would release \( 10^{14} \text{J} \) of energy only a very small fraction of the nugget will annihilate in the time it takes to cross the earth’s surface. As the nuggets carry sufficient momentum to traverse the entire atmosphere the limiting factor is the amount of atmospheric mass which they encounter.

This energy will be deposited in the form of thermal radiation from the nugget as well as relativistic particles and high energy gamma rays emitted in the nuclear interactions. The prospects for direct detection of secondary particles was discussed in [4]. This work focusses instead on the prospect of radio frequency detection. Both the thermal spectrum and the geo-synchrotron emission from the emitted particles will contribute to the radio spectrum, the magnitude and relative strength of these two emission mechanisms will be approximated in section II.

The total scale of the radio band spectrum is determined by the rate at which atmospheric molecules are
annihilated within the nugget. This rate was estimated in [4] where it was shown to increase exponentially with the growing atmospheric density until the point at which the thermal energy produced by annihilations is sufficient to deflect further incoming matter. At this point the annihilation rate reaches an equilibrium point and does not increase further. The exact value of the equilibrium rate depends on details of emission from the quark surface but should occur when the surface temperature is on the order of 10 keV. For this temperature scale the annihilation rate saturates a few kilometers above the earth’s surface. Above this height the annihilation rate is simply determined by atmospheric density and the physical cross section of the nugget.

\[
\Gamma_{an} = \sigma_N v_N n_{at}(h) \quad h > h_{eq}
\]
\[
\approx \sigma_N v_N n_{at}(h_{eq}) \quad h < h_{eq}
\]

Where \(\sigma_N\) is the physical cross section of the nugget (on the order of \(10^{-10} cm^2\) for the nugget mass range considered here), and \(h_{eq}\) is the height at which the equilibrium annihilation rate is reached.

II. RADIO FREQUENCY EMISSION

Emission in the radio band arrises through two distinct processes: thermal emission from the surface of the quark nugget as it is heated by annihilations and geo-synchrotron emission from relativistic charged particles generated in nuclear annihilations.

A. Thermal emission

A quark nugget passing through the atmosphere will generate a thermal spectrum extending across a wide range of energies including the radio band. The thermal emission spectrum was first calculated for nuggets in the galactic centre [17] where the thermal energy emitted at frequency \(\omega\) by a nugget of temperature \(T\) was calculated to be,

\[
\frac{dE}{dt d\omega} = \frac{3}{4 \pi^2} \rho^3 \sqrt{\frac{T}{m_e}} \left(1 + \frac{\omega}{T}\right) e^{-\omega/T} \left(17 - 12 \ln\left(\frac{\omega}{2T}\right)\right)
\]

This spectrum is modified from a simple black body spectrum by the presence of an electrosphere surrounding the quark matter and is suppressed with respect to black body radiation for temperatures below the electron mass \((m_e)\). The nugget temperature is determined by the rate at which matter is annihilated within the nugget and, as such, will be much higher for a nugget in the earth’s atmosphere than for nuggets in the interstellar medium. The evolution of a nugget’s temperature as it moves through the atmosphere was described in [4] where it was found that the temperature typically peaks in the 10s of keV range. At this temperature the emission of radiation in the radio band is well described by the \(\omega < T\) limit and the spectrum may be taken as

\[
\frac{dE}{dt d\omega} \approx (10^{-10} Js^{-1} Mhz^{-1}) \times \left(\frac{T}{10 keV}\right)^{13/4} \left(\frac{R}{10^{-5} cm}\right)^2 \ln\left(\frac{2T}{\omega}\right)
\]

In this form it is clear that thermal emission generates a relatively flat (log dependance) spectral contribution across all radio frequencies. Thermal emission will occur uniformly over the nugget surface so that the intensity of the thermal component of the spectrum is simply obtained by dividing expression (4) by \(4\pi\) multiplied by the square of the distance between the nugget and the observer.

