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Spatial distribution of the accretion luminosity of isolated neutron stars and black holes in the Galaxy

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Abstract. We present here a computer model of the spatial distribution of the luminosity, produced by old isolated neutron stars and black holes accreting from the interstellar medium. We show that the luminosity distributions in the Galaxy have a ring structure, with a maximum at $\approx 5kpc$ radius.

Key words: stars: neutron – black hole physics – Galaxy: stellar content

1. Introduction

Old isolated neutron stars (NS) and black holes (BH) form a large populations of galactic objects (about 10^8-10^9 objects in the Galaxy), but most of them are unobserved today. Less than 10^3 young NS appear as radio pulsars, and no isolated BH has been observed (probably, some of them are detected, for example, in the $ROSAT$ survey, but no one is identified). This article will be concerned only about isolated compact objects, that will simply designated as NS or BH.

During the last years, the spatial distribution and other properties of NS became of great interest, because NS can be observed by the *ROSAT* satellite in soft X-rays due to accretion from the interstellar medium (ISM) (see, for example, Treves & Colpi 1991). Several sources of this type have been observed (Walter et al. 1996). BH also can appear as similar X-ray sources (Heckler & Kolb 1996) with some differences in spectrum and temporal behaviour (absence of pulsations, for example). That is why we try here to obtain a picture of the distribution of the accretion luminosity of these sources.

Fast rotation and/or a strong magnetic field can prevent accretion onto the surface of the NS. In this case the X-ray luminosity will be very low (except for transient sources due to the formation of an envelope around the NS: see Popov 1994 and Lipunov & Popov 1995). Here we consider only accreting NS. Most NS are in the stage of accretion, because their magneto-rotational evolution usually finishes at this stage approximately 10^8 years after their birth. The NS properties (periods etc.) in the stage of accretion depend upon the magnetic field decay (see Konenkov & Popov 1997). BH, of course, can only be seen as accretors.

In the articles of Gurevich et al. (1993)and of Prokhorov & Postnov (1993, 1994) it was shown that the population of NS forms a ring (or toroidal) structure in the Galaxy. The distribution of the ISM (see, for example, Bochkarev 1992) also has a ring structure. The maxima of both distributions roughly coincide.

Therefore, most of the NS (and probably BH) are located in the dense regions of the ISM. Thus the accretion luminosity in these regions should be high. The results of computer simulations of this situation are presented in this paper.

The trajectories of NS and BH were computed directly for a specified initial velocity distribution, the Galaxy gravitational potential and the distribution of the ISM density. Preliminary results of such computations for NS for δ- function and maxwellian velocity distributions were presented in Popov & Prokhorov (1998, paper I).

In Sect. 2 we briefly describe our model. In Sect. 3 the results and a short discussion are presented. The last section contains the conclusions.

2. The model

We solved numerically the system of differential equations of motions in the Galactic potential, taken in the form (Paczynski 1990):

$$\Phi_i(R,Z) = GM_i / \left(R^2 + [a_i + (Z^2 + b_i^2)^{1/2}]^2 \right)^{1/2}$$

with a quasi-spherical halo with a density distribution:

$$\rho = \frac{\rho_0}{1 + (d/d_0)}, \quad d^2 = R^2 + Z^2.$$

Here R and Z are the cylindrical coordinates, d the radius in the quasi-spherical halo. The parameters of the potential are given in the following table, ρ_0 being determined from the halo mass, M_0.

