Progress of Pulsar Astronomy in the Last Decade

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CTA-Japan Meeting 2017 Dec 18/19 2017
• Our understandings of pulsars in the last ten years have been advanced by *Fermi* and the coordinated MWL follow-ups since 2008.

• Review a few major achievements in pulsar science.

• Prospects of CTA in the light of these achievements.
Magnificent 7 in EGRET Era
A New Era of Pulsar Astronomy

By now, there are 205 gamma-ray selected pulsars.

Abdo et al. (2013)
What’s New?

- Radio-quiet gamma-ray pulsars
- Variable pulsar wind nebula
- Millisecond pulsars (MSPs)
- Globular clusters
- Variable gamma-ray pulsar (PSR J2021+4026)
- Gamma-ray binaries
Importance of Synergy among X-ray, Gamma-ray & Radio

- Different wavelengths reflects different astrophysical processes / emission regions.

- Theoretically, properties in one energy band can help to constrain the properties in the others.

- Observationally, the limitations of observations in a particular wavelength can be complemented by the other bands.
Geminga

- The 1st RQ-PSR - Geminga

- Its gamma-ray emission was detected by the experiments in the early-days - SAS-2, COS-B.
Geminga

Detection of a possible X-ray counterpart in COS-B error box with *Einstein* (Bignami et al. 1983)
Geminga

- Discovery of 0.237s period in X-ray by ROSAT. (You have more photons in X-ray)

- The X-ray ephemeris enabled the gamma-ray pulsation to be uncovered.
High Energy Pulsar Magnetospheric Radiation

Wang et al. (2014)
Gamma-ray emission from Geminga

\[
\frac{dN}{dE} = N_0 E^{-\Gamma} \exp\left(-\frac{E}{E_0}\right) \text{cm}^{-2} \text{s}^{-1} \text{GeV}^{-1}.
\]

\[E^2 \text{ Flux (erg cm}^{-2} \text{s}^{-1})\]

\[\begin{array}{c}
10^{-8} \\
10^{-9} \\
10^{-10} \\
10^{-11} \\
10^{-12} \\
\end{array}\]

\[\begin{array}{c}
10^{-1} \\
1 \\
10 \\
\end{array}\]

Energy (GeV)

Abdo et al. (2010)
X-ray emission from Geminga

PL: Photon Index~1.7

BB1: kT~45 eV

BB2: kT~0.2 keV

Caraveo et al. (2004)

Animation courtesy: ESA
Emission beyond the Magnetosphere

- Most of the rotational energy are lost through the relativistic pulsar wind outflow.
- Typical speed of pulsar $\sim 250$ km/s
- Producing bow-shock

Illustration courtesy: Dany Page
Extended X-rays from Geminga

Hui et al. (2017a)
Fast X-ray variabilities of Geminga PWN

Hui et al. (2017a)
Fast X-ray variabilities of Geminga PWN

Hui et al. (2017a)

Variability occurred at ~0.8c.

The fastest X-ray variation in PWN observed!
Extended TeV emission is detected by HAWC and Milagro.

13 sigma in 1-50 TeV by HAWC.

Spatial extent of ~few tens of pc.

Questions for follow-up

- Align with proper motion?
- Counterpart in GeV?
- Variability?
Differences between RQ and RL gamma-ray Pulsars

Abdo et al. (2013)

- In 2PC, there are 35 RQ PSRs and 42 non-recycled RL PSRs.
- Allow a meaningful statistical analysis.
Differences between RQ and RL gamma-ray Pulsars

- Spectral shape of RQ and RL gamma-ray PSRs are apparently different.

Hui et al. (2017b)
Differences between RQ and RL gamma-ray Pulsars

- While the B-field at the stellar surfaces of RL and RQ PSRs are comparable,
- B-field at the light cylinder of these two populations are significant different.

Hui et al. (2017b)
Differences between RQ and RL gamma-ray Pulsars

Hui et al. (2017b)

- Gamma-ray to X-ray flux ratios of RQ gamma-ray PSRs are apparently higher.

Hui et al. (2017b)
Differences between RQ and RL gamma-ray Pulsars

Hui et al. (2017b)
Millisecond Pulsars (MSPs)

Source: ATNF Pulsar Catalog

Animation courtesy: CXC
Zoo of MSPs

- **Black Widows** (P<20 hrs, $M_c < 0.05 \, M_{\text{sun}}$)
- **Redbacks** (P<20 hrs, $M_c \sim 0.2-0.4 \, M_{\text{sun}}$)
- **Isolated MSPs**
- **Wide-Orbit MSP/WD binaries**
- **MSP-Planet binary**
A millisecond pulsar in an eclipsing binary

A. S. FRUCHTER, D. R. STINEBRING & J. H. TAYLOR

Joseph Henry Laboratories and Physics Department, Princeton University, Princeton, New Jersey 08544, USA

We have discovered a remarkable pulsar with period 1.6 ms, moving in a nearly circular 9.17-h orbit around a low-mass companion star. At an observing frequency of 430 MHz, the pulsar, PSR1957 + 20, is eclipsed once each orbit for about 50 minutes. For a few minutes before an eclipse becomes complete, and for more than 20 minutes after the signal reappears, the pulses are delayed by as much as several hundred microseconds—presumably as a result of propagation through plasma surrounding the companion. The pulsar’s orbit about the system barycentre has a radius of 0.089 light seconds projected on to the line of sight. The observed orbital period and size, together with the fact that eclipses occur, imply a surprisingly low companion mass, only a few per cent of the mass of the Sun.
Black Widows

Ahnen et al. (2017)
Intrabinary Shock of Black Widow

Huang et al. (2012)

Wu et al. (2012)

Reynold et al. (2007)
Bow Shock of Black Widow

Huang et al. (2012)
VHE Emission from Black Widow Bowshock?

X-ray observations put strong constraints on the IC model

Bednarek & Sitarek (2013)
VHE Emission from Black Widow Bowshock?

Ahnen et al. (2017)
State-change in the "transition" binary millisecond pulsar J1023+0038

ATel #5513; B. W. Stappers (University of Manchester), A. Archibald (ASTRON), C. Bassa (ASTRON), J. Hessels (ASTRON), G. Janssen (ASTRON), V. Kasp Lyne (University of Manchester), A. Patruno (University of Leiden Linear Accelerator Lab).
Distributed as an Instant Email Notice Transient
Credential Certification: Ben Stappers (ben.stappers@mail.astro.uva.nl)

Optical Observations of the Binary MSP J1023+0038 in a New Accreting State

ATel #5514; J. P. Halpern (Columbia U.), E. Gaidos (U. Hawaii Manoa), A. Sheffield, A. M. Price-Whelan, S. Bogdanov (Columbia U.)
on 25 Oct 2013; 19:10 UT
Credential Certification: Jules Halpern (jules@astro.columbia.edu)
Redback

Halpern et al. (2013)

Takata et al. (2014)
Intrabinary Shock from Redbacks

PSR J1723–2837

Hui et al. (2014)

PSR J2129-0429

Hui et al. (2015a)
VHE Emission from Redback PW?

Bednarek (2014)
X-ray Luminosities of MSPs

X-ray conversion efficiencies of MSP are comparable with non-recycled PSRs

Lee et al. submitted
Redbacks vs Black Widows

Rotational and orbital parameters of RBs and BWs are comparable.

Lee et al. submitted
Redback vs Black Widows

X-ray emission of RBs are stronger and harder than BWs.

With these updated X-ray results, we can refine the feasibility of observing RB/BW with CTA.
Why the population of MSPs expands considerably?
Treasure Hunting in UFOs

There is plenty of discovery space in the unidentified Fermi Objects (UFOs)
Treasure Hunting in UFOs

Hui et al. (2015b)

|b| > 10°; Detection Significance > 10σ

- Our Target
- AGN
- Young PSR
- Millisecond PSR

Variability Index

Curve Significance
Coupling Classification with Automatic Feature Selection

1. Conventional classifications require some knowledge of the gamma-ray properties of different classes of objects which can be far from complete in view of the relatively short history of gamma-ray astronomy.

2. Instead of relying on a prior knowledge, automatic classification let the data “speak for themselves” and generate the classification model.

3. In the previous attempts of classifying gamma-ray sources with machine learning techniques (e.g. Saz Parkinson et al. 2016 ApJ 820 8), the power of automatic feature selection has not be fully exploited.

4. By coupling the classifiers with automatic feature selection algorithms, we aim to

   i) Improving the prediction accuracy
   ii) Provide a more cost-effective prediction model
   iii) Enhancing the discovery power in data mining
Coupling Classification with Automatic Feature Selection

Leung et al. in prep
### Coupling Classification with Automatic Feature Selection

<table>
<thead>
<tr>
<th>Importance Rank</th>
<th>PSR/AGN</th>
<th>YNG/MSP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Variability_Index</td>
<td>Unc_Energy_Flux100</td>
</tr>
<tr>
<td>2</td>
<td>Signif_Curve</td>
<td>GLAT</td>
</tr>
<tr>
<td>3</td>
<td>Spectral_Index</td>
<td>Flux_Density</td>
</tr>
<tr>
<td>4</td>
<td>hr45</td>
<td>Signif_Curve</td>
</tr>
<tr>
<td>5</td>
<td>Unc_Flux1000</td>
<td>hr34</td>
</tr>
<tr>
<td>6</td>
<td>SED1000_3000</td>
<td>hr23</td>
</tr>
<tr>
<td>7</td>
<td>Flux1000_3000</td>
<td>Spectral_Index</td>
</tr>
<tr>
<td>8</td>
<td>hr23</td>
<td>hr45</td>
</tr>
<tr>
<td>9</td>
<td>Unc_Energy_Flux100</td>
<td>-</td>
</tr>
</tbody>
</table>

Leung et al. in prep
Coupling Classification with Automatic Feature Selection

![ROC Train of AGN&PSR using LR](image1)

ROC Train of YGN&MSP using LR

<table>
<thead>
<tr>
<th>Prediction Model</th>
<th>PSR/AGN classification</th>
<th>YNG/MSP classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Our method</td>
<td>98.2%</td>
<td>95.7%</td>
</tr>
<tr>
<td>Saz Parkinson et al. (2016) [1]</td>
<td>94.9%</td>
<td>90.7%</td>
</tr>
</tbody>
</table>

Leung et al. in prep
Unidentified TeV sources

~30% of currently detected TeV sources are unidentified.

Source: TeVCat
Impacts of Automatic Feature Selection in CTA era

• Improving the performance of classification.

• Instructing us in how to construct a cost-effective catalog so as to minimize the redundancy.

• Identifying features that we don’t expect and advancing our understanding of emission nature of a specific class.
Hope we can do even better in the next golden era of gamma-ray astronomy!