Artificial Intelligence for Astrophysics

Nicolò Pinciroli, PhD student

in collaboration with prof. Piero Fraternali and the HEAG at AO Roma.

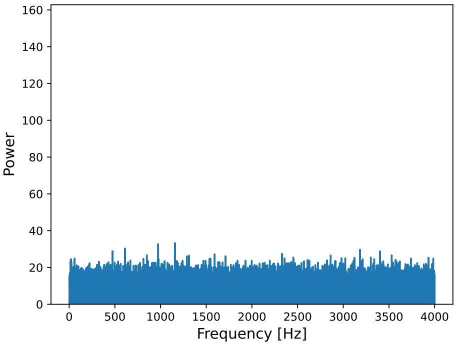
POLITECNICO
MILANO 1863

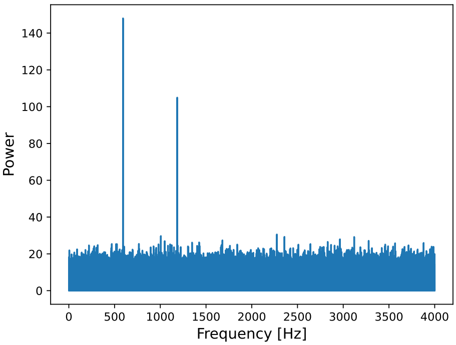
28^{th} September 2022

Introduction

Problem statement

Recover a signal affected by phenomena that change its phase or period in a relatively short time, hindering their detection using traditional techniques.
A specific example is the one of **accreting pulsars**.





Motivation

- Events' arrival times are influenced by the **Doppler effect** (and by the variation of the orbital period T_{orb} due to accretion)
- Computing the initial times of events allows reconstructing a time series
- If an object has periodic behavior, the Fourier transform allows determining the period from the correct series

Solution

Finding the **orbital parameters** optimal combination to reconstruct a **periodic** time series

- For each combination of orbital parameters, the Fourier transform is computed
- For each spectrum, the maximum power is determined
- Each orbital parameters combination is associated with the corresponding maximum power in the spectrum

Finding the **orbital parameters** optimal combination to reconstruct a **periodic** time series

- Exhaustive (grid) search on all combinations of orbital parameters $\implies$ computationally **expensive**
- Targeted research on some combinations of orbital parameters

Advantages of targeted research

- Drastic reduction of computing times
- Increase of the number of data that can be analyzed
- Possibility of discovering new pulsating objects

How to do a **targeted research**

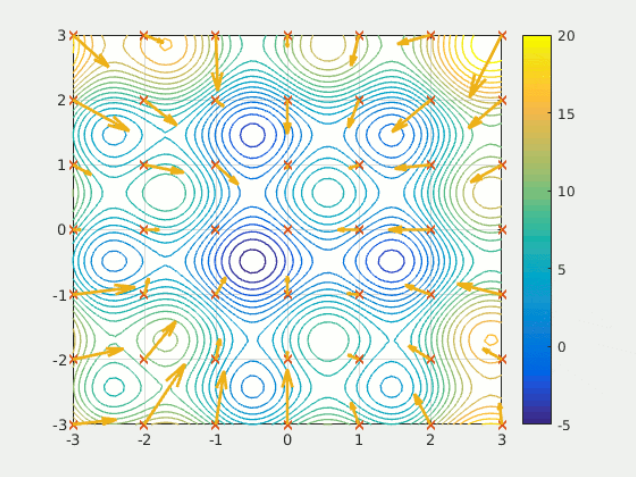
- A targeted search uses **information** on the **previous** trials to **generate** subsequent orbital parameter combinations $\implies$ generate new points in a space $\mathbb{R}^n$
- **Evolutionary algorithms** are inspired by natural processes to generate new points in space


Evolutionary algorithms

Fundamental principles

- In nature, living beings **evolve**, or **communicate** with each other in search of food
- The living things that are **fitter for the environment** survive or are more successful
- **Simple** beings **coordinate** to achieve common goals