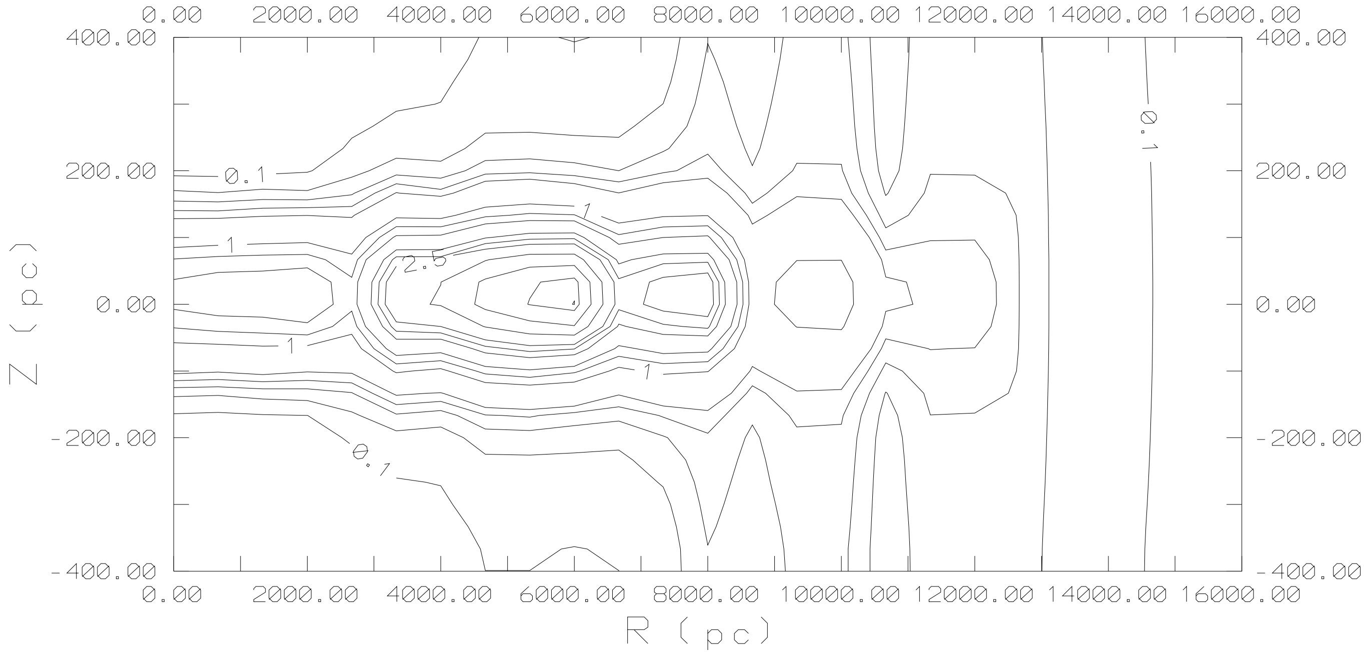

Fig. 1. The density distribution in particle per cubic centimeter in the R-Z plane.

Disk	a_D=0	b_D=277 pc	$M_D = 1.12 \cdot 10^{10} M_\odot$
Bulge	a_B=3.7 kpc	b_B=200 pc	$M_B = 8.07 \cdot 10^{10} M_\odot$
Halo		d_0=277 pc	$M_0 = 5.0 \cdot 10^{10} M_\odot$

The density in our model is constant in time. The local density is calculated using data and formulae from Bochkarev (1992) and Zane et al. (1995). n is total gas density, n_{HI} and n_{H_2} are the densities of the neutral and molecular hydrogen, $n_0(R)$, $n_2(R)$ and $n_3(R)$ are the values of the densities for $Z = 0$.

$$n(R, Z) = n_{HI} + 2 \cdot n_{H_2}$$

$$n_{H_2} = n_2(R)\, exp \left[\frac{-Z^2}{2 \cdot (70pc)^2} \right]$$

For $0\, kpc \le R \le 3.4\, kpc$ we assumed:

$$n_{HI} = n_0(R) exp \left[\frac{-Z^2}{2 \cdot (140\, pc \cdot R/2\, kpc)^2} \right],$$

For $0\, kpc \le R \le 2\, kpc$ $n_0(R)$ was assumed to be uniform:

$$n_0(R < 2kpc) = n(R = 2kpc)$$

Of course, this is not accurate for small R, so for the very central part of the Galaxy our results are only a rough estimate (see Zane et al. (1996) for detailed calculation of the NS emission from the Galactic center region). For $3.4\, kpc \le R \le 8.5\, kpc$ we assumed

$$n_{HI} = 0.345\, exp \left[\frac{-Z^2}{2 \cdot (212\, pc)^2} \right] +$$

$$0.107\, exp \left[\frac{-Z^2}{2 \cdot (530\, pc)^2} \right] +$$

$$0.064\, exp \left[\frac{-Z}{403\, pc} \right]$$

For $8.5\, kpc \le R \le 16\, kpc$ we assumed

$$n_{HI} = n_3(R)\, exp \left[\frac{-Z^2}{2 \cdot (530\, pc \cdot R/8.5\, kpc)^2} \right]$$

$n_0(R)$, n_2 and $n_3(R)$ being taken from Bochkarev (1992).

