GALACTIC COLLAPSED OBJECTS

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Abstract

Our Galaxy contains some $10^8 \div 10^9$ collapsed objects (neutron stars and black holes). Our knowledge of them is based on less than 2000 objects identified as radio pulsars, members of X-ray binaries and magnetars. In this review I shall briefly discuss some of their properties such as masses, magnetic fields and rotation.

1 Introduction

I was asked to give a review on galactic collapsed objects (GCOs). I should start with their definition which is rather simple: they include neutron stars (NSs) and black holes (BHs). Both types of objects are formed in the process of a dynamical collapse. Collapsed objects do not include white dwarfs, which are compact but not collapsed objects as they are not products of a collapse. They are formed instead in the process of a very slow contraction of the degenerate core of a star. This process takes place on a long nuclear time scale.

As the subject of my review is very broad, I have, necessarily, to make some arbitrary selection of the topics to be discussed. I will start with brief discussion of the numbers of collapsed objects in our Galaxy. Then, I will discuss the present state of our knowledge of the masses, magnetic fields and
rotation of GCOs. These are the areas in which substantial progress was made during the recent few years.

2 Population of the Galactic Collapsed Objects

According to different estimates, there are some $10^8 \div 10^9$ NSs and about one order of magnitude less (some $10^7 \div 10^8$) BHs in our Galaxy. These estimates are based on the analysis of the observations of X-ray Novae systems and radio pulsars on one side, and on the stellar population synthesis calculations on the other. Overwhelming majority of the GCOs are, for different reasons, difficult to observe solitary objects. Inventory of the identified GCOs contains less than 2000 objects. They include about 320 interacting binaries (seen as X-ray binaries) which contain about 170 recognized NSs (102 X-ray pulsars and 70 X-ray bursters) and about 50 BH candidates (BHCs). The nature of about 100 remaining GCOs in X-ray binaries is not clearly established yet, although in some $\sim 50$ cases there are indications for NSs. About 1500 GCOs are seen as radio pulsars. Majority of them are solitary objects but about 60 are found in non-interacting binaries. In addition, we observe about 14 young solitary NSs which are still hot enough to emit thermal radiation from their surfaces (most of them are also seen as radio pulsars). We observe also about 14 magnetars (solitary NSs with extremely strong magnetic fields: $\sim 10^{14} \div 10^{15}$ G). Vast majority of our knowledge about GCOs is derived from the objects listed above, especially from the X-ray binaries.

3 Masses

3.1 Neutron stars

Until recently, it was generally believed that there exists strong observational evidence indicating that all observed NSs have (for some unclear reasons) masses close to $\sim 1.4 \, M_\odot$ ("canonical mass" of a NS). This is no longer true. The radio pulsar PSR J0737−3039B, detected recently (Lyne et al., 2004) was found to be a companion of an earlier known millisecond pulsar PSR J0737−3039A. This discovery provided us with the first "true" binary pulsar (both components are pulsars). The masses of two pulsars are $1.337 \pm 0.005 \, M_\odot$ and $1.250 \pm 0.005 \, M_\odot$. The second value is the lowest, precisely determined, mass of a NS, found so far.
At the high end of the masses, the determinations are less precise. The highest mass determined so far belongs to 4U 1700-37 and is equal \(2.44 \pm 0.27\) M\(_\odot\) (Clark et al. 2002) but the neutron star nature of the compact object in this system is not well established. The X-ray burster 4U 1820–30 was once claimed to have mass \(\sim 2.2\) M\(_\odot\) (Zhang et al. 1998). This estimate was based on application of the beat frequency model to the interpretation of the kHz quasi-periodic oscillations (kHz QPOs) observed for that burster. However, the beat frequency model is no longer valid (see Section 5.3.2). The best case, at present, for high mass NS is Vela X-1. The most recent determination (Quaintrell et al. 2003) gives for its mass \(2.27 \pm 0.17\) M\(_\odot\) or \(1.88 \pm 0.13\) M\(_\odot\) (depending on the assumption about the inclination of the orbit and the Roche lobe filling factor). At the 95% confidence level, the lower limit is \(\sim 1.6\) M\(_\odot\).

