Fermi Bubbles in Scalar Field Dark Matter halos

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In recent times, the Scalar Field Dark Matter (SFDMM) model (also called Fuzzy, Wave, Ultralight dark matter model) has received much attention due to its success in describing dark matter on both cosmological and galactic scales. Several challenges of the Cold Dark Matter (CDM) model can be explained very easily and naturally by the SFDMM model. Two of these challenges are to describe the anomalous trajectories of satellite galaxies called the Vast Polar Structure (VPOS) and to explain the Fermi Bubbles (FB) observed in our galaxy. In Phys.Rev.D103(2021)083535 [1] an alternative explanation for VPOS was shown using the SFDMM excited states, explaining the anomalous trajectories in a natural and simple way. In this work we use the same dark matter structure to show that these excited states of the SFDMM can provide a very simple and natural explanation for the FB, assuming that the SFDMM is a kind of dark boson. If this assumption is correct, we should see FB in several more galaxies and continue to see gamma-ray events at higher energies, these observations would take place in the near future and could be crucial to the ultimate answer to the nature of dark matter.

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 Doubtless the nature of the Dark Matter (DM) is one of the most challenging open questions for science [2]. The Λ Cold Dark Matter (LCDM) model has been able to explain all the cosmological observations we have so far, maybe with the exception of the so-called H₀ tension [3]. Nevertheless, at galactic scales, this model has several strong challenges to explain, as some of the observed features of the galaxies are not sufficiently well explained by the model or the needed physics complicates too much the model [4, 5]. This is why people look for alternatives that can solve these problems in a more convincing way. One of the alternatives that do so is the Scalar Field Dark Matter (SFDMM) model, which explains the universe at cosmological scales with the same accuracy as the LCDM model [6, 7], but is able to explain the galaxies with much simpler physics in a natural way [8]. The model has been rediscovered several times as Fuzzy [9], Wave [10, 11], BEC [12] DM, and more recently as Ultra-light DM [13]. The SFDMM model has still a long history, there are some isolated works in the 90’s of the past century [14, 15], but the systematic study of this model began at the end of the 90’s with the study of galaxies. In [16, 17] it was found that the SFDMM model explains the rotation curves in galaxies, while in [6, 7] it was shown that the model explains the cosmological observations and contains a natural cut-off of the mass power spectrum that allows adjusting the number of satellite galaxies around the host. In [18] numerical simulations for the collapse of the SFDMM were performed and in [19] it was shown that the density profile of the SFDMM is core. In [20, 21] SFDMM with multi-states, finite temperature and symmetry breaking were studied. All of these results were recently corroborated several times with numerical simulations by various groups [11, 22–26].

One of the most interesting results of this model is that it is capable of explaining the anisotropic distribution of satellite galaxies around their host galaxies, observed in the Milky Way, Andromeda, and Cen A systems. This is possible if the excited states of the scalar fields are taken into account [1]. SFDMM satisfies the Schrödinger-Poisson equations, where systems can be in the ground state, or excited states, or both, like atoms. The first non-spherically symmetric excited state is 8-shaped, as in atoms, where spherical harmonic functions with atomic number l ≠ 0 lost their spherically symmetric form. In the case of SFDMM it is very similar, the shape 8 of the halo density hijacks the trajectories of the satellite galaxies to align with the polar orbits, breaking the isotropic structure of the satellites around the galaxies, see fig.1. All DM models that exist so far predict that the distribution of satellite galaxies around large galaxies should be homogeneous, with the exception of SFDMM, which naturally predicts the correct trajectories of the satellite galaxies. This has been one of the great predictions of the SFDMM model so far.

In this work, we use precisely this form of the excited states of the dark matter halo to explain a new observation that has so far been unexplained, the Fermi Bubbles (FB) [27]. The idea is the following. We consider that the internal symmetry of the SFDMM is the group U(1). The corresponding Lagrangian then contains a new charge q, which we assume must be dark. Because of this the SFDMM can interact with the electromagnetic field of the standard model, but not (directly) with other particles. In this case, in the present work, we show that there must be photon emissions, caused by the interaction of SFDMM with photons coming from starlight or the CMB, that have enough energy to be seen as X-rays, gamma rays, or even more energetic radiation. This is
enough to give an alternative explanation of what we see as FB.