Fundamental principles



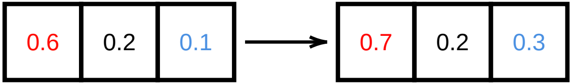
Source

Genetic algorithms

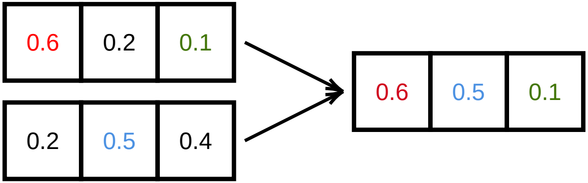
- Each point in a space $\mathbb{R}^n$ is represented by a **chromosome**
- Each coordinate of a point is called **gene**
- The **best** chromosomes are more likely to survive and combine with other chromosomes

Genetic algorithms – fundamental operations

- **Mutation**: one or more genes change randomly



- **Crossover**: two chromosomes combine together



- **Selection**: given a set of chromosomes, only the best survive

Every operation is associated with a different probability.

Algorithm structure

- **Initialization**: generation of a random set of chromosomes
- **Selection**: the best chromosomes are selected, the others are eliminated
- **Evolution**: the selected chromosomes are combined with each other using crossover operations or mutate
- **Termination**

Parameters choice

- **Crossover** favors the exploitation of information from previous trials
- **Mutation** favors the exploration of space

One of the biggest difficulties is **balancing** mutation and crossover probabilities.

Application

Combinations representation

- A combination of orbital parameters comprises three parameters: ϕ, T_{orb} e $a_X \sin i$
- A gene refers to an orbital parameter
- A chromosome is a set of three orbital parameters
- A chromosome is associated with a **cost**, which is the opposite of the maximum power of the corresponding spectrum

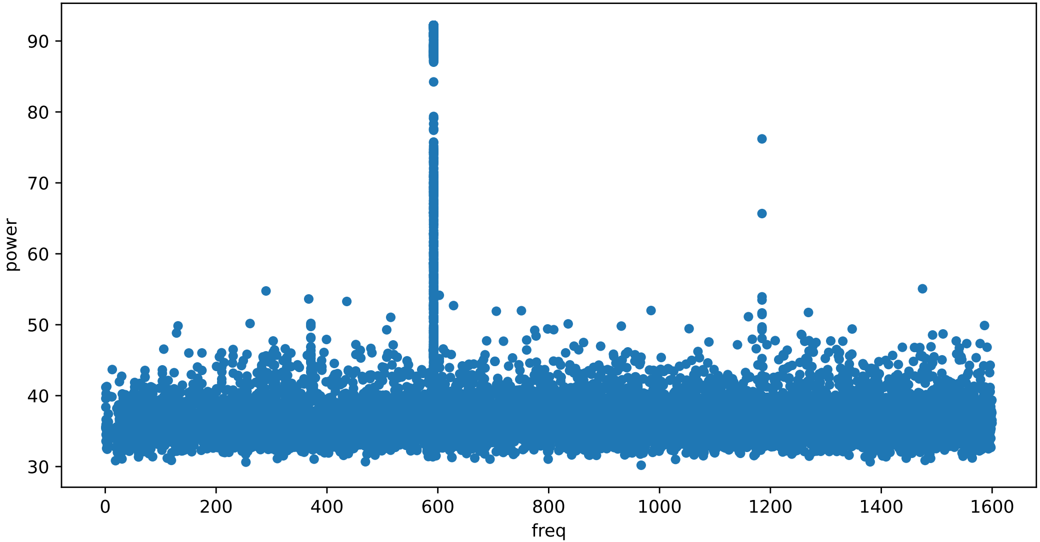
The goal is **minimizing the cost** $\implies$ maximizing power

- Compared to exhaustive search, reducing the number of iterations by a factor of at least $100 \implies$ **from 3 months to 1 day**
- Identification of sub-optimal orbital parameters on data in **X-rays** and **optical**

