YOUNG CLOSE ISOLATED COMPACT OBJECTS

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We suggest that the seven radio-quiet isolated neutron stars observed with ROSAT are young cooling objects associated to recent near-by supernova explosions which formed runaway stars and the Local Bubble, affecting the topology of the interstellar medium in the vicinity of the Sun (within a few hundred parsecs). In the aftermath of these explosions, a few black holes might have been formed, according to the local initial mass function. We thus discuss the possibility of determining approximate positions of close-by isolated black holes using data on runaway stars and simple calculations of binary evolution and disruption.

Молодые близкие одиночные компактные объекты
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В этой статье мы обсуждаем различные наблюдательные проявления близких компактных объектов (нейтронных звезд и черных дыр), с учетом событий, происходящий при взрывах сверхновых. Мы предполагаем, что семь радиотихих одиночных нейтронных звезд, обнаруженных с борта ИСЗ ROSAT, являются молодыми остывающими объектами, которые связаны с недавними вспышками сверхновых в результате которых образовались убегающие звезды, сформировалась местная каверна (Local Bubble) и другие близкие структуры в межзвездной среде. Мы обсуждаем возможность определения положения близких одиночных черных дыр, используя данные о движении убегающих звезд и о механике распада двойных систем.

X-ray observations of neutron stars and black holes of stellar origin have been probing, over the entire Galaxy, properties of their interior and of their environment. But the recent discovery of a number of isolated neutron stars in the outskirts of the Sun provides a new tool to study how they evolve and from where they originate.

In this paper at first we discuss the properties of the seven ROSAT radio-quiet isolated neutron star (INS) candidates showing that the cooling hypothesis for their X-ray emission is the most viable (see [19] and [36] for recent reviews and [40] for data on the latest candidate). Then we try to connect these seven young INSs with different objects in the solar vicinity. Finally we discuss a possibility to observe close-by isolated black holes (IBHs).

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1. Neutron stars

It is now widely believed that young INS can appear, in the Galactic disk, as sources of different nature: radio pulsars, soft-gamma repeaters (SGRs), anomalous X-ray pulsars (AXPs), radio-quiet compact X-ray sources in supernova (SNa) remnants.

Here we will focus on seven ROSAT INSs, for which it was suggested that they are close-by sources showing no sign of pulsar activity.

1.1. Accretion versus cooling

In the early 70's it was suggested by Shvartsman [29], [30] and Ostriker et al. [21] that INSs and IBHs can be observable due to accretion of the interstellar medium (ISM). INSs can also be observed when they are young and incandescent due to thermal emission of their hot surface mainly in soft X-rays.

Soon after the discovery of the first of the seven sources [38], it was clear that two different mechanisms could equally explain the nature of the emission: accretion onto the (old) INS [35] or cooling of the young INS (see [19], [20] for a recent discussion). Early in the study of the detectability of INSs, it seemed plausible that *accretors* by far outnumber *coolers*, since the stage during which a young cooling INS is hot enough to be observed in soft X-rays is very short, about 1 Myr or less, against few Gyr lifetime of a typical accreting NS. However, later it was recognized that accreting INSs might be rare objects and this holds if NSs acquire at birth very high peculiar velocities ~ 200 km s^{-1} (as observed in the pulsar sample [5], [17]). This would imply an exceedingly low accretion rate, and in turn a very low intrinsic luminosity, undetectable with present capabilities. Population synthesis studies [24] have show that with the inclusion of a velocity distribution function that accounts for the observed high kick velocities, most of the INSs are now in the stage of *ejector* (see [15] for detailed explanation of NS evolutionary stages or [4] for a brief description). It is worth noting that if strongly magnetized INSs with very high spatial velocities are situated in low density ISM regions then it is possible that most of them spend significant part of their lives as *georotators*, because the light cylinder radius, $R_l = c/\omega$, is larger than the radius of gravitational capture, $R_G = 2GM/v^2$. Such INSs leave the *ejector* stage earlier than those that live in a normal ISM [34].

The periods P of the observed objects (for four of the ROSAT INSs) have been found to fall in a rather narrow interval of 5-23 seconds, and they could be explained in both hypothesis. In the accretion scenario one has to allow for magnetic field decay [14], [39], because at a constant field $B \sim 10^{12}$ G, the periods of an old *accretor* is much longer [16], [26]. Under the cooling hypothesis there are no restrictions on the period P, though its value can provide clues on the magneto-rotational evolution of the objects. Indeed, in the case of young cooling objects periods as long as such observed can be explained if the INSs are *magnetars* [6], i.e. has very strong magnetic field. The large braking implied by a high field would lead to an "accelerated"slow-down of the pulsar. But to explain the clustering observed, the magnetic field later has to decay (as customarily advocated in magnetars for explaining the high quiescent luminosity of SGRs and AXPs [33]). This would lead to a saturation of P occurring when the decay is advanced enough to almost freeze the action of braking torques [3]. If ROSAT INSs are magnetars or are their close relatives (or descendant) than the fraction of magnetars among all NSs can be higher than previously estimated. Is the cooling hypothesis, which seem preferable on theoretical ground, testable from observation? Clues would come from any direct determination of the peculiar velocity for the seven sources. Accretion can be certainly excluded when the velocity exceeds 40-60 km s^{-1} under the most favorable conditions in the ISM.

