Poland 2023

16th International Olympiad on Astronomy and Astrophysics 2023

Proceedings

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Silesia, Poland

International Olympiad on Astronomy and Astrophysics

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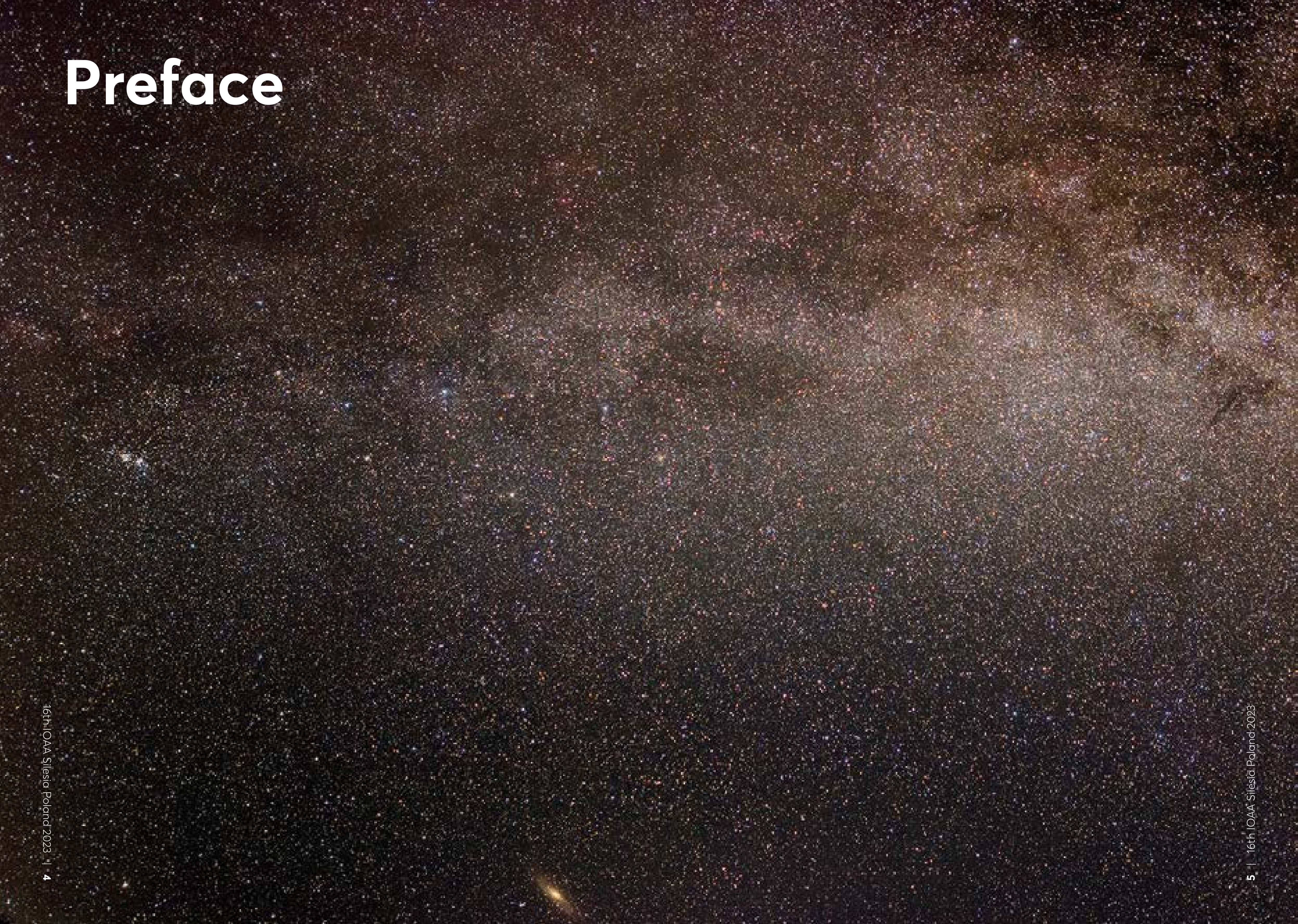
Preface



Dear Readers,

After the conclusion of the 16th IOAA, it is a time for celebration but also time for self-reflection. Looking back, we can safely say that the 16th IOAA in Poland set new benchmarks on how to run a successful event both academically and administratively. The questions designed were innovative, especially those for the data analysis, planetarium and sky observations. The jury members grading the answersheets were well versed in their tasks and the leaders of the academic programme marshalled this team superbly. From an administrative point of view, the event was executed in a flawless manner. The lodging/boarding arrangements for both students as well as leaders, the examination venues, the ceremonies, the excursions, everything was well thought out. The organising team from Silesian planetarium, led personally by the planetarium director, worked tirelessly and they had full backing of the city, provincial and federal government.

From the participants point of view, this was the first IOAA where the number of participating countries crossed 50, with the inclusion of several new countries. The competition field is also getting stronger with more countries winning some awards or other than ever before. This year students from 42 countries won at least one award and students from 16 countries won gold medals. These are very healthy trends and augur well for the future of IOAA. Again a part of the credit should go to organisers, who designed a well balanced competition, giving fair chances to participants from all countries.

Poland has a long and illustrious tradition of doing Astronomy as well as a long history of conducting national astronomy Olympiads. With events like these we clearly see how this long experience translates into a world class event which the host country can be proud of. Let us hope that the future hosts uphold the lofty standards set by Polish organisers and take future IOAA to new heights.

Professor Aniket Sule
President of The Intenational Olympiad on Astronomy and Astrophysics

Ladies and Gentlemen,

The 16th International Olympiad on Astronomy and Astrophysics is already behind us. Those were extraordinary days. For the second time in history, our voivodeship had the honor of hosting the most outstanding young space enthusiasts from all over the world. While the Olympiad participants were solving difficult theoretical and observational tasks, we were facing equally complicated logistic and organizational challenges. And we succeeded! When, during the closing ceremony of the Olympiad, I handed out medals to the participants and winners on stage, I felt proud in my heart not only for these young enthusiasts of astronomy and astrophysics, but also for a whole host of people thanks to whom the Olympiad turned out to be a success: employees of the Silesian Planetarium, volunteers, officials of the Silesian Marshal's Office and all the people who made this event an important part of the history of our region.

I am glad that we met at the Planetarium - Silesian Science Park, which, thanks to the Voivodeship's own funds and funding from the European Union, is currently one of the most modern institutions of this kind in the world. I know that our projection system - especially the analog stars - made a great impression on the participants during the Olympic presentations.

It was a great honor for me to have the opportunity to meet the next generation of astronomers who, in just a few years, working in international research teams, will be looking for answers to the most important questions that humans have been asking since the beginning of our species.

The 16th International Olympiad on Astronomy and Astrophysics was held on the 550th anniversary of the birth of the great Polish astronomer Nicolaus Copernicus. As we all know, thanks to him our civilization could look at the Earth's place in the Universe from a completely new perspective. I am convinced that in your scientific work you will also break established patterns to reveal further secrets the Universe that are still hidden to us.

Jakub Chełstowski
Marshal of the Silesian Voivodeship

Ladies and Gentlemen,

For the second time in its history, the Silesian Planetarium received the privilege of organizing the International Olympiad on Astronomy and Astrophysics. This extraordinary time is already behind us. Many good emotions and memories still remain after several days spent together. However, as we know very well, human memory can be unreliable and that is why in this book we have included important information related to this event. These several days of olympic competition were preceded by several months of preparations.

I would like to thank all the people who made it possible to organize and conduct the competition in the Silesian Voivodeship, especially the President of the IOAA, Professor Aniket Sule, and the General Secretary of the IOAA, Natasza Dragovic. During each IOAA, the work of leaders and observers is extremely important, as they not only inspired their students to take up astronomy and astrophysics, but also diligently, day after day, supported participants while translating the olympic tasks into their native languages. I would like to express my special appreciation to the authors of the tasks, who made sure that they were not only difficult, but also interesting and attractive, as well as to the judges - they did a truly great job during the Olympiad. I would like also to thank the employees of the Planetarium - Silesian Science Park, officials of the Silesian Marshal's Office, volunteers and guides of individual teams. Thanks to the involvement of all these people, the event went smoothly. The organization of the 16th International Olympiad on Astronomy and Astrophysics was possible thanks to the support of our Partners: the Ministry of Education and Science of Republic of Poland, the Empiria i Wiedza Foundation, the European City of Science Katowice 2024, the Upper Silesian-Zagłębie Metropolis GZM, and the Copernican Academy. The media patron of the Olympics was the TVP Nauka channel. Thank you very much.

Finally, I would like to thank the person who was the good spirit of this project from the very beginning and supported us from the moment it turned out that it was possible to organize this event. This is the Marshal of the Silesian Voivodeship, Mr. Jakub Chełstowski. Thanks to him, we were able to overcome many obstacles and many doors were opened for us.

I wish all participants and organizers of the 17th International Olympiad in Astronomy and Astrophysics in Brazil the same positive energy and emotions that accompanied us this year in Poland.

Stefan Janta
Director of Planetarium – Silesian Science Park

Ladies and Gentlemen,

International Olympiad on Astronomy and Astrophysics is the biggest event for young astronomers - knowledge enthusiasts who transform their youthful passion into true scientific interest.

In order for these young people to be able to challenge themselves and demonstrate their knowledge and skills, great commitment of mature professionals, astronomers, educators, and their patrons - Leaders are needed. This commitment involves both preparing teams before the competition and intense, hard work during the competition itself. This includes participation in IBM, discussion on the content of tasks, their translations, evaluation of solutions, determining the final results during moderation and adoption of the final ranking. All these tasks, although they remain in the shadow, are crucial to the proper conduct of the Olympiad.

LOC, consisted of employees of the Silesian Planetarium and members of the Main Committee of the Astronomy Olympiad, was responsible for creating a favorable work environment.

Already during the competition, the fast operating Olympiad Office was quickly preparing copies of tasks and scans of solutions, organizing transport and solving simple, everyday problems. In addition, the LOC ensured the smooth running of IBM, giving leaders space to create fair but demanding tasks. The IBM meeting itself ran extremely smoothly in an atmosphere of constructive discourse, thanks to the work of people involved in SOC who prepared the tasks to a very high standard. An extension of the SOC's work was also the large team of judges who reliably assessed several dozen thousand pages of solutions.

We are very proud of the words of the President of the IOAA who appreciated the high level of organization of the competition and the involvement of all people involved in creating this project.

As the organizers of IOAA 2023, we are extremely grateful to all Leaders and Observers for their excellent substantive preparation, great openness and professionalism, which resulted in successful and fruitful cooperation. Thanks to this, we were able to create a competition together that for many young participants was an event they will remember for the rest of their lives.

Damian Jabłeka
Deputy Director of Planetarium – Silesian Science Park

Dear Friends,

It was one of the most demanding organizational ventures in the history of the Silesian Planetarium and at the same time an extremely important project in our careers.

200 days of daily work. Over 100 hours of talk time. 30 weekly all-day meetings. However, the statistics do not reflect the commitment of the entire team of people involved in the project. The Olympiad in the Silesian Voivodeship has been organized not only thanks to the funds obtained from our partners (although, of course, it would not have been possible to organize it without them), but also thanks to the huge commitment, dedication and daily work of our people. Today we know that our dream has come true.

And we dreamed of 10 successful days of the Olympiad, which would run smoothly.

We looked with joy at the faces of the participants and leaders - we saw new acquaintances and bonds being formed across all divisions, which will surely pay off in the future. The greatest reward for our effort was your smile.

And although the 16th International Olympiad on Astronomy and Astrophysics has become history, we will always remember you.

Paweł Jędrzejczak
Administrative Manager of The Silesian Planetarium

"He stopped the sun, moved the earth,
"And he was the member of the Polish Tribe"

the author of this short poem is unknown, but there is no doubt that this famous epigram is about Nicolaus Copernicus - the "Sarmatian astronomer", as he was described in a letter written by Philip Melanchthon, an outstanding humanist of the time. He called Copernicus's revolutionary theory "madness" ("Some people consider it an outstanding feat when one commits such madness as that Sarmatian astronomer did, who moved the earth and stopped the sun"). However, the science and history agreed with Nicolaus Copernicus, who created the actual model of the Solar System and changed the perception of the world.

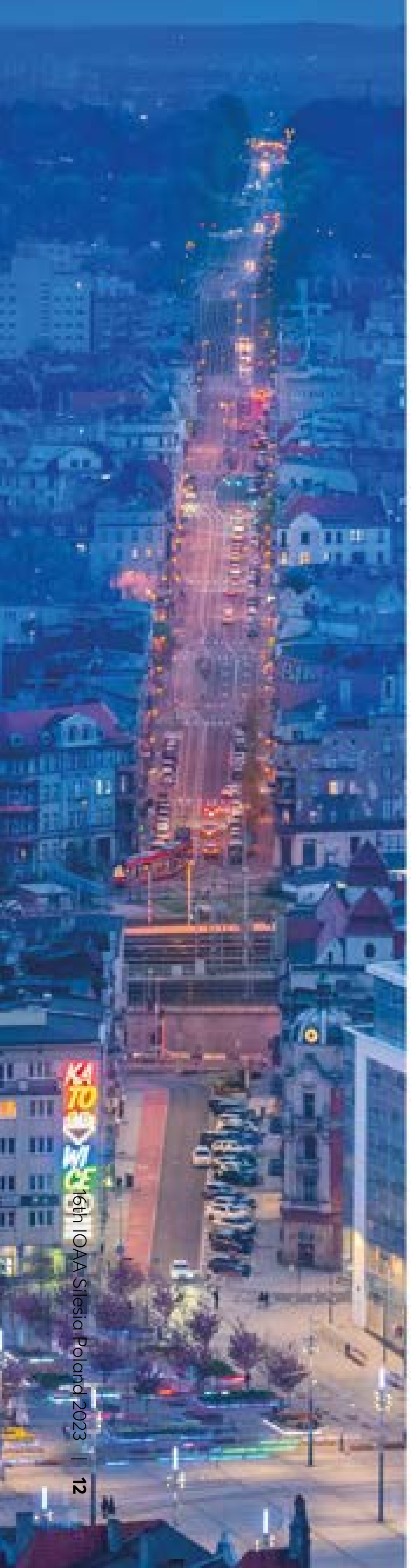
It is no coincidence that the 16th IOAA was held in the Silesian Planetarium in Chorzów. Its   construction started in 1953 during the Copernicus Year. After exactly seventy years, 16th INTERNATIONAL OLYMPIAD ON ASTRONOMY AND ASTROPHYSICS was organized there to emphasize the significance on the 550th anniversary of the astronomer's birth. The year 2023 has been designated by the Senate of the Republic of Poland as the Year of Nicolaus Copernicus.

