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# Searching for isolated stellar-mass black hole candidates by analyzing the kinematics of their former companions in disrupted binary systems

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**Abstract.** We performed a search for isolated stellar-mass black hole candidates based on the fact that more than 50% of radio pulsars have originated in binary systems, now disrupted, where the other component could have evolved into a black hole prior to the second supernova event in the system which caused its disruption. To this end, several relatively young isolated pulsars with known parallaxes fitting the selection criteria were traced back to their presumed birth locations. These areas were then analyzed for possible black hole candidates based on the astrometric, photometric, and spectral data available. We present the results for the first 4 pulsars in our sample, J0139+5814, J0922+0638, J0358+5413, and J1395+1616. Several possible candidates were selected for further analysis.

**Key words:** radio pulsars – black holes – kinematics

## 1. Introduction

At least 50% of all stars are known to be members of binary and multiple systems (Batten (1967), Duquennoy & Mayor (1991), Halbwachs et al. (2003)) and therefore, many of the relatively young neutron stars (NS), observed as radio pulsars, as well as stellar-mass black holes (BH) must have originated in high-mass binaries. In BH+NS pairs, the more massive BH would have formed in the first supernova explosion of the system. About 40% of the pairs withstand this first event (Bethe & Brown (1998)), whereas the second supernova, in which a pulsar is born, generally disrupts the system. The kick that pulsars receive in the process would explain their high velocities (see, e.g., Hobbs et al. (2005)). Tracing the pulsars back to their birthplaces can therefore help to restrict the BH-candidate search area (see, e.g., Prokhorov & Popov (2002), Chmyreva et al. (2010)), where the objects of interest could be located. Theories predict that such sources would have featureless flat spectra covering the entire electromagnetic range (see Beskin & Karpov (2005) and references therein), similar to those of DC dwarfs and BL Lacertae, and would exhibit very fast variability.

Proper motions can be used to distinguish between galactic and extragalactic sources.

## 2. Method

We created an initial sample of 16 isolated radio pulsars with measured proper motions and parallaxes, relatively small spin-down ages, and no previous associations that fit our criteria. Using the available data, we simulated 100,000 trajectories for each pulsar, tracing them back according to their age estimates, and computed the (sky-projected) 3-sigma contours of their assumed birthplaces. In this work, we review the birthplaces of 4 pulsars, J0139+5814, J0922+0638, J0358+5413, and J1935+1616 - the youngest in our sample.

To select objects that are of interest, we used publicly available databases, including (but not limited to) the following: ROSAT, FERMI, XMM-Newton, FIRST, WISE, 2MASS, GALEX, SDSS, SIMBAD, ATNF, NED, LAMOST. We first selected all non-optical sources that fall into the 3-sigma contours of the pulsar birth locations. These non-optical sources were then cross-identified within their positional error ellipses. We then searched for optical counterparts for these sources, using the SDSS database (where available), and other catalogs otherwise. Color, spectral, and proper motion data were then used to classify the possible identifications and reject the candidates that do not fit the criteria. The candidates that are promising were then selected for further investigation - the subject of our future work.

## 3. Results

The birthplace of our first pulsar, PSR J0139+5814, did not yield any BH candidates. While three x-ray sources are present in the region, it is contaminated by several bright stars, and many of the optical sources are flagged for unreliable photometry, making it difficult to obtain any conclusive cross matches. The objects with acceptable photometry are mostly main sequence stars, with several galaxies and quasars. The remaining three pulsars, J0922+0638, J0358+5413, and J1935+1616, contain several objects of interest within their birth locations. Below we discuss the possible BH candidates collectively in all three locations.

The three regions together contain about 250 x-ray sources, 5 (non-GRB) gamma ray sources, and 1800 radio sources, as well as numerous IR, UV, and optical sources. To perform the initial cross-match between the sources, we used the Aladin software (which can be found at http://aladin.u-strasbg.fr/). Among other useful tools that it provides, it allows one to cross-match different online catalogs within a specified coordinate error. We performed the cross-match in an automated mode, using 1-sigma positional error ellipses, which yielded 37 x-ray/radio matches. We then visually inspected the areas, coming up with a further 20 matches, bringing the total up to 57. The optical sources that fall into the 1-sigma coordinate error ellipses of the selected candidates were then reviewed. Given the large position errors of some x-ray and radio sources, several optical objects can be identified with a given source. After eliminating objects with stellar, galactic, or quasar spectra (where available), visual galaxies and extended sources, a total of 94 objects remained. We then used color-color diagrams to classify them further. While using the same photometric system for all candidates would have been preferable, the available photometry is inhomogeneous, and we therefore used SDSS ugriz, BVR, or JHK according to the data available for each object. The plot for the objects with SDSS data available is shown in Fig 1.