Thus, we start with the Lagrangian

$$\mathcal{L} = (\nabla_\mu \Phi + iqB_\mu \Phi)(\nabla^\mu \Phi^* - iqB^\mu \Phi^*) - m^2\Phi \Phi^* - \frac{1}{4} B_{\mu \nu} B^{\mu \nu} - \frac{1}{4} B'_{\mu \nu} B'^{\mu \nu} - \delta \frac{1}{2} B_{\mu \nu} B'^{\mu \nu}$$  \hspace{1cm} (1)

where $B_\mu$ is the dark gauge field of the SFDM, with fundamental charge $q$ and Faraday tensor $B_{\mu \nu} = B_{\mu \nu} - B_{\nu \mu}$, whereas $B'_{\mu \nu} = B'_{\mu \nu} - B'_{\nu \mu}$ is the would-be electromagnetic gauge field of the standard model and $\delta$ a kinetic coupling constant between these two fields. By construction, there is not ad hoc coupling between the scalar field $\Phi$ or $B_\mu$, and the rest of the field components of the standard model. The scalar field is the dark matter of the universe and has the dominant part of the gravitational field, the electromagnetic fields are small and their contribution to the gravity of the system is negligible. The scalar field fulfills the Klein-Gordon equation, which non-relativistic limit is the Schrödinger equation, while the Einstein equations in this limit reduce to the Poisson equation. Therefore the field equations we are dealing with reduce to the Schrödinger-Poisson system. Numerical evolutions of this system have been performed in [28] and the result is that the density profile of the scalar field resembles that of the Legendre function $P_l^m(\cos(\theta))$ of the hydrogen atom, with quantum numbers $l$ and $m$, which implies that the SFDM profile looks like the one in fig.1. This reminds us very well of the shape of the FB in the galaxy. Furthermore, the central density $\rho_c$, and the energy $E_\Phi$ of the system are (see also [13], appendix B)

$$\rho_c = \left(\frac{Gm^2}{\hbar^2}\right)^3 \frac{M^4\rho_n}{l^2} \hspace{1cm} (2)$$

$$E_\Phi = \left(\frac{GMm}{\hbar}\right)^2 \epsilon_n \hspace{1cm} (3)$$

$$r_{1/2} = \frac{Gm^2}{\hbar^2} f_n \hspace{1cm} (4)$$

where $r_{1/2}$ is the radius containing half of the whole scalar field of the system in the corresponding state $n$, and $\rho_n$, and $\epsilon_n$ are the dimensionless central density and energy eigenvalue that represent the excited state $n$, respectively. In Fig.1 we show the mass density projections of a SFDM halo consisting of a ground state and an excited state. If, for example, we consider a galaxy like the Milky Way, let say, with $M = 1.5 \times 10^{12} M_\odot$, and an effective scalar field dark mass $m = 0.5 \times 10^{-24}$eV, as found convenient to explain the trajectories of satellite galaxies in this galaxy, the resulting central density is $\rho_c = 5.4 \times 10^8 M_\odot$/kpc$^3 = 3.7 \times 10^{-23}$gr/cm$^3$ for the ground state, and $\rho_c = 2.2 \times 10^7 M_\odot$/kpc$^3 = 1.5 \times 10^{-24}$gr/cm$^3$ for the first excited state of the system. While the dark matter particles energy of the system obtained for the ground state is $E_\Phi = 2.8 \times 10^{18}$GeV and for the excited state the numerical simulation finds $E_\Phi = 5.4 \times 10^{17}$GeV, contained in a radius $r_{1/2} = 9$ kpc for the ground state and $r_{1/2} = 53$ kpc for the excited state.