With the determination of the proper motion of one of the seven sources, RX J1856-3754, (that implies a velocity at birth of 200 km s^{-1} [37]) it is now rather clear that the cooling hypothesis holds for this sources, and it is tempting to consider the possibility that the emission of all the seven ROSAT sources have the same nature. This calls again for a statistical study. To this purpose, in [25] we compared both hypothesis (*accretors* and *coolers*) in an attempt to explain the observed Log N – Log S distribution for the ROSAT INSs. We obtained that at low fluxes ($< 10^{-13}$ erg cm^{-2} s^{-1}) *accretors* outnumber *coolers*. But at brighter fluxes, where the seven ROSAT INSs are situated, *coolers* can be more abundant. Interestingly, we found that to explain these seven objects in terms of cooling INSs it is necessary to assume that the spatial density of NSs is about half an order of magnitude higher than what inferred from radio pulsars statistics. Are we then living in an overdense region or is it a global feature? If global, we have to assume that most young NSs do not pass through the stage of a radio pulsar, or that this stage is shorter than we have estimated. Such hypothesis finds support in recent observations [12], but the fraction of radio-quiet INSs in the whole galactic population of NSs is a number quite uncertain. Most probably it is not as high as it is necessary to interpret the "magnificent seven"ROSAT INSs. So it is more probable that such an over-density is a local phenomenon, both in space (< 1 kpc) and in time (< 100 Myr), and we next we will explore in more details the neighborhoods of the Sun.

1.2. The ROSAT sources and the Gould Belt

In connection with young INSs and IBHs we are mostly interested in massive stars and recent star formation activity close to the Sun (in our future calculations of *coolers* we plan to include the realistic distribution of young stellar complexes around the Sun). In that sense the solar vicinity is dominated by the Gould Belt and related OB-associations (see [23] for a detailed description of the Gould Belt).

The Gould Belt is a disk-like structure. Its inclination to the Galactic plane is about $18°$; the diameter is about 750-1000 pc, and its center is located about 150-250 pc from the Sun.

The age of the Gould Belt is estimated to be about 30-70 Myr. This implies that the most massive stars are now about 7-10 $M_\odot$ and that recently there was a period of frequent explosions of massive stars, producing NSs and BHs, with nearly constant rate [18]. The SNa rate in the Gould Belt is about 20-30 per Myr [13].

We see direct consequences of these explosions in the form of runaway stars. In 700 pc around the Sun 56 runaway stars are known [10]. Only few of them can result from star-star interactions. Others are products of SNa explosions in binary systems. For some of them, the corresponding compact objects have been identified or suggested [11], [13], [37].

Clearly the seven ROSAT INSs can be the outcome of recent SNae in the Gould Belt and related

OB-associations. In that case we can easily explain the increased rate of NS formation around the Sun, and it is not necessary to assume very a high fraction of radio-silent young INSs overall in the Galaxy. Also one can predict the existence of more radio-quiet INSs within 1 kpc around the Sun, which are remnants of >50 recent SNae. For objects with age ~ 1 Myr, the corresponding X-ray dim sources can be discovered (see for example objects HIP 22061, 29678 in table 5 in [10]), but as long as the NSs receive large kick velocities at birth it is very difficult to predict their present positions. For BHs the situation can be opposite as their kicks could be much lower.

All these explosions should leave their imprints on the structure of the local ISM. Indeed, several local cavities are observed. The most well known is the Local Bubble [28]. It was suggested [31], [18] that the Local Bubble is a result of 3-6 (or even more) recent SNa explosions. We argue that at least some of the "magnificent seven"sources are remnants of these recent explosions.

2. Black holes and the Gould Belt

SNa explosions produce not only NSs, but also BHs. Having dozens of SNae in the solar vicinity during the last 10 Myr we can expect several BHs to have formed during the same period in the solar neighborhood.

Usually it is accepted that BHs are one order of magnitude less abundant than NSs. This estimate comes from the critical mass for BH formation. If this mass is about 35 $M_{\odot}$ then the fraction of BHs is about 10% (see discussion on BH fraction in [7], [8]). So we can expect about 5 BHs correlated to 56 runaway stars. If there are 20-30 SNae per Myr in the Gould Belt, than we can expect $\sim$ 6-12 IBHs younger than few Myr. Kick velocity for BHs is unknown, but it is reasonable to assume, that it is much lower than for NSs. If it is so, all these BHs still should be around us.