Quantitative results

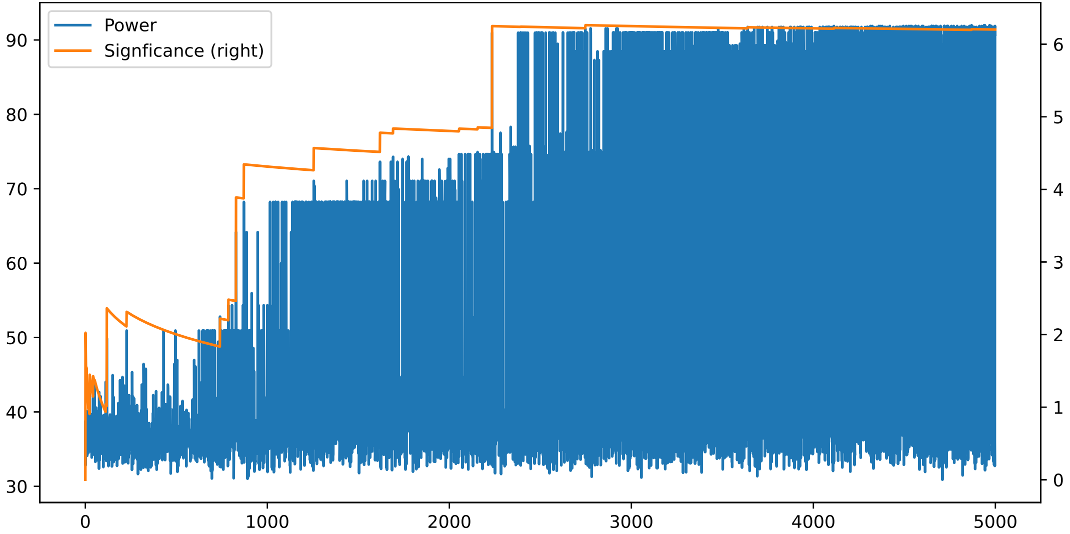
Object	Type	Number of combinations		Speedup
		Genetic algorithm	Grid search	
J1023+0038	Optical	9928	$12 \div 64$	$\approx 100\times$
3XMM J004301.4+41307	X ray	7355	$35 \div 343$	$\approx 130\times$
3XMM J004232.1+411314	X ray	2691	$4 \div 64$	$\approx 360\times$

J1023+0038



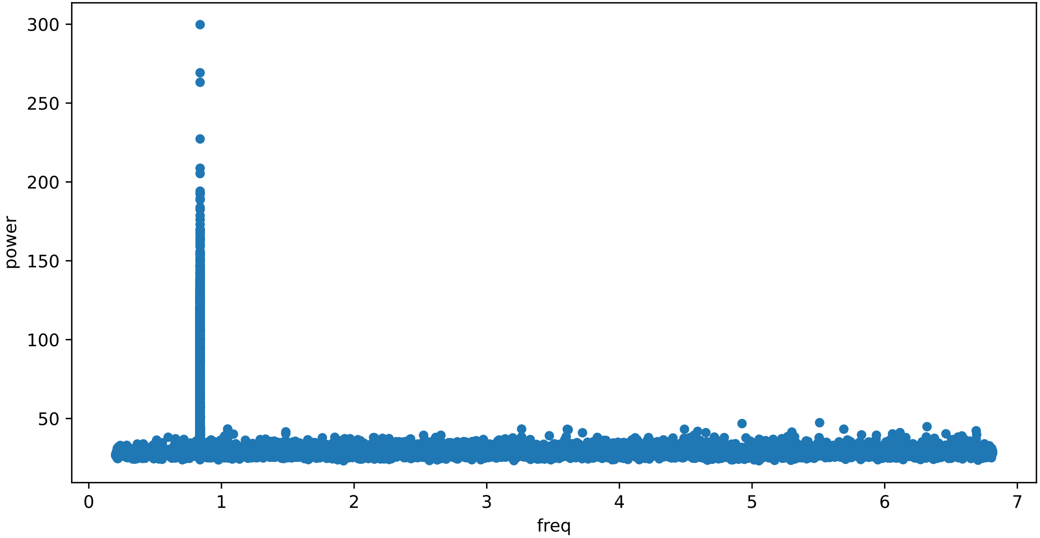
power
90
80
70
60
50
40
30
0
200
400
600
800
1000
1200
1400
1600
freq

