The Low-Frequency Pulsar Renaissance



Supporting top researchers from anywhere in the world



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Nederlandse Organisatie voor Wetenschappelijk Onderzoek



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Pulsars are extreme stars

R = 12 km







 $M = 1.4 M_{Sun}$







v_{spin} > 716 Hz v_t = 0.2 c





Only 0.01% of Galactic neutron stars show detectable pulsations





NEUTRON STAR

Pulsars are cosmic lighthouses

RADIATION BEAM

Spin-down Luminosity

Energy budget



- ~ 100% pair-plasma wind
- ~ 0.1% g-rays
- ~ 0.01% X-rays
- ~ 0.000001% optical
- ~ 0.000000001% radio

$$\dot{E} = 4\pi^2 I \dot{P} P^{-3}$$

= 3.95 × 10³¹ erg s⁻¹ $\left(\frac{\dot{P}}{10^{-15}}\right) \left(\frac{P}{s}\right)^{-3}$

General assumptions:

 $M = 1.4 M_{\odot}$ R = 10 km $I = 10^{45} \text{ g cm}^2$ Pure dipole spin-down

Pulsars are precision clocks

ROTATION AXIS

NEUTRON STAR

RADIATION BEAM

RADIATION BEAM

See talk by Tiburzi

Bill Saxton / NRAO

Pulsar Science



Kramer & Stappers 2015

Propagation Effects





Hassall

Stappers, JH et al. 2011



LOFAR has detected >250 pulsars so far

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J0006+1834		J0033+57	B0037+56	B0045+33	B0052+51	B0053+47	0106+4855	 B0105+65	B0105+68	B0114+58	J0137+1654	B0136+57	J0152+0948	B0153+39		\nearrow	1380 MHz
man and a start and a start and a start	mahan				way August	, history physics		MMMMM				-holy(glybed)				\square	328 MHz
J0205+6449	J0212+5222	B0226+70	B0301+19	воз20+39 Д	J0324+5239)0329+1654	B0331+45	J0413+58	B0402+61	B0410+69	J0417+35	J0419+44	J0435+27	B0450+55		m	184 MHz
B0458+46	B0523+11	M B0525+21	B0531+21	B0540+23	J0611+30	B0609+37	B0626+24	J0646+0905	J0647+0913	B0643+80	B0656+14	B0655+64	J0711+0931	B0751+32	1	$\$	176 MHz
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B1322+83	J1503+2111	B1508+55	B1530+27	B1541+09	J1549+2113	J1612+2008	J1627+1419	B1633+24	J1645+1012	J1649+2533	J1652+2651	J1720+2150	, J1740+1000	B1737+13	1	\sim	152 MHz
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J1837+1221	J1838+1650	B1839+56 ∬	B1839+09	J1842+1332	J1843+2024	B1842+14	J1848+0826	J1849+2423	B1848+13	B1848+12	J1853+0853	B1852+10	J1859+1526	J1900+30		\sim	129 MHz
J1901+1306	J1903+2225	بيبينين المينينين J1906+1854	/ B1905+39	J1908+2351	الدونية (مدينية) J1909+1859	1911+1758	م ىيىيە B1910+20	l J1912+2525	برندید J1913+3732	B1915+22	B1918+26	 B1919+21	J1927+0911			\sim	121 MHz
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B1930+13	J1937+2950	J1941+1026	J1941+1341	B1942+17	B1944+17	J1947+0915	B1946+35	J1951+1123	B1949+14	J1953+1149	B1953+50	J1956+0838	J1959+3620	J2002+1637		$\wedge \wedge$	67 MHZ
B2000+40	J2007+0809	المحسب J2007+0910	J2008+2513	J2015+2524	مارم ایک ایک	B2016+28	N B2020+28	B2021+51	B2022+50	J2024+48	B2025+21	J2027+4557	B2028+22	J2030+55	·	\sim	52 MHz
12036+2835	B2034+19	B2036+53	12040+1657		1045+0912		B2045+56	P047+5029	12048+2255	B2053+21	B2053+36	P102+38	مردعة ميسم. 12111+2106	P111+40		\sim	44 MHz
	-	Heren Librar			deputip		HUNHALAM		phythology		NAMPAN PANA					\sim	36 MHz
B2110+27	B2113+14	B2122+13	J2139+2242	B2148+63	J2151+2315	J2155+2813	J2156+2618	B2154+40	J2203+50	J2205+1444	J2206+6151	B2210+29	J2215+1538	B2217+47		man	28 MHz
12222+2923	/ B2224+65	B2227+61	12234+2114		2243+1518		I B2303+30	B2303+46	2307+2225	M B2306+55](B2310+42	JL B2315+21	2319+6411		0.35 0.40 0.4	5 0.50 Spin Phase	0.55 0.60