IBHs are not expected to be bright objects. Close-by IBH can be observed due to accretion from the ISM ([30], [9]), or due to a micro-lensing effect ([1], see also [22]). That is why it is important to know their positions on the sky. Close massive runaway stars give us a chance to calculate an approximate positions of close-by young IBHs. Among runaway stars we can distinguish the most massive: λ Cep, ζ Pup, HIP 38518 and ξ Per [10]. Their masses are larger than ~ 33 $M_{\odot}$. It means, that the companion (actually the *primary* in the original binary) was even more massive on the main sequence stage. So, the most likely product of the explosion of such a massive star should be a BH.

If the present velocities of runaway stars are known, one can estimate their ages and places of birth. This has been done by Hoogefwerf et al. [10]. To calculate the present position of a BH we have to know the binary parameters, i.e., the masses of stars before the explosion, the BH mass, the eccentricity of the orbit before the explosion, the orbit orientation, and finally the kick velocity of the BH. Some parameters can be inferred from the observation of the secondary star. Also we can give a zero kick to the BH and zero orbital eccentricity. Below we briefly comment on that choice. Other parameters should be varied within assumed ranges.

As we do not know the exact mechanism of SNa explosion any value of a BH kick velocity would be speculative. But in all mechanisms BH kicks should be smaller than those of NSs. In particular, in [27] the authors argue that the magneto-rotational mechanism of SNae explosion (suggested in 70's by Bisnovatyi-Kogan) is the most favored from the point of view of mass distribution of compact objects. In this mechanism fastly rotating protoNS form increasing superstrong toroidal magnetic field (up to 10^{17} G), which drives the envelope ejection. In this case BHs should receive kicks much smaller than those of NSs. We assume BH kick to be zero (but note, that in [8] it was suggested that in disrupted binaries one has to expect mostly low mass BHs, $M_{bh} \sim 3\,M_{\odot}$, which receive a modest kick ~ 50 km s^{-1} at their birth). In the binary systems which are the progenitor of runaway stars we can expect circularization of orbits due to tidal interaction, i.e. eccentricity in such binaries should be zero. As far as the present velocities of secondaries are high we can expect close systems ($a \sim 1000\,R_{\odot}$) with nearly ideal circularization.

Given these parameters and still leaving undetermined the orientation of the orbital plane of a binary, what remains to discuss are the masses of the primary component before the explosion and of the BH. In the case of two massive companions and in the most probable situation, the mass of the primary before the explosion is close to that of the secondary. These circularized systems with equal mass stars will survive the explosion if the kick is strictly zero, since less than one half of the total mass will be swept out. So, for systems producing run-away stars the most probable primary's mass is as close as that requested for binary disruption, i.e.:

$$M_1 = M_2 + 2 \cdot M_{bh}. \tag{1}$$

That leads to restrictions on the orbital separation: it should be larger than about 100 $R_{\odot}$ to avoid mass transfer. On the other hand it has to be smaller than ~ 2000 $R_{\odot}$, to guarantee that the velocity of the secondary component after SNa explosion is in agreement with observations.

Strong mass loss due to stellar winds also leads to relatively low masses for BH progenitor (before the explosion), as far as more massive stars loose mass due to stellar winds faster than low mass stars, so for two stars with initially very different masses this difference will become smaller before the explosion.

Results of [7], [8] suggest that massive stars with $M > 40 M_{\odot}$ produce BHs without SNae, so for such cases binaries will survive BH formation. This argument once again brings us to require the lowest masses for the primaries that are permitted according to the condition of binary disruption. Masses should then fall within a relatively narrow interval close to critical mass of BH formation.

Masses of BHs are determined now for nearly a dozen of candidates in binary systems, mainly with low-mass companions. Most of these determinations are concentrated around ~ 7-$10\ M_{\odot}$, but the potentially cover a relatively wide range from 3 up to 50 solar masses [2], [27] (see the theoretical expectations of the BH mass spectrum, which is different from the observed one due to selection effects [8]).

Given these constrains we are in the process of studying the dynamics of the runaway BHs in the solar proximity and work is in progress.

3. Conclusions

We conclude that the seven radio-quiet ROSAT INSs can be connected with recent SNa explosions, which produced nearby runaway stars and peculiar features in the local ISM including the Local Bubble.

We suggest a way to find approximate positions of close IBHs from knowledge of nearby runaway stars and from calculations of binary disruptions. We estimate a number of close IBHs as > 5 with ages < 3-4 Myr.

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