The total gas density distribution in the R-Z plane used in our computations is shown in Fig. 1.

In our model we assumed that the birthrate of NS and BH is proportional to the square of the local density. Stars were assumed to be born in the Galactic plane (Z=0) with circular velocities plus additional isotropic kick velocities.

For the kick velocity distribution we used the formula from Lipunov et al. (1996). This formula was constructed as an analytical approximation of the three-dimensional velocity distribution of radio pulsars from Lyne & Lorimer (1994).

$$f_{LL}(V) \propto \frac{x^{0.19}}{(1 + x^{6.72})^{1/2}},$$

V being the space velocity of the compact object, V_{char} a characteristic velocity, $x = V/V_{char}$ and f_{LL} the probability (see the detailed description of the analytical approximation in Lipunov et al. (1996)). This formula reproduces the observed distribution with a mean velocity of 350 km/s for V_{char}=400 km/s. This velocity distribution seems more likely than a δ- function and a Maxwellian distribution, which we used in Paper I. Kick velocities were taken equal for the NS and the BH. It is possible however that BH have lower kick velocities because of their higher masses (see White and van Paradijs, 1996). One of

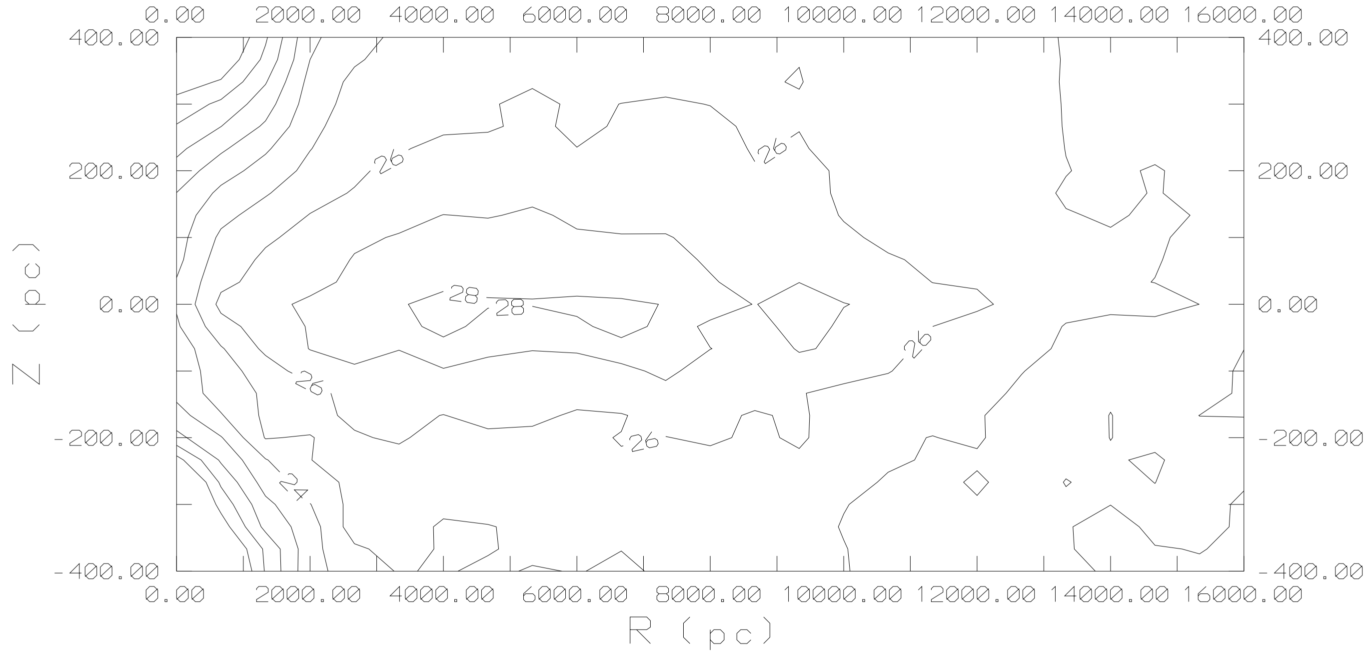

Fig. 2. The accretion luminosity distribution in the R-Z plane for neutron stars for a characteristic kick velocity 200 km/s. The luminosity is in ergs per second per cubic parsec. $N_{NS} = 10^9$

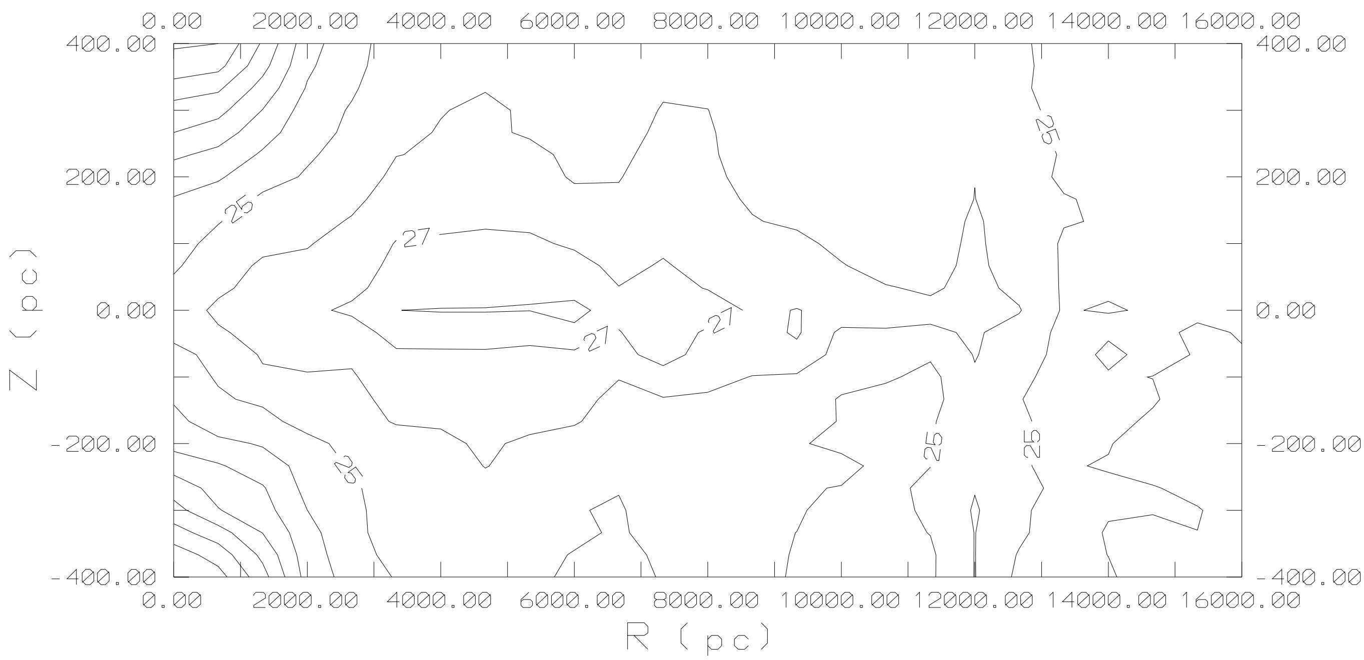

Fig. 3. The accretion luminosity distribution in the R-Z plane for neutron stars for a characteristic kick velocity 400 km/s. The luminosity is in ergs per second per cubic parsec. $N_{NS} = 10^9$

the reasons to make computations for V_{char}=200 km/s was to explore this situation.