The anniversary of the birth of Nicolaus Copernicus is an opportunity not only to celebrate and recall the great merits of this outstanding astronomer, but also to remind the international community of the importance of discoveries and this extraordinary scientific revolution in the history of mankind.

Like other Renaissance scientists, this outstanding astronomer did more than just make a revolution and "moved the earth". He was also a multi-talented man, full of passion and courage, he was interested in medicine, mathematics, law, cartography, diplomacy, philospohy and even military strategy. He was driven by curiosity about the world. His persistence, determination and perseverance in pursuing the truth helped him make important, breakthrough discoveries.

Let this Copernican attitude be a model for young people, let persistence, determination and courage be the basis for actions that - regardless of the results achieved - are the culmination of previous achievements and a reflection of the passion for astronomy.

Artur Górecki,
Director of The Department of General Education and Curriculum at the Ministry of Education and Science.



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41	2,3	2,5
municipalities and communes	million residents	thousand km²

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Górnośląsko-Zagłębiowska Metropolia surprises visitors with a multitude of diverse attractions - from post-industrial monuments, cultural routes, concerts, exhibitions, performances, to parks, gardens and nature reserves.
Visitors can find unique places here, such as the Silesian Park - the largest in Europe, the Industrial Monuments Route - the most interesting industrial tourism route in Poland or the Historic Silver Mine - a UNESCO World Heritage Site.

Metropolia is also home to exceptional cultural events - performances, concerts and major music festivals - from the classic Gorczycki Festival, to Tauron Nowa Muzyka and Off Festival. They attract tens of thousands of fans, from Poland and abroad.

Read more at: metropoliagzm.pl

Katowice — European City of Science 2024

Katowice is one of the most dynamically developing cities in the Silesian-Dąbrowa agglomeration. In 2022, it was announced as the European City of Science 2024 (EMN2024). The most important task of EMN 2024 is to provide residents with access to knowledge, so that in Katowice and in the other cities across region it is possible to solve everyday problems thanks to the science. The title is the result of the efforts of the city of Katowice and seven universities of the Academic Consortium - Katowice City of Science. The beginning of close cooperation was the organization of the Silesian Science Festival KATOWICE - one of the largest European popular science events.EMN2024 will show the richness of the European scientific landscape, the importance of international research without borders, as well as support for self-education and multi-generational interest in science. The main pillars of EMN 2024 are: events related to the EMN2024 celebrations, scientific excellence and building the infrastructure of the city of science.

Pillars of the European City of Science 2024:

- 50 thematic weeks, during which scientists and residents of the city will be able to talk and cooperate within 50 ideas of the city of science.
- Science and scientific excellence — a series of events related to the future of scientific research, the most important of which is the EuroScience Open Forum conference.
- Changes in the urban infrastructure and work on the Green Science Zone and the Network Science Center, which are to be the scientific heart of Katowice.

The activities carried out as part of the preparation of the EMN 2024 celebrations are part of 6 thematic paths:

- climate and environment,
- health and quality of life,
- industries of the future,
- social innovations,
- industrial and cultural heritage,
- creation and criticism

The celebration of the European City of Science 2024 will show that not only Katowice, but the entire voivodship is undergoing transformation towards modern technologies and a knowledge-based economy.

The Copernicus Academy

The Copernicus Academy is a new institution in the system of Polish science. It is an international scientific corporation, which is shown in the most visible way by its following members - half of the researchers are from Poland, and the other half are foreign scientists. It consists of scientists who deal with the same areas of science as Copernicus - astronomy, economics, medicine, law, philosophy and theology.

In February 2023, the Academy organized the 1st World Copernican Congress, where several hundred researchers and guests, including five Nobel Prize winners, participated in discussions and expert panels at the highest level over three days. Only a few months later, at the Royal Castle in Warsaw, the first Copernican Awards in history were awarded, which is a form of Poland's appreciation of the achievements of researchers who push the boundaries of our knowledge of humanity.

Dear,
When Galileo presented the "principle of relativity", it was a denial of the laws formulated by Aristotle that had been cultivated for two thousand years. Despite the pressures associated with promoting a theory that overturned all contemporary knowledge, he put forward a hypothesis that became the foundation of the theory of relativity, quantum theory and almost all modern physics, leading to the creation of, among others, modern media such as radio and television. The insight, persistence and determination that he showed in trying to prove his thesis are the qualities that also led you to this place.
However, no path will take you further if you do not know where you are going. The same law is used when planning the trajectories of space vehicles so that they can safely reach a precisely selected location in the solar system. In an ideal world, it is enough to give the rocket only the right speed, but the classical laws of motion verify how important the internal GPS is.
Openness, internal value map and willingness to challenge the status quo are the system that controls the ferry of your development. I wish you the courage to reach high, question commonly accepted truths and share knowledge. You too - with every observation, bold thesis, you can completely change the way you think about man and his place in the world.
Empiria i Wiedza Foundation - established to create the firmament of Polish education, discover and develop talents. I hope that the 16th International Olympiad in Astronomy and Astrophysics will be a great opportunity for you to "hold back the Sun and move the Earth", and that it will bring us Polish Nobel Prize winners in the future, which I sincerely wish you.

