Welcome to SpaceCode Challenge 2025!

Hosted by the Space Technology and Astronomy Cell (STAC), IIT Mandi

The Challenge starts at 13th January 00:00

Submissions will close at 15th January 00:00

Welcome to this year's exciting **SpaceCode Challenge**! Get ready to explore the wonders of computational astronomy as you tackle the challenges we've prepared for you. The competition consists of three main computational problems that will test your understanding of the *code behind the exostars and pulsars*. These tasks will require you to demonstrate your skills in data analysis, algorithm design, and visualization.

This year's challenge is designed as a 2-day hackathon, where participants will work in teams of two or three to solve the problems and showcase their solutions. The competition is open to all levels, so whether you're a beginner or an advanced coder, you'll find an opportunity to apply your knowledge and learn something new.

In addition to the computational tasks, we've included a set of purely theoretical problems. These problems do not require computational effort but will challenge your conceptual understanding and creativity. Tackling these problems could provide you with a slight edge in the competition.

Register your team at: `https://t.ly/wFABc`

Don't miss to complete your submission at: `https://t.ly/_K-pI`

Computational Questions

Problem 01: Analysis of Exoplanets Based on Orbital Time Period

The discovery of exoplanets has been one of the most exciting fields of astrophysics over the past few decades. With the advent of advanced detection techniques, such as the Radial Velocity (RV) method, a large number of exoplanets have been identified, providing valuable insights into the diversity of planetary systems. One of the most important aspects of studying exoplanets is understanding their orbital properties, including the orbital period, which is the time it takes for a planet to complete one revolution around its host star.

The Radial Velocity method detects exoplanets by measuring the periodic changes in the star's radial velocity as it moves in response to the gravitational pull of an orbiting planet. These variations in velocity cause a Doppler shift in the star's spectral lines, which can be observed to infer the characteristics of the planet, such as its mass and orbit.

An online catalog of all known exoplanets can be accessed from the following link:
`https://exoplanet.eu/catalog/`

This catalog provides detailed data on a vast number of exoplanets, including their orbital parameters, discovery methods, and host star properties.

Your task is to analyze the exoplanet data available on the above mentioned website by generating a histogram plot that shows the number of exoplanets discovered as a function of their orbital time period around their host stars.

Building Your Dataset:

- Open the provided URL.
- Under the "Status" drop-down menu, select **"Confirmed"** to focus on exoplanets that have been verified through observations.
- Under the "Detection" drop-down menu, select **"Radial Velocity"** to filter the data for planets discovered using the Radial Velocity method.
- Set the X-axis range for the histogram to **0 to 400 Earth days** to focus on planets with observable orbital periods that are relevant for the Radial Velocity method as planets with extremely long or short periods might skew the plot.

Analysis and Insights:

After creating the histogram plot, answer the following questions based on your observations:
- **Why do most of the exoplanets discovered using the radial velocity method exhibit short orbital periods (e.g., less than 50 Earth days)?** Explore the reasons behind the prevalence of these short-period exoplanets. Consider factors such as observational limitations, sensitivity of the radial velocity method, and the nature of planetary orbits. You should take into account the fact that planets closer to their host stars cause larger Doppler shifts, making them easier to detect. In addition, explore any biases introduced by the detection methods and how they might favor short-period exoplanets.
- **Why is it that there are so few exoplanets discovered with orbital time periods of several hundred days, similar to Earth, Venus, or Mars's orbital time period around the Sun?** Discuss why planets with longer orbital periods, like those in the habitable zone (e.g., Earth-like planets), are less frequently detected using the Radial Velocity method. Consider the technical challenges in detecting smaller Doppler shifts caused by planets with longer periods, as well as the limitations of current observational technology. Additionally, we discuss how these factors affect the detection rate of Earth-like planets and the significance of this in our search for potentially habitable exoplanets.

Deliverables:

- A histogram plot showing the distribution of exoplanets' orbital periods using radial velocity data.
- A detailed analysis addressing the above questions and offering insights into why the distribution shows a concentration of short-period exoplanets.
- The Python code (or equivalent) used to generate the plot and perform the analysis.

Problem 02: Radial Velocity Method for Finding Exoplanets

The Radial Velocity (RV) method is one of the most effective techniques for detecting exoplanets. By observing the Doppler shifts in a star's spectral lines, caused by its motion due to an orbiting exoplanet, astronomers can infer the presence and properties of these planets. The wobble of the star, induced by the gravitational pull of the planet, leads to periodic shifts in its velocity, observable as changes in the star's light spectrum.