There is a hope that the case for a high mass NS will get stronger in a few years time. The hope is based on a close \((P_{\text{orb}} = 0.626)\) binary system containing the pulsar PSR J0751+1807 and a low mass \((\sim 0.19\) M\(_\odot\)) white dwarf. The present estimate of the pulsar mass gives \(2.1^{+0.4}_{-0.5}\) M\(_\odot\) (95% confidence, Nice et al. 2004). The present day lower limit is therefore \(\sim 1.6\) M\(_\odot\), similar as for Vela X-1. However, the precision of determinations based on pulsars timing increases dramatically with the interval of timing. Therefore (as opposed to the case of Vela X-1), after next few years of observations, the mass of PSR J0751+1807 will be known with much higher precision.

To summarize, the presently determined masses of the NSs are in the range \(1.25\) M\(_\odot\) to \(\sim 2.0 \pm 0.4\) M\(_\odot\). The undisputed interval is only \(1.25\) to \(\sim 1.6\) M\(_\odot\) (still substantially wider than \(1.34\) to \(1.44\) M\(_\odot\) which was an official interval for a long time).

### 3.2 Black Holes

The lowest mass galactic BHs, found so far, are: 2S 0921–630 \((2.0 \div 4.3\) M\(_\odot\), Shahbaz et al. 2004; however, the black hole nature of the compact object in this system is not well established) and GRO J0422+32 \((3.97 \pm 0.95\) M\(_\odot\), Gelino and Harrison 2003). On the high end of the mass scale there are also two leaders: Cyg X-1 \((20 \pm 5\) M\(_\odot\), Ziolkowski 2004a, 2005) and GRS 1915+105 \((21 \pm 9\) M\(_\odot\), Kaiser et al. 2004).

The supermassive black hole Sgr A*, residing in the center of our Galaxy, is a special case. It is not a stellar mass BH like the objects discussed above. However, it is a galactic compact object and, as such, should be mentioned.
in our review. According to current estimates, its mass is in the range \(3 \div 4 \times 10^6 \, M_\odot\). I shall return to this object, while discussing the spins of black holes (Section 6.2).

## 4 Magnetic Fields

### 4.1 Neutron Stars

#### 4.1.1 Radio Pulsars

Applying generally accepted magnetic dipole rotator model to explain the evolution of radio pulsars, one can easily calculate the strength of the magnetic field of any radio pulsar from the two very precisely measured observables: pulse period and its derivative. From large amount of the pulsars timing data we know that young pulsars are born with magnetic fields in the range \(3 \times 10^{11}\) to \(9 \times 10^{13}\) G (Manchester et al. 2004). We know also that magnetic fields of solitary non-interacting NSs do not decay substantially with time (at least on time scales of up to ~\(10^8\) years). It seems, however, that magnetic fields of NSs experiencing accretion of matter from binary companions do decay. The evidence comes from old radio pulsars that were spun up during process of accretion and are seen now as, so called, recycled pulsars (or millisecond pulsars). These recycled pulsars have now magnetic fields in the range \(8 \times 10^7\) to \(2 \times 10^{10}\) G (Ziolkowski 1997).