B. Geo-synchrotron emission

As a quark nugget moves through the atmosphere nuclear annihilations generate a large number of secondary particles. Some fraction of these particles, dominated by relativistic muons, escape from the nugget into the atmosphere. These secondary particles are deflected by earth’s magnetic field generating synchrotron radiation. Note that, as acceleration is perpendicular to velocity, the particle velocity remains constant so long as energy losses through synchrotron emission and interactions with the atmosphere remain small. For relativistic particles in the earth’s magnetic field the synchrotron radius is much longer than the total path length so that the the deflection of the particles is relatively small. In this limit we can linearize the equations of motion of a particle within a constant magnetic field.

\[
\vec{v}(t) = \vec{v}_0 + \vec{v}_0 t \approx \vec{v}_0 + \frac{q}{m_\gamma} \vec{v}_0 \times \vec{B}_0
\]

Where \(v_0\) is the initial velocity of the charged particle which, in the case of muons produced in QCD scale processes at the quark surface should be on the order of \(v_0 \approx 0.9c\). The acceleration term in this expression will lead to the production of synchrotron radiation. The resulting radiation is beamed along the direction of the velocity so that (in the small deflection limit) we need only consider the radiation emitted by particles with initial velocities directed towards the observer.

Unlike a conventional air shower the dominant mechanism generating relativistic particles is not direct pair production but complex many body interactions at the

\footnote{As a consistency check it may be noted that the total emitted synchrotron radiation, given by integrating expression 15 over all angles and the lifetime of the muon, is well below the initial kinetic energy}
quark matter surface. In the model considered here these processes may be summarized by two simple parameters the mean velocity of the muons emitted ($\beta_0$) and the number of muons emitted per nuclear annihilation ($f_\mu$).

While they could in principle be calculated within a particular quark matter model the introduction of these parameters, intended to capture only the approximate scale of the radio signal, allows for a discussion of the general properties of the synchrotron emission without detailed and model specific nuclear calculations.

It is the uncertainty in these two parameters which will dominate the uncertainties in all the calculations which follow. The total number of muons directly sets the overall scale of the resulting radio signal produced by geo-synchrotron effects. As such this scale is estimated here only at the order of magnitude level. While the general shape of the resulting radio spectrum is relatively robust its exact details are dependent on the energy distribution of the muons escaping from the nugget. Both the total emission rate and the energy spectrum depend on the efficiency of energy transfer through the quark matter of the nugget. The calculation of the mode and efficiency of energy transfer in high density QCD is a complicated and phase dependent problem beyond the scope of this paper which seeks only to demonstrate the feasibility of detecting quark nugget induced air showers rather than to make highly specific calculations of the resultant emission spectrum.

Muons produced through nuclear interactions within the quark nugget necessarily carry nuclear scale energies and thus $\beta_0 \sim 0.9 - 0.99$. The muon production coefficient is more difficult to estimate but, in the simplified picture where a nuclear annihilation in the quark matter produces a muon with properties relatively close to their vacuum values, it may be estimated that only those muons emitted in the direction of the surface will escape (the remainder being thermalized within the nugget.) The sharpness of the quark surface will also result in a high likelihood of an outgoing muon being reflected back into the quark matter. The combination of these two effects suggests a muon production coefficient on the order $f_\mu \approx 0.1 - 0.01$.

While muon production does not occur through direct pair production the process is charge independent so $\mu^+$ and $\mu^-$ production proceed at the same rate. In this case it is relatively simple to evaluate the electric field resulting from a single muon pair in the small $\omega_B$ limit. This field at leading order is,

$$|\mathcal{E}(r, t)| = \frac{q}{2\pi\epsilon_0 c R(t)} \frac{\omega_B \beta_0 \sin\theta_{eB}}{\gamma (1 - \beta_0)^2}$$  \hspace{1cm} (6)

