Stable Compact Dark Matter Objects in Planetary Systems

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Abstract. Stable Compact Dark Matter Objects (SCDMO) of planet scale mass and much smaller radii are considered in planet systems with a central star on highly eccentric orbits of SCDMO crossing the star. Possible connections of the presence of these SCDMO in a planet system with specific interactions with planets and the star, in particular, with triggering of cycles of activity of the central star are suggested to study in experiments in the solar system.

1. Introduction
Stable Compact Dark Matter Objects (SCDMO) of planet scale masses are considered in this article to be gravitationally-bound objects from Dark Matter (DM) particles. These SCDMO may be almost stable relative the Antonov’s gravothermal instability [1], annihilation of particle-antiparticle pairs, evaporation [2], and tidal disruption by planets and the central star: SCDMO has to be much denser than centers of stars and may be much less massive than typical planets in the solar system.

The first fluctuations with masses about the Earth scale and radii about radius of the solar system [3-5] are typical for the high-redshift Universe in theories where the DM particles are cold (such as ΛCDM) and some of these fluctuations may be the origins for SCDMO at present. These properties of the initial fluctuations as well as SCDMO don’t depend on the unknown nature of dark matter particles, and on their masses, in particular.

The formation of such SCDMO of dark matter can be caused by rare super dense fluctuations in the spectrum of inflationary perturbations with subsequent phase transitions. It begins in the era of radiation dominance in Universe. The evolution of the central part of SCDMO occurs as a result of a gravothermal catastrophe [1] with the formation of an almost isothermal profile. Further, these high density SCDMO develop as isolated objects consisting of randomly unequal number of particles and antiparticles with high rate of annihilation up to the stable states from particles (SCDMO) or antiparticles (SCDMO) only. Because of high density these SCDMO can’t be destroyed by tidal interactions during the formation of the larger structures in Universe.

During the process of evolution of SCDMO, complete annihilation of all pairs of particles and antiparticles occurs. Therefore, SCDMO may be consisted either only of dark matter particles (SCDMO) or only of antiparticles (SCDMO) and have an average density much higher than densities in centers of stars to satisfy the Roche limit.

In the standard cold dark matter cosmological model, the energy density in the Universe is balanced by approximately 4% baryonic matter, 23% cold dark matter and 73% dark energy. Cold dark matter refers to gravitationally interacting matter that is hypothesized to be in the...
form of particles and antiparticles. From the particle physics aspect, new particles arise in almost all extensions to the standard model of particle physics, and the lowest mass particle is stable due to a new symmetry. Dark matter particle candidates include (among many others), neutralinos, the lightest Kaluza-Klein particle, axions, and sterile neutrinos. There is no a physical reason for one candidate to be more favorable than another, but neutralinos are the most studied because they are experimentally accessible at present. Neutralinos arise in supersymmetric extensions to the standard model of particle physics [6,7], and they are part of a class of dark matter candidates, called WIMPs (Weakly Interacting Massive Particles).

In cosmological models [3,4] with cold dark matter, structures are formed and grow as a result of contraction and combining smaller objects [5]. The simulation [8] reveals the tendency to quasi-fractal nature of DM clustering: the isolated dark matter objects contain the same relative amount of the substructure and both have internal density profiles with sharp edges.

The present understanding of SCDMO with the theoretical motivation for their presence in planet systems is discussed in this article. As well, possible connections of a SCDMO with direct and indirect appearance in planet systems such as specific interactions with planets and excitation of cycles of the activity of the central star are suggested to study in experiments.

2. Physical properties of SCDMO

In order to detect SCDMO in direct or indirect experiments, it is first necessary to determine the distribution of dark matter within the virialized region of SCDMO. This can be done by assuming a density distribution. The numerical works finds that dark matter within the virialized region is described by an NFW profile [9]:

\[
\rho(r) = \rho_s \left( \frac{r}{r_s} \right)^{-1} \left( 1 + \frac{r}{r_s} \right)^{-2},
\]

where \(\rho_s\) is the characteristic density, and \(r_s\) is the scale radius. These two parameters specify the density \(\rho(r)\), mass \(m(r)\), and mean density \(\bar{\rho}(r)\) of an isolated SCDMO at arbitrary distance from its center \(r\):

\[
m(r) = 4\pi \rho_s r_s^3 \left[\ln \left(1 + \frac{r}{r_s}\right) - \left(1 + \frac{r}{r_s}\right)^{-1}\right] \approx \frac{2\pi \rho_s r_s^2}{4} \left(1 + \frac{3r}{4r_s}\right)^{-1} \quad \text{at } r < r_s,
\]

\[
\bar{\rho}(r) = 3\rho_s \left( \frac{r_s}{r} \right)^3 \left[\ln \left(1 + \frac{r}{r_s}\right) - \left(1 + \frac{r}{r_s}\right)^{-1}\right] \approx \frac{3\rho_s r_s^2}{4r} \left(1 + \frac{3r}{4r_s}\right)^{-1} \quad \text{at } r < r_s.
\]