Because of the kinetic mixing among dark and visible gauge fields [in Eq. (1)], dark matter quanta do actually interact weakly with the last and can therefore pass energy via scattering processes to the photons that surround the galaxy, essentially starlight photons and those from the Extragalactic Background Light (EBL) and the CMB. Such a coupling arises when one puts the gauge kinetic terms in canonical form through the linear transformation [29]

$$\begin{pmatrix} B_\mu \\ B'_\mu \end{pmatrix} = \begin{pmatrix} 1 & -S_\delta \\ 0 & C_\delta \end{pmatrix} \begin{pmatrix} A'_\mu \\ A_\mu \end{pmatrix}$$  \hspace{1cm} (5)

where $C_\delta = 1/\sqrt{1 - \delta^2}$, $S_\delta = \delta/\sqrt{1 - \delta^2}$ and $A_\mu$ is the visible photon. The so defined dark photon, $A'_\mu$, would remain uncoupled to Standard Model (SM) fields. The visible photon, though, gets coupled to the dark matter field, since the transformed covariant derivative becomes $D_\mu \Phi = (\nabla_\mu + iqA'_\mu + iqA_\mu)\Phi$, where we identified the dark matter electric (milli-)charge as $g = -q\delta/\sqrt{1 - \delta^2}$. Existence of such a coupling is all we need in what follows and we assume so. Observable bounds from white dwarfs and red giants exist for $g$ on about $10^{-12} - 10^{-13}$ for dark masses down to the eV range [30]. We will assume the softer one here, although the phenomenology can still be accommodated for a somewhat smaller charge.

Since background photons are vastly sub-energetic compared to dark matter particles, the former would suffer inverse Compton (IC) scattering when passing through the galactic $\Phi$ configurations, gaining enough energy to become gamma rays. Due to the almost negligible mass of $\Phi$, the cross section of this process goes as $\sigma \approx h^2g^4/(4\pi s)$, where the center of mass energy parameter is given as $s = 2E_\Phi E_{\gamma\gamma}c^2$, and therefore

$$\sigma \approx \left(\frac{g}{10^{-12}}\right)^4 \left(\frac{10^4 GeV^2}{E_\Phi E_{\gamma\gamma}}\right) \cdot 1.55 \times 10^{-77} \text{cm}^2 .$$  \hspace{1cm} (6)

The radiated energy per unit time per DM particle becomes

$$\frac{dE}{dt} = \frac{4}{3} \sigma c g^2 \beta U_\gamma$$  \hspace{1cm} (7)

where $\gamma$ is the Lorentz factor of the DM with a velocity $\beta$ and $U_\gamma$ is the (isotropic) photon background energy density. For CMB $U_{\gamma CMB} = 0.26 eV/cm^3$. Therefore, the total number of scatterings per unit time per DM particle would be

$$\frac{dN}{dt} = \frac{c \sigma N_\gamma}{1.91 \times 10^{-64} s^{-1}} ,$$  \hspace{1cm} (9)

where we have used CMB background photon number density, $N_{\gamma CMB} \approx 411$ cm$^{-3}$ as a reference.
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lobe, and the average DM particle density within the
dM and $V_{dM}$ the contained volume of the lobe along the
direction of observation, of depth $R$. The factor $1/4\pi$ follows
the assumption that the emission is isotropic. Since the Earth is located about 8 kpc from galactic cen-
ter, whereas the dark field density forms a quasi spherical
lobe of about $R \sim 50$ kpc across, when looking towards the
center of the lobe, with an aperture of one degree squared, one gets $V_{dM} \approx \frac{1}{4}d\Omega R^2 \approx 3.3 \times 10^{65}$ cm$^3$, which renders with previous numbers
$$\frac{dN_T}{dt} \approx 5 \text{s}^{-1} \cdot (\eta_{DM} \cdot \text{cm}^3).$$
This represents its maximum expected value. The number of gamma events should reduce as we move our observations away from the lobe center, depleting to zero as we reach the border of the lobe.

