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Letter to the Editor

Planets orbiting Quark Nova compact remnants

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Abstract. We explore planet formation in the Quark Nova scenario. If a millisecond pulsar explodes as a Quark Nova, a protoplanetary disk can be formed out of the metal rich fall-back material. The propeller mechanism transfers angular momentum from the born quark star to the disk that will go through viscous evolution with later plausible grain condensation and planet formation. As a result, earth-size planets on circular orbits may form within short radii from the central quark star. The planets in the PSR 1257+12 system can be explained by our model if the Quark Nova compact remnant is born with a period of ~0.5 ms following the explosion. We suggest that a good portion of the Quark Nova remnants may harbour planetary systems.

Key words. pulsars: individual: PSR 1257+12 – planetary systems: formation

1. Introduction

The first planetary system beyond our own was found orbiting the millisecond pulsar PSR 1257+12 (Wolszczan & Frail 1992; Wolszczan 1994). There are observations of three planets, $M_1 = 0.015 M_\oplus / \sin i_1$, $M_2 = 3.4 M_\oplus / \sin i_1$ and $M_3 = 2.8 M_\oplus / \sin i_3$, with the semimajor axes $r_1 = 0.19$ AU, $r_2 = 0.36$ AU and $r_3 = 0.47$ AU, respectively. Here i_i is the inclination of the orbit with respect to the observer. The planets have very small eccentricities, i.e. their orbits are practically circular. The nature and origin of these planets is still unknown and debated (see e.g. Lin et al. 1991; Phinney & Hansen 1993; Podsiadlowski 1993; Miller & Hamilton 2001). Models can be divided roughly into two classes depending on whether the planets are formed before or after the supernova (SN) explosion. In the pre-SN scenarios the planets form in a planetary disk before their host star exploded as a supernova. In the PSR 1257+12 system the three innermost planets would have been inside the envelope of the progenitor star before the explosion, evaporating or spiraling to the center of the star. Planets surviving the supernova explosion could have been far away from the star, and they could have migrated to their present distances. It is argued that this scenario is not very probable (Miller & Hamilton 2001). It has also been argued that the explosion would unbind planets initially present, and any remaining planets would have high eccentricities (Podsiadlowski 1993).

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More attention has been focused on post-SN scenarios. Summarizing the work of Miller & Hamilton (2001), it was found that if the planets form before or during the possible spin-up period of the pulsar (following accretion from a companion star which may also provide the disk material) they will be evaporated by the accretion luminosity unless the disk is thick enough. If the planets are formed after the spin-up they must be created from some remnant disk, but then the particle luminosity from the neutron star (NS) is sufficient to disperse a tenuous disk material faster than it can be supplied. Added to that, the disk must be optically thick to the high energy particles of the pulsar wind as to allow for planet formation. That is, the disk must have a mass of at least $\sim 10^{28}$ g inside a radius of 0.19 AU (the radius of the innermost planet in the PSR 1257+12 system; see Miller & Hamilton 2001 for more details). The SN recoil scenario (Phinney & Hansen 1993) where the NS receives a kick in the direction of the companion as to capture enough matter from the companion is favored. This scenario also implies that many isolated NSs (maybe up to around 10%) may have planets in orbit around them and must thus await further observational evidence.

In general, it seems that very special circumstances are required to produce planets around a pulsar. Any model must demonstrate that the disk can expand to the appropriate radius with suitable conditions for planet formation on reasonable time scales (Bodenheimer 1993). Furthermore, the mechanism cannot be too efficient, or otherwise more planetary systems would have been observed around the other nine isolated millisecond pulsars in the Galactic disk. In this letter, we offer an alternative model related to the Quark Nova (QN) phenomenon (Ouyed et al. 2002, 2003). In the QN explosion a protoplanetary disk forms from the fall-back matter. The disk matter gains angular momentum from the central quark star (QS) via the propeller mechanism. The effect of viscosity on the disk evolution later allow for planet formation. We describe these features and show how the points mentioned earlier are dealt with.

This letter is presented as follows: In Sect. 2 we review the concept of QN. Section 3 deals with the angular momentum transport and the disk formation. The evolution of the disk is described in Sect. 4 where planetary formation is briefly discussed. We conclude by applying our model to the PSR 1257+12 system in Sect. 5.

2. Quark Nova

In the QN scenario (see Ouyed et al. 2002, 2003) the quark core of a neutron star (NS) shrinks to the corresponding stable compact/quark object before the contamination of the entire star. By contracting, and physically separating from the overlaying material (hadronic envelope which is mostly made of crust material), the core drives the collapse (free-fall) of the left-out matter leading to both gravitational energy and phase transition energy release as high as 10^{53} ergs. The QN-ejecta consist mainly of the NS metal-rich material outer layers. The accretion rate of the corresponding fall-back material is (see Ouyed et al. 2003)

$$\dot{m} \simeq 10^{28}\,\mathrm{g/s}\left(\frac{\rho_{\rm ff}}{10^6\ \mathrm{g/cm^3}}\right)\left(\frac{R}{10\,\mathrm{km}}\right)^{3/2}\left(\frac{M}{1.5\,M_\odot}\right)^{1/2}, \tag{1}$$

where $\rho_{\rm ff}$ is the density of fall-back matter (10^6 g/cm^3, representing the neutron star crust material), R is the radius of the QS and M its mass.