In the numerical simulations \(r_s\) is approximately equal to the virial radius \(r_{vir}\) of the SCDMO. Obviously, the real profile of SCDMO in a planet system has most likely evolved from this initial distribution of dark matter, to a distribution which is the result of tidal interactions with planets and the central star. These processes are very difficult to accurately model. Nevertheless, it is a reasonable assumption to consider the internal density profile for isolated SCDMO up to the distances where the mean densities satisfy the Roche limits in the planet system with a sharp edge at \(r > r_s\) as a model density distribution for all further estimations with

\[
\rho(r_s) \approx \frac{1}{4} \rho_s,
\]

\[
m(r_s) \approx \frac{8}{7} \frac{\pi \rho_s r_s^3}{4}, \quad \text{and}
\]

\[
\bar{\rho}(r_s) \approx \frac{3}{4} \rho_s.
\]

It should be noted that light SCDMO in planet systems are almost non-detectable on orbits with small (planet-like) eccentricity.
Another situation with SCDMO orbits at extremely high eccentricity is considered in this article. In this case SCDMO may be close to planet orbits and move inside the central star interacting sometimes strongly enough to produce some observable effects. Moreover, because of these interactions with the planets and with the extended Sun, the trajectory of this SCDMO is expected to be with high perihelion precession and strong fluctuations inside the Sun. Because SCDMO is assumed to be stable relative to tidal disruption even in the center of the central star the minimal possible mean density of SCDMO is determined by the Roche limit:

$$\rho_{SCDMO}(r_s) > 2.44^3 \rho_{star}(0). \quad (7)$$

Then at \( r = r_s \) equations (3,4) lead to the following stability relation for \( \rho_s \):

$$\rho_s > 25 \rho_{star}(0). \quad (8)$$

and equation (2) leads to estimation for the mass of SCDMO on extremely high eccentric orbit in the planetary system:

$$m_{SCDMO} > 61 r_s^3 \rho_{star}(0). \quad (9)$$

On the other hand \( m_{SCDMO} \) is limited in planetary system by astronomical observations of evolution of planet orbits (perihelion precessions and so on). In particular, in the solar system this means that

$$m_{SCDMO} \lesssim 10^{-6} M_\odot. \quad (10)$$

For radius of SCDMO the estimation (7) leads to

$$r_{SCDMO} \lesssim 10^3 km \quad (11)$$

with mean density

$$\bar{\rho}_{SCDMO} \sim 2 \frac{kg}{cm^3}. \quad (12)$$

3. Annihilation of SCDMO and gravitational waves

For the so dense SCDMO all particle-antiparticle pairs may be annihilated already and SCDMO are expected to consist purely from dark matter particles (SCDMO) or from dark matter antiparticles (\( SCDMO \)) and can’t be observed due to annihilation process inside SCDMO.

Nevertheless, binary systems of SCDMO-\( SCDMO \) could be observed, in particular, due to their annihilation at the merging stage, as well as due to radiation of gravitational waves, as well as specific for merging of SCDMO-SCDMO binary systems without the annihilation.

Another possibility to detect SCDMO is concerned with SCDMO on the highly eccentric orbit in the solar system due to radiation of a pulse of specific gravitational waves every 11 years at the solar cycle minimum when SCDMO is orbiting inside of the Sun.

4. Solar cycle periodicity and solar activity due to SCDMO on a highly eccentric orbit

Mean-field theory appears appropriate to describe the solar dynamo. The \( \alpha \Omega \) dynamo yields a cyclic mean magnetic field, including the butterfly diagram. In spite of this apparent success many difficulties persist. In particular, the solar cycle exhibits long-term variation: Most prominent is the Maunder minimum in the 17th century. There are essentially three ideas how to account for such grand minima and related variations within the framework of the \( \alpha \Omega \) dynamo: 1) Fluctuating \( \alpha \)-effect, 2) the path to chaos [10], and 3) a solar tsunami occurring in the Sun’s interior shear-fluid layer [11].

In this article the possible presence of SCDMO on a highly eccentric orbit in the solar system is suggested to consider as a trigger for the solar cycles. As well, this allows to predict trajectory
of SCDMO by searching for initial conditions for the highly eccentric orbit with period about 11 year and with excitations of the Sun by SCDMO to be close to the observed solar activity and then may be to detect SCDMO via to small anomalies in astronomical data.