For each star we computed the exact trajectory and the accretion luminosity. The accretion luminosity was calculated using Bondi's formula:

$$L = \left(\frac{GM\dot{M}}{R_{lib}}\right)$$

$$\dot{M} = 2\pi\left(\frac{(GM)^2\rho(R,Z)}{(V_s^2+V^2)^{3/2}}\right)$$

.

The sound velocity, V_s, was taken to be 10 km/s everywhere. We used a mass $M_{NS} = 1.4 M_{\odot}$ for NS and $M_{BH} = 10 M_{\odot}$ for BH. $\rho = n m_H$ is the density, m_H being the mass of the hydrogen atom. The radii, R_{lib}, where the energy is liberated,

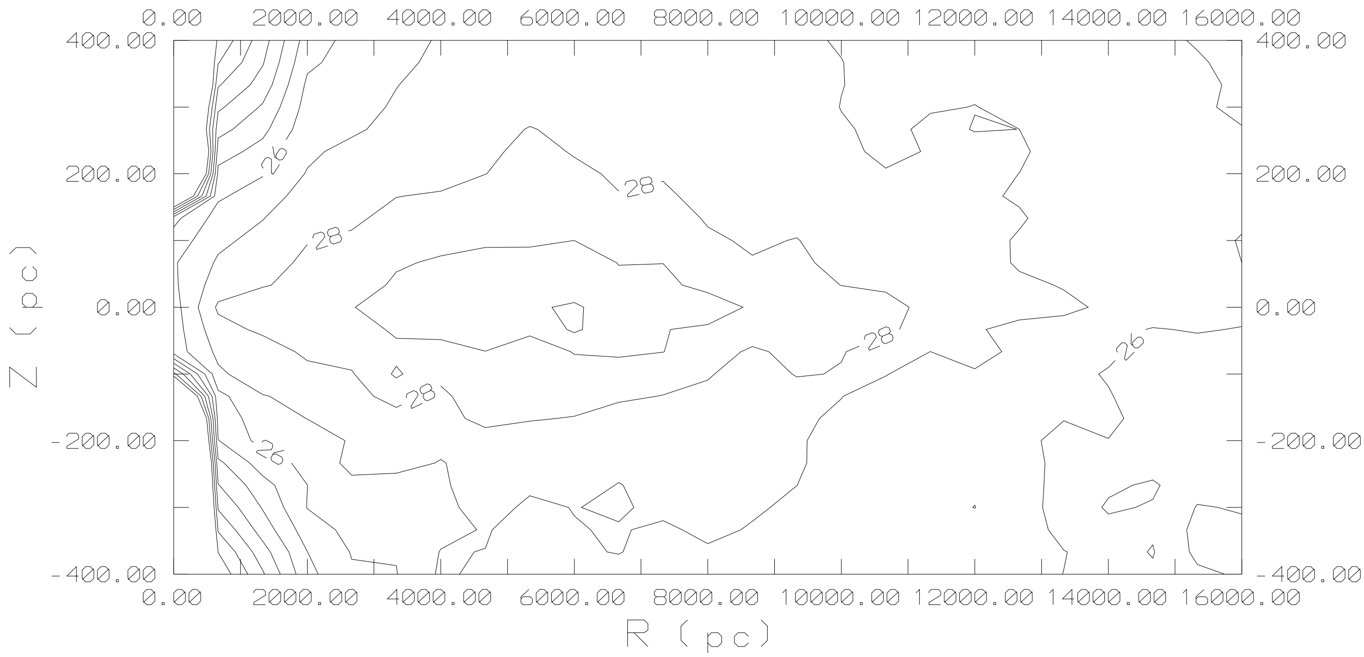

Fig. 4. The accretion luminosity distribution in the R-Z plane for black holes for a characteristic kick velocity 200 km/s. The luminosity is in ergs per second per cubic parsec. N_{BH} = 10^8