#### 4.1.2 Accreting Neutron Stars

Accreting NSs are seen either as X-ray pulsars (102 objects) or as X-ray bursters (70 objects). There are also few tens of X-ray emitters that are suspected NSs (for which neither pulses nor bursts were detected so far). The estimates of magnetic field are most easy to make for X-ray pulsars. There are two ways of estimating the field. One is based on the cyclotron absorption lines which are now observed for some 15 X-ray pulsars. Attributing the observed lines to electrons, one gets magnetic fields in the range \(10^{12}\) to \(10^{13}\) G (Makishima et al. 1999, Grove et al. 1995). Another method is based on the assumption that accreting NSs rotate at equilibrium periods (this assumption is not true for slow, wind powered accretors). The estimate using this assumption gives, for classical X-ray pulsars, magnetic fields in the range \(2 \times 10^{11}\) to \(2.5 \times 10^{13}\) G (see e.g Ziolkowski 2001). The second method may be applied also for non-pulsing accretors, if we know their spin periods (e.g. from kHz QPOs – see Section 4). In this way, one
gets values in the range $10^8$ to $10^9$ G for NSs (mostly X-ray bursters) in low mass X-ray binaries (LMXBs). Similar values are obtained for accreting millisecond pulsars, discovered recently in a few LMXBs.

### 4.1.3 Magnetars

Magnetars (5 soft gamma repeaters and 9 anomalous X-ray pulsars) are solitary NSs with extremely strong magnetic fields (by about two orders of magnitude stronger than typical young radio pulsars). Applying classical magnetic dipole rotator model (used for radio pulsars – see Section 4.1.1 above) one gets magnetic fields in the range $10^{14} \div 10^{15}$ G (see e.g. Ziolkowski 2002). We should remember, however, that this model does not give an accurate estimate of magnetic field for magnetars, as other mechanisms of spin-down (e.g. strong relativistic winds) are also present in these objects. Quite recently, an independent method based on cyclotron lines was used to estimate the magnetic fields of magnetars. Cyclotron lines, presumably produced by proton gas, were observed in X-ray spectra of three magnetars: SGR 1806−20 ($B \approx 1.0 \times 10^{15}$ G, Ibrahim et al. 2002), RXS 1708−4009 ($B \approx 1.6 \times 10^{15}$ G, Rea et al. 2003) and 1E 1207−52 ($B \approx 1.6 \times 10^{14}$ G, De Luca et al. 2004). The last of these objects exhibits four harmonic cyclotron lines at energies equal 0.7, 1.4, 2.1 and 2.8 keV. All these estimates roughly agree with those based on spin period and its derivative (assuming magnetic dipole radiation as the main spin-down mechanism). Attributing the observed cyclotron lines to electron gas would result in magnetic fields of the discussed objects equal $\sim 5 \times 10^{11}$ G, $\sim 9 \times 10^{11}$ G and $\sim 8 \times 10^{10}$ G, respectively. However, such interpretation is very doubtful as it explains none of the well known properties of magnetars.

One should note that some classical radio pulsars have very strong magnetic fields ($\sim 9 \times 10^{13}$ G, McLaughlin et al. 2004) comparable to the weakest magnetic fields found in magnetars. Yet, their other properties (X-ray emission and the total energy output) are completely different from those of magnetars. It seems that the strength of the magnetic field is not the only parameter distinguishing magnetars from the rest of the NSs population.

### 4.2 Black Holes

Practically, nothing is known about magnetic fields of galactic BHs (but there are, of course, some theoretical speculations). We have only indirect evidence (from some gamma ray bursts) that in some special cases stellar
mass BHs may probably possess very powerful magnetic fields. The strength of the possible magnetic fields around some of the observed galactic BHs, remains an entirely open question.

5 Rotation of Neutron Stars

The evolution of spin of a given NS depends on the mechanism powering its energetics (all forms of energy output). From this point of view, we can distinguish three classes of NSs: rotation powered (radio pulsars), magnetic field powered (magnetars) and accretion powered (X-ray pulsars, X-ray bursters and some X-ray emitters in LMXBs). I shall discuss only briefly the first two classes and devote somewhat more time to the third class, as a substantial progress was achieved recently in this area.

5.1 Rotation Powered Neutron Stars

Both classical radio pulsars and the recycled ones produce their emission (mainly in the form of magnetic dipole radiation) at the expense of their rotational energy. The observed spin periods of classical radio pulsars are in the range from 16 ms to 8 s (the spin correlates very well with the age – the older the pulsar, the longer the spin period). The recycled pulsars (spun-up in the process of accretion of matter from the companion during their past evolution) have the present spin periods in the range from 1.6 ms to ∼100 s.

