Report - Optical Counterparts for Pulsar candidates using Gaia

Link to GitHub

The Dataset of pulsars that I used

These are the pulsars that I used, directly from the paper on arXiv

Number 16 I added manually to test something.

	S.No.	Name	RA (hh:mm:ss)	DEC (dd:mm:ss)	References	d (kpc)	θmax	θcand	rcand (pc)
1	1	J0030+0451	00:30:27.42826	+04:51:39.711	Matthews et al. (2016)	0.34	7.28″	3.2″ & 7.19″	0.005
2	2	J0711-6830	07:11:54.189114	+04:51:39.711	Reardon et al. (2016)	0.11	22.5″	7.98″,16.39″…	0.004,0.008…
3	3	J0740+6620	07:40:45.798	+66:20:33.65	Guillemot et al. (2016)	0.93	2.66″	4.86″	0.02
4	4	J0922-52	09:22:00	-52:00:00	Mickaliger et al. (2012)	0.35	7.07″	6.3″ & 8.7″	0.010,0.014
5	5	J1536-4948	15:36:24.016	-49:48:45.39	Roy et al. (2012)	0.98	2.52″	3.6″	0.017
6	6	J1546-59	15:46:00	-59:00:00	Mickaliger et al. (2012)	3.89	0.63″	1.1″	0.020
7	7	J1652-48	16:52:9	-48:45	Knispel et al. (2013)	4.39	0.56″	1.1″	0.023
8	8	J1658-5324	16:58:39.34359	-53:24:07.003	Camilo et al. (2015)	0.88	2.81″	2.3″	0.009
9	9	J1730-2304	17:30:21.66624	-53:24:07.003	Reardon et al. (2016)	0.62	3.99″	2.1″ & 3.6″	0.006,0.01
10	10	J1744-1134	17:44:29.407190	-53:24:07.003	Matthews et al. (2016)	0.39	6.26″	2.7″	0.005
11	11	J1801-1417	18:01:51.073331	-53:24:07.003	Desvignes et al. (2016)	1.1	2.25″	4.7″ & 5.9″	0.025,0.031
12	12	J1843-1448	18:43:01.375	-14:48:12.61	Lorimer et al. (2015)	3.47	0.71″	1.06″	0.017
13	13	J1902-70	19:02:00	-70:00:00	Ray et al. (2012)	0.92	2.69″	4.3″	0.019
14	14	J1905+0400	19:05:28.273436	+04:00:10.8830	Gonzalez et al. (2011)	1.7	1.45″	2.4″ & 3.1″	0.019,0.025
15	15	B1937+21	19:39:38.561227	+21:34:59.12567	Matthews et al. (2016)	3.5	0.70″	2.2″	0.037
16	16	J1843-1113	18:43:41.26	-11:13:31.07	2nd Paper/ D16	4.568	<null>	<null>	<null>

Execution

My plan was from the coordinate of the pulsar I do a cone search first around each pulsar with a radius of 2 * arcsec up until $\pm 20\%$ (= tol) around the pulsar distance

After loading in the CSV file, I first converted the RA and DEC from sexagesimal coordinates to degrees using SkyCoord. Why? Because Gaia ADQL expects decimal degrees in ICRS.

Here are all the columns that I retrieved using my ADQL query to gaiadr3.gaia_source

```
gaia.source_id, gaia.ra, gaia.dec,
gaia.parallax, gaia.parallax_error,
gaia.pmra, gaia.pmdec, gaia.pmra_error, gaia.pmdec_error,
gaia.phot_g_mean_mag, gaia.bp_rp,
gaia.ruwe, gaia.astrometric_excess_noise,
gaia.phot_bp_rp_excess_factor
```

(All this was different for each pulsar as I had a loop running that would call this query function)

After receiving back the data I stored it in a pandas Dataframe, I then went towards Parallax and distance handling.
Gaia parallax is in milliarcseconds (mas) → `distance_pc = 1000 / parallax_mas`

(I did find this information while doing this , but I'm not really sure I understand it at this moment: Caveat: naive inversion is only reliable when `parallax_over_error` is sufficiently high (commonly >~5). For low S/N parallexes you must use a Bayesian estimator (e.g., Bailer-Jones distances) or treat parallax as a noisy constraint.)

I also had a parallax filter, that removed a match from Pulsar 9 after filtering

- `"parallax"` is not NaN (missing)
- `"parallax"` is positive (> 0)
- `"parallax_error"` is positive (> 0)

I then found the angular seperation between the pulsars and their Gaia candidate every time using SkyCoord.

I also find the Absolute Magnitude using $M = m\ - 5\log_{10}\frac{d}{10}$

[d - distance in Parsecs ; m = apparent magnitude (phot_g_mean_mag)]

I then tag the data with their name and distance and append it to matches.

After the loop , I save the current data as “gaia_matches_raw.csv”

(here I still got 1 match for 1 pulsar)

I then apply some more filters , namely :

- RUWE < 1.4 ; Renormalized Unit Weight Error; Gaia’s global goodness-of-fit; values $\gtrsim$1.4–1.6 indicate astrometric problems (binary, crowding, extended source).

This part I’m not sure I understand fully, I just saw others doing the same and decided to do it. Nevertheless it didn’t change my matches.

My question was if RUWE ≥ 1.4-1.6 indicate unresolved binaries, why wouldn’t I want that in my matches?