Zuzanna Piasecka
CEO
Empiria i Wiedza Fundation

16th IOAA

Organizing Committee

Stefan Janta
→ Director of Planetarium – Silesian Science Park

Damian Jabłeka
→ Deputy Director of Planetarium – Silesian Science Park

Waldemar Ogłoza
→ LOC, SOC, Head of IBM, coordinator of tasks preparation

Grzegorz Przybyła
→ IBM Support

Anna Skrzypecka
→ Head of IOAA Office

Paweł Jędrzejczak
→ Main Guide

Michał Rostański
→ Leaders' Main Guide

Jarosław Juszkiewicz
→ Newsletter and booklet editor

Ewa Prudło
→ Main acountant

Agata Spruś
→ Main Guide

Grażyna Salamon
→ Supporting accountant

Grzegorz Stachowski
→ LOC, SOC, Head of IBM, tasks editor

Rafał Bączkowicz
→ Tasks logistics, information technology services in Wisła

Krzysztof Dwornik
→ Tasks logistics

Aleksandra Chrzan
→ Main Guide

Jolanta Brol
→ Public procurement manager

Joanna Nowakowska
→ Tasks scanning

Bogusława Zagoła
→ Tasks scanning

Krystyna Dybek
→ Planetarium staff supporting LOC

Michał Błaszkiewicz
→ Head of obervational task

Katarzyna Matejka
→ Tasks scanning

Katarzyna Gajda
→ Tasks Implementation Coordinator

Justyna Redczuk
→ Office of IOAA

Daria Pilich
→ Office of IOAA

Agata Chuchra- Konrad
→ IBM Support

Agata Szkodzińska
→ Planetarium staff supporting LOC

Anna Gamon
→ Planetarium staff supporting LOC

Ariel Głąb
→ Information technology services in Chorzów

Michał Pisalnik
→ Information technology services in Chorzów

Agata Sikora
→ Planetarium staff supporting LOC

Anna Kurowska
→ Planetarium staff supporting LOC

Patrycja Kajzer
→ Planetarium staff supporting LOC

Mariola Jurkowska
→ Planetarium staff supporting LOC

Bożena Gąska
→ Planetarium staff supporting LOC

Marta Karmańska
→ Planetarium staff supporting LOC

Filip Krawczyk
→ Planetarium staff supporting LOC

Anna Moj
→ Planetarium staff supporting LOC

Piotr Czwordon
→ Technical services

Dariusz Katarzyński
→ Planetarium staff supporting LOC

Tasks Authors

Waldemar Ogłoza

Jerzy Kuczyński

Przemysław Mróz

Andrzej Sołtan

Paweł Rudawy

Zofia Kaczmarek

Tadeusz Firszt

Dariusz Graczyk

Grzegorz Przybyła

Anna Marciniak

Przemysław Żołądek

Damian Jabłeka

Grzegorz Stachowski

Judges

Katarzyna Bajan

Daniel Błażewicz

Szymon Cedrowski

Maksymilian Celiński

Jacek Czakański

Bartłomiej Dębski

Marek Drożdż

Filip Ficek

Tadeusz Firszt

Artur Gawrysiak

Dariusz Graczyk

Karolina Jarosik

Zofia Kaczmarek

Mateusz Kapusta

Grzegorz Kondrat

Oskar Kopczyński

Aleksandra Kowalska

Jerzy Kuczyński

Patryk Liniewicz

Piotr Łubis

Przemysław Mróz

Janusz Nicewicz

Wioletta Ogłoza

Waldemar Ogłoza

Anna Olchowy

Artur Paczuski

Bartłomiej Pokrzywka

Halina Prętka-Ziomek

Grzegorz Przybyła

Alicaj Pucek

Grzegorz Stachowski

Konrad Szymański

Roland Wiśniewski

Anna Wójtowicz

Marcin Wrona

Joanna Żak

Students – participants of the 16th IOAA

Maria Arakelyan
Armenia

Areg Barseghyan
Armenia

Artavazd Harutyunyan
Armenia

Vyacheslav Petrosyan
Armenia

Taylan Algan
Austria

Elias Koschier
Austria

Thomas Riedle
Austria

Vincent Karl Willis
Austria

Nijat Abbasov
Azerbaijan

Ogtay Latifli
Azerbaijan

Gandab Mammadova
Azerbaijan

Nazrin Miriyeva
Azerbaijan

Atilla Muradlı
Azerbaijan

Adnan Bin Alamgir
Bangladesh

Md Bayezid Bostami
Bangladesh

Arnob Datta
Bangladesh

Hritom Sarker Oyon
Bangladesh

Adiba Amira Siddiqa
Bangladesh

Murilo De Andrade Porfirio
Brazil

Paulo Henrique Dos Santos Silva
Brazil

Gabriel Hemetrio De Menezes
Brazil

Mariana Naves Tana
Brazil

Paulo Otavio Portela Santana
Brazil

Mihail Bankov
Bulgaria

Bayan Gechev
Bulgaria

Konstantin Krastev
Bulgaria

Lora Lukmanova
Bulgaria

Vladimir Milanov
Bulgaria

Hongyi Huang
Canada

Zander Li
Canada

Eleanor Liu
Canada

Tian Pu
Canada

Debbie Wang
Canada

Jiahang Chen
China

Youmo Lai
China

Haiqi Su
China

Boyu Wang
China

Chen Ziru
China

Gabriel Baracaldo Garcia
Colombia

Juan Camilo Hernández Clavijo
Colombia

Juanita Lamprea Carrillo
Colombia

Juan José Sánchez Medina
Colombia

Marko Ercegović
Croatia

Mihael Lovrić
Croatia

Barbara Mustapić
Croatia

Vid Krešimir Pavčnik
Croatia

Viktor Vuković
Croatia

Kyriakos Dymiotis
Cyprus

Angel Hadjisoteriou
Cyprus

Ara Mahdessian
Cyprus

Michalis Platanis
Cyprus

Achilleas Thomas
Cyprus

David Bálek
Czech Republic

Jakub Hadač
Czech Republic

Martin Kudrna
Czech Republic

Matouš Mišta
Czech Republic

Tomáš Patsch
Czech Republic

Aaron Andrango
Ecuador

Emilio Clavón
Ecuador

Matias Navarrete
Ecuador

Zoe Parra
Ecuador

Paolo Suasti
Ecuador

Juan Mazariego
El Salvador

Luis Antonio Rivera Pérez
El Salvador

Karla Solano
El Salvador

Violeta Jürgens
Estonia

Karolin Laud
Estonia

Ralf Robert Paabo
Estonia

Saskia Põldmaa
Estonia

Mihkel Rannut
Estonia

James Kennedy
United Kingdom

Ryan Lin
United Kingdom

Charlotte Stevenson
United Kingdom

Frederick Weir
United Kingdom

Benjamin Woodrow
United Kingdom

Bidzina Gagnidze
Georgia

Andria Manjavidze
Georgia

Dachi Tchotashvili
Georgia

Luka Tvalavadze
Georgia

Irakli Ugulava
Georgia

Lasse Paul Blum
Germany

Maximilian Kirchner
Germany

Luise Köhler
Germany

Anton Nüske
Germany

Christian Vogel
Germany

Prodromos Fotiadis
Greece

Georgios Melistas
Greece

Lampros Tegos
Greece

George Tsoumpos
Greece

Orestis Zikoulis
Greece

Dorottya Elekes
Hungary

Zsóka Horváth
Hungary

Sándor István Sarkadi
Hungary

Blanka Schmercz
Hungary

Gergely Péter Vári
Hungary

Zahran Nizar Fadhlan
Indonesia

Ferdinand Ferdinand
Indonesia

Bryan Herdianto
Indonesia

Dzaky Rafiansyah
Indonesia

Indra Rhamadan
Indonesia

Md Sahil Akhtar
India

Tejeswar Koduru
India

Rajdeep Mishra
India

Sainavaneet Mukund
India

Akarsh Raj Sahay
India

Amir Mahdi Esmaeili Taheri
Iran

Sarina Farzadnasab
Iran

Seyed Amir Hossein Moosavifard
Iran

Mahdi Ostadmohammadi
Iran

Arvin Rasulzadeh
Iran

Rion Fuchigami
Japan

Haru Hayakawa
Japan

Taichi Shimokobe
Japan

Daiki Tsukahara
Japan

Yuto Yamada
Japan

Damir Alenov
Kazakhstan

Ualikhan Kylyshbek
Kazakhstan

Akhmajon Tabarov
Kazakhstan

Bekassyl Yelubay
Kazakhstan

Sunnatov Zanggar
Kazakhstan

Islam Alybaev
Kazakhstan

Taisiia Ri
Kazakhstan

Sayd Yanshansin
Kazakhstan

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South Korea

Dohyun Kwon
South Korea

Hakjin Lee
South Korea

Jinwoo Park
South Korea

Minkyu Song
South Korea

Abdullah Algziwi
Saudi Arabia

Ernests Lazdāns
Latvia

Toms Ozoliņš
Latvia

Iļja Niks Stoligvo
Latvia

Viesturs Streļčs
Latvia

Olita Anastasija Zadoroznaja
Latvia

Emilijus Latakas
Lithuania

Pijus Tydmanas
Lithuania

Saulė Vaidelytė
Lithuania

Jokūbas Viršilas
Lithuania

Rapolas Žygus
Lithuania

Sunyit Singh A/L Gurdial Singh
Malaysia

Jing Chen Loh
Malaysia

Zhi Zheng Ong
Malaysia

Zhi Qi Tan
Malaysia

Yee Yin Tang
Malaysia

Piyush Adhikari
Nepal

Kishor Baniya
Nepal

Ankita Bhattarai
Nepal

Sandip Khadka
Nepal

Sudip Rokaya
Nepal

Fredrik Breirem Neumann
Norway

Om Saxena
Norway

Nataniel Skjøndal - Bar
Norway

Ricardo Sonda Guiraudeli
Norway

Sigurd Svorkmo – Lundberg
Norway

Eisha Muddassir
Pakistan

Moiz Muddassir
Pakistan

Shirin Mumtaz
Pakistan

Ahmed Piracha
Pakistan

Abdullah Umer
Pakistan

Valeria Fernanda Acosta Peña
Peru

Manuel Mario Nadir Gilvonio Saez
Peru

Luis Fabian Sanchez Romero
Peru

Joshua Dominicus Lao Tola Castañeda
Peru

Patrick Gabriel Abeleda
Philippines

Mohammad Nur Casib
Philippines

Sean Ken Galanza
Philippines

Caesar Lopez
Philippines

Yanna Lorraine Tenorio
Philippines

Gniewosz Armista
Poland

Michał Jagodziński
Poland

Piotr Jędrzejczyk
Poland

Krzysztof Król
Poland

Maksymilian Wdowiarz - Bilski
Poland

Pedro Azóia
Portugal

Filipa Cabrita
Portugal

Bruno Casanova Ralha
Portugal

Madalena Mota
Portugal

Cátia Silva
Portugal

Andrei-Darius Dragomir
Romania

Mendel Emanuel Mendelsohn
Romania

Ciocârlan Mihai-Bogdan
Romania

Vladimir George Necula
Romania

Teofil Voicu
Romania

Zehan Huang
Singapore

Kane Kiat Leng
Singapore

Cheng Ian Lim
Singapore

Kai Wen Teo
Singapore

Yi Xuan Tong
Singapore

Peter Andolšek
Slovenia

Žan Arsov
Slovenia

Miha Brvar
Slovenia

Žan Ambrožič
Slovenia

Marija Judež
Slovenia

Ognjen Janković
Serbia

Tadija Jelesijević
Serbia

Aleksa Mikić
Serbia

Mihailo Radovanović
Serbia

Janko Stokić
Serbia

Terézia Hanáková
Slovakia

Lukáš Hudák
Slovakia

Ondrej Juhás
Slovakia

Mário Tlamka
Slovakia

Filip Závadský
Slovakia

Teo Alvånger
Sweden

Ida Grimheden
Sweden

Jiachen Mi
Sweden

Alexander Stridh
Sweden

Philip Wetterberg
Sweden

Supakorn Paisancharoen
Thailand

Sutthawish Phonglorpisit
Thailand

Kittiphat Pongarunotai
Thailand

Phanuphat Srisukhawasu
Thailand

Wongwaran Upawong
Thailand

Yiğit Karaca
Türkiye

Mehmet Öztürk
Türkiye

Egemen Saritekin
Türkiye

Tuna Tülümen
Türkiye

Kaan Üstün
Türkiye

Prathit Jindal
United Arab Emirates

Fida Mohammed Shebeaun
United Arab Emirates

Naina Verma
United Arab Emirates

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Ukraine

Eduard Palant
Ukraine

Viktoriia Voitiuk
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Andrii Zahika
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Diana Zazubyk
Ukraine

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USA

Evan Kim
USA

David Lee
USA

David Zhang
USA

Ba Linh Nguyen
Vietnam

Ngoc Phuong Anh Nguyen
Vietnam

The Minh Pham
Vietnam

Thanh Hai Thai
Vietnam

Thai Vu Tran
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Afghanistan

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Austria

Abdullah Bazarov
Azerbaijan

Famil Mustafa
Azerbaijan

Ahmad Abdullah Rifat
Bangladesh

Fahim Rajit Hossain Shwadhin
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Ukraine

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United Kingdom

Lam Son Ha
Vietnam

Thi Lam Le
Vietnam

Guides

Kornel Księżak
Saudi Arabia

Katarzyna Łęgosz
Armenia

Krzysztof Nadulicz
Austria

Rafał Najda
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United Arab Emirates

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United States of America

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Robert Sobczak

Włodzimierz Humeniuk

Media Coverage

Paweł Mikołaczyk — PAMEDIA

Piotr Margraf — PAMEDIA

Local Police support

The organizers of the 16th International Olympiad on Astronomy and Astrophysics would like to especially thank the police head – quarters in Chorzów for their commitment and help in securing planetary tasks.

Schedule

Day 1 → 10th August 2023 Thursday

Arrival to Poland – transfer from the airports/train stations to the hotels.
The registration of participants at the hotels.

18.00—23.00	Dinner at the hotel restaurant

Day 2 → 11th August 2023 Friday

Students

07.30—09.15	Breakfast
09.20	Meeting point in the parking lot
09.30—10.30	Transfer to The International Congress Centre (ICC)
11.00—14.00	16th IOAA Opening Ceremony
14.00—14.15	Handing over of electronic devices and saying goodbye to Team Leaders
14.15—15.15	Transfer to the hotel
15.15—16.30	Lunch
16.30—19.00	Free time and group activites at the hotel
19.00—20.00	Dinner

Team Leaders

07.00—08.30	Breakfast
08.30	Meeting point in the parking lot
08.45—10.45	Transfer to The International Congress Centre (ICC)
11.00—14.00	16th IOAA Opening Ceremony
14.00—14.15	Collecting electronic devices and saying goodbye to Students
14.15—15.00	Lunch at the ICC
15.00—15.20	Transfer to the Silesian Planetarium
15.20—16.30	Planetarium visit
16.30—18.20	Transfer to the hotel
18.30—21.00	IBM. Group competition
21.00—22.00	Dinner
22.00	Translations and printing

Day 3 → 12th August 2023 Saturday

Students

07.30—09.00	Breakfast
09.00—12.00	Free time and group activities at the hotel
12.00—13.00	Lunch
13.30	Meeting point in the parking lot
13.45—14.45	Transfer to the ICC
15.00—16.30	Group competition
16.30—16.50	Transfer to the Planetarium
17.00—18.15	Planetarium visit
18.30—19.15	Transfer to the hotel
19.30—20.45	Dinner

Team Leaders

08.00—09.00	Breakfast
09.00—13.30	IBM. Theory Round
13.30—14.30	Lunch
14.30—19.30	IBM. Theory Round
19.30—20.30	Dinner
20.30	Translations and printing

Day 4 → 13th August 2023 Sunday

Students

07.00—08.00	Breakfast
08.00	Meeting point in the parking lot
08.15—09.15	Transfer to the ICC
09.30—15.00	Theory round
15.00—16.00	Transfer to the hotel
16.00—17.30	Lunch
17.30—20.00	Free time, telescopes
19.30—20.30	Dinner

Team Leaders

07.00—09.30	Breakfast
09.30—13.30	IBM. Observation and planetarium round
13.30—14.30	Lunch
14.30—19.30	IBM. Data analysis round
20.00—21.30	Dinner
21.30	Translations and printing

Day 5 → 14th August 2023 Monday

Students

07.00—08.30	Breakfast
08.30—09.30	Transfer to the ICC (group 1)
09.15—10.15	Transfer to the ICC (group 2)
10.00—10.45	Transfer to the ICC (group 3)
10.45—11.45	Transfer to the ICC (group 4)
11.30—12.30	Transfer to the ICC (group 5)
10.00—15.00	Observation round
12.00—13.00	Transfer to the hotel (group 1)
12.45—13.45	Transfer to the hotel (group 2)
13.30—14.30	Transfer to the hotel (group 3)
14.15—15.15	Transfer to the hotel (group 4)
15.00—16.00	Transfer to the hotel (group 5)
16.00—17.00	Lunch
17.00—19.00	Free time and group activities at the hotel
19.00—20.30	Dinner
21.00—23.00	Bonfire and night observation

Team Leaders

07.00—09.30	Breakfast
09.30—13.30	IBM. IOAA working matters
13.30—14.45	Lunch
14.45	Meeting point in the parking lot
15.00—15.30	Transfer to the Czantoria Cable Railway
15.30—19.00	Czantoria Cable Railway, hiking, toboggan run, free time
19.15—19.45	Transfer to the hotel
20.00—00.00	Dinner and party

Day 6 → 15th August 2023 Tuesday

Students

07.30—08.30	Breakfast
08.30	Meeting point in the parking lot
08.45—09.45	Transfer to the ICC
10.00—13.00	Data analysis round
13.15—14.15	Transfer to the hotel
14.30—16.00	Lunch
16.00—19.00	Free time and group activities at the hotel
19.00—20.30	Dinner

Team Leaders

07.30—08.45	Breakfast
08.45	Meeting point in the parking lot
09.00—10.30	Transfer to Guido Coal Mine
10.30—15.00	Sightseeing of Guido Mine (lunch during the trip)
15.00—15.30	Transfer to the Planetarium
15.30—17.30	Guided tours in groups
17.30—19.00	Country's sky presentation
19.00—20.30	Transfer to the hotel
21.00—22.00	Dinner

Day 7 → 16th August 2023 Wednesday

Students

07.00—08.00	Breakfast
08.15—09.15	Transfer to the Planetarium (group 1)
09.00—10.00	Transfer to the Planetarium (group 2)
09.45—10.45	Transfer to the Planetarium (group 3)
10.30—11.30	Transfer to the Planetarium (group 4)
11.15—12.15	Transfer to the Planetarium (group 5)
09.30—14.30	Planetarium round
12.00—16.00	Lunch (each group has lunch after their round)
16.30—19.15	Visiting the Planetarium exhibitions
19.30—20.30	Transfer to the hotel
20.30—21.30	Dinner

Team Leaders

08.00—09.00	Breakfast
09.00—13.00	IBM
13.00—14.00	Lunch
14.00—20.00	Moderation
20.00—21.00	Dinner
21.00—00.00	Night observation/moderation

Day 8 → 17th August 2023 Thursday

Students

08.00—09.30	Breakfast
08.45—09.15	Transfer to the Ogrodzieniec Castle (group 1 and 2)
10.15—10.45	Transfer to the Ogrodzieniec Castle (group 3 and 4)
11.45—12.15	Transfer to the Ogrodzieniec Castle (group 5 and 6)
09.30—14.15	Guided tour in groups
11.15—11.45	Transfer to the hotel (group 1 and 2)
12.45—13.15	Transfer to the hotel (group 3 and 4)
14.15—14.45	Transfer to the hotel (group 5 and 6)
14.30—15.30	Lunch
15.30—17.00	Free time
17.00—21.00	Cultural evening

Team Leaders

07.30—09.00	Breakfast
08.30—14.30	Moderation
14.00—15.00	Lunch
15.00—17.00	Transfer to student's hotel
17.00—21.00	Cultural evening
21.00—23.00	Transfer to the hotel

Day 9 → 18th August 2023 Friday

Students

07.00—08.30	Breakfast
08.30	Meeting point in the parking lot
08.45—09.45	Transfer to Guido Coal Mine (group 1)
09.15—10.15	Transfer to Guido Coal Mine (group 2)
09.45—10.45	Transfer to Guido Coal Mine (group 3)
10.00—14.15	Guided tours in groups
13.00—13.30	Transfer to the botanical garden (group 1)
13.45—14.15	Transfer to the botanical garden (group 2)
14.15—14.45	Transfer to the botanical garden (group 3)
13.30—18.00	Group activities in the botanical garden (lunch during a trip)
17.00—18.00	Transfer to the hotel (group 1)
17.30—18.30	Transfer to the hotel (group 2)
18.00—19.00	Transfer to the hotel (group 3)
19.00—20.30	Dinner

Team Leader

07.30—09.00	Breakfast
09.00—15.00	Moderation
15.00—16.30	Lunch
17.00—19.00	Final IBM
19.00—20.00	Dinner
20.00—22.00	Final IBM

Day 10 → 19th August 2023 Saturday

Students

08.00—09.15	Breakfast
09.15	Meeting point in the parking lot
09.30—10.30	Transfer to The International Congress Centre (ICC)
11.00—14.00	Closing Ceremony
14.00—15.15	Lunch at the ICC
15.30—16.30	Transfer to the hotel
16.30—19.00	Free time
19.00 -20.30	Dinner

Team Leaders

07.00—08.45	Breakfast
08.45	Meeting point in the parking lot
09.00—10.30	Transfer to The International Congress Centre (ICC)
11.00—14.00	Closing Ceremony
14.00—15.15	Lunch at the ICC
15.30—17.00	Transfer to the hotel
17.00—19.00	Free time
19.00—20.30	Dinner

Day 11 → 20th August 2023 Sunday

Departures – transfer to the airport/train station

07.00—10.00	Breakfast

Tasks

General Marking Scheme

Using incorrect physical concept (despite correct answers)	No points given
Giving correct answer without detailed calculation	Deduct 50% of the marks for that part
Minor mistakes in the calculations, e.g., wrong signs, symbols, substitutions	Deduct 20% of the marks for that part
Units missing from final answers	Deduct 0.5 pts
Too few or too many significant figures in the final answer	Deduct 0.5 pts
Error resulting from another error in an earlier part for which the student already lost marks, if the answer is physically reasonable.	Full points (i.e., no deductions)
Error resulting from another error in an earlier part, where the student should have realised the answer was physically unreasonable.	Deduct 20% of the marks for that part

For example, if due to an error in an earlier part, the student calculates the mass of a star as 2.5×10^{30} kg *instead of* 2×10^{30} kg*, they will only lose marks for the earlier part. However, if, for the same reason, a student calculates the mass as* 2×10^{25} kg*, they should realize this is wrong (a few times the Earth's mass) and thus should lose some marks for this part as well.*

Table of Constants

Fundamental constants

Speed of light in vacuum	c	=	2.998×10^{8} m s^{-1}
Planck constant	h	=	6.626×10^{-34} J s
Boltzmann constant	k_B	=	1.381×10^{-23} J K^{-1}
Stefan-Boltzmann constant	σ	=	5.670×10^{-8} W m^{-2} K^{-4}
Elementary charge	e	=	1.602×10^{-19} C
Universal gravitational constant	G	=	6.674×10^{-11} N m^2 kg^{-2}
Universal electric constant	ϵ_0	=	8.854×10^{-12} m^{-3}kg^{-1}s^{4}A^2
Universal gas constant	R	=	8.315 J mol^{-1} K^{-1}
Avogadro constant	N_A	=	6.022×10^{23} mol^{-1}
Wien's displacement constant	$b=\lambda_m T$	=	2.898×10^{-3} m K
Mass of electron	m_e	=	9.109×10^{-31} kg
Mass of proton	m_p	=	1.673×10^{-27} kg
Mass of neutron	m_n	=	1.675×10^{-27} kg
Mass of Helium nucleus	m_{He}	=	6.645×10^{-27} kg
Atomic mass unit (a.m.u., Dalton)		=	1.661×10^{-27} kg