5.2 Magnetic Field Powered Neutron Stars

The spin periods of all magnetars are confined to a narrow range of 5 to 12 s (5.16 ÷ 11.77). Their spin periods evolve (increase) so fast that it is difficult to catch them at shorter spin periods (at early phase of their evolution).

5.3 Accretion Powered Neutron Stars

5.3.1 X-Ray Pulsars

The spin periods of accreting X-ray pulsars span seven orders of magnitude – from 1.7 ms to 10^4 s. Most of these periods are probably equilibrium periods (corresponding to the balance between spin-up accretion torque and spin-down propeller torque – see e.g. Ziolkowski 1997). The exception are slow, wind powered, pulsars associated with supergiant companions and,
possibly, some extremely slow pulsars associated with Be stars (Ziolkowski 2001).

5.3.2 Accreting Non-Pulsing Neutron Stars

In addition to $\sim 100$ X-ray pulsars there are about 100 accreting NSs that are not pulsators. Most of them are members of LMXBs and are usually seen as X-ray bursters. Since long time it was believed that these LMXBs are progenitors of recycled radio pulsars. Therefore, the expected spin periods for NSs in these systems were of the order of a few milliseconds. However, the observational confirmation of these expectations appeared to be very difficult. The breakthrough came with the discovery of specific variability of their X-ray emission – so called high frequency quasi-periodic oscillations or kHz QPOs (van der Klis et al. 1996, van der Klis 2000). Two types of kHz QPOs were detected in NSs sources: pair QPOs and burst QPOs.

- **Pair kHz QPOs**

  Pair QPOs are simultaneous oscillations at two frequencies: lower $\nu_L$ (210 to 1050 Hz) and higher $\nu_H$ (500 to 1300 Hz). Both frequencies vary by a factor of up to 2 for a given source and both increase with the increasing X-ray luminosity (or accretion rate). However, the separation $\Delta \nu = \nu_H - \nu_L$ for a given source (as its X-ray luminosity varies) remains approximately constant.

- **Burst kHz QPOs**

  Burst QPOs are observed during Type I (thermonuclear) bursts of some X-ray bursters (13 so far; their parameters are given in Table 1). Their frequencies are in the range 270 to 620 Hz. These frequencies remain constant and reproducible for a given source (i.e. they stay the same during consecutive bursts). It was noticed that, for a given source, the burst frequency $\nu_B$ was approximately equal either to $\Delta \nu$ (the separation between two pair frequencies) or $2 \times \Delta \nu$.

- **Beat frequency model of kHz QPOs**

  Soon after the discovery of kHz QPOs, an interpretation known as "beat frequency model" (BFM) was proposed (Miller et al. 1998). This model
Table 1: Burst QPOs Observed in Low Mass X-Ray Binaries (Chakrabarty 2004).

| Name             | $\nu_{\text{QPO}}$ [Hz] | Orbital Period |
|------------------|--------------------------|----------------|
| 4U 1916-05       | 270                      | 50$^m$         |
| XTE J1814-338    | 314                      | 4$^h$27        |
| 4U 1702-429      | 330                      |                |
| 4U 1728-34       | 363                      |                |
| SAX J1808.4-3658 | 401                      | 2$^h$01        |
| SAX J1748.9-2021 | 410                      |                |
| KS 1731-260      | 524                      |                |
| Aql X –1         | 549                      | 19$^h$0        |
| X1658 –298       | 567                      | 7$^h$11        |
| 4U 1636-53       | 581                      | 3$^h$8         |
| X1743 -29        | 589                      |                |
| SAX J1750.8-2900 | 601                      |                |
| 4U 1608-52       | 619                      |                |

assumed that the higher of the pair QPO frequencies corresponds (at least approximately) to the Keplerian angular velocity at the inner edge of the disc (it may vary if the inner radius of the disc changes e.g. due to variable accretion rate) and the lower one is the beat frequency between this Keplerian frequency and the spin of the neutron star. In this way, the difference of the two pair QPO frequencies (which is approximately constant for a given source) corresponds to the spin of the neutron star. The burst QPO frequency reflects directly the spin of the neutron star (or is equal twice the spin frequency if two hot spots develop on the surface of a NS during the burst.

