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Binary pulsars as probes of a Galactic dark matter disk

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ABSTRACT

As a binary pulsar moves through a wind of dark matter particles, the resulting dynamical friction modifies the binary's orbit. We study this effect for the double disk dark matter (DDDM) scenario, where a fraction of the dark matter is dissipative and settles into a thin disk. For binaries within the dark disk, this effect is enhanced due to the higher dark matter density and lower velocity dispersion of the dark disk, and due to its co-rotation with the baryonic disk. We estimate the effect and compare it with observations for two different limits in the Knudsen number (Kn). First, in the case where DDDM is effectively collisionless within the characteristic scale of the binary ($Kn \gg 1$) and ignoring the possible interaction between the pair of dark matter wakes. Second, in the fully collisional case ($Kn \ll 1$), where a fluid description can be adopted and the interaction of the pair of wakes is taken into account. We find that the change in the orbital period is of the same order of magnitude in both limits. A comparison with observations reveals good prospects to probe currently allowed DDDM models with timing data from binary pulsars in the near future. We finally comment on the possibility of extending the analysis to the intermediate (rarefied gas) case with $Kn \sim 1$.

1. Introduction

Unraveling the nature of dark matter (DM) is among the most fundamental frontiers of modern physics. Despite the growing body of gravitational evidence pointing to this new form of matter, its properties as a particle remain elusive. Given the lack of any convincing signature of non-gravitational DM interactions, the gravitational effect of DM on ordinary matter remains the only *direct* source of observational information about DM properties.

Among the many gravitational DM probes, binary pulsars have been recently proposed as a novel way of deriving model-independent upper bounds on the dark-matter density at different distances from the Galactic center [1]. The presence of DM modifies the binary's orbit due to dynamical friction as the binary moves through the DM ambient medium. Given the extraordinary precision achieved in the measurement of the orbital properties of pulsar binaries, it was concluded in [1] that these objects could be used to put constraints on the central DM density of the Milky Way. Isolated and binary pulsars have also been suggested to explore the scenarios of ultra-light DM candidates, see [2–5].

In this paper we argue that the potential of binary pulsars as precise probes of the DM distribution increases substantially if one assumes that a fraction of the DM in our galaxy is distributed in a thin disk coplanar and co-rotating with the luminous disk. Such a possibility is materialized in models such as the Partially Interacting DM (PIDM) scenario proposed by [6,7], where a small fraction of the DM can lose energy to collapse into a thin 'dark disk' (in an analogous way as ordinary matter assembles into disk galaxies). This so-called Double-Disk-Dark-Matter (DDDM) scenario has a distinct prediction for the DM phase space distribution in the disk, characterized by a high density, co-rotation with the luminous disk, and small velocity dispersion. Despite its striking features, the possibility of such dark disk remains observationally allowed [8] and there are already different methods suggested for its detection [9,10]. In the following we argue that all these effects increase the dynamical friction induced in binary systems. Remarkably, the enhancement is such that the sensitivities of current measurements of binary pulsars near the galactic plane are reasonably close to probe currently allowed DDDM scenarios. Notice that our results may be applied to any model where DM is expected to generate a disk with properties similar to those of the DDDM scenario, e.g. [11–14].

Our work is organized as follows: in Section 2 we summarize the features of the DDDM model relevant for our analysis. Section 3 describes the dynamical friction for the collisionless DM case and ignoring the interaction of the wakes. We also compare our predictions with observations in that section under the assumption of co-rotation of the DDDM dark disk with the center of mass

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of the binary. In Section 4 we extend this analysis to the case of large Knudsen numbers and including the wakes' interactions. We conclude and present our outlook in Section 5.

2. DDDM model

The DDDM scenario discussed in [6,7] proposes the existence of a subdominant component of the DM sector that has dissipative dynamics. It consists of a massless $U(1)_D$ gauge boson, with fine structure α_D and interactions with two new fields: a heavy fermion X and a light fermion C, with opposite charges $q_x = 1 = -q_C$ under $U(1)_D$. The thermal history of this scenario is described in detail in [6]. In the following, we only describe the elements of the formation of a dark disk relevant to our purposes.

The formation of a dark disk occurs in an analogous way to baryonic matter assembling into galactic disks. The fraction of DM that is dissipative would fall into the gravitational well of the protohalos predominantly made of the non-interacting DM fraction, which has acquired angular momentum through tidal torques with the surrounding environment. At the time of accretion, part of the DDDM might be in the form of atomic-like states made of heavy and light DM. These dark atoms will become fully ionized due to shock heating during the virialization of the halo leaving a population of free X and C fermions. This dark plasma cools through Compton scattering and Bremsstrhalung off background dark photons [15]. Since the plasma carries angular momentum it will form a rotationally supported dark disk as it dissipates energy and collapses due to gravity. Torques between the dark and baryonic disks will tend to align them into a steady configuration. In the following, we assume that this state has been reached with both disks being aligned and co-rotating.[1]

The cooling process is important in our discussion because it sets the *vertical* velocity dispersion of the disk, which is approximately given by the final temperature of the cooled plasma: $\sigma_z^2 \approx T_{\rm cooled}/m_X$, where m_X is the mass of the heavy fermion X. In [6], assuming the ionization fraction to be between 1% and 10%, the authors estimate $T_{\rm cooled} \sim (0.02 - 0.2)B_{XC}$, where $B_{XC} = \alpha_D^2 m_C/2$ is the binding energy of the ground state of the dark atom and m_C is the mass of the light fermion C. For instance, for $m_X = 100$ GeV, $m_C = 1$ MeV and $\alpha_D = 0.1$ this estimate results in $\sigma_z \sim 9.5$ km/s for the region of parameter space where cooling is efficient (see Fig. 5 and Fig. 7 of [6]). This dispersion is at least an order of magnitude smaller than the typical one in the solar neighborhood for a Milky-Way-size halo formed of collisionless DM particles ($\sigma_{1\rm D} \sim 100 - 130$ km/s; e.g. [16]), where the DM orbits are no longer circular. As we will see below, a low velocity dispersion plays a key role in the constraining power of binary pulsars in the DDDM scenario.