Where $\sin\theta_{eB}$ is the angle between the initial muon velocity and the earth’s magnetic field and $R(t)$ is the distance between the muon and the observation point. This may be transformed into momentum space as,

$$|\mathcal{E}(\vec{r}, \omega)| = \frac{q}{(2\pi)^{3/2}\epsilon_0} \frac{\omega_B \sin\theta_{eB}}{\epsilon^2 \gamma (1 - \beta_0)^2} |\mathcal{I}(R, \omega)|$$  \hspace{1cm} (7)

Where I have defined the integral

$$|\mathcal{I}(R, \omega)|^2 = \left( \int_{\Delta R/R_0}^1 \frac{dx}{x} \cos \left( \frac{R_0 \omega}{c \beta_0} x \right) \right)^2$$

$$+ \left( \int_{\Delta R/R_0}^1 \frac{dx}{x} \sin \left( \frac{R_0 \omega}{c \beta_0} x \right) \right)^2$$  \hspace{1cm} (8)

With $R_0$ being the nugget to observer distance and $\Delta R$ the smallest separation between the emitting muon and the observer. Note that the relevant timescale in determining the frequency dependence of the synchrotron radiation is the length of time for which the emitting particle pair remains relativistic. It should also be noted that all information about the shower geometry is carried by the sine function and the unitless integral. This expression then allows us to estimate the scale of the field strength based purely on the numerical coefficient.

$$|\mathcal{E}(\vec{r}, \omega)| \approx \left( \frac{10^{-10} \mu V}{m^{-1} M Hz^{-1}} \right) \times \frac{B}{0.5 G} \frac{\sin\theta_{eB} |\mathcal{I}|}{\gamma (1 - \beta)^2}$$  \hspace{1cm} (9)

As should be expected the contribution of a single particle pair is relatively weak. In order to determine the total field strength associated with the shower this value must be scaled up by the total number of particles contributing to the radio emission along a given line of sight.

The basic properties of a nugget induced air shower can be demonstrated in the geometrically simplified case where the quark nugget moves through the atmosphere vertically. In this case the earth’s magnetic field may be taken to lie in the x-z plane with an inclination angle $\theta_B$ and the observation position on the earth’s surface a distance from the shower centre ($R$) and a angle relative to the horizontal component of the magnetic field ($\phi$). Due to the beaming of the synchrotron radiation only muons with an initial velocity directed very nearly towards the earth’s surface at the time the muon is emitted. This approximation breaks down if the muons actual reach the detector, and a short distance cutoff must be added for points sufficiently close to the shower core. In the following calculations the integral 8 will be cutoff when the minimum separation distance ($\Delta R$) becomes comparable to the separation distance of the muon pair.

### III. Electric Field Magnitude

The expression (7) gives the momentum space electric field strength resulting from a single muon pair. In order to determine the total field strength at the earth’s surface we now sum over all muon pairs emitted towards the observer at a given moment. The nuclear annihilation rate for a given height is given in expression (2) so that
the total number of muons produced is determined by multiplying this rate by the muon production coefficient \((f_\mu)\) as discussed above. The rate of muon production from a specific point on the nugget surface depends on the local flux of material onto the quark surface which is proportional to the area perpendicular to the nugget’s velocity.

\[
\frac{dN_\mu}{d\Omega
dt} = \frac{\Gamma_{an}f_\mu}{2\pi} \frac{\cos\phi}{\mu N}
\]

(10)

Here \(\phi\) is the angle between the direction of emission and the nugget’s velocity. As stated above, muon emission is dominantly perpendicular to the quark surface so that the angular position of emission on the nugget’s surface fully determines the direction of the resulting synchrotron radiation. As such, in the vertical shower case, the radiation detected a distance \(b\) from the shower centre when the nugget is at a height \(h_N\) has

\[
\frac{dN_\mu}{d\Omega
dt} = \frac{\Gamma_{an}}{2\pi} \frac{h_N}{\sqrt{h_N^2 + b^2}}
\]

(11)