Astronomical data

Hubble constant	H_0	=	70 km s^{-1} Mpc^{-1}
North Ecliptic Pole (J2000.0)	$(\alpha_E,\ \delta_E)$		$(18^h00^m00^s, +66°33'39'')$
North Galactic Pole (J2000.0)	$(\alpha_G,\ \delta_G)$		$(12^h51^m26^s, +27°07'42'')$
1 jansky	1 Jy	=	10^{-26} W m^{-2} Hz^{-1}
1 parsec	1 pc	=	3.086×10^{16} m 206 265 au 3.262 ly
1 astronomical unit (au)	1 au	=	1.496×10^{11} m
1 sidereal day	T_{SD}	=	23.93444 h $23^h56^m04^s$
1 tropical year		=	365.2422 solar days
1 sidereal year		=	365.2564 solar days

Gauss's formulae

Spherical law of cosines: $\cos a = \cos b\cos c + \sin b \sin c\cos A$

Spherical law of sines: $\frac{\sin A}{\sin a} = \frac{\sin B}{\sin b} = \frac{\sin C}{\sin c}$

Approximations

$(1+x)^n \approx 1+nx$

$(1+x)(1+y)\approx 1+x+y$ if $x\ll 1$ and $y \ll 1$

The Sun

Solar luminosity	$L_\odot$	=	3.826×10^{26} W
Apparent angular diameter of Sun	$\theta_\odot$	=	$32'$
Effective temperature of Sun	$T_{\mathrm{eff},\odot}$	=	5778 K
Apparent visual magnitude		=	-26.75
Absolute visual magnitude		=	+4.82
Apparent bolometric magnitude		=	-26.83
Absolute bolometric magnitude		=	+4.74
Distance of the Sun from the Galactic centre		≈	8 kpc

The Earth and Moon

Obliquity of the ecliptic (Earth)	ϵ	=	$23.5'$
Platonic year (period of precession of Earth's axis)		=	25 765 years
Apparent visual magnitude of full Moon		=	−12.74
Apparent angular diameter of Moon	θ_L	=	$31'$
Inclination of the lunar orbit to the ecliptic		=	$05°08'43''$
Inclination of the lunar equator to its orbital plane		=	6.687°
Lunar sidereal month	T_SL	=	27.321661 d 655.71986 h
Synodic month		=	29.530589 d
Tropical month		=	27.321582 d
Anomalistic month		=	27.554550 d
Draconic month		=	27.212221 d

The Solar System

Object	Mean radius [km]	Mass [kg]	Semimajor axis [au]	Eccentricity
Sun	695 700	1.988×10^{30}	—	—
Mercury	2 440	3.301×10^{23}	0.387	0.206
Venus	6 052	4.867×10^{24}	0.723	0.007
Earth	6 378	5.972×10^{24}	1.000	0.016 710
Moon	1 737	7.346×10^{22}	3.844×10^5 km	0.054 900 (range 0.026 − 0.077)
Mars	3 390	6.417×10^{23}	1.524	0.093
Jupiter	69 911	1.898×10^{27}	5.203	0.048
Saturn	58 232	5.683×10^{26}	9.537	0.054
Uranus	25 362	8.681×10^{25}	19.189	0.047
Neptune	24 622	1.024×10^{26}	30.070	0.009

Group Competition: Instructions

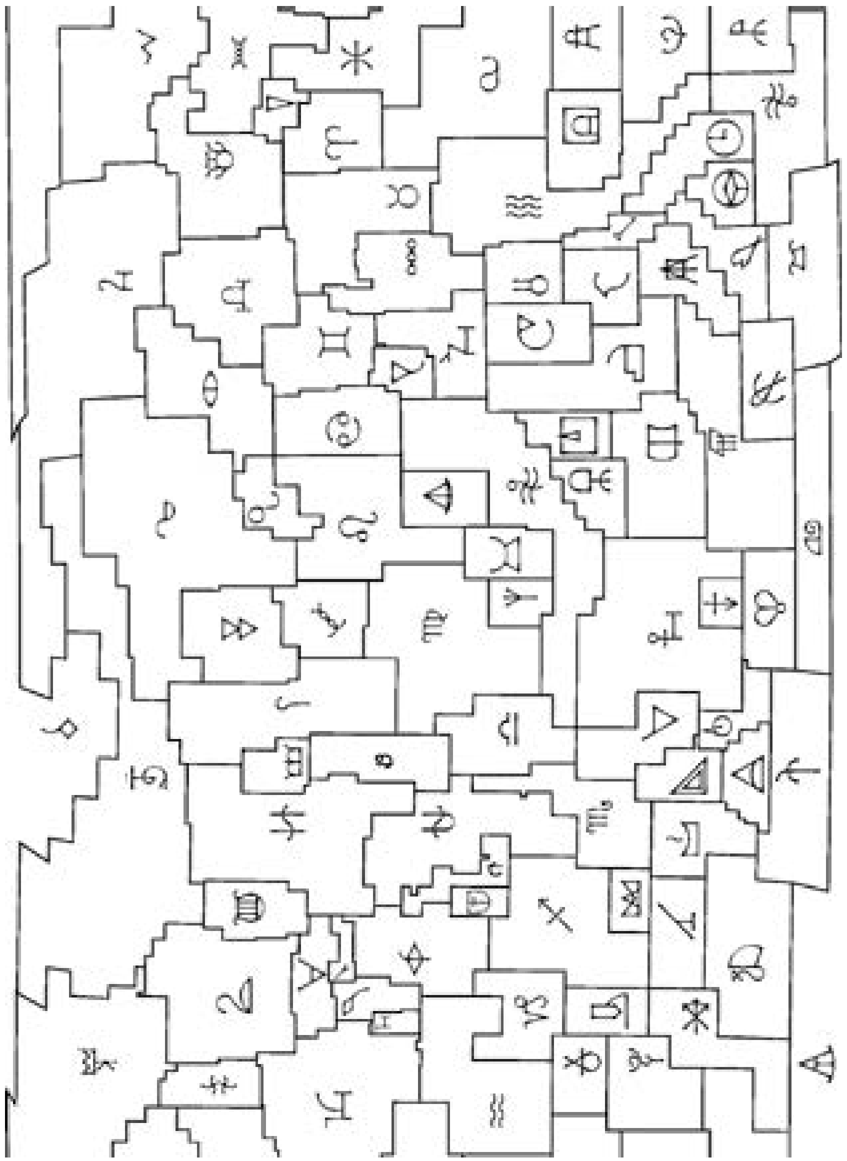
- For this round, the participants will be grouped by random selection into 5-person teams, each representing a named asteroid. Each participant in the group will be from a different country. The selection will take place near the beginning of the IOAA, so that the team members can get to know each other.
- Please remember the name and number of your asteroid, as this will also be used to identify your place during the Planetarium and Observation rounds.
- The group competition consists of several tasks, which you will receive in a sealed envelope. Each team works together at one table under the supervision of the guides to solve the tasks. You are not allowed to communicate with participants from other teams during the round.
- Dedicated answer sheets are provided for writing your answers. Enter the final answers into the appropriate boxes in the answer sheet (marked A).
- Open the envelopes on the START signal given by the judges. Time is measured from this moment; the winning team will be the one which finishes in the shortest total time, after any time penalties (for example for incorrect or missing answers) are applied. The time penalties are explained in each task.
- When you have solved all the problems, hand your answer sheets to the guide, who will note the total time.
- The maximum time available for the round is 90 minutes. After this time any remaining answer sheets should be handed in.
- The completed answer sheets will then be marked by the jury, who will apply time penalties as appropriate. The winning team will be announced at the closing ceremony.
- Everything you need will be provided on the table (calculator, office supplies, geometrical instruments, paper, table of constants).
- For one of the tasks, all the screens in the room will simultaneously display a video at a specified time (the video will be repeated several times).

Group Competition 1: ‘Crossword’

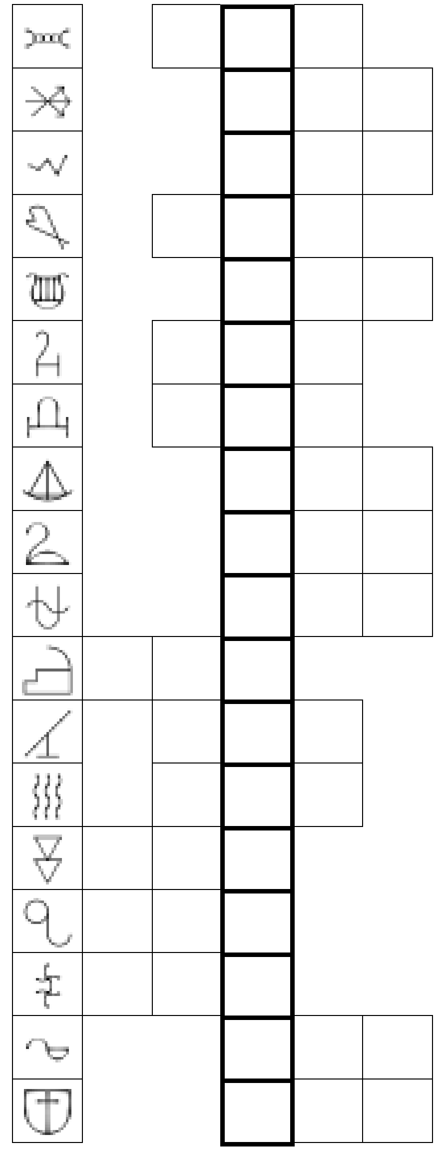
For each row of the table in the answer sheet, write in the three-letter IAU abbreviation of the constellation corresponding to the symbol. Your final answer is formed by the vertical column outlined in bold.

Hint: Mercator-projection sky map of constellations marked with symbols, below.

Penalties: empty space or wrong constellation: +1 minute



Crossword – Answer Sheet



Group Competition 2: ‘Reply to Arecibo Message’

During IOAA 2023, a reply to the message sent by the Arecibo radio telescope in 1974 finally reached Earth. A video recording of the transmission will be played on the monitors during the round. Decode the transmission and write the hidden message on the answer sheet.

The recording will begin playing 30 minutes after the start of the competition, and play continuously in a loop for a total of 30 minutes.

Penalties: missing or incorrect answer: +15 minutes

Group Competition 3: ‘Mars loop’

(a) On the provided graph paper, plot the X and Y positions of Earth and Mars in the heliocentric system over time using the data from the table, and draw vectors connecting the corresponding positions of Earth and Mars on each day.

(b) Using a ruler and set square, translate each vector to a common origin while preserving their lengths and directions. Connect the ends of the translated vectors with a curve representing the position of Mars in the geocentric system.

(c) From the plot, read off the minimal Earth–Mars distance, the duration of retrograde motion and the angle by which Mars moves backwards. Give your answers on the answer sheet.

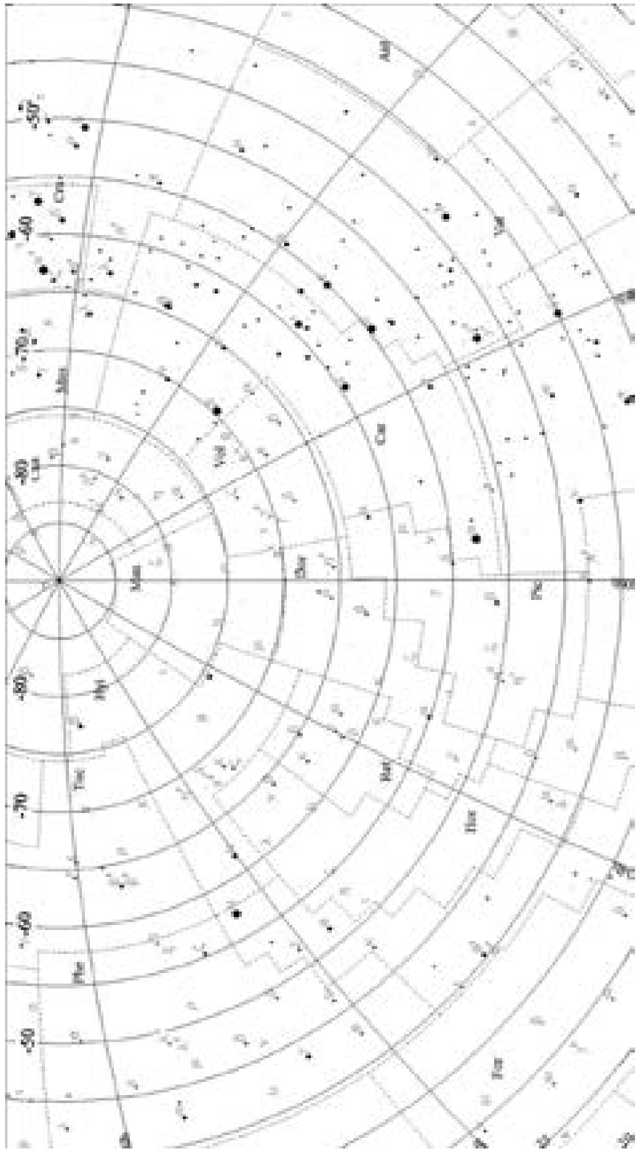
Penalties: missing or incorrect drawing for part (b) +10 minutes; missing or out of range answers: +5 minutes for each part.