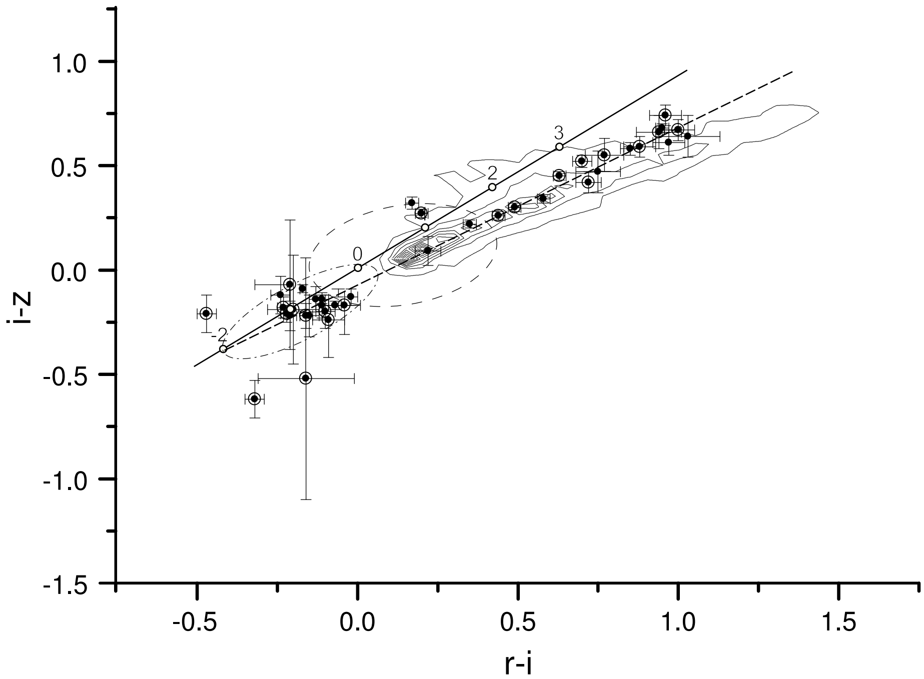


**Figure 1.** Color-color diagram for the sources with available SDSS measurements (black dots with error bars). Sources with measured proper motions are additionally marked by circles. The contours show the stellar locus, computed from the background stars in the regions under consideration. The dashed ellipse shows the approximate position of quasars in the diagram, and the dashed-and-dotted ellipse – that of white dwarfs (see, e.g., Collinge et al. (2005), Girven et al. (2011)). The solid and dashed diagonal lines show the positions of power-law and blackbody spectrum sources, respectively.

We rejected the sources that fall into the discarded categories (main sequence stars, etc) in the color-color plots, and kept the candidates located in the regions dominated by quasars and white dwarfs. A total of 14 sources identified in the x-ray, optical, and radio ranges remained after individual inspection. Their SEDs are shown in Fig 2.

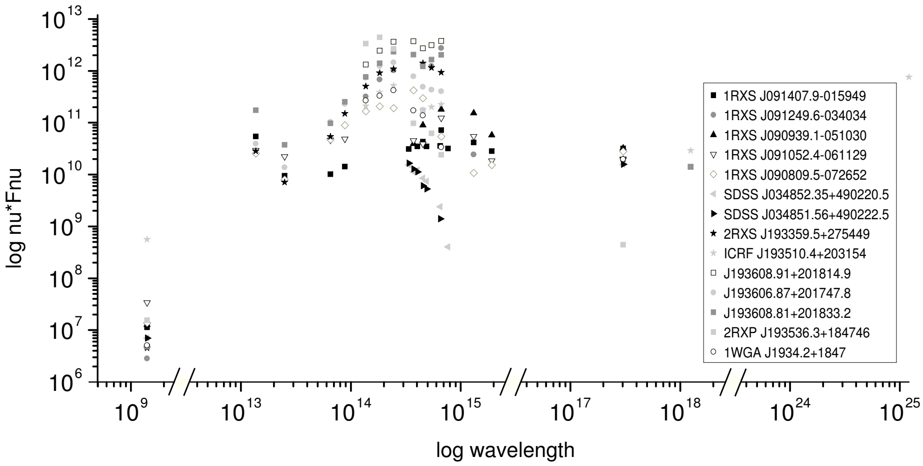


**Figure 2.** Spectra of the 14 selected candidates with a hard-energy range component.

Of the 14 sources, the ones with a flat continuous spectrum (especially in the optical-gamma range) are of special interest. Given the large errors in the hard-energy range, at least half of the selected sources fall under that category. Unfortunately, no optical spectra are available for these sources, and we therefore can not classify them with certainty: they may be BL Lacertae, which have similar observational manifestations, or other types of x-ray sources. As a comparison, to show the similarities of these types of objects to our selection, we show the spectra of 3 well studied BL Lacertae in Fig 3.