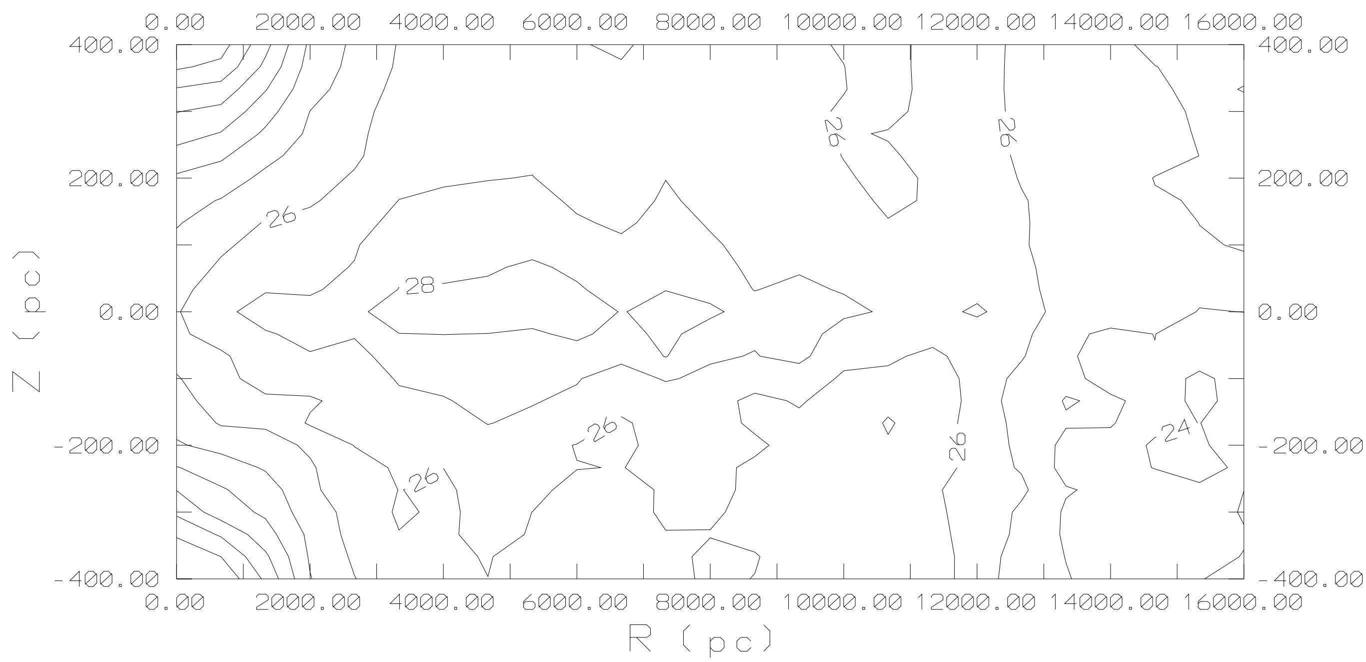

Fig. 5. The accretion luminosity distribution in the R-Z plane for black holes for a characteristic kick velocity 400 km/s. The luminosity is in ergs per second per cubic parsec. N_{BH} = 10^8

were assumed to be equal to 10 km for NS and 90 km (i.e. $3 \cdot R_g$, $R_g = 2GM/c^2$) for BH. Calculations used a grid with a cell size 100 pc in the R-direction and 10 pc in the Z-direction. The luminosity is given on the figures in ergs per second per cubic parsec.

For the normalization of our results we assumed that $N_{NS} = 10^9$ and $N_{BH} = 10^8$ in the considered volume of the Galaxy. For a Salpeter mass function with α=2.35 the ratio of NS to BH is about 10 if NS are formed from stars with masses between $10M_\odot$ and $\approx 45-50M_\odot$, and BH from stars with masses higher than $\approx 45-50M_\odot$. Motch et al. (1997) argued that $N_{NS} = 10^9$ can be ruled out, $N_{NS} = 10^8$ being a more probable value, but for the calculations of the distribution the total number is not so important, and for other numbers of compact objects the results (i.e. the value of the luminosity) can be easily scaled. It should be mentioned, as suggested by the unknown referee,