Heliocentric Equatorial Positions				
	EARTH		MARS	
Date	X [au]	Y [au]	X [au]	Y [au]
2022 Sep 01	0.9375	-0.3431	1.3235	0.4704
2022 Sep 11	0.9846	-0.1928	1.2724	0.5972
2022 Sep 21	1.0033	-0.0370	1.2082	0.7178
2022 Oct 01	0.9928	0.1198	1.1320	0.8312
2022 Oct 11	0.9530	0.2731	1.0448	0.9366
2022 Oct 21	0.8850	0.4184	0.9477	1.0331
2022 Oct 31	0.7905	0.5512	0.8417	1.1200
2022 Nov 10	0.6722	0.6673	0.7282	1.1967
2022 Nov 20	0.5336	0.7631	0.6082	1.2630
2022 Nov 30	0.3785	0.8356	0.4830	1.3184
2022 Dec 10	0.2119	0.8824	0.3537	1.3628
2022 Dec 20	0.0387	0.9020	0.2216	1.3960
2022 Dec 30	-0.1357	0.8936	0.0877	1.4182
2023 Jan 09	-0.3058	0.8574	-0.0468	1.4294
2023 Jan 19	-0.4665	0.7947	-0.1810	1.4297
2023 Jan 29	-0.6128	0.7073	-0.3139	1.4194
2023 Feb 08	-0.7401	0.5981	-0.4445	1.3988
2023 Feb 18	-0.8447	0.4705	-0.5719	1.3682
2023 Feb 28	-0.9234	0.3284	-0.6954	1.3280
2023 Mar 10	-0.9740	0.1765	-0.8140	1.2787
2023 Mar 20	-0.9954	0.0191	-0.9272	1.2207
2023 Mar 30	-0.9868	-0.1387	-1.0341	1.1545
2023 Apr 09	-0.9491	-0.2925	-1.1342	1.0807
2023 Apr 19	-0.8835	-0.4377	-1.2268	0.9998
2023 Apr 29	-0.7920	-0.5702	-1.3115	0.9124

Group Competition 4: ‘Southern Pole Star’

On the map of the southern sky in the answer sheet, draw the southern precession circle and determine the year, nearest to the present date, in which the star δ Velorum will become the southern pole star as a result of precession. The map is presented in the equidistant projection.

Penalties: missing or incorrect answer +10 minutes



Group Competition 5: ‘Astrolabe’

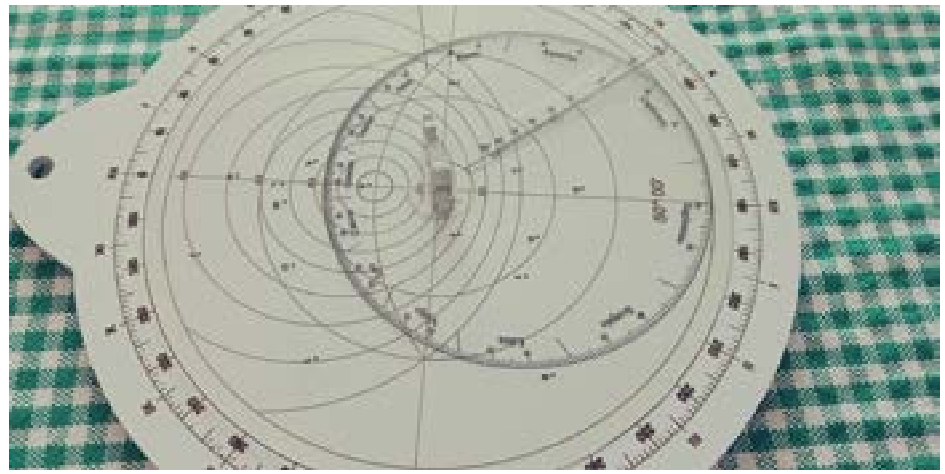
An astrolabe helps you determine the positions of selected stars relative to the horizon at a given time. The base, or ‘mater’, is marked with the horizon, curves of constant altitude, the pole, tropics, prime vertical and celestial equator (for latitude 50°N). The two movable transparent parts are the ‘rete’ and the ‘rule’. The ‘rete’ shows the positions of certain stars, one from each constellation, as seen from outside the celestial sphere, as well as the ecliptic divided into the signs of the Zodiac. Finally the ‘rule‘ is a scale which lets you determine the positions of stars in declination.

(a) Identify the stars marked with letters on the rete and complete the table in the answer sheet. Give the name or Bayer designation and constellation, and the right ascension and declination (within ±0.25 h and ±5°). Mark the star which was the source of the alien transmission from Task 2.

Penalties: missing or incorrect names or incorrect coordinates: +1 minute each; wrong source star: +1 minute.

(b) For the date of Nicolaus Copernicus’s birthday (19 February) determine the right ascension and declination of the Sun (within ±0.25 h and ±5°), and the times of sunrise and sunset (within ±0.25 h).

Penalties: missing or incorrect coordinates: +5 minutes; missing or incorrect times: +5 minutes.



Group Competition 6: 'Saros'

Use the following table of lunar eclipses from the last 25 years to predict when the next lunar eclipse clearly visible from Poland (50°N, 19°E) will occur. Give the date and predicted hour on the answer sheet.

Penalties: for a missing answer +10 minutes, eclipse with weak visibility +1 minute

Date	Time UT	Type	JD
1991 Dec 21	10:33:60	Partial	2448602.940
1992 Jun 15	04:57:57	Partial	2448788.707
1992 Dec 09	23:45:05	Total	2448966.49
1993 Jun 04	13:01:26	Total	2449143.042
1993 Nov 29	06:27:06	Total	2449320.769
1994 May 25	03:31:20	Partial	2449497.647
1995 Apr 15	12:19:04	Partial	2449823.013
1996 Apr 04	00:10:47	Total	2450177.508
1996 Sep 27	02:55:24	Total	2450353.622
1997 Mar 24	04:40:28	Partial	2450531.694
1997 Sep 16	18:47:42	Total	2450708.283
1999 Jul 28	11:34:46	Partial	2451387.983
2000 Jan 21	04:44:34	Total	2451564.698
2000 Jul 16	13:56:39	Total	2451742.081
2001 Jan 09	20:21:40	Total	2451919.349
2001 Jul 05	14:56:23	Partial	2452096.115
2003 May 16	03:41:13	Total	2452775.653
2003 Nov 09	01:19:38	Total	2452952.556
2004 May 04	20:31:17	Total	2453130.345
2004 Oct 28	03:05:11	Total	2453306.628
2005 Oct 17	12:04:27	Partial	2453661.003
2006 Sep 07	18:52:25	Partial	2453986.286
2007 Mar 03	23:21:59	Total	2454163.474
2007 Aug 28	10:38:27	Total	2454340.943
2008 Feb 21	03:27:09	Total	2454517.644
2008 Aug 16	21:11:12	Partial	2454695.383
2009 Dec 31	19:23:46	Partial	2455197.308
2010 Jun 26	11:39:34	Partial	2455373.986
2010 Dec 21	08:18:04	Total	2455551.846
2011 Jun 15	20:13:43	Total	2455728.343
2011 Dec 10	14:32:56	Total	2455906.106
2012 Jun 04	11:04:20	Partial	2456082.961
2013 Apr 25	20:08:38	Partial	2456408.34
2014 Apr 15	07:46:48	Total	2456762.824
2014 Oct 08	10:55:44	Total	2456938.956
2015 Apr 04	12:01:24	Total	2457117.001
2015 Sep 28	02:48:17	Total	2457293.617
2017 Aug 07	18:21:38	Partial	2457983.265
2018 Jan 31	13:31:00	Total	2458150.063
2018 Jul 27	20:22:54	Total	2458327.349
2019 Jan 21	05:13:27	Total	2458504.717
2019 Jul 16	21:31:55	Partial	2458681.397
2021 May 26	11:19:53	Total	2459360.972
2021 Nov 19	09:04:06	Partial	2459537.878
2022 May 16	04:12:42	Total	2459715.676
2022 Nov 08	11:00:22	Total	2459891.958

Theory: Instructions

- **Do not touch envelopes until the start of the examination.**
- The theoretical examination lasts for 5 hours and is worth a total of 250 marks.
- There are **Answer Sheets** for carrying out detailed work and **Working Sheets** for rough work, which are already marked with your student code and question number.
- ***Use only the answer sheets for a particular question for your answer. Please write only on the printed side of the sheet. Do not use the reverse side.*** If you have written something on any sheet which you do not want to be evaluated, cross it out.
- Use as many mathematical expressions as you think may help the evaluator to better understand your solutions. The evaluator may not understand your language. If it is necessary to explain something in words, please use short phrases (if possible in English).
- You are not allowed to leave your work desk without permission. If you need any assistance (malfunctioning calculator, need to visit a restroom, etc.), please draw the attention of the supervisor.
- The beginning and end of the examination will be indicated by the supervisor. The remaining time will be displayed on a clock.
- At the end of the examination you must stop writing immediately. Put everything back in the envelope and leave it on the table.
- Once all envelopes are collected, your student guide will escort you out of the examination room.
- A list of constants and useful relations are included in the envelope.

Theory 1: 'Neptune'

Given that Neptune will be at opposition on 21 September 2024, calculate in which year Neptune was last at opposition near the time of the northern-hemisphere spring equinox. Assume that the orbits of Earth and Neptune are circular.

(5 points)

Theory 2: 'Magnetic field'

An emission line of wavelength $\lambda = 600$ nm was observed in the spectrum of a white dwarf. Assuming that it originates from the interaction of a free non-relativistic electron with a magnetic field,

(a) calculate the magnetic flux density of the field;

(b) estimate the wavelength of another spectral line, the discovery of which could confirm that the lines originate from particles of a plasma interacting with the magnetic field.

(5 points)

Theory 3: 'Microlensing'

A faint subdwarf star ($I = 20.4\,\text{mag}$) in the Galactic bulge was observed to brighten to $I' = 15.2\,\text{mag}$ as a result of gravitational microlensing, allowing a high-resolution spectrum to be obtained with the UVES spectrograph on the Very Large Telescope (mirror diameter 8.2 m).

Estimate the diameter of the telescope needed to obtain a spectrum of the same quality with the same instrument and exposure time for this star at its normal apparent brightness. The fiber aperture is small enough so that the sky background is negligible.

(5 points)

Theory 4: 'Europa'

(a) Assuming that the ice covering the ocean on Jupiter's moon Europa is 6 km thick, that the surface temperature on the night side of Europa is 100 K and that the temperature at the ice-water boundary is 273 K, calculate the total power corresponding to the heat emitted from the interior of this moon.

(b) On Earth, the mean geothermal heat flux measured at the continental surface is $70 \times 10^{-3}\,\text{W}\text{m}^{-2}$ and originates mainly from radioactive decay. Is the heat emanating from the interior of Europa more likely to come from radioactive decay or tidal forces? Assume that Earth and Europa have a similar isotopic composition. (Select the correct answer on the answer sheet and show your working.)

(10 points)

Notes: the heat passing through a wall with a surface area S and thickness d in time t is described by the formula:

$$Q = \lambda S \Delta T t / d,$$

where λ stands for thermal conductivity and ΔT for the temperature difference.

The thermal conductivity of ice $\lambda = 3\,\text{W}\text{m}^{-1}\text{K}^{-1}$. The mass and radius of Europa are 4.8×10^{22} kg and 1561 km.

Theory 5: 'Dark Energy'

Observations indicate that the expansion of the Universe is accelerating. Fluctuations of the cosmic microwave background favour a flat (Euclidean) geometry, in which the total mass density (i.e. density of matter and equivalent mass density of all forms of energy) should be equal to the so-called critical density:

$$\rho_{\text{cr}} = \frac{3\,H_0^2}{8\,\pi\,G},$$

where H_0 is the present value of the Hubble constant. However, the total density of matter (luminous and dark) is estimated at

$$\rho_{\text{m},0} \approx 2.8 \cdot 10^{-27}\,\text{kg}\,\text{m}^{-3}.$$

To resolve this discrepancy, the standard cosmological model assumes that the Universe is filled with a mysterious 'dark energy' of constant energy density ε_Λ.

Determine the value of ε_Λ and calculate for which redshift in the past the energy density equivalent to matter was equal to the density of dark energy. Neglect the contribution of electromagnetic radiation.

(12 points)

Theory 6: 'Bolometer'

The entrance cavity of a particular bolometer is a cone with an opening angle of 30°, the surface of which has an energy absorption coefficient of $a = 0.99$. Assume that there is no scattering of the incident radiation on the walls of the cavity, only multiple mirror-like (specular) reflections. The bolometer is connected to a cooler which keeps the bolometer cavity surface at practically 0 K temperature. The instrument is orbiting at 2 au from the Sun and is pointed directly at the centre of the Solar disk.

Calculate the temperature of a black body which would radiate the same amount of energy from a unit surface area as the bolometer opening does per unit surface area.

Note: the opening angle is defined as twice the angle between the axis of the cone and its generatrix.

(13 points)

Theory 7: ‘Libration’

As a result of libration, studied among others by Johannes Hevelius, more than half of the Moon’s surface can be observed from Earth. Assume that the observer is geocentric.

(a) Estimate ϕ_B, the maximum angle of libration in latitude. The axial tilt (obliquity) of the Moon with respect to its orbital plane is $\alpha = 6°41'$.

(b) Estimate ϕ_L, the maximum angle of libration in longitude. Assume that the Moon is always aligned with the same side facing towards the second focus F2 of its orbit, and that the eccentricity of the Moon’s orbit e changes between 0.044 and 0.064 on a timescale of several months.

(c) Estimate the fraction of the Moon’s surface which can be seen from Earth.

(d) Calculate how many months (lunations) are needed for an observer to see the Moon’s surface determined in part (c).

(20 points)

Theory 8: ‘Neutrinos’

In a simplified model of a supernova explosion, the core of a star, composed of pure iron ${}^{56}_{26}\mathrm{Fe}$ nuclei with a total mass of 1 $M_\odot$, changes into a neutron star composed of individual electrons, protons and neutrons in numerical proportions of 1:1:8. This process is called ‘neutronization’ and results in the emission of a large number of neutrinos.

Calculate the solar neutrino flux on Earth. How much larger would the flux of neutrinos reaching the Earth from the supernova be than the steady neutrino emission of the Sun, if the supernova exploded in the centre of the Galaxy and the process of neutronization of the core took about 0.01 s? Give an order-of-magnitude answer.

(20 points)

Theory 9: ‘Second eclipse’

For each of two eclipsing binary systems, Bolek and Lolek, the primary eclipses were observed with very high cadence as depicted below:

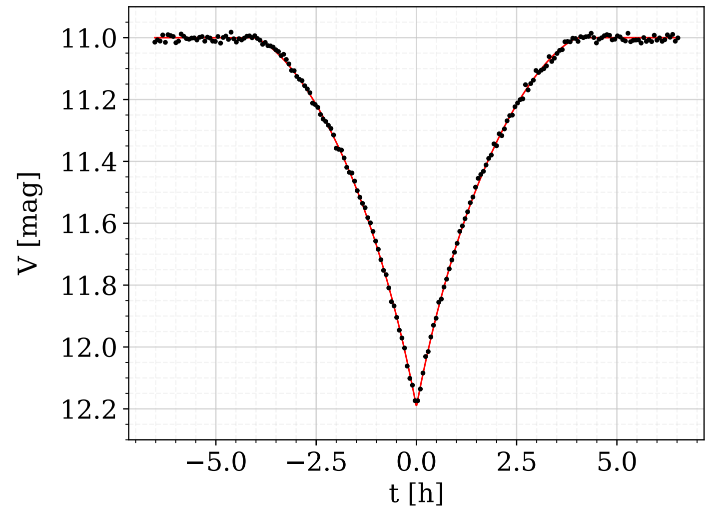


Figure 1: Observed lightcurve for system Bolek.