The interaction between the dark matter $\Phi$ and the normal photon is through the IC scattering, where the dark matter has an enormous energy and gives part of it to the normal photon. If $m_\phi \ll E_{\gamma i}$, which is the case because $m_\phi \sim 10^{-24}$ eV is very small compared with the energy of the surround photons, the IC scattering final energy during this process is given by

$$E_{\gamma f} = \frac{m_\phi c^2}{\sqrt{1 - \frac{v^2}{c^2}}} \left(1 + \frac{v}{c} \cos(\theta)\right)$$
$$= E_\Phi \left(1 + \frac{v}{c} \cos(\theta)\right)$$

where $\theta$ is the collision angle as observed in the local frame where the dark matter particle is at rest. Observe that if $m_\phi$ is so small, the huge energy of the dark matter particles come from their velocity $v \sim c$, such that the quotient $v/c \sim 1$, i.e. the Lorentz factor $\gamma \gg 1$. The final energy then runs as $0 < E_{\gamma f} < E_\Phi$. If this result is right, we have to observe the emitted light in all frequencies until the so high energies like $E_\Phi$. This emitted light can be seen in the FB and in the next generation of high energy light detectors.

The second conclusion is that, if this hypothesis is correct, we have to see FB in several galaxies, especially in large ones. The number of events we should see depends on the angle at which the collisions occur, so we only see some events at these energies, the rest are either because the angles of the collisions do not produce visible energies or because the energies are larger than our detectors can see for now.

The differential gamma flux that should be observed from the bubble can be calculated in a similar fashion as the flux produced from IC with electrons, and goes as $\Phi$

$$\frac{dN_{tot}}{ddE} = \int \int N_E(\gamma) d\gamma \left(\frac{dN_{\gamma}}{ddE}\right)$$

where $dN_E = N_E(\gamma)d\gamma$ is the differential number of scatter particles and $dN_{\gamma}/ddE$ is the scattered photon spectrum per scatter. Adapting the corresponding expression for the last to the SFDM case, we proceed by approximating the unknown dark matter distribution in terms of the Lorentz factor $\gamma$ as a power low distribution $N_E(\gamma) = K \gamma^{-p}$ for some region between a minimum and maximum particle velocity $\gamma_0 < \gamma < \gamma_m$, and 0 otherwise. We also take $n(E)$ to follow a standard black-body distribution. With this, equation (14) can be integrated to give $\Phi$

$$\frac{dN_{tot}}{ddE} = 1 \frac{r_0^2}{\hbar^3c^2} K(kT)^{(p+5)/2} F(p) E^{-(p+1)/2}$$

FIG. 1: Three-dimensional density plot of the mass density $|\Phi|^2 = |\Phi_{100}|^2 + |\Phi_{210}|^2$ of the SFDM halo in the multi-state ($\Phi_{100}, \Phi_{210}$) configuration. In the left panel the total mass density is plotted. In the middle (right) panel, the individual contribution to the mass density of the ground (excited) state $|\Phi_{100}|^2$ ($|\Phi_{210}|^2$) is plotted. The $y < 0$ part of the density is not plotted for a better appreciation of the inner part.
where $r_0^2 = 3\sigma/8\pi$.

If we now substitute the value of $\sigma$ from the equation (6) into $r_0$, we set $p = 3$, which implies $F(p) = 11.54$, we put $kT \sim 10^3\text{GeV}$ and we assume that $K \sim 10^9\text{cm}^{-3}$, we obtain that

$$\frac{dN_{\text{tot}}}{dtdE} \sim \frac{6.7 \times 10^{-4}}{\pi^2 E^2} \frac{1}{\text{GeV cm}^2\text{s}^{-2}\text{sr}} \quad (16)$$

which is very similar to the observed FB spectrum by FermiLat [32].

In conclusion, because of the quantum character of SFDM, this is the only DM model that allows predicting a DM density profile with bubbles, as in atoms. With this axially symmetric shape of the profile, the SFDM model is able to explain not only the rotation curves in the galaxies but also the observed anomalous behavior of the satellite galaxies, the VPOS, in a very natural way [1]. Now, in this work, we show that this DM profile can explain the FB observed in galaxies, provided that the SFDM has a milli-charge consistent with currents observational bounds. It is extremely interesting that the SFDM model can explain in such a natural way so many observable features of the galaxies and the cosmos, without further physical complications, even such unexpected observations as the VPOS or the FB. If this hypothesis is correct, we should see FBs in more large galaxies and gamma rays at higher energies in the near future.

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