In order to determine the total number of muons contributing to the observed flux we must estimate the solid angle of the nugget surface which contributes to the synchrotron radiation along a given line of sight. To do this we note that the intensity of the radiation has an angular dependence which scales as \(S \sim (1 - \beta \cos\theta)^4\) which, for \(\beta\) close to one, is sharply peaked around zero. As such I take as the angular scale of emission the angle at which the intensity falls to half its peak value. This angle is defined by the expression

\[
\left(\frac{1 - \beta}{1 - \beta \cos\theta_{1/2}}\right)^4 = \frac{1}{2}
\]

\[
\theta_{1/2}^2 \approx 0.38 \left(\frac{1 - \beta}{\beta}\right)
\]

(12)

Where the second expression uses the small angle approximation. The relevant solid angle of the nugget surface is then given by \(d\Omega \approx \theta_{1/2}^2\) and the total number of muons emitted towards the observer at a given time is,

\[
\frac{dN_\mu}{dt} = \Gamma_{an}f_\mu \frac{\theta_{1/2}^2}{2\pi} \frac{h_N}{\sqrt{h_N^2 + b^2}}
\]

(13)

Finally we note that the nugget’s velocity is much smaller than that of the emitted muons so that its height changes very little over the time scale on which the muons emit synchrotron radiation. This time scale depends on interaction rates with the surrounding atmosphere and a full calculation of energy loss rate for a muon is rather complicated. In order to estimate the time scale involved I will simply note that muons lose energy to the surrounding atmosphere much slower than electrons and assume that the muon energy is roughly constant until it decays to an electron at which point it is rapidly stopped as it scatters off atmospheric molecules. In this approximation the muon lifetime sets the timescale over which the emitting particle remains relativistic \(^2\). Under these approximation the number of muons contributing to the radiation flux when the nugget is at a given height may be approximated as,

\[
N_\mu(h_N) = \Gamma_{an}f_\mu \frac{\theta_{1/2}^2}{2\pi} \frac{h_N}{\sqrt{h_N^2 + b^2}}
\]

(14)

where \(\tau_\mu\) is the muon lifetime and \(\gamma\) is the initial muon boost factor. Multiplying this expression by the electric field contribution from a single muon pair \((7)\) will then give the total field strength when the nugget is at a given height. Figure 1 shows the electric field strength generated by geosynchrotron emission when the nugget is at different heights. Figure 2 shows the lateral profile of electric field strength as received at the surface. Note that the oscillations appearing in the field strength arise from the unphysical assumption that all muons are emitted at the same energy. Averaging over a range of initial muon energies would erase this effect but would not change the scale of the emission or the basic form of the spectrum.

**IV. TOTAL INTENSITY**

Finally I determine the total intensity resulting from the passage of a nugget through the atmosphere. The

\(^2\) This is a serious simplification of the very complicated propagation of the secondary particles of an extensive air shower a full treatment of which would involve far more detailed simulations. However, the uncertainty inherent in the initial particle production rate and energy spectrum is great enough that a detailed numerical treatment is not warranted at present.
magnitude of the Poynting vector is given by,
\[ |\vec{S}| = \frac{dE}{dt \, dA} = \frac{\vec{E}^2}{\mu_0 c} \] (15)

Or, in momentum space
\[ \frac{dE}{d\omega \, dA} = \frac{\left| \mathcal{E}(\omega) \right|^2}{\mu_0 c} \] (16)

With the field strength for a single muon pair given by (7). This radiation is emitted as long as the muon remains relativistic, as argued above this timescale may be roughly estimated by the observer frame muon lifetime. In this case the observed flux per charge pair can be approximated as,
\[ \frac{dE}{d\omega \, dt \, dA} = \frac{1}{\gamma \tau_\mu} \frac{|\mathcal{E}|^2}{\mu_0 c} \] (17)