• The bursting pulsars

The next breakthrough came with the discovery of the accreting millisecond pulsars (6 known so far, see Wijnands 2005 for the most recent
Table 2: Millisecond X-Ray Pulsars (Wijnands 2005).

| Name               | $\nu_{\text{QPO}}$ [Hz] | Orbital Period |
|--------------------|--------------------------|----------------|
| XTE J0929-314      | 185                      | 43$^m$6        |
| XTE J1807-294      | 191                      | 41$^m$         |
| XTE J1814-338      | 314                      | 4$^h$27        |
| SAX J1808.4-3658   | 401                      | 2$^h$01        |
| XTE J1751-305      | 435                      | 42$^m$4        |
| IGR J00291+5934    | 599                      | 2$^h$45        |

review). Their parameters are given in Table 2. Since they are pulsars, we know unequivocally their spin periods (they are in the range 1.67 to 5.40 msec). Two of these pulsars were found to be also X-ray bursters exhibiting burst QPOs (compare Table 1). These two objects provided strong evidence that frequencies of burst QPOs reflect the true spin frequencies of the NSs in these systems. In addition, they were found to produce also pair QPOs! To our big surprise, we found that while in one of these sources (SAX J1808.4−3658) the difference $\Delta \nu$ was approximately equal to the spin frequency, in another (XTE J1807-294) it was equal about half of the spin frequency! This second case meant the end of the beat frequency model ($\Delta \nu$ in this model might be equal twice the true spin frequency but cannot be equal half of the spin frequency). The two bursting pulsars confirmed the dichotomy found earlier from kHz QPOs: slow rotators ($\nu_{\text{spin}} \lesssim 400$ Hz) have $\Delta \nu \approx \nu_B$, while fast rotators ($\nu_{\text{spin}} \gtrsim 400$ Hz) have $\Delta \nu \approx 0.5 \times \nu_B$.

- **On the rotation of NSs in LMXBs (summary)**

  The accreting millisecond pulsars provided unequivocal evidence that NSs in LMXBs do indeed rotate at millisecond periods as expected from the analysis of recycled radio pulsars. The presently measured periods are in the range 1.62 to 5.40 msec. The most promising theoretical explanation
Table 3: High Frequency QPOs Observed in BHC Binary Systems (Remillard et al. 2002, McClintock and Remillard 2003, Ziolkowski 2004b, Kaiser et al. 2004).

| Name                  | \( \nu_{\text{QPO}} \) [Hz] | \( M_{\text{BH}} \) [M\(_\odot\)] | comments |
|-----------------------|-----------------------------|-----------------------------|----------|
| GRO J1655−40          | 300±23                      | 450±20                      |          |
|                       | 184±26                      | 272±20                      |          |
| XTE J1550−564         | 41±1                        | 67±5                        |          |
|                       | 113                         | 164±2                       |          |
|                       | 328±4                       | 495                         |          |
| GRS 1915+105          | 184±5                       | 9±1                         | 1.5 \( \sigma \) |
| 4U 1630−472           | 193±4                       | 240                         |          |
| XTE J1859+226         | 250                         | 6.3±0.3                     |          |

NOTE: 495 Hz QPO in GRS 1915+105 was detected at only 1.5 \( \sigma \) significance level of the observed kHz QPOs seems to be the parametric epicyclic resonance theory (Abramowicz and Kluzniak 2001, Lee et al. 2004). I shall describe it briefly after discussing the spins of black holes (Section 7).