J1023+0038

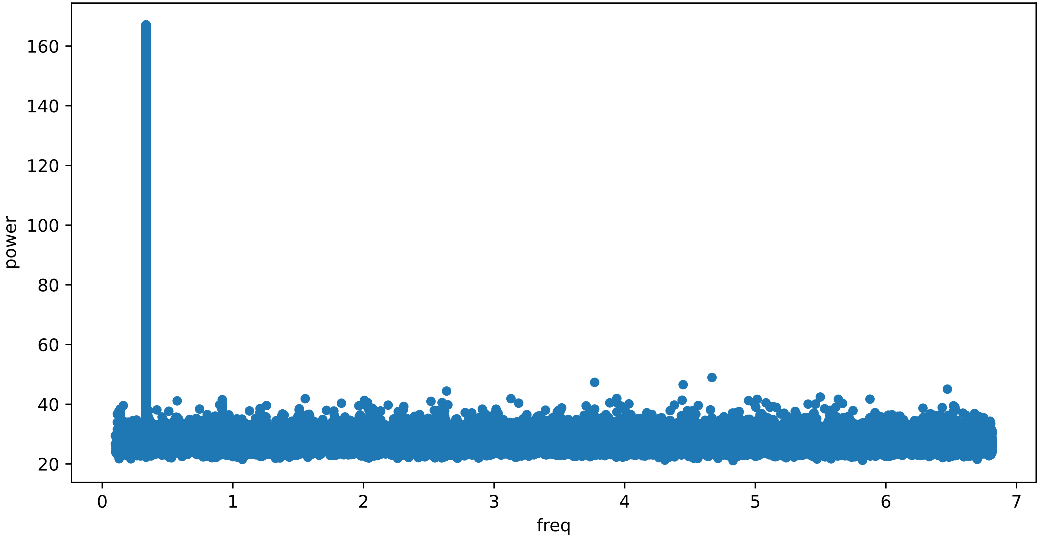


Power
Signficance (right)
90
80
70
60
50
40
30
6
5
4
3
2
1
0
0
1000
2000
3000
4000
5000

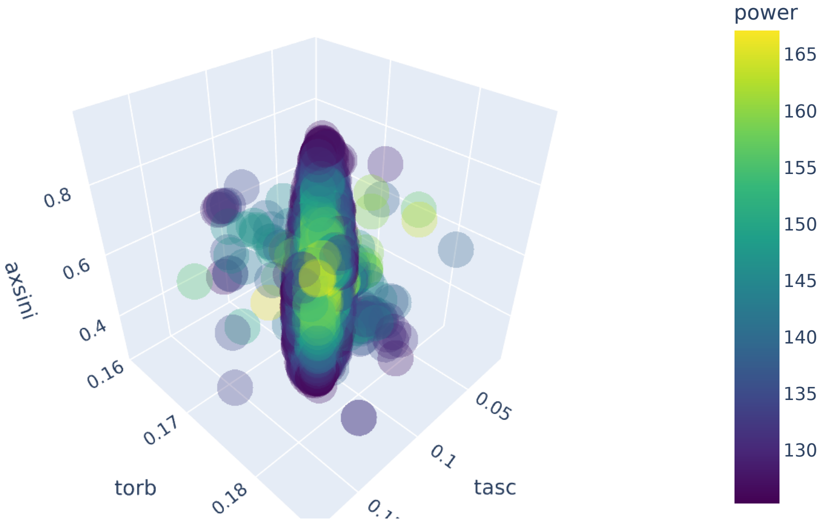
3XMM J004301.4+41307



3XMM J004232.1+411314



3XMM J004232.1+411314




Future work

Future work

- Application of the algorithm to sources not yet studied
- Comparison between different **evolutionary algorithms**
- Collection of enough labelled data to take advantage of **Machine Learning** techniques