Pilia et al. 2016

Bilous et al. 2016

Why Pulsars at < 300MHz

Emission mechanism

- Steep spectral indices
- Spectral turnover
- Profile evolution
- Moding

Interstellar medium

- Precision dispersion measure
- Scattering
- Precision rotation measures
- "Scintellometry"

Surveys

- Huge field-of-view
- Ultra-steep-spectrum sources

Low-Freq Pulsar Telescopes







Arecibo Puerto Rico

MWA Australia **LWA** New Mexico



GMRT India



GBT West Virginia



LOFAR Netherlands

Pulsar magnetospheres & moding

Moding Pulsars



LOFAR





LWA

GMRT





XMM-Newton

Radio/X-ray moding in B0943+10



Radio/X-ray moding in B0943+10



Probed this more deeply using a 4x longer campaign

Evolving modes in B0943+10



LOFAR data

LWA data

Mereghetti et al. 2016

Evolving modes in B0943+10

Systematic profile drift during B-mode



Increase in X-ray pulse fraction during B-mode?

Bilous et al. 2014

Mereghetti et al. 2016

Mode-switching in PSR B0823+26



Discovery of a 170x fainter Quiet-mode

Successful radio/X-ray campaign in Spring 2017

Sobey et al. 2015



Pulsar magnetospheres



Hassall et al. (2012)



van Haarlem et al. (2013)

DM law works to 1/100,000

Probing the ISM

See also talks by Tan & Bassa

Cyclic Spectroscopy



Horizontal bars indicate scattering time, T, as inferred from the diffractive bandwidth, $\Delta\nu_d$

Archibald et al. 2014

Cyclic Spectroscopy



Smoothed to ~2kHz resolution

Smoothed to ~2kHz resolution

 $\Delta \nu_{\rm d} = \frac{1}{2\pi\tau}$

Solid line: best-fit power-law Dotted line: power-law of -4

Probes scattering in a previously unreachable regime

Archibald et al. 2014

Pulsar Timing Array nanoHZ gravitational waves



Sesana

Pulse echoes from the ISM



PSR B2217+27

Echoes are from refraction by structures in the ISM.

Nature of structure is still debated.

Also seen in PSR B1508+55.

Michilli et al., in prep.

Pulse echoes from the ISM



Similar phenomenon previously seen in the Crab Pulsar.

Origin: narrow filaments in the Crab Nebula.

Michilli et al., in prep.

Pulsar Polarimetry





Noutsos et al. 2015

LOFAR data

Bilous

Pulsar RM Catalog



ATNF catalog RMs

significantly more precise

Pulsar Searches

See also talks by Tan & Bassa

Observing/Processing



- Processing on Cartesius: 3hrs/pointing/24-core node.
- ~2PB of data collected and archived.
- Also started coherent dedispersion searches on DRAGNET GPU cluster.

Exotic Pulsar Systems



"Diamond Planet" Bailes et al. 2012



First exoplanets Wolszczan et al. 1992



PSR-BH "The Holy Grail" Someone et al. 20??



"Double Pulsar" Lyne et al. 2004



Galactic Center Magnetar Eatough et al. 2013

LOTAAS LOFAR Tied-Array All-Sky Survey

http://www.astron.nl/lotaas

219 coh. beams 3 incoh. beams

> LOFAR "Superterp" (innermost I2 HBA sub-stations)

LOTAAS Collaboration

Jason Hessels, Sotiris Sanidas, Vlad Kondratiev, Sally Cooper, Daniele Michilli, Chia Min Tan, Cees Bassa, Ziggy Pleunis, Joeri van Leeuwen + LOFAR PWG

Find sporadic sources



See poster by Michilli

Find low-lum nearby sources



P = 476ms DM = 6.5pc/cc d ~ 0.5kpc



P = 33ms DM = 3.0pc/cc d ~ 0.1kpc

A complementary population



Millisecond pulsars

See also talks by Polzin & Bassa

Millisecond Pulsars



The premier low-frequency sample

Kondratiev et al. 2016

Find millisecond pulsars

Many of the fastest-spinning MSPs have ultra-steep spectra

J1810+1744 - 1.66ms

0.5Jy at I35MHz! α ~ -2.6



Bassa et al. 2016

B1937+21 - 1.56ms



Kondratiev et al. 2016

Scattered out for LOFAR $\alpha \sim -2.6$

Eclipsing pulsars



Hessels; Archibald et al. 2013

See also talk by Polzin

Fermi Gamma-Ray Space Telescope





First LOFAR Millisecond Pulsar Discovery



First pulsar found < 200MHz

Pleunis et al., submitted

Ultra-dense matter

Neutron star equation-of-state



2MSun Pulsar Demorest et al. 2010

716Hz Pulsar Hessels et al. 2006

Summary

Low-frequency radio pulsar observations:

- Probe pulsar magnetospheres.
- Probe the interstellar medium.
- Find pulsars, especially millisecond pulsars, missed at higher frequencies.