The rotational period of the newly formed QS can easily spin up to millisecond periods (here we adopt a period of $P = 2$ ms) and acquire magnetic field of the order of $B \simeq 10^{13}$–10^{15} G. The newly born QS is defined by three characteristic radii: the Keplerian "co-rotation radius"

$$R_{\rm c} = 27\,\mathrm{km}\left(\frac{M}{1.5\,M_\odot}\right)^{1/3}\left(\frac{P}{2\,\mathrm{ms}}\right)^{2/3}, \tag{2}$$

the magnetospheric radius at which the ram pressure of the infalling matter balances the magnetic pressure

$$R_{\rm m} = \left(\frac{B^2R^6}{2\dot{m}\sqrt{2GM}}\right)^{2/7} = 55\,\mathrm{km}\left(\frac{B}{4\times10^{14}\,\mathrm{G}}\right)^{4/7} \times\left(\frac{10^{28}\,\mathrm{g/s}}{\dot{m}}\right)^{2/7}\left(\frac{R}{10\,\mathrm{km}}\right)^{12/7}\left(\frac{1.5\,M_\odot}{M}\right)^{1/7}, \tag{3}$$

(see, e.g. Frank et al. 1992), and the light cylinder

$$R_{\rm lc} = \frac{c}{\Omega} = 96\,\mathrm{km}\left(\frac{P}{2\,\mathrm{ms}}\right)\cdot \tag{4}$$

Given our fiducial values, the QS is born in the propeller regime, i.e. $R_{\rm c} < R_{\rm m} < R_{\rm lc}$ (Schwartzman 1970; Illarionov & Sunyaev 1975), where the infalling material may be accelerated in a wind that carries away angular momentum from the magnetosphere and hence from the QS itself. It is plausible that a reasonable fraction of QNe remnants undergo a propeller phase after the explosion.

The angular momentum propelled away per unit time is (Menou et al. 1999)

$$\dot{L}_{\rm prop.} = 1.9\times10^{45}\,\mathrm{erg}\left(\frac{\dot{m}}{10^{28}\,\mathrm{g/s}}\right)\left(\frac{R_{\rm m}}{55\,\mathrm{km}}\right)^2\left(\frac{2\,\mathrm{ms}}{P_{\rm i}}\right)\cdot \tag{5}$$

The total angular momentum released in approximately 100 s (the propeller lifespan; see Ouyed et al. 2003) is thus of the order of 1.9×10^{47} erg · s carried away by 10^{30} g of fall-back material. We note that a QS period can be as small as 0.5 ms with the limit set by the Kepler frequency (e.g., Glendenning 1997). In most cases the fastest spin period is smaller than 1 ms; this is close to the limit on how fast a gravitationally bound star (like NS) can rotate before being ripped off by centrifugal forces. That is, the angular momentum extracted by the propelled matter can easily be as high as $\sim10^{48}$ erg · s if $P_{\rm i} \sim 0.5$ ms. It is still only 5−10% of the total initial angular momentum of the QS. Energy losses by gravitational waves are likely to be important for very short periods of QS, spinning down the star. Therefore much larger angular momentum transfers than described above are possible only in a very short period of time (some seconds), which requires larger accretion rates and therefore larger amounts of fall-back matter.

Using Eq. (11) in Ouyed et al. (2003), we estimate that in 100 s, the QS with $P_{\rm i} = 2$ ms would have spun down (due to the propeller) by 30% to reach a $P_{\rm f} = 2.6$ ms period. Given the initial rotational energy of the QS

$$E_{\rm i,rot.} = 5.9\times10^{51}\,\mathrm{erg}\left(\frac{M}{1.5\,M_\odot}\right)\left(\frac{R}{10\,\mathrm{km}}\right)^2\left(\frac{2\,\mathrm{ms}}{P_{\rm i}}\right)^2, \tag{6}$$

this implies $\sim2\times10^{51}$ erg in rotational energy is lost to the propelled material.