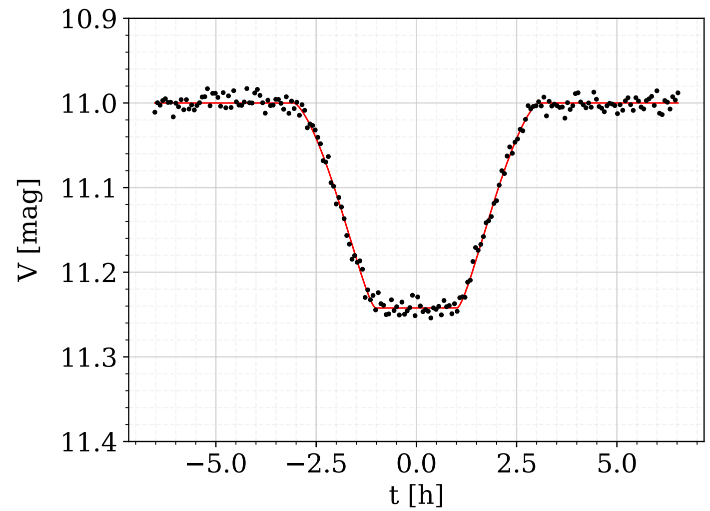


Figure 2: Observed lightcurve for system Lolek.

In the figures, t is the time in hours relative to the moment of minimum and V is the brightness in the V (visible) band in magnitudes. The points are the measurements and the line is the fitted model of the shape of the eclipse.

You can assume that in both cases the eclipses are central ($i = 90°$) and last for a very small fraction of the orbital period, limb darkening is negligible, and the orbits have low eccentricity.

On the Answer Sheet, draw the predicted shape of the light curve for each of the secondary eclipses. Write down the equations and calculations leading to your predictions.

(20 points)

Theory 10: 'Aldebaran'

On 9 March 1497, Nicolaus Copernicus observed the occultation of Aldebaran by the Moon from Bologna. In his work *De revolutionibus orbium cœlestium* (Book VI, Chapter 27) Copernicus described the event: "I saw the star touching the dark edge of the Moon and disappearing at the end of the 5th hour of the night between the horns of the Moon, closer to the south horn by a third of the Moon's diameter."

Assuming that the occultation was observed on the local meridian, that at maximum occultation Aldebaran was $0.32'$ above the southern edge of the Moon, and that the apparent angular diameter of the Moon as seen from Bologna was $31.5'$, solve the following tasks:

(a) Find the latitude φ_1 of a place with the same longitude as Bologna, from which Aldebaran would have appeared to pass behind the centre of the Moon.

(b) Find the duration of the occultation as seen from latitude φ_1 if Aldebaran appeared to pass along the diameter of the lunar disk. For simplicity, also assume that the Moon and the observer are moving linearly at constant speed, that the Moon's orbit is circular and that the declination of the Moon does not change during the occultation.

(c) Find the topocentric angular velocity of the Moon against the background stars during the occultation for an observer at latitude φ_1, in arcmin/hour, applying the same assumptions as in part (b).

(d) Estimate the range of the Moon's topocentric angular velocities (against the background stars) in arcmin/hour at latitude φ_1, assuming a circular orbit. Show how this result can be justified by expressing the relative velocity of the Moon and observer in terms of their velocity vectors.

The declination of Aldebaran was $\delta_A = 15.37°$ in 1497 (due to precession), and the latitude of Bologna is $\varphi_B = 44.44°$ N.

(25 points)

Theory 11: 'X-ray emission from galaxy clusters'

Clusters of galaxies are strong X-ray sources. It has been established that the emission mechanism is thermal bremsstrahlung (free-free radiation) from a hot hydrogen and helium plasma inside the cluster. The luminosity L_X (in Watts) of each component of the plasma is described by the formula:

$$L_X = 6 \times 10^{-41} N_e N_X T^{\frac{1}{2}} V Z_X^2,$$

where the symbols represent:

$X-$ Hydrogen (H) or Helium (He),
N_e- number density of electrons [m^{-3}],
N_X- number density of ions X [m^{-3}],
Z_X- atomic number of ion X,
$T-$ temperature of the plasma [K],
$V-$ volume occupied by the plasma [m^3].

(a) Determine the total mass (in solar masses) of the plasma which emits the X-rays, assuming that:

- the plasma is fully ionized with 1 helium ion for every 10 hydrogen ions;
- $L_{\text{total}} = 1.0 \times 10^{37}\,\mathrm{W}$,
- $T = 80 \times 10^6\,\mathrm{K}$,
- the plasma is uniformly distributed in a sphere of radius $R = 500\,\mathrm{kpc}$,
- self-absorption is negligible.

(16 points)

The photons of the cosmic microwave background (CMB) interact with plasma in a process known as inverse Compton scattering. The CMB normally has a thermal blackbody spectrum at a temperature of 2.73 K. However, interaction with the plasma leads to distortion of the CMB spectrum (known as the Sunyaev–Zeldovich effect).

(b) Estimate the mean free path of CMB photons in the plasma, i.e. the average distance travelled by a photon before interacting with an electron. Express it in Mpc. The effective cross section for photon–electron interactions is $\sigma = 6.65 \times 10^{-29}\,\mathrm{m}^2$. (5 points)

(c) Estimate the typical energy of CMB photons. (3 points)

(d) The energy of CMB photons can be increased by a factor of up to $(1+\beta)/(1-\beta)$ due to the inverse Compton scattering, where $v = \beta c$ is the velocity of electrons. Estimate the energy of scattered CMB photons. (6 points)

(Total: 30 points)

Theory 12: 'DART'

The Double Asteroid Redirection Test (DART) was a NASA mission to evaluate a method of planetary defense against near-Earth objects. The spacecraft hit Dimorphos, a moon of the asteroid Didymos, to study how the impact affected its orbit.

(a) Calculate the expected orbital period change (in minutes), assuming that the collision was head-on, central, and perfectly inelastic.

Assume that before the impact Dimorphos orbited Didymos on a circular orbit with a period of $P = 11.92$ h. The masses of Dimorphos and Didymos are $m = 4.3 \times 10^9$ kg and $M = 5.6 \times 10^{11}$ kg, respectively. The mass and speed of the DART spacecraft relative to Dimorphos at a moment of impact were $m_\mathrm{s} = 580\,\mathrm{kg}$ and $v_\mathrm{s} = 6.1\,\mathrm{km\,s^{-1}}$. Neglect the gravitational influence of other bodies.

(20 points)

(b) In reality, the orbital period of Dimorphos was observed to be changed by $\Delta P_0 = -33\,\mathrm{min}$. This is due to the momentum transfer associated with the recoil of the ejected debris: the spacecraft was absorbed by the asteroid, but the impact excavated some material from the asteroid and ejected it into space. Calculate the momentum of the ejected debris and express it as a fraction of the momentum of Dimorphos before the collision. You can assume that the mass of the ejected material is much smaller than the mass of Dimorphos.

(15 points)

(c) Calculate the velocity change (in $\mathrm{mm\,s^{-1}}$) of Dimorphos as a result of the impact, taking into account the effect of the ejected debris.

(5 points)

(Total: 40 points)

Theory 13: 'LISA'

The Laser Interferometer Space Antenna (LISA) is a proposed experiment to detect low-frequency gravitational waves. It consists of three spacecraft arranged in an equilateral triangle. A passing gravitational wave changes the distance between the spacecraft, which can be precisely measured (more details are given in the notes below).

One of the sources of low-frequency gravitational waves are compact binary star systems, for example binary white dwarfs. Such a system was recently discovered at a distance of 2.34 kpc from the Sun. The orbital period of the binary was found to be 414.79 s and is changing at a rate of $-7.49 \times 10^{-4}\,\mathrm{s\,yr^{-1}}$ due to the emission of gravitational waves.

(a) Check if this binary system can be detected by LISA. (25 points)

(b) Calculate the chirp mass. (5 points)

(c) Determine the masses of both components knowing that the ratio between the radius of one of the components to the semi-major axis of the orbit is 0.139, and assuming both components follow the mass–radius relation for white dwarfs given in the table below.

(15 points)

(Total: 45 points)

Notes:

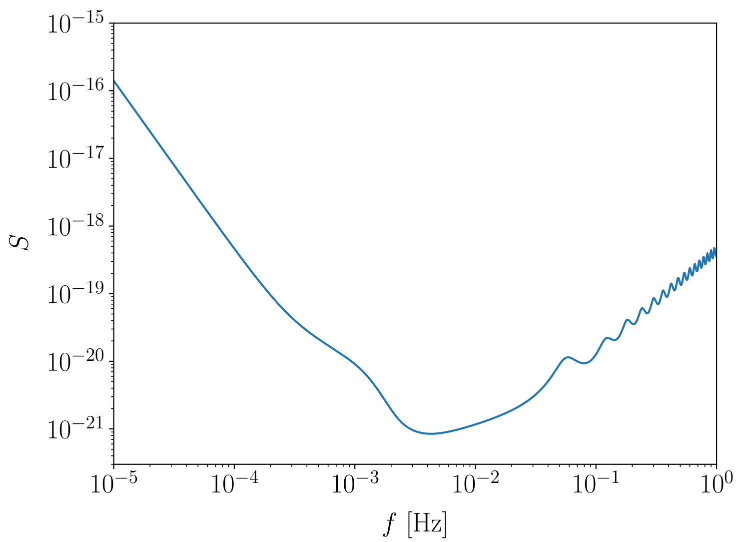
1. A binary star system with an orbital period P emits gravitational waves with a frequency of $f = 2/P$.

2. LISA measures a dimensionless quantity called the characteristic strain amplitude, S, given by
$$S = h\sqrt{fT_\mathrm{obs}},$$
where $T_\mathrm{obs} = 4\,\mathrm{yr}$ is the expected duration of the mission. h is the gravitational wave strain, given by:
$$h = \frac{2(G\mathcal{M})^{5/3}(\pi f)^{2/3}}{c^4 D},$$
where $\mathcal{M}$ is the so-called chirp mass, f is the frequency of the gravitational wave and D is the distance to the system. If we denote the masses of the components of the binary as M_1 and M_2, then the chirp mass is given by:
$$\mathcal{M} = \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}}.$$
The expected sensitivity of LISA as a function of a gravitational wave frequency is presented on the figure below.

3. The semi-major axis a of the binary system changes due to the emission of gravitational waves at a rate:
$$\frac{\Delta a}{\Delta t} = -\frac{64}{5}\frac{G^3}{c^5}\frac{M_1 M_2 (M_1 + M_2)}{a^3}.$$

M ($M_\odot$)	R ($R_\odot$)
0.48	0.0144
0.50	0.0147
0.52	0.0150
0.54	0.0153
0.56	0.0156
0.58	0.0159
0.60	0.0162
0.62	0.0165
0.64	0.0168

Mass–radius relation for white dwarfs based on theoretical models of Althaus et al. (2013) for white dwarfs of $log_g = 7.7$.



The expected sensitivity of LISA as a function of gravitational wave frequency.

Observation Round: Procedure

You have 30 minutes to read the questions and plan your observations. Do not talk to other participants. When you are shown the sign to 'GO NOW' by the supervisor, follow the directions to the telescope location taking with you the questions, clipboard and pen/pencil (a red light will be provided at the telescope). Keep your distance from other participants and do not talk to them. Show your badge and code to the assistant at your telescope.

You will have a total of 30 minutes to complete the observing tasks, starting when all participants are ready. At the end of 30 minutes take your papers and clipboard (leave the light) and wait until called to leave the observing location.

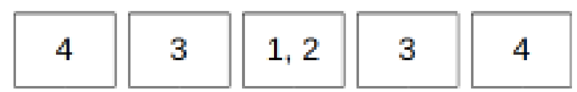
Follow the directions back to the preparation hall. Keep your distance from other participants and do not talk to them.

You will have another 30 minutes to process your observations and complete the answer sheet (there will be a calculator, geometrical instruments etc.). If you had any technical problems you can write a report for your team leader on the form in the answer sheets. At the end of 30 minutes place your answer sheets and the report in the envelope and wait at your desk until directed to leave the hall.

Observation Round: General Instructions

Scientists have discovered a crashed alien flying saucer. High up inside the hold, they found several screens transmitting views of the sky and telescopes have been set up to let you see them clearly from the level of the deck. Use your telescope to observe the (simulated) targets on the screens and record your results.

There are 5 screens on the opposite side: the central one will display video for tasks 1 and 2, the other four will display static images for tasks 3 and 4. The two screens closer to the centre will display the (same) image for task 3, and the two outer screens will display the (same) image for task 4. Point your telescope at the screens furthest away from you.