The electric field generated by all particles moving towards the observer at a given time add coherently so that this may be translated to a total flux from all particles by multiplying the field strength by the total number of contributing muon pairs which is half the value determined in (14).
\[ \frac{dE}{d\omega \, dt \, dA} = \frac{1}{\gamma \tau_\mu} \frac{|\mathcal{E}|^2}{\mu_0 c} \] (18)

I want to add to this the intensity contribution from the thermal spectrum (3). As the thermal radiation is emitted uniformly from the nugget’s surface the total intensity at a given position is simply given by
\[ \frac{dE}{d\omega \, dt \, dA} = \frac{1}{4\pi(b^2 + h_N^2)} \frac{dE}{d\omega \, dt} \] (19)

The intensity of both the thermal and synchrotron radiation components are plotted in 3. In the range of frequencies relevant to most current and planned experiments the thermal emission has only a minimal impact on the total intensity. If however observations are extended into the Ghz range the thermal component, with its relatively flat spectrum will become increasingly important.

Finally, it should be noted that the delivered intensity evolves on a timescale much longer than that generated by an air shower triggered by a single ultrahigh energy proton or nuclei. The timescale in this model is set by the time it takes for the quark nugget to pass through the earth’s atmosphere. Assuming that the quark nuggets carry velocities at a typical galactic scale of \( \sim 200 \text{km/s} \) the rise in intensity will take place over tens of milliseconds. Figure 4 shows the rise in intensity as a function of time.

V. DETECTION PROSPECTS

Having established the basic properties of the radio band emission generated by an antiquark nugget passing through the atmosphere it is possible to speculate on the possibility for such an event to be observed using present or planned detectors. In this context two features of the emission are of particular relevance: the total emission strength and the lateral extent of the emission at the surface.
As shown in the lateral profile plotted in figure 2 the radio band emission extends out to kilometer scales. As such theses events may be observed over a extended area surrounding the shower core. Of particular interest in this context are radio detection facilities associated with large scale cosmic ray detectors. The coincident arrival a radio pulse with a millisecond duration and a particle shower would be a strong smoking gun signal as all known phenomenon capable of generating a large number of secondary particles evolve on much shorter (nanosecond) timescales.

Of particular interest here are experiments such as the Auger Engineering Radio Array (AERA), LOPES at the KASCADE-Grande array, and CODALEMA. Each of these radio detection experiments have a sufficient spatial extent to observe kilometer scale events and a sensitivity to the tens of Mhz range across which both the geosynchrotron and thermal emission generated by the nugget will extend. See [1], [2], [3] and references therein for details of these experiments.

Provided that timing cuts do not remove this type of long duration radio pulse these experiments should be very capable of setting strict limits on the flux of anti-quark nuggets in the mass range favoured by fits to the galactic emission as discussed in section (IA) as they accumulate further data.

It has also been suggested that the balloon-borne ANITA experiment [26] may be sensitive to the thermal emission generated by the passage of an antiquark nugget through the the radio transparent Antarctic ice [27]. Data currently under analysis by the ANITA collaboration is likely to place constraints on the quark nugget flux across much of the preferred mass range.

VI. CONCLUSION

This paper has aimed to demonstrate the feasibility of detecting the presence of dark matter in the form of heavy nuggets of quark matter using radio frequency detectors. The passage of a quark nugget through the atmosphere will induce an extensive air showers involving many secondary charged particles which subsequently emit synchrotron radiation across the Mhz band as they are deflected by the earth’s magnetic field. The resulting radio emission is likely to be detectable up to a few kilometers from the shower core. As such these events should be readily detectable by experiments intended to observe radio emission from ultra high energy cosmic rays.

While the intensity and event rate of these showers may be at a similar scale to that of air showers initiated by a single ultra high energy proton or nucleus antiquark nugget induced events have several easily observable distinguishing properties.

The nuggets require a time scale on the order of tens of milliseconds to traverse the earth’s atmosphere and will generate a synchrotron signal over much of this time. As such the radio signal will be have a duration much longer than that of typical cosmic ray events which evolve on time scales orders of magnitude faster.