3. Torus formation

In order to keep some material bound to the star the propelled matter must first interact with the dense infalling matter, releasing energy and angular momentum to it. Indeed, the potential energy of the propelled matter, $-GMm_{\rm prop.}/R \sim -10^{50}$ erg, is not small enough in comparison to its rotational energy. The most realistic view of the process is the following: the matter propelled away will collide with the infalling matter. From the numbers above it is straightforward to see that propelled matter should interact with 10−20 times more matter (from the surroundings) to remain bound. This mixed matter (the propelled and the falling-back matter exchanging the angular momentum) through viscous effects evolves into a torus. The more accurate study of the angular momentum transfer between the propelled matter and the surroundings would certainly require the use of numerical simulations and is beyond the scope of this paper. Here, and in order to carry on with our investigation, we assume that the outcome of this process is a torus or a protoplanetary disk.

The evolution of the torus is governed by the angular momentum transfer due to turbulent viscosity (Shakura & Sunyaev 1973)

$$\nu = \alpha c_{\rm s} H = \alpha \frac{c_{\rm s}^2}{\Omega} = \alpha \Omega H^2 \,, \tag{7}$$

where the parameter $\alpha \simeq (H_{\rm t}/H)(v_{\rm t}/c_{\rm s}) \leq 1$. Here, $H_{\rm t}$ is the largest eddy size while H is the vertical height of the disk. The radial diffusion timescale is $\tau_\nu(r) \simeq r^2/\nu$, and if the viscosity is described by the above expression for α, the viscous evolution time of this torus is $\tau_\nu(r) = \alpha^{-1}(r/H)^2\Omega^{-1}$ where $\Omega(r)$ is the angular velocity at radius r. That is, the torus will expand within a few seconds to a distance of 10^3–10^4 km since $r/H \sim 1$ (the ratio of the disk radius and the scale height) and assuming $\alpha \sim 0.01$–1.

In these early phases the accretion to the QS is large, so the viscous time scale for most of the torus to be accreted is at best a few Keplerian orbital times. Nevertheless, we expect the star to remain bare for two reasons: i) the propeller is still efficient at deflecting matter and ii) the star's surface temperature is very high (>10 MeV). Therefore, it is natural to expect that any normal matter that managed to evade the propeller is ejected away as a hot wind[1]. The torus is also very dense and would likely survive the hot wind and any radiation field.

4. Disk formation and evolution

The torus described above will further expand to form a disk. The formation and evolution of such a disk is also governed by the angular momentum transfer due to turbulent viscosity. While most of the matter is accreted to the QS, most of the angular momentum is carried out with the part of matter demigrated to some larger distances.

If one approximates $H \sim (0.01 - 0.1)r$ and $\alpha \sim 0.01$, the viscous timescale for the disk reaching $r = 1$ AU is $\tau_\nu(r) \sim 10^3$–10^5 yrs. The volume of a disk with $r \sim 10^{13}$ cm and with a scale height $H \sim 10^{12}$ cm is roughly $\pi r^2 H \sim 10^{38}$ cm^3. With the total mass of 10^{28}–10^{29} g, the average density is 10^{-10}–10^{-9} g/cm^3, corresponding to an average proton density of 10^{14}–10^{15} cm^{-3}. The number density of particles is expected to be lower since the disk is rich in heavy nuclei.

At later stages, the QS surface temperature would have decreased allowing for crust formation (channelled along the field line). The kinetic energy of the subsequently accreted gas may be transformed into emission of the QS atmosphere in the following way (e.g., Xu 2000): The magnetic field channels the gas motion along the field lines to the QS. In this case, the kinetic energy of ions at the surface is about 100 MeV/nucleon, which is 5 times greater than the Coulomb barrier at the quark surface (Alcock et al. 1986). Accreted particles penetrate through the quark surface, and they are dissolved into quark matter. As a result, the quark core is heated at the magnetic poles. The process of heat transport through the core is very fast because of the very high heat conductivity of quark matter, and therefore the quark core is nearly isothermal. Then the energy that is released in the process of gas accretion is radiated from the normal-matter atmosphere (the crust) more or less isotropically. However, this process occurs much later in the evolution, the disk then being geometrically thin enough to survive photodissociation as discussed below.

The luminosity can be estimated conservatively as follows: if all matter from the disk is accreted to the central object within reversed viscous timescale, the rate should be at most $\sim 10^{29}$ g/10^5 yr $\sim 3 \times 10^{16}$ g/s, which is roughly 0.03 of the maximum rate corresponding to the Eddington luminosity. When accreted to the surface of the QS, the total released energy in radiation is $L = \eta \dot{m} c^2$, where η is the accretion efficiency; in our case conservatively $\eta \sim 0.15$ (it seems appropriate as a first approximation to take the accretion efficiency of QSs to be close to that of black holes and of neutron stars). The QS luminosity, the disk geometry and viscous dissipation will define the temperature of the disk. The dissipation can be neglected considering the above mentioned accretion rates (see e.g. Ruden 1993). The black body temperature of a perfectly absorbing plane with its surface inclined at an angle $\tan\beta = H/2r = 0.005$ to the radiation is $T = [L \tan\beta/(\sigma 4\pi r^2)]^{1/4} \sim 1330$ K at $r = 0.2$ AU and less than 600 K at $r = 1$ AU (using $\eta = 0.15$). Conservative upper limits to the temperature are 3500 K and 1600 K, respectively, if we assume $L = L_{\rm E}$ (Eddington luminosity). Lower luminosities and temperatures are plausible in our case where a rapidly rotating compact object accretes matter which in the very final stages almost corotates with the surface. Therefore the efficiency can be small ($\eta \sim 0.05$; Sibgatullin & Sunyaev 2000; the matter "softly" lands onto the surface).