ICRF J193510.4+203154 (shown by light grey stars in Fig 2), is classified in the literature as a blazar candidate, and is the only object in our sample to be a confirmed gamma ray source. It has a relatively flat spectrum, and will be studied in detail in our future work. Another interesting candidate, 1WGA J1934.2+1847 (open black circles in Fig 2), is the only one with an x-ray identification to have a reliable proper motion of the order of 60 mas $\mathrm{yr}^{-1}$, which marks it as a galactic source. Both of these sources are projected onto the birthplace of pulsar J1935+1616, which has a transverse velocity of about 280 km $\mathrm{s}^{-1}$. The associated BH candidate, being more massive, would be slower. Taking this value as a full space velocity estimate and an upper limit, a proper motion of 60 mas $\mathrm{yr}^{-1}$ would place our candidate at a maximum distance of 1000 pc. Smaller distances yield the expected smaller velocities: 140 km $\mathrm{s}^{-1}$,

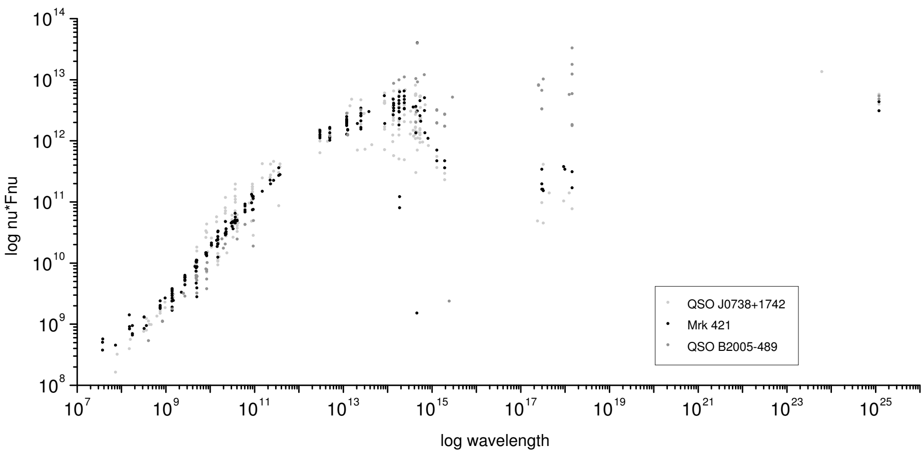


**Figure 3.** Spectra of 3 BL Lacertae, shown for comparison.

60 $\mathrm{km\,s^{-1}}$, and 30 $\mathrm{km\,s^{-1}}$ for 500 pc, 200 pc, and 100 pc, correspondingly. This candidate will also be studied in the future.

In addition to these 14 sources, the pulsar birthplaces also contain a number of objects classified as blue objects and white dwarfs. Although these sources have no identifications in the high-energy spectral ranges, they are also similar in observational properties to our objects of interest. The 8 non-xray sources that fit our initial selection criteria are: J091605.73+000802.2, WD 0913+005, NCBJ042564, J035738.16+525934.4, NCBG049657, J034322.47+463222.2, J034922.72+481013.7, and J034545.92+491718.9. Most of them have measured proper motions. The only source with an available spectrum is WD 0913+005, classified in SIMBAD as a DC spectral type white dwarf. It has a quasi-featureless, although noisy, spectrum, and a proper motion of about 40 $\mathrm{mas\,yr^{-1}}$. Our simulations have shown that the birthplace of J0922+0638, where WD 0913+005 is located (in projection), stretches in distance over almost 2.5 kpc, the wing of the distribution closest to us being well within the observation limit for nearby BH. The velocity of WD 0913+005 would be 90 $\mathrm{km\,s^{-1}}$, 40 $\mathrm{km\,s^{-1}}$, and 20 $\mathrm{km\,s^{-1}}$ for 500 pc, 200 pc, and 100 pc, respectively.

These 22 candidates (14 with a hard component and 8 without one) will be studied in detail in our upcoming paper. They will be investigated for fast variability, and obtaining their optical spectra in order to reject the sources with lines is also a priority.

## 4. Conclusions

We have analyzed the birth locations of pulsars J0139+5814, J0922+0638, J0358+5413, and J1935+1616 for possible BH candidates. We selected 22 candidates for further investigation, including 14 sources with hard-energy range components, and 8 sources without such. Our future work will concentrate on obtaining information on their possible fast variability, as well as their spectra, which would allow us to classify them further and select the ones that fit the observational criteria for stellar-mass BH.

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