I then add a filter that flags solutions which have excess of (2) Astrometric Noise ; Using (astrometric_excess_noise)

After all this I ended up with one match to one pulsar

Saved the data to gaia_matches_filtered.csv

gaia_matches_filtered

I then made some plots, but since I got only one match, it didn’t make much sense

The match & Pulsar

The pulsar was - `J1843−1448`

Gaia Source id - 4103495111344644480

Parameter	Value	Description/Interpretation
source_id	4103495111344644480	Unique Gaia DR3 object identifier
RA (deg)	280.7561460834939	Right ascension in degrees (J2000, ICRS)
Dec (deg)	-14.80364714484038	Declination in degrees (J2000, ICRS)
parallax (mas)	0.35976485	Gaia parallax in milliarcseconds
parallax_error (mas)	0.19761348	Parallax uncertainty (1σ, milliarcseconds)
parallax S/N	1.82	Significance: low (<3 is generally low-confidence for distance)
dist_pc (from parallax)	2779.59	Inverse parallax, in parsecs (1/parallax in arcseconds × 1000)
target_dist_pc	3470.0	Pulsar's estimated distance, for comparison
sep_arcsec	1.54	Angular separation from pulsar position (arcsec)
pmra (mas/yr)	-2.68	Proper motion in RA
pmdec (mas/yr)	1.85	Proper motion in Dec
pmra_error (mas/yr)	0.19	Uncertainty in RA proper motion
pmdec_error (mas/yr)	0.17	Uncertainty in Dec proper motion
phot_g_mean_mag	18.57	Apparent G-band magnitude (faint)
bp_rp	1.50	Gaia color (BP - RP)
M_G (abs mag)	6.35	Absolute G-band magnitude
ruwe	0.98	**Well within threshold**—astrometric solution is trustworthy
astrometric_excess_noise	0.0	**Perfect:** no unexplained astrometric noise
phot_bp_rp_excess_factor	1.29	Indicates quality of photometric colors; ~1.3 is typical

Searching up this pulsar, I found out from a paper that its an Isolated MSP

> PSRs J1552−4937 and J1843−1448 bring the total number of isolated MSPs known in the Galactic disc to 37

the 2015 paper

Gaia's algorithms also strongly classify this as a star through 26 observations

- `classprob_dsc_combmod_star = 1.00`
- `classprob_dsc_combmod_galaxy ≈ 0`
- `classprob_dsc_combmod_quasar ≈ 0`

I think the star with Gaia Source_id 4103495111344644480 can be a candidate counterpart

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After Adding PSR J1012+5307 , which is known to be a Binary System with a white dwarf companion , and changing up the filters :

- Search Radius = 5 * arcsec
- Distance Tol = 1.0 ($\pm 100\%$ of PSR distance)

I got 11 matches before RUWE / Noise Filter and 9 after.

Out of these most parallaxes are low-significance (S/N < 3), except for J1012+5307 and one match in J1843−1448.

Again decided to change up the filters :

- Search Radius = 3 * arcsec
- Distance Tol = 0.8 ($\pm 80\%$)

Now, this time I ended up with 6, 6 Matches

Pulsar	Source ID	Parallax (mas)	Error (mas)	S/N	Distance (pc, Gaia)	Reliable?
J1546−59	5834212557702108288	0.341	0.377	0.90	2936	**No** (very low)
J1546−59	5834212557702111104	0.398	0.119	3.34	2514	**Marginal/Borderline**
J1843−1448	4103495111344644480	0.360	0.198	1.82	2779	**No** (low)
J1843−1448	4103495115680543616	0.708	0.107	6.62	1412	**Yes** (robust)
J1843−1113	4106823440438736384	1.063	0.519	2.05	941	**No** (low)
J1012+5307	851610861391010944	1.745	0.291	6.00	573	**Yes** (robust)

Comparing with ATNF Pulsar Distance catalog

Pulsar	Source ID	Gaia Distance	Parallax (mas)	P_Error (mas)	Parallax S/N	ATNF Distance (pc)	Distance Used (kpc)	Delta (%)
J1546−59	5834212557702108288	2936.2	0.341	0.377	0.90	—	3.89	-24.5
J1546−59	5834212557702111104	2514.4	0.398	0.119	3.34	—	3.89	-35.4
J1843−1448	4103495111344644480	2779.6	0.360	0.198	1.82	3473 (DM)	3.47	-19.9
J1843−1448	4103495115680543616	1412.0	0.708	0.107	6.62	3473 (DM)	3.47	-59.3
J1843−1113	4106823440438736384	941.0	1.063	0.519	2.05	1256	4.568 (now 1256)	-25.1
J1012+5307	851610861391010944	573.1	1.745	0.291	6.00	855	0.84	-32.9

J1546-59 is not part of ATNF pulsar catalogue

Only J1843-1448 and J1012+5307 are reliable from Gaia data, since they have high S/N (≥5)

Something weird with J1843-1113 → Online sources tell me the Pulsar Distance is 4568.0 pc - This is what I used to get the match, but ATNF says 1256 ±470 pc (PX) and NASA Fermi - Gamma Ray Space Telescope says 1600 ± 400 pc (PC), But ATNF DM I get 1707 pc

I changed the used distance to 1256 (also did 1600) for J1843-1113 , and still got the same match (4106823440438736384)

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