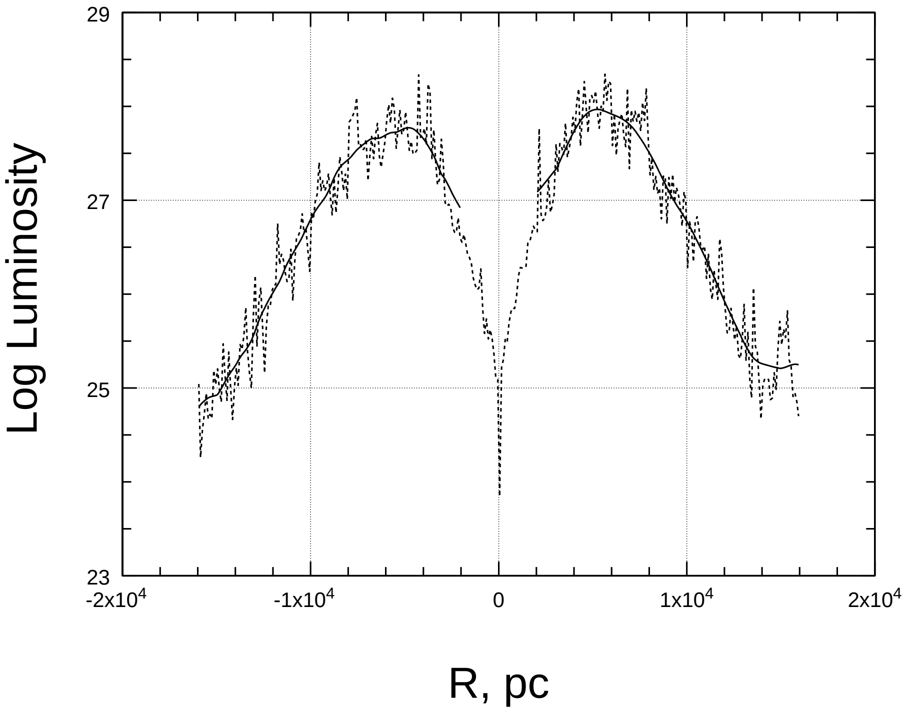

Fig. 6. Slice at Z=+5 pc for NS for a characteristic kick velocity 200 km/s. N_{NS} = 10^9. The accretion luminosity is in ergs per second per cubic parsec. The solid line is a smoothed curve.

that N_{NS} = 10^9 is required to explain that the present heavy element abundance in the Galaxy is about Z=0.02.

3. Results and discussion

In Figs. 2-5 we show as a radial cut through the Galactic disk the results for two characteristic values of the velocity distribution for NS and BH. The scales for R and Z axes are different in order to show clearly the structure in Z direction. Differences between the luminosity distribution for $Z > 0$ and $Z < 0$ demonstrate the accuracy of the statistical computations (curves were not smoothed).

Fig. 6 shows the luminosity in the Galactic plane as a function of radius for a characteristic kick velocity V_{char}= 200 km/s. The figure is not completely symmetric. The right hand part corresponds to the azimutal angles 0-180 degrees, the left to – 180-360 degrees. The differences between the left and the right parts of the curve give an indication of the accuracy of our computations.

4. Concluding remarks

As can be seen from the figures, the distribution of the accretion luminosity in R-Z plane forms a toroidal (ring) structure with maximum at approximately 5 kpc.

As expected, BH give higher luminosity than NS, as they have greater masses. But if the total number of BH is significantly lower than the number of NS, their contribution to the luminosity can be less than the contribution of NS. The total accretion lumiunosity of the Galaxy for N_{NS} = 10^9 and N_{BH} = 10^8 is about $10^{39} - 10^{40}$*erg/s*. For a characteristic velocity of 200 km/s the maximum of the distribution is situated approximately at 5.0 kpc for NS and at 4.8 kpc for BH. For NS with a characteristic velocity of 400 km/s maximum is located at 5.5 kpc, and for BH at 5.0 kpc. This result is also expected because of the higher masses of the BH.

The toroidal structure of the luminosity distribution of NS and BH is an interesting and important feature of the Galactic potential. As one can expect, for low characteristic kick velocities and for BH we have a higher luminosity.

As we made very general assumptions, we argue, that such a distribution is not unique for our Galaxy, and all spiral galaxies can have such a distribution of the accretion luminosity, associated with accreting NS and BH.

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