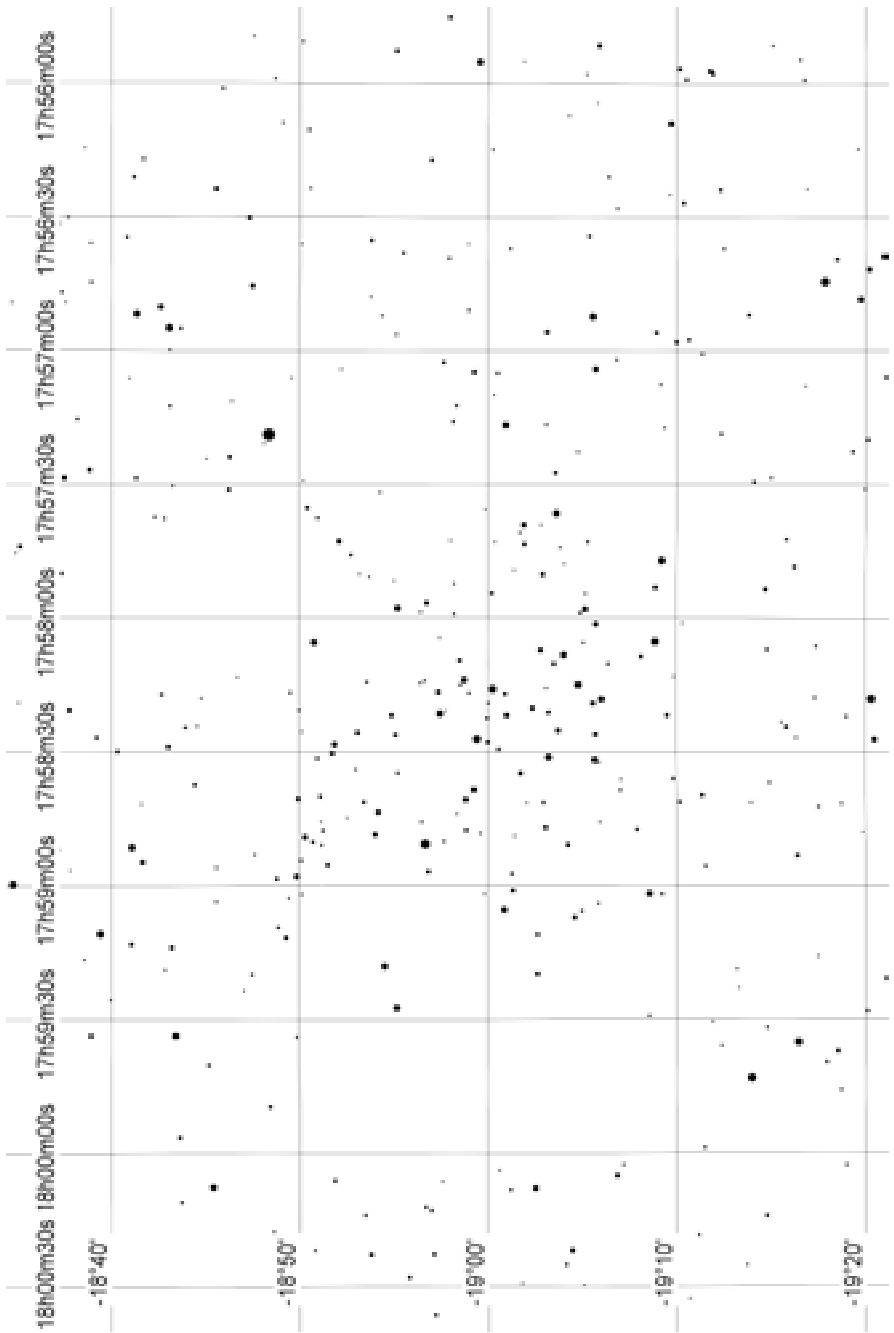


You will have a total of 30 minutes to complete the observing tasks, however tasks 1 and 2 will only be displayed once: just as with real observations you will only have one opportunity to collect the data. There will be two clocks visible showing the time remaining in the round.

At the start of the round a clock on the central screen will show the simulated time at the observer's location. The clock will have the correct orientation when seen through the telescope. The time will be shown for 3 minutes after which it will disappear; use this to set a start time for your observations.

Caution: the scale of the field of view is different between the video and still images.

Observation: Map 1 (Question 1 and Question 2)



Observation 1: 'Asteroid occultation'

Calculations based on the orbital elements predict that an asteroid will occult the star HD 163390 for 21 s, with the maximum occultation (mid-time) occurring at 23:03:32 UT. However, the ephemeris is not perfect and the prediction may be wrong by up to 20 s for the time and by 10s for the duration.

Based on your observations, find the true mid-time and duration of the occultation. To identify the star use Map 1 and the following coordinates:

HD 163390 RA: $17^{\mathrm{h}}\ 58^{\mathrm{m}}\ 05^{\mathrm{s}}$ DEC: $-18^\circ\ 50'\ 46.14''$

The map and the sky are in the same epoch.

(15 points)

Answer Sheet

Mid-time of occultation	± error	Duration of occultation	± error

Observation 2: 'Starlink'

In the same star field as for Question 1, a 'train' of Starlink satellites will appear near the meridian of $17^{\mathrm{h}}\ 59^{\mathrm{m}}$ at around 23:05 UT. Their passage will last for around three minutes.

You may assume that the centre of the star field is at an altitude of 20° and that the satellites are 400 km above the Earth's surface moving on circular orbits with equal distances between them. You may also assume that satellites will move vertically (perpendicular to the horizon).

(a) Measure the angular velocity of the satellites as seen by an observer on the simulated sky.

(b) Measure the time interval between the passes of successive satellites and mark their path on the sky chart (Map 1).

(c) Calculate the theoretical angular velocity of the satellites as seen by the observer, using the information given in the question.

(d) Estimate the distance in km between two consecutive satellites.

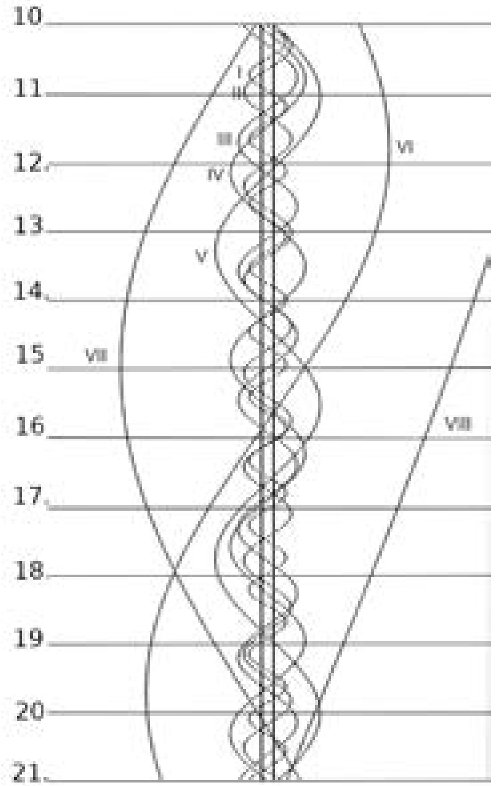
Constants: $G = 6.674 \times 10^{-11}\mathrm{Nm^2kg^{-2}}$; $M_{\mathrm{Earth}} = 5.972 \times 10^{24}\mathrm{kg}$; $R_{\mathrm{Earth}} = 6378\mathrm{km}$.

(15 points)

Observation 3: ‘Planetary Moons’

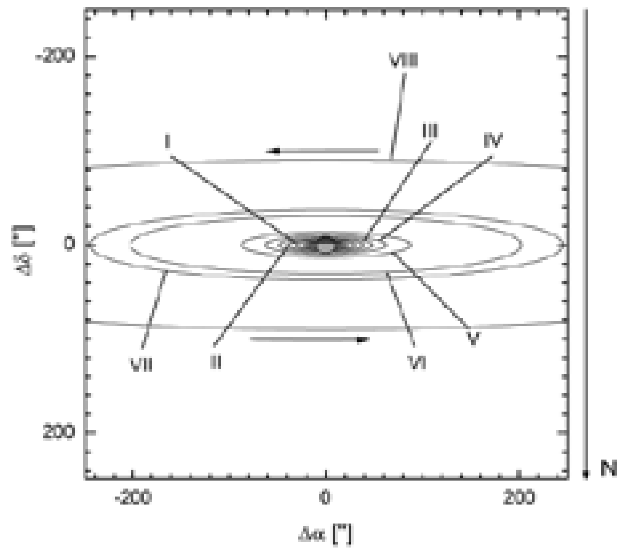
The screen will display an image of one of the planets of the Solar System as seen on August 15, 2023, at 00:00 UT. Identify any five moons and mark them on the answer sheet (you may use the moon position chart attached below and the table showing their brightness).

(10 points)



The moon position chart. The numbers on the left indicate the days of August 2023 (at midnight UT).

Number	Name	Magnitude
I	Mimas	13.0
II	Enceladus	11.8
III	Tethys	10.4
IV	Dione	10.6
V	Rhea	9.9
VI	Titan	8.5
VII	Hyperion	14.4
VIII	Japetus	11.0



The moon position chart – moon numbers (I, II, . . .) as above.

Answer sheet

Mark the positions of any 5 moons with a dot on the following image and label them with their numbers (I, II, . . .).

Observation 4: ‘Supernova’

The other screen presents the view of a galaxy and a bright (mag < 11) object which was not visible previously. Estimate the right ascension (RA) and declination (DEC) coordinates of this star and estimate its magnitude. You may use Map 2, with stellar coordinates and a list of magnitudes.

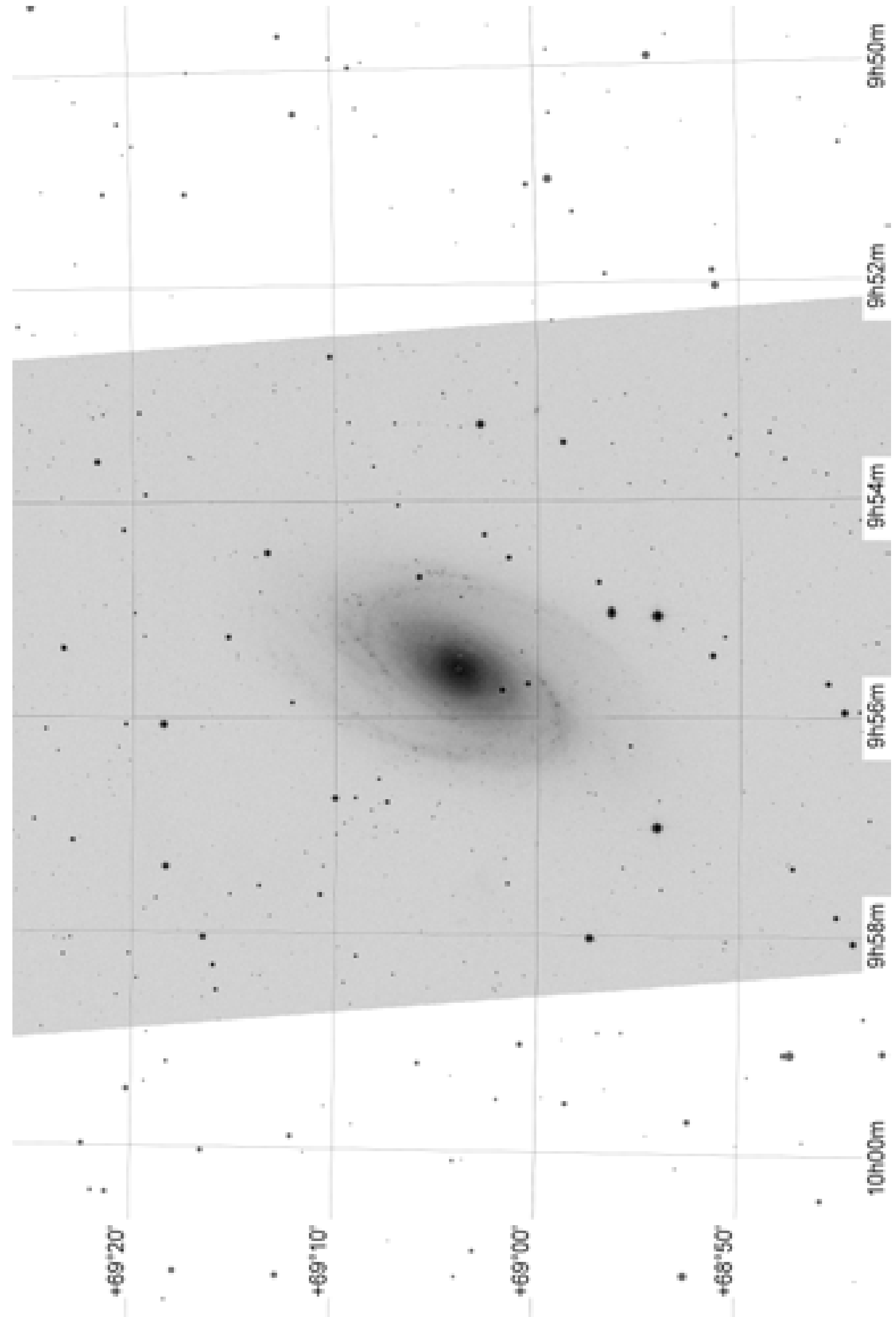
(10 points)

Star	RA J2000			DEC J2000			mag
	h	m	s	deg	m	s	
BD+69 541	9	55	2.7	68	56	22	10.3715
Gaia DR2 1070097015969362560	9	53	27.9	68	58	43	11.2281
Gaia DR2 1070144329329069568	9	53	17.7	69	2	48	10.0785
Gaia DR2 1070453463896461952	9	57	0.8	68	54	6	8.9148
Gaia DR2 1070455010084791680	9	55	25.9	68	51	21	11.4722
Gaia DR2 1070459408131195776	9	58	1.6	68	57	24	10.2003
Gaia DR2 1070467070352960512	9	55	4.4	68	54	5	9.1615
Gaia DR2 1070467379590606976	9	55	1	68	56	22	10.4605
Gaia DR2 1070468169864590208	9	54	45.3	68	56	59	12.2097
Gaia DR2 1070469475534553728	9	55	41.4	69	0	30	11.7856
Gaia DR2 1070470265808536448	9	55	45	69	1	46	11.2905
Gaia DR2 1070470609404512512	9	55	33.2	69	3	55	13.3020
Gaia DR2 1070472293033168640	9	54	53.2	69	3	48	14.2845
Gaia DR2 1070473186386370176	9	54	42.3	69	5	52	11.6033
Gaia DR2 1070476794158817152	9	57	38.8	69	10	44	12.6348
Gaia DR2 1070476858581360384	9	56	47.1	69	7	27	12.7259
Gaia DR2 1070476897238038272	9	56	34.4	69	7	51	13.6578
Gaia DR2 1070477240835421440	9	56	44.8	69	9	1	13.7626
Gaia DR2 1070477305257957888	9	56	45.1	69	10	1	11.4495
Gaia DR2 1070522934990509312	9	55	15.4	69	15	19	12.0436
Gaia DR2 1070523111086221568	9	54	28.6	69	13	22	11.0704
HD85458	9	55	4	68	54	6	9.1615

Answer Sheet

Right ascension	Declination	est. magnitude

Observation: Map 2



Data Analysis: Instructions

- **Do not touch envelopes until the start of the examination.**
- The data analysis examination lasts for 3 hours and is worth a total of 125 marks.
- There are **Answer Sheets** for carrying out detailed work and **Working Sheets** for rough work, which are already marked with your student code and question number.
- ***Use only the answer sheets for a particular question for your answer. Please write only on the printed side of the sheet. Do not use the reverse side.*** If you have written something on any sheet which you do not want to be evaluated, cross it out.
- Use as many mathematical expressions as you think may help the evaluator to better understand your solutions. The evaluator may not understand your language. If it is necessary to explain something in words, please use short phrases (if possible in English).
- You are not allowed to leave your work desk without permission. If you need any assistance (malfunctioning calculator, need to visit a restroom, etc.), please draw the attention of the supervisor.
- The beginning and end of the examination will be indicated by the supervisor. The remaining time will be displayed on a clock.
- At the end of the examination you must stop writing immediately. Put everything back in the envelope and leave it on the table.
- Once all envelopes are collected, your student guide will escort you out of the examination room.
- A list of constants and useful relations are included in the envelope.