The nuggets carry galactic scale velocities and their flux will show a seasonal variation, however, any microscopic particle with so small a velocity will be insufficiently energetic to initiate an extensive air shower. Consequently, the detection of a seasonal variation in the air shower rate would be a strong indicator of a quark nugget contribution to this flux.

The composite nature of the primary particle in a quark nugget initiated air shower means that there is a thermal component to the spectrum in addition to the geosynchrotron emission generated by the secondary particles. While the thermal component is significantly lower than the synchrotron signal at the frequencies typically observed it’s contribution increases at higher frequencies and may well be observable as distinct from the synchrotron signal.

If, as argued above, large scale cosmic ray detectors are also capable of observing the air showers induced by dark matter in the form of heavy nuggets of quark matter than these properties will allow the two components to be readily distinguished through observations at radio frequencies.

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[1] D. Ardouin et al., Astropart.Phys. 31, 192 (2009).
[2] T. Huege and Collaboration, Nucl.Instrum.Meth. A662, S72 (2012).
[3] J. Kelley, (2012), arXiv:1205.2104v1.
[4] K. Lawson, Phys. Rev. D 83 (2011), arXiv:1011.3288v3.
[5] A. R. Zhitnitsky, JCAP 10, 010 (2003), arXiv:hep-ph/0202161.
[6] D. H. Oaknin and A. Zhitnitsky, Phys. Rev. D 71, 023519 (2005), arXiv:hep-ph/0309086.
[7] E. Witten, Phys. Rev. D 30, 272 (1984).
[8] A. Zhitnitsky, Phys. Rev. D 76, 103518 (2007), arXiv:astro-ph/0607361.
[9] E. T. Herrin, D. C. Rosenbaum, and V. L. Teplitz, Phys. Rev. D 73, 043511 (2006), arXiv:astro-ph/0505584.
[10] D. H. Oaknin and A. R. Zhitnitsky, Phys. Rev. Lett. 94, 101301 (2005), arXiv:hep-ph/0406146.
[11] P. Jean et al., Astron. Astrophys. 445, 579 (2006), arXiv:astro-ph/0509298.
[12] K. Lawson and A. R. Zhitnitsky, JCAP 0801, 022 (2008), arXiv:0704.3064 [astro-ph].
[13] M. M. Forbes, K. Lawson, and A. R. Zhitnitsky, Phys. Rev. D 82, 083510 (2010), 0910.4541.
[14] A. W. Strong, I. V. Moskalenko, and O. Reimer, Astrophys. J. 613, 962 (2004), arXiv:astro-ph/0406254.
[15] M. M. Forbes and A. R. Zhitnitsky, JCAP 0801, 023 (2008), arXiv:astro-ph/0611506.
[16] M. P. Muno et al., Astrophys. J. 613, 326 (2004), arXiv:astro-ph/0402087.
[17] M. M. Forbes and A. R. Zhitnitsky, Phys. Rev. D 78, 083505 (2008), 0802.3830.
[18] D. P. Finkbeiner, Astrophys. J. 614, 186 (2004), arXiv:astro-ph/0311547.
[19] K. Lawson and A. R. Zhitnitsky, Phys. Lett. B. 724, 17 (2013).
[20] D. Fixsen et al., The Astrophysical Journal 734 (2011).
[21] M. Ackermann et al., Phys.Rev.Lett. 107, 241302 (2011).
[22] M. Ackermann et al., JCAP 1005, 025 (2010).
[23] A. Abdo et al., JCAP 1004, 014 (2010).
[24] Pierre Auger, J. Abraham et al., Phys. Rev. Lett. 101, 061101 (2008), 0806.4302.
[25] P. Belli et al., Phys. Rev. D 61, 023512 (2000), hep-ph/9903501.
[26] P. Gorham et al., Astropart.Phys. 32, 10 (2009).
[27] P. Gorham, Phys.Rev. D 86 (2012).