For this purpose the differential equations for the solar system have been solved numerically at a special choice of initial conditions for point-like SCDMO, standard initial conditions [12] for all point-like planets, the center of finite-size Sun (in the standard solar model [13]), to consider triggering of the solar dynamo by SCDMO due to generation of magnetic fields and the dynamical friction [14-16] acting along the trajectory of the supersonic SCDMO inside the convective zone of the Sun in the orbital cycles with perihelion radius $r_{\text{per}} < r_{\odot}$:

$$\frac{d\vec{v}_{\text{SCDMO}}}{dt} = -4\pi \ln(\Lambda) G^2 m_{\text{SCDMO}} \rho_{\odot} (|\vec{r}_{\text{SCDMO}}(t) - \vec{r}_{\odot}(t)|) \frac{\vec{v}_{\text{SCDMO}}(t)}{v_{\text{SCDMO}}(t)^3},$$

where $\ln(\Lambda) \sim 10$ is the Coulomb logarithm at its convenient choice, $G$ is the Newton gravitational constant, $\vec{r}_{\text{SCDMO}}(t)$ and $\vec{v}_{\text{SCDMO}}(t)$ are coordinates and velocity of SCDMO on its trajectory.

Equation (13) lead to the following kinetic energy ($E_{\text{SCDMO}}$) loss by SCDMO in the each cycle of the SCDMO orbit associated with the solar cycle in this article:

$$\Delta E_{\text{SCDMO}} = 4\pi \ln(\Lambda) G^2 m_{\text{SCDMO}}^2 \int \rho_{\odot} (|\vec{r}_{\text{SCDMO}}(t) - \vec{r}_{\odot}(t)|) \frac{\vec{v}_{\text{SCDMO}}(t)}{v_{\text{SCDMO}}(t)^3} dt,$$

what is small enough to neglect:

$$\frac{\Delta E_{\text{SCDMO}}}{E_{\text{SCDMO}}} \sim \ln(\Lambda) \frac{m_{\text{SCDMO}}}{M_{\odot}} < 10^{-5}.$$ (15)

In addition to the kinetic energy-momentum losses the SCDMO induce an electrical current along its trajectory in the Sun and produce corresponding magnetic fields triggering the solar dynamo in solar cycles and drifting in convective zone to the solar surface.

In this way a solar cycle activity depends on the trajectory of SCDMO in the Sun (Figure 1). This trajectory is strongly dependent on interaction with the planets. The suitable initial conditions for SCDMO have been found to reproduce the solar activity from the Maunder minimum up to the present (Figure 1) and to predict a possible solar activity with the next minimum in the future. Therefore the SCDMO on the high eccentric orbit can play a role of a triggering clock for the solar cycle and essentially enhance the planet influence on the solar cycle amplitudes.

Figure 1. Solar cycle activities are presented in sunspot number index (red line), irradiance variation data (solid blue line) with 1-σ uncertainties (dashed blue lines), and the calculated excitations by SCDMO (black thick vertical line segments) at arbitrary scale.
5. Conclusion
SCDMO of planet scale mass are interesting, not only because they are linked to the nature of dark matter, but also because a detection of their presence in planet systems would provide insight into structure formation at extremely early times in Universe. SCDMO may be playing a role of a trigger in the solar cycle, that give a possibility to predict its trajectory exactly enough for direct observations of the SCDMO. The detection of SCDMO would first and foremost show that the dark matter particles are cold. In addition, it will place constraints on the value of the kinetic decoupling temperature and mass of the dark matter particle. Any detection of sub-planet mass SCDMO would provide insights into merging of binary SCDMO-SCDMO with radiation of gravitational waves and sometimes with annihilation (for SCDMO-SCDMO), a task unattainable by other observations. Sub-planet mass SCDMO are very interesting objects for further investigations.

References
[1] Padmanabhan T 1989 Astrophysical Journal Supplement Series 71 651
[2] Spitzer L and Saslaw W C 1966 Astrophysical Journal 143 400
[3] Peebles P J 1982 Astrophysical Journal 263 1
[4] Blumenthal G R, Faber S M, Primack J R and Rees M J 1984 Nature 311 517
[5] Diemand J, Kuhlen M, Madau P, Zemp M, Moore B, Potter D and Stadel J 2008 Nature 454 735
[6] Jungman G, Kamionkowski M and Griest K 1996 Phys. Rept. 267 195
[7] Bertone G, Hooper D and Silk J 2005 Phys. Rept. 405 279
[8] Diemand J, Kuhlen M, Madau P, Zemp M, Moore B, Potter D and Stadel J 2008 Nature 454 735
[9] Navarro J F, Frenk C S and White S D M 1996 Astrophysical Journal 462 563
[10] Stix M 2001 Astronomical and Astrophysical Transactions 20 417
[11] Dikpati M, McIntosh S W, Chatterjee S, Banerjee D, Yellin-Bergovoy R and Srivastava A 2019 Nature Scientific Reports 9 2035
[12] Folkner W M, Williams J G, Boggs D H, Park R S and Kuchynka P 2014 IPN Progress Report 42-196 1
[13] Christensen-Dalsgaard J 1998 Space Science Reviews 85 19
[14] Chandrasekhar S 1943 Astrophysical Journal 97 255
[15] Chandrasekhar S 1943 Astrophysical Journal 97 263
[16] Chandrasekhar S 1943 Astrophysical Journal 98 54