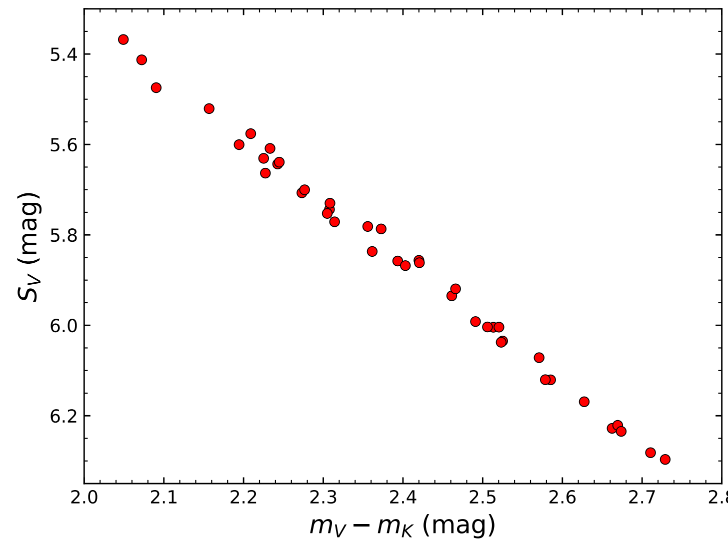
Data Analysis 1: 'Distance to the Large Magellanic Cloud'

In 2019 an international collaboration led by Polish astronomers measured, with very high precision and accuracy, the distance to the Large Magellanic Cloud (LMC), a satellite galaxy of the Milky Way. In this way they set the zero point of the extragalactic distance scale, which allowed for a very precise measurement of the Hubble constant. Their method involved measuring the distances to 20 eclipsing binary stars in the LMC, using the concept of the surface brightness S_V of a star defined as:

$$S_V = m_V + 5\log_{10}\theta,$$

where m_V is the magnitude of a star in the optical V band and θ is the angular diameter of the star on the sky in milliarcseconds (mas).

The quantity S_V can be understood as the magnitude of a star with an angular diameter of 1 mas. An empirical relation has been established between S_V and the colour index $(m_V - m_K)$, where m_V and m_K are magnitudes in the V-band and infrared K-band. This is shown in the figure below for giant stars of spectral types G and K.



Using this relation, the distance to an eclipsing binary system can be determined by deriving the physical radii of the components (using photometry and spectroscopy), and comparing these with the angular diameters predicted by the S_V – $(m_V - m_K)$ relation.

The table below gives the parameters of three detached eclipsing binary stars. R_1 and R_2 are the radii of each component, V_{1+2} and K_{1+2} are the total brightness in magnitudes of the binary in the V- and K-bands, and L_2/L_1 is the luminosity ratio of the components in each band.

source ID	R_1 [$R_\odot$]	R_2 [$R_\odot$]	V_{1+2} [mag]	K_{1+2} [mag]	L_2/L_1 (V)	L_2/L_1 (K)
OGLE LMC-ECL-03160	17.03	37.42	16.73	14.10	2.80	4.23
OGLE LMC-ECL-10567	24.60	36.64	16.15	13.83	1.41	1.99
OGLE LMC-ECL-18365	37.30	15.94	16.27	14.01	0.206	0.188

Apply the method outlined above to the three eclipsing binary systems and calculate the distance to the LMC in kiloparsecs. Estimate the total error of the result. Assume that the fitting of the S_V – $(m_V - m_K)$ relation contributes to a bias of up to 0.8% in all measurements simultaneously.

(Total: 50 points)

Hint: in your calculations keep at least three significant figures and two decimal places. Assume that interstellar extinction is negligible and that the angular size of the LMC is small.

Data Analysis 2: 'Isolated black hole'

In 2022, two independent groups reported the discovery of an isolated black hole based on observations of the gravitational microlensing event OGLE-2011-BLG-0462. In this problem, we will analyze data from the Hubble Space Telescope to reproduce their findings.

Gravitational microlensing occurs when the light of a distant star (the 'source') is bent and magnified by the gravitational field of an intervening object (the 'lens'). The characteristic angular scale of gravitational microlensing events, called the angular Einstein radius θ_E, depends on the mass M and distance D_ℓ from the Earth to the lens:

$$\theta_\mathrm{E} = \sqrt{\frac{4GM}{c^2}\frac{D_s - D_\ell}{D_s D_\ell}},$$

where D_s is the distance to the source star. For typical microlensing events observed in the Milky Way, the source stars are in the Galactic bulge, near the Galactic center, so $D_s \approx 8\,\mathrm{kpc}$.

(a) Calculate the angular Einstein radius in milliarcseconds (mas) for an example lens of $1\,M_\odot$ located at a distance of 1 kpc. (2 points)

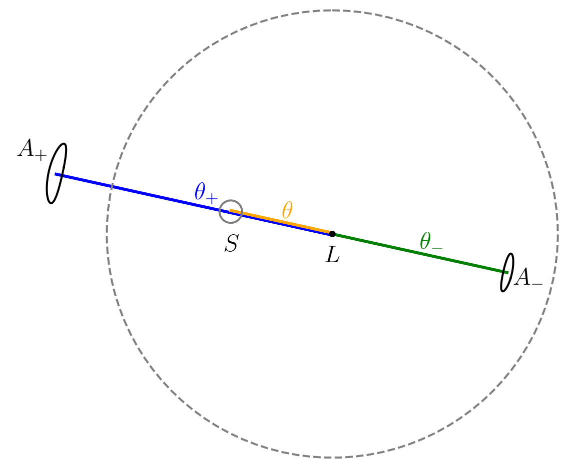
Suppose that at time t the lens and the source are separated by an angle $\theta \equiv u(t)\theta_\mathrm{E}$ on the sky. Two images of the source are created on a line through the positions of the source and the lens, at angular distances θ_+ and θ_- from the lens given by:

$$\theta_\pm = \frac{1}{2}\left(u \pm \sqrt{u^2+4}\right)\theta_\mathrm{E}.$$

These two images are magnified, relative to the unlensed brightness of the source. The absolute magnification of the images is:

$$A_\pm = \frac{1}{2}\left(\frac{u^2+2}{u\sqrt{u^2+4}} \pm 1\right).$$

The image below shows the geometry of the event. The position of the lens is marked as L, the unlensed position of the source is marked as S, while A_+ and A_- mark the positions of the two images of the source. The dashed circle has a radius of one Einstein radius.

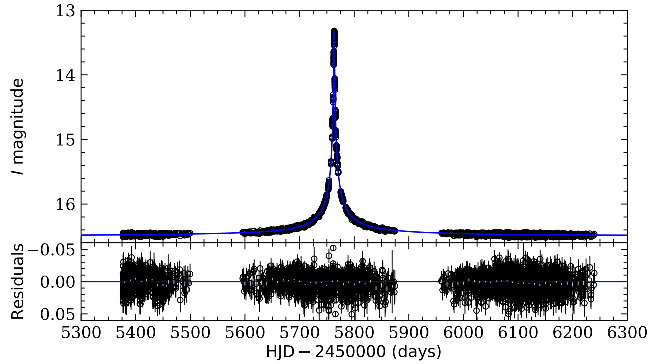


(b) Current telescopes cannot normally resolve this pair of images, but only measure the position of the image centroid, i.e. the brightness-weighted mean of the positions of the two images. Derive an expression for the angular separation θ_c of the image centroid relative to the lens as a function of u and θ_E. (8 points)

(c) Derive an expression for the source deflection $\Delta\theta$, i.e. the difference between the location of the centroid and the unlensed position of the source, as a function of u and θ_E. What is the source deflection when the lens and the source are nearly perfectly aligned ($u \approx 0$)? (4 points)

The source and lens are moving relative to each other in the sky. Thus, both the total magnification of the images and the position of the centroid changes with time, resulting in observable photometric and astrometric microlensing effects. For now, we assume that the source-lens relative motion is rectilinear.

The plot below shows the light curve of the gravitational microlensing event OGLE-2011-BLG-0462, discovered by the OGLE sky survey led by astronomers from the University of Warsaw. The solid line shows the best-fitting light curve model. The Einstein timescale of the event, i.e. the time needed for the source to move by one angular Einstein radius relative to the lens, was $t_\mathrm{E} = 247$ days. The event peaked on 21 July 2011 (HJD = 2455763). The minimal separation between the lens and the source was $u_0 \approx 0$.



The table below shows the measured positions of the source star against the background objects in the East and North directions based on images from the Hubble Space Telescope.

HJD	E position (mas)	N position (mas)
2455765.2	2.58 ± 0.13	7.29 ± 0.16
2455865.7	2.32 ± 0.12	5.44 ± 0.24
2456179.7	0.46 ± 0.14	1.62 ± 0.08
2456195.8	0.88 ± 0.36	1.56 ± 0.77
2456426.2	-1.02 ± 0.21	-0.94 ± 0.12
2456587.7	-2.04 ± 0.07	-1.88 ± 0.40
2456956.6	-4.54 ± 0.25	-5.16 ± 0.29
2457995.2	-11.14 ± 0.12	-15.14 ± 0.17

(d) Plot the measured positions of the source star against the background objects in the East and North directions as a function of time. (10 points)

(e) The observed motion of the source star is the sum of two effects: rectilinear proper motion of the source and astrometric microlensing effects. Calculate the proper motion (in mas/year) of the source in the East and North directions and its uncertainty. (8 points)

(f) After subtracting the effects of proper motion from the data, calculate and plot the total resultant astrometric deflection as a function of u. Neglect the uncertainty of the proper motion determination. (20 points)

(g) Analyse the data to determine the angular Einstein radius $\theta_{\rm E}$ of the event and its uncertainty. (Hint: it may be helpful to linearise the expression for $\Delta\theta$).

(16 points)

(h) For long-timescale events such as OGLE-2011-BLG-0462, the rectilinear approximation of the relative lens-source proper motion is not strictly true and the orbital motion of the Earth has to be taken into account. This allows measurement of a dimensionless quantity called the microlensing parallax, defined as $\pi_{\rm E} = (\pi_l - \pi_s)/\theta_{\rm E}$, where π_l and π_s are parallaxes of the lens and the source, respectively.

For this event $\pi_{\rm E} = 0.095 \pm 0.009$. Rearrange the expression for $\theta_{\rm E}$ given earlier to calculate the mass of the lens in solar masses and its uncertainty.

(7 points)

(Total: 75 points)

Planetarium Round: Procedure

You will have 30 minutes to read the questions and prepare, 30 minutes inside the planetarium and 30 minutes to process your observations and complete the answer sheet.

The preparation area is outside the planetarium. Go to the table matching the name of your team for the Group Competition. It will also be marked with the sector, row and seat number assigned to you inside the planetarium.

Open the envelope only when the supervisor gives the command to ‘START’. You have 30 minutes, the supervisor will give the remaining time e.g. “10 minutes left”, “2 minutes left”. On the command ‘STOP’, stop working but do not leave your place until you are shown the ‘GO NOW’ sign. Take only your question papers, clipboard and pen/pencil (leave the atlas). Follow the directions into the planetarium keeping your distance from other participants and take your place. Do not talk to other participants.

During the tasks you may stand up to get a better view, but do not move around, change seats, talk to other participants, or shine your light at others or at the sky. **The light must be pointed down at all times.**

The round is in 3 parts of 10 minutes each. The first part is for task 1. The second part is for task 2. The third part is for task 3. At 5, 2 and 1 minute before the end a warning will appear briefly on the sky.

At the end of the round wait in your seat until shown the ‘GO NOW’ sign. Follow the directions to the processing area and find the table matching your team as before (leave the light). Keep your distance from other participants and do not talk to them. After everybody is seated you will have 30 minutes to process your observations and complete the answer sheet (there will be a calculator, geometrical instruments etc. and a clock displaying the remaining time). At the end of 30 minutes place your answer sheets in the envelope and wait at your desk until told to leave the area.

Planetarium Round 1: 'Knowledge of the sky'

The projector will display the sky as seen from near the equator (0°N, 19°E). The rotation of the sky will be stopped for about 2 minutes for part (a), then it will start to rotate for parts (b) and (c). The objects for parts (b) and (c) will be displayed simultaneously.

(Projection time 10 minutes)

(a) A meteor shower will be visible in the sky. Determine the constellation of the radiant and estimate its right ascension and declination coordinates.

Constellation	right ascension	declination

(3 points)

(b) Identify which of the following variable stars visible in the sky are in low (write 'DIM') or high (write 'BRIGHT') brightness states. The mean magnitude as shown in the atlas and the magnitude range are given for each star.

Name	atlas mag.	mag. range	DIM / BRIGHT
γ Cas (*Cih*)	2	1.6 — 3.0	
δ Cep	4	3.5 — 4.4	
μ Cep (*Erakis*)	4	3.4 — 5.1	
β Per (*Algol*)	2	2.2 — 3.4	
o Cet (*Mira*)	3.5	2.0 - 10.1	
χ Cyg	4.5	3.3 - 14.1	
L^2 Pup	4.5	2.6 — 6	
δ Sco (*Dschubba*)	2	1.6 — 2.3	

(8 points)

(c) Identify the constellations whose borders are marked and give their IAU abbreviations.

(9 points)

(Total: 20 points)

Planetarium Round 2: 'Retrograde Mars'

The projector will display Mars moving relative to the background stars over one season of visibility (1.5 years) starting from the heliacal rising, chosen so that Mars will be at maximum ecliptic latitude at opposition.

The ecliptic will also be displayed, marked with the positions of the Sun during the year and the current date. The Sun will always be below the horizon.

Synodic period of Mars = 780 days.

(Projection time 10 minutes)

(a) Record the following quantities:

i.	the dates of quadrature (when the elongation of Mars is 90°)	
ii.	the date of the beginning of retrograde motion	
	and the date of the end of retrograde motion	
iii.	the date of opposition	
iv.	the ecliptic latitude at opposition	
v.	the width in ecliptic longitude of the loop made by the planet	

(8 points)

Based on your observations and assuming the orbits of Earth and Mars are circular,