Simulations of the formation and evolution of a DDDM disk have not been performed yet, and thus its final distribution remains an analytical approximation, which has been modeled as an isothermal sheet [17], with a density given by:

$$\rho(R, z) = \frac{\epsilon_{\rm disk} M_{\rm DM}^{\rm gal}}{8\pi R_d^2 z_d} e^{-R/R_d} \,{\rm sech}^2(z/2z_d), \tag{1}$$

where R is the radial distance in the plane of the disk and z indicates the height above the disk midplane; R_d and z_d are the scale lengths of the disk in the radial and vertical directions, respectively. The mass fraction of DM in the halo of the Milky Way that could be in the form of a disk is denoted by $\epsilon_{\rm disk} \equiv M_{\rm DDDM}^{\rm disk}/M_{\rm DM}^{\rm gal}$. The parameters of the disk, regardless of the PIDM nature, are constrained by the kinematics of the stars in the solar neighborhood ($R = R_\odot$). In particular, the surface density of the disk below a certain height z_0,

$$\Sigma_{\rm disk}(R_\odot, |z| < z_0) \equiv \int_{-z_0}^{z_0} \rho(R_\odot, z)\,{\rm d}z\,, \tag{2}$$

is strongly constrained by local stellar kinematics for $z_0 \lesssim 1$ kpc. If the scale length R_d is assumed to be similar to that of the baryonic disk of the Milky Way, $R_d \sim 3$ kpc, and since the DDDM will be thin ($z_d \ll z_0 \sim 1$ kpc), then Eq. (2) reduces to:

$$\Sigma_{\rm disk}(R_\odot, |z| < 1\,{\rm kpc}) \sim \frac{\epsilon_{\rm disk} M_{DM}^{gal}}{2\pi R_d^2} e^{-R_\odot/R_d}. \tag{3}$$

Given that we are assuming $R_d \sim 3$ kpc and $R_\odot \sim 8$ kpc, and the total halo mass of the Milky Way is $\sim 10^{12}\,M_\odot$, then a constraint on Eq. (3) translates into a constrain on $\epsilon_{\rm disk}$. A compilation of current bounds on the local surface and volume densities of total matter and visible matter is given in [8] (see their Table 1). For instance, using the results from [18], the surface density of non-baryonic matter is constrained to be:

$$\Sigma_{\rm dark}(R_\odot, |z| < 1.1{\rm kpc}) = 30 \pm 4 \frac{M_\odot}{{\rm pc}^2}, \tag{4}$$

which implies $\epsilon_{\rm disk} < 0.025$, i.e., only a few percent of the total halo mass can be in the form of DDDM. An updated analysis on the constraints on a dark disk by [8] concluded that depending on the method (standard static or one including non-equilibrium features in the tracer stars), the upper bound (95% confidence interval) on $\Sigma_{\rm disk}$ lies between $3 - 13\ M_\odot/{\rm pc}^2$ for a thin disk ($z_d = 10$ pc), while for a thick disk ($z_d = 100$ pc), the upper bound changes to $7 - 32\ M_\odot/{\rm pc}^2$ (the bound for the non-equilibrium method was extracted from Fig. 10 of [8]). A thin dark disk model with these characteristics has been invoked to potentially explain the apparent periodicity of comet impacts on Earth [19]. One finds:

$$\rho_0^{\rm DDDM} \equiv \rho(R_\odot, z=0) = \frac{\Sigma_{\rm disk}(R_\odot)}{4z_d}, \tag{5}$$

$$\sigma_z^2 = 8\pi G \rho_0^{\rm DDDM} z_d^2, \tag{6}$$

for the midplane density and the vertical velocity dispersion of the disk, respectively. Thus, the stellar kinematic upper bounds on the dark disk, imply for a thick disk ($z_d = 100$ pc):

$$\rho_0^{\rm DDDM}({\rm thick}) \lesssim 3\ {\rm GeV/cm}^3, \quad \sigma_z({\rm thick}) \lesssim 9\,{\rm km/s}, \tag{7}$$

while for a thin disk ($z_d = 10$ pc):

$$\rho_0^{\rm DDDM}({\rm thin}) \lesssim 12\ {\rm GeV/cm}^3, \quad \sigma_z({\rm thin}) \lesssim 2\,{\rm km/s}. \tag{8}$$

This is the range of values of interest for our purposes.

3. Effect for collisionless DDDM and non-interacting wake pair

In this section we follow closely the approach of [1] and study a binary system with masses m_1 and m_2 moving through a distribution of *collisionless* DM with a local constant density $\rho_{\rm DM}$. This assumption is justified as long as the local mean free path for self-interactions is much larger than the characteristic scale of the DM wakes induced by dynamical friction in the orbital time of the binary. As done in [1], we ignore the possible interaction of the wakes. We comment on the collisional regime and the expected (small) influence of the wakes' interaction in Section 4.

[1] Even when this condition is not fully satisfied, a systematic study of all binary systems may allow to exclude the presence of a dark disk.