In this problem, you will work with both synthetic and real radial velocity data. You will generate RV curves for hypothetical star-exoplanet systems, simulating the dynamics based on provided parameters such as stellar mass, planetary mass, and orbital period. Additionally, you will analyze real RV data for the star 51 Pegasi, the first Sun-like star found to host an exoplanet using this method.

This exercise is designed to help you understand the fundamental principles of orbital mechanics and data analysis in exoplanet detection. You will visualize the generated data, study periodic signals through periodogram analysis, and interpret key orbital properties such as eccentricity, mass, and orbital period. Through this, you will gain practical insight into the RV method, a cornerstone of modern exoplanetary science.

Analysis of 51 Pegasi Data:

Data: Download the radial velocity data for the star 51 Pegasi (the first main-sequence star around which an exoplanet was discovered) from the following link:

`https://drive.google.com/file/d/1fOckX-ElhDkeRA2xOyb0mxUF23lgbP3_/view`

The data set consists of:

- **Column 1:** Time in Julian date
- **Column 2:** Radial velocity (m/s)
- **Column 3:** Uncertainty in radial velocity (m/s)

Tasks:

1. Create a detailed plot of the radial velocity data with time on the X-axis and the measured radial velocity on the Y-axis. Represent each data point as a large, filled circle for clarity. Ensure that the plot is well-labeled, with axis titles, and consider adding gridlines for better readability and accuracy.

2. From the scatter plot, make an initial estimation of the orbital period of the exoplanet. Look for repeating cycles or patterns in the data that may indicate the periodic motion of the star caused by the gravitational pull of the orbiting planet.

3. Perform a Lomb-Scargle periodogram analysis to more rigorously estimate the orbital period. Use the following formula to compute the periodogram:

$$P_{LS} = \arg\max \left(\frac{1}{N} \sum_{i=1}^{N} \left(\mathrm{RV}_i \cos(\omega t_i) + \mathrm{RV}_i \sin(\omega t_i) \right) \right)$$

where RV_i represents the radial velocity at time t_i, and ω is the angular frequency. Carefully explain the steps and justify the choice of parameters used in your periodogram analysis.

4. Using the orbital period derived from the periodogram analysis, fold the radial velocity data onto a single orbital cycle. This requires calculating the phase of each observation relative to the period. Afterward, plot the folded radial velocity curve, showing the periodic motion of the star, and discuss any noticeable trends or noise present in the data.

Tools:

Use `Python` and the `SciPy` library for periodogram analysis.

Deliverables:

- Scatter plot of time vs. radial velocity with large filled circles for each data point.
- Initial estimate of the orbital period based on the scatter plot.
- Lomb-Scargle periodogram showing the estimated orbital period, with a clear explanation of the method and parameters used.
- Folded radial velocity curve, plotted using the orbital period obtained from the periodogram analysis.

Problem 03: Pulsars in Deep Space

Pulsars are highly magnetized, rotating neutron stars that emit beams of electromagnetic radiation from their magnetic poles. This radiation is observable from Earth only when the beam of emission is directed toward us, creating a pulsed appearance. Often referred to as cosmic lighthouses, pulsars provide invaluable insights into the fundamental physics of neutron stars, the interstellar medium, and even serve as cosmic clocks for testing general relativity.

In this challenge, your task is to develop a classifier that separates real astronomical signals originating from pulsars from man-made radio frequency interference (RFI). The astronomical signals of interest are emitted by pulsars, which are the ultra-dense remnants of exploded stars. However, these signals are often obscured or mimicked by RFI, making the classification task both challenging and critical.

Dataset:

You are provided with two datasets for this challenge:

1. **Numerical Features Dataset:** A dataset consisting of eight numerical features per sample, extracted from the pulsar signals. This data set is suitable for traditional machine learning models such as random forests, support vector machines (SVM), and neural networks.
   Testing & Training files for this dataset are available at `https://t.ly/6WL6Q` and `https://t.ly/z6Co_`.

2. **Image Dataset:** A dataset of images representing the raw signal data from which the numerical features were derived. This data set is particularly suitable for convolutional neural network (CNN)-based classification. The image dataset can be accessed at the following link:

$$https://as595.github.io/HTRU1/$$

   Scroll down on the webpage for instructions on how to load the dataset using `PyTorch`.

Tasks:

1. **Data Preprocessing:** Load and preprocess both the numerical features dataset and the image dataset. For the numerical dataset, ensure proper handling of missing values, scaling, and splitting into training and validation sets. For the image data set, apply necessary transformations, such as resizing, normalization, and batching, to make it compatible with CNN models.

