

## MONTE-CARLO SIMULATION OF NEUTRON STAR ORBITS IN THE GALAXY

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## ABSTRACT

In this paper, the numerical results concerning different orbits of a 3D axisymmetric non-rotating galactic potential are presented. We use Paczyński's gravitational potential with different birth velocity distributions for the isolated old Neutron Star (NS) population. We note some smooth non-constant segments corresponding to regular orbits as well as the characterization of their chaoticity. This is strongly related to the effect of different kick velocities due to supernovae mass-loss and natal kicks to the newly-formed NS. We further confirm that the dynamical motion of the isolated old NSs in the gravitational field becomes obvious, with some significant diffraction in the symmetry of their orbital characteristics.

*Key words:* Pulsar: general — galaxies: the Galaxy, gravitational potential — Galaxy: disk — galaxies: kinematics and dynamics — stars: statistics

## 1. INTRODUCTION

Isolated old ( $\geq 1$  Gyr) Neutron Stars (NSs) have attracted much attention because of the hope that their properties could be used to constrain poorly understood behavior (Haberl 2007; Kaplan 2008). Studying their orbital dynamics in a known gravitational potential is very significant to our understanding the Galactic gravitational field, as well as the evolution of the Galactic disk structure itself. One would hope that isolated old NSs may be detected as soft X-ray sources (0.5–2 keV) in the *eRosita* all-sky survey (Merloni et al. 2012; Doroshenko et al. 2014). Numerical simulations of isolated NSs have been made by many authors to determine their spatial distribution in the Galaxy (e.g. Paczyński 1990; Wei, et al. 2010; Taani, et al. 2012; Taani, 2014).

The aim of the present work is to improve the model developed in Wei et al. (2010) for studying the dynamical orbital evolution of isolated old NSs (excluding millisecond and binary pulsars and those in globular clusters) and their distribution as a function of their initial position distribution, initial velocity distribution and of the Paczyński Galactic gravitational potential. We adopt the velocity distributions of NSs at birth from Arzoumanian et al. (2002) and Faucher-Giguère and Kaspi (2006). We perform integration of NS velocities using Monte Carlo integration techniques with different conditions developed for this purpose. We also aim to obtain NS trajectories under a variety of assumptions.

## 2. GRAVITATIONAL POTENTIAL

We model the gravitational potential of the Galaxy following Paczyński (1990) (hereafter P90)

$$\Phi = \Phi_{sph} + \Phi_{disk} + \Phi_{halo} , \quad (1)$$

The basic components of the Milky Way are the visible *disk* ( $\Phi_{disk}$ ) and *spheroid* ( $\Phi_{sph}$ ), and the invisible dark matter *halo* ( $\Phi_{halo}$ ). For the bulge (spheroid), we adopt a Plummer sphere, and for the disk a Miyamoto-Nagai potential which is added in order to reproduce the scale length of the disk. For the dark matter halo we adopt a logarithmic (modified sphere) potential, which produces a flat rotation curve at large radius. These components are parametrized to match observations (see Miyamoto & Nagai 1975 and Paczyński 1990 for details).

The spherical Miyamoto-Nagai potential (1975) has the advantage that its potential can be calculated analytically. This can be described as

$$\Phi_i(R, z) = - \frac{GM_i}{\sqrt{R^2 + [a_i + (z^2 + b_i^2)^{1/2}]^2}}, \quad (2)$$

$$R^2 = x^2 + y^2, \quad (3)$$

where  $z$  is the vertical distance from the Galactic plane, and  $R$  the radial distance perpendicular to the Galactic central axis. The subscript “i” represents “sph” and “disk”, respectively. The numerical values of the parameters in the potential are, (for the spheroid component)  $a_{sph} = 0.0$  kpc,  $b_{sph} = 0.28$  kpc and  $M_{sph} = 1.12 \times 10^{10} M_{\odot}$ ; (for the disk component)  $a_{disk} = 3.7$  kpc,  $b_{disk} = 0.20$  kpc and  $M_{disk} = 8.01 \times 10^{10} M_{\odot}$ .

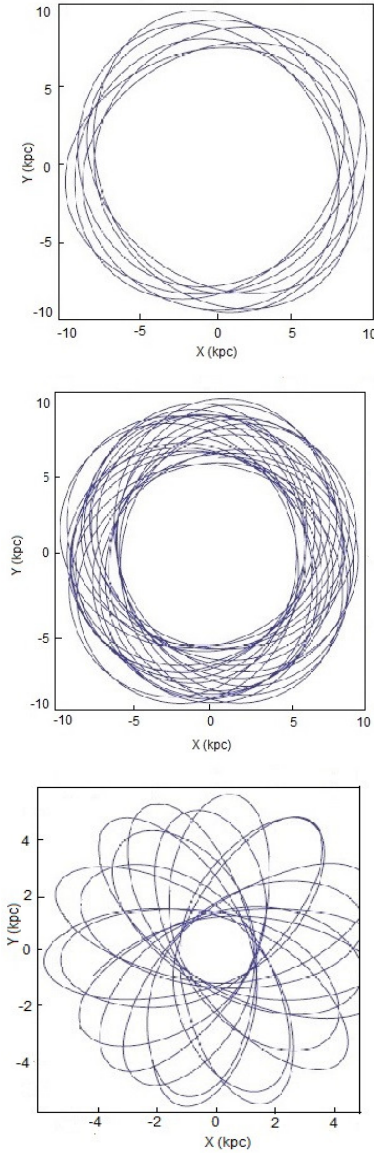


Figure 1. 3-D orbits of NSs. A typical orbit in the above gravitational potential forms a rosette orbit.

The halo component of the Galactic gravitational potential is:

$$\Phi_{\text{halo}} = \frac{GM_{\text{halo}}}{r_c} \left[ \frac{1}{2} \ln \left( 1 + \frac{R^2 + z^2}{r_c^2} \right) + \frac{r_c}{\sqrt{R^2 + z^2}} \arctan \left( \frac{\sqrt{R^2 + z^2}}{r_c} \right) \right] \quad (4)$$

where  $r_c = 6.0$  kpc and  $M_{\text{halo}} = 5.0 \times 10^{10} M_{\odot}$ . The initial circular rotation velocity of the NS is determined by

$$v_{\text{circ}} = \left( R \frac{d\Phi}{dR} \right)^{1/2}, \quad (5)$$

where  $\Phi$  is the Paczyński's gravitational potential in Eq. (2).

### 3. DISCUSSIONS AND CONCLUSIONS

Using Paczyński's gravitational potential we plot the Poincaré section for  $x > 0$ , and fix  $y = 0$  to investigate the dynamical 3-D orbits of NSs. We find that there are some non-symmetric orbits by varying the initial parameters as illustrated in Fig. 1. The dynamical evolution of NS orbit behavior can be understood in terms of the action of the Galactic gravitational field, with the effects of high supernova kick velocities on the initial orbital parameters, plus the physical properties during the accretion phase.

Future work will go further in detecting old NSs via accretion of the interstellar medium material which may make them radiate; and their weak luminosity could be then detected as soft X-ray sources (0.5–2 keV). However, the *eROSITA* all-sky survey has excellent potential for this kind of study, and it should significantly improve our knowledge of Galactic NSs over the next decade. *eROSITA* will be about 20 times more sensitive than the ROSAT all sky survey in the soft X-ray band (Merloni et al. 2012).

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