6 Rotation of Black Holes

6.1 kHz QPOs

Black Holes Candidates (BHCs) in X-ray binaries also exhibit high frequency QPOs. These oscillations are termed kHz QPOs, similarly as for NSs, although their frequencies are lower: 41 to 450 Hz (see Table 3).
The most striking feature of these QPOs is the fact, that in most of the systems the QPO frequencies form sets of precise integral harmonics. The fundamental frequency seems to be unique characteristic of each black hole and, presumably, depends only on its mass and spin. We observe 2:3 harmonics in GRO J1655−40 and XTE J1550-564 and 1:2:3 harmonics in GRS 1915+105. This last system shows, additionally, an independent set of 3:5 harmonics (41 and 67 Hz). One can also consider the set of 113 and 164 Hz QPOs (2:3). All theories discussing BHCs QPOs predict that the frequencies should scale with the mass of the compact object like $M^{-1}$. In addition, they should increase with the increasing spin of the black hole. McClintock and Remillard (2003) found an empirical fit using higher frequency in the 2:3 twin peak QPOs: $\nu_3 \approx 2.8(M_\odot/M)$ kHz. Abramowicz et al. (2004a) noticed that Sgr A* (supermassive black hole in a center of Milky Way) also satisfies this relation if one assumes that the, recently reported, 17 minute infrared flare period corresponds to an appropriate QPO frequency.

6.2 Spins of BHCs (summary)

- **From high frequency QPOs**

Abramowicz et al. (2004a,b) used the parametric epicyclic resonance theory to interpret the kHz QPOs observed in three galactic microquasars: GRO J1655−40, XTE J1550−564 and GRS 1915+105. They estimated the dimensionless angular momentum of these BHCs to be in the range 0.7 to 0.99.

- **From accretion discs spectra**

Analysis of accretion discs spectra of microquasars GRO J1655−40 and GRS 1915+105 suggests that their dimensionless angular momentum is in the range 0.6 to 0.9 (Zhang et al. 1997, Gierliński et al. 2001).

- **Sgr A**

Recently, Aschenbach et al. (2004) made use of 17 minute infrared flare period and five different X-ray flare periodicities (100, 219, 700, 1150 and 2250 s) to estimate the mass and angular momentum of the central Milky Way black hole. The interpretation included Lense-Thirring precession and epicyclic resonance oscillations. They got $2.72 \times 10^6 M_\odot$ for the mass (somewhat less than the usual value $3.6 \times 10^6 M_\odot$) and 0.994 for the angular momentum.
7 Parametric Epicyclic Resonance Theory

The authors of this theory (Abramowicz and Kluźniak 2001, Abramowicz et al. 2004a,b, Kluźniak et al. 2004, Lee et al. 2004) noticed that General Relativity (unlike Newtonian gravity) predicts independent frequencies of epicyclical oscillation for each spatial coordinate for a blob of matter on a perturbed orbit around rotating compact object. Modeling done by these authors demonstrates that there are locations at the inner accretion disc where the coordinate epicyclical frequencies (e.g. the radial and the azimuthal ones) form small integral ratios like 3:2, 2:1, 3:1 etc. A non-linear resonance develops at such locations leading to the enhancement of the oscillations and producing the observed QPOs. Modeling indicates also that, if there is a periodical perturbing force operating in the inner disc, then the oscillations are excited at the locations where the difference between the coordinate frequencies is equal to the frequency of the perturbing force or to the half of that frequency.

Parametric epicyclic resonance theory applies both to BHCs QPOs and to the NSs QPOs. It provides a natural and elegant explanation of the small integral ratios found for the frequencies of BHCs QPOs. As far as NSs are concerned, the observations suggest that a perturbing force operating at the spin frequency of the NS is present in the inner disc. Such perturbing action of a rotating NS is not surprising (magnetic field, surface features etc.) The explanation of the observational facts is again natural and elegant.

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