2. **Model Development:**
   - Use the numerical features dataset to train and evaluate classification models, such as Random Forests, SVMs, or fully connected Neural Networks.
   - For the image dataset, design and train a Convolutional Neural Network (CNN) model to classify pulsar signals and RFI.

3. **Performance Evaluation:** Evaluate your models on both datasets using appropriate metrics such as accuracy, precision, recall, F1 score, and ROC-AUC. Emphasize minimizing false positives (RFI misclassified as pulsars) while maximizing true positives.

4. **Comparison and Discussion:** Compare the performance of your models trained in the numerical data set with those trained in the image data set. Discuss the advantages and limitations of each approach and suggest scenarios where one might be preferred over the other.

Tools:

- Use `Python` and libraries such as `scikit-learn`, `PyTorch`, or `TensorFlow` for implementing and training models.
- Explore visualization tools like `matplotlib` or `seaborn` to better understand the data and model outputs.

Deliverables:

- Preprocessed datasets, including any code used for data cleaning and transformation.
- Well-documented code for all implemented models.
- A report detailing.
- Visualization of results, including confusion matrices, ROC curves, and feature importance (if applicable).

Theoretical Questions

Problem 04: Orbital Resonances
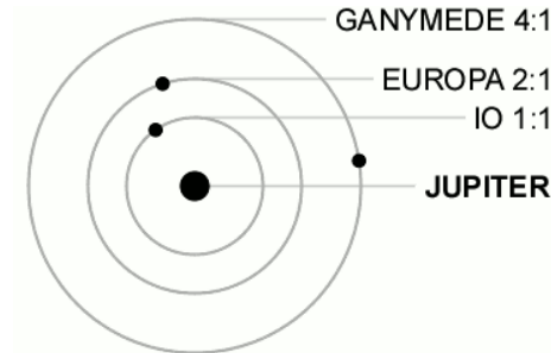
Jupiter's moons Io, Europa, and Ganymede in a 4:2:1 orbital resonance.

Question: Orbital resonances are not just theoretical. Jupiter's moons—Io, Europa, and Ganymede are in a 4:2:1 resonance, causing significant tidal heating on Io, making it the most volcanically active body in the solar system. Just imagine about similar effects which might occur in exoplanetary systems. Two planets orbit a Sun-like star in a 3:2 mean-motion resonance. The semi-major axis of the inner planet is $0.8\,\text{AU}$.

1. Derive the orbital period of the inner planet using Kepler's Third Law:

$$T^2 = \frac{a^3}{M_\odot}.$$

   Assume $M_\odot$ as the mass of the star.

2. Calculate the semi-major axis and orbital period of the outer planet based on the resonance ratio.

3. Discuss the potential impact of such a resonance on the system's long-term stability and the habitability of the planets.

Problem 05: Escape Velocity from a White Dwarf

Question: White dwarfs are remnants of stars like our Sun. If matter is pulled from a companion star onto a white dwarf, it can ignite runaway nuclear fusion, resulting in a Type Ia supernova. These explosions are so bright they can outshine entire galaxies! Such a white dwarf has a mass of $1.4\,M_\odot$ and a radius of $0.008\,R_\odot$:

1. Derive the escape velocity formula using the conservation of energy.

2. Calculate the escape velocity and express it as a fraction of the speed of light c. Using Basics of 11th Physics will be enough.

3. Discuss how the high escape velocity affects the physics of matter near the white dwarf, particularly electron degeneracy and accretion disks.

Submit Your Solutions Here

Submission Guidelines:

Please make sure to follow these simple instructions when submitting your solutions:

1. Submission Link: `https://t.ly/_K-pI` (Active till 15th January 00:00 hours)

2. Include the data file(s) you worked on (e.g., .csv or .txt file with RV measurements and corresponding times).

3. Attach a `.zip` file containing all the relevant files for your submission. Rename this as `<YourTeamName>_SCC.zip`.

4. Submit `.py` files or Jupyter notebooks (`.ipynb`) for computational tasks with any necessary visualizations.

5. Provide a neat PDF of your theoretical solutions, typed or handwritten (if handwritten, ensure legibility).

6. Include a **explanatory document** (Word, PDF, or similar) explaining your approach to each task.

7. Number your submissions by question (e.g., `<YourTeamName>_SCC_Q1.ext` etc.) for clarity.

For Queries and Support:

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Best of Luck!

Wishing you an insightful and thrilling journey through the cosmos.

Space Technology and Astronomy Cell (STAC)
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"Andhera Kayam Rahe!"