Since the baryon density of the disk is $n \sim 10^{14}$–10^{15} cm^{-3}, the mean free path of photons is $\lambda = 1/(n\sigma_{\rm T}) \sim 10^9$–$10^{10}$ cm. Therefore radiation does not penetrate the inner parts of the optically thick disk, and it can cool to the temperatures estimated above. Added to that, the high energy wind particles cannot penetrate it either, since the Coulomb cross section is larger than the Thomson cross section. Therefore the disk can easily protect the forming dust grains (and later planetesimals) from the possible radiation of the QS. Iron and most of the other chemical components will condense into dust grains when the disk has cooled to temperatures below 1500 K (see e.g. Lewis 1995). The condensation timescale for different dust grains (e.g. Sedlmayr 1994) can range from a few months to several tens of years. The dense metal rich environment with a viscous timescale that is longer than the condensation timescale makes the QN disk suitable for dust grain formation. The growth of these grains and later planetesimals (see e.g. Lissauer 1993; Ruden 1999) will lead to the plausible formation of planetary bodies up to a few earth masses, with small (up to few AU) circular orbits.

5. The PSR 1257+12 system

Before applying our model to the case of PSR 1257+12, we note that there has been some observational evidence of a planet or a companion orbiting the pulsar system PSR 1620-26,

[1] The physics for calculations of gas outflow from the crust is similar for both NSs and QSs (Usov 1997).

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with a mass around $0.01\,M_\odot/\sin i$ and the semimajor axis of around 40 AU (Joshi & Rasio 1997). This is however a triple system in a globular cluster and the formation history might be very different from the one we are considering here (see e.g. models of Sigurdsson 1993; Ford et al. 2000).

The three confirmed planets of the PSR 1257+12 have a total mass of $\sim 4 \times 10^{28}$ g. Most of the disk material (more than 90%) in our model would have fallen back to the QS leaving only $(0.01 - 0.1) \times 10^{30} = 10^{28} - 10^{29}$ g orbiting the QS. The total angular momentum of the PSR 1257+12 planets is $\sim 1.3 \times 10^{48}$ erg · s, which is an order of magnitude higher than our estimates (see Sect. 2.). This can be accounted for (without stretching the model) by considering a longer propeller life span ($\gg$100 s) and/or a faster spinning QS ($P_{\rm i} \sim 0.5$ ms), which could then provide as much angular momentum as there is in the PSR 1257+12 planets[2].

The difficult challenge, however, is to explain the dipole magnetic field of PSR 1257+12 which is estimated[3] at $B \approx 8.8 \times 10^8$ G. With such a weak field the propeller would not have worked making it difficult to form a protoplanetary disk. In our model, the role of the propeller is two-fold: i) it supplies enough angular momentum for disk formation and ii) it delays the formation of the crust thus drastically reducing accretion luminosity and stellar wind during the early stages of disk formation. One possibility is that the magnetic field has decayed. While this hypothesis would have difficulty if PSR 1257+12 is a NS (see Camilo et al. 1994 for a discussion) this is not necessarily the case if one assumes that PSR 1257+12 is a QS: an interesting feature of such an object is the plausible decay of the magnetic field due to the Meissner effect at its surface (Ouyed et al. 2003b), a notion which remains to be confirmed. We thus argue that PSR 1257+12 might be a QN compact remnant (born as a millisecond QS) which experienced such a phenomenon. Finally, comparing the QN rate of 1 per million years per galaxy to that of the SN rate of 2×10^4 per million years per galaxy, on average 1 in 2×10^4 compact objects are QN remnants. We suggest that a good portion of this QS population may harbour a planetary system as described in this work.

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[2] However, if the speculated large outer planet does exist (Wolszczan 1996; Joshi & Rasio 1997), the angular momentum will be far too small to explain its formation via the mechanism described here, even if parameters are stretched to their limits.

[3] PSR 1257+12 has a period of $P = 6.219 \times 10^{-3}$ s, and a period derivative of $\dot{P} = 1.2 \times 10^{-19}$, which implies a dipole magnetic field of $B = 3 \times 10^{19} (P\dot{P})^{1/2} \approx 8.8 \times 10^8$ G in the standard magnetic dipole radiation spin-down models.