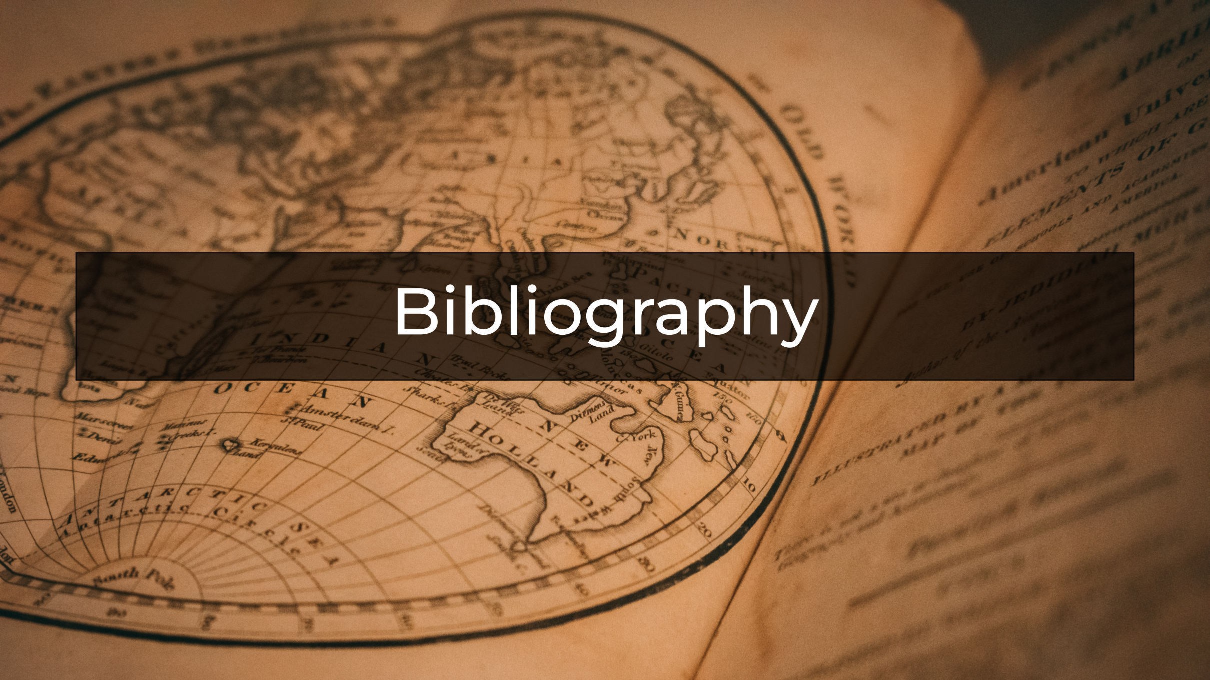

Acknowledgments

Acknowledgments

- prof. Piero Fraternali, my supervisor at Politecnico
- prof. Gianluca Israel, for having provided data (and guidance!)
- prof. Stefano Covino, for having introduced time series topics in his course at Insubria
- High Energy Astrophysics Group at AO Roma, for having discussed about applications of Genetic Algorithms to their data
- prof. Saleh Alaliyat, who taught Genetic Algorithms at NTNU i Aalesund, Norway, in the Simulation and Visualization programme


Thank you for the attention

Bibliography



Bibliography

[Amb+17] Filippo Ambrosino et al. “Optical pulsations from a transitional millisecond pulsar”. In: *Nature Astronomy* 1.12 (2017), pp. 854–858.

[Cas+18] Guillermo A Rodrıguez Castillo et al. “Discovery of a 3 s Spinning Neutron Star in a 4.15 hr Orbit in the Brightest Hard X-Ray Source in M31”. In: *The Astrophysical Journal Letters* 861.2 (2018), p. L26.

[Cro+73] Jack L Crosby et al. *Computer simulation in genetics.* 1973.

[Esp+16] P Esposito et al. “EXTraS discovery of an 1.2-s X-ray pulsar in M 31”. In: *Monthly Notices of the Royal Astronomical Society: Letters* 457.1 (2016), pp. L5–L9.

[FB+70] Alex Fraser, Donald Burnell, et al. “Computer models in genetics.”. In: *Computer models in genetics.* (1970).

[Fra57] Alex S Fraser. “Simulation of genetic systems by automatic digital computers I. Introduction”. In: *Australian journal of biological sciences* 10.4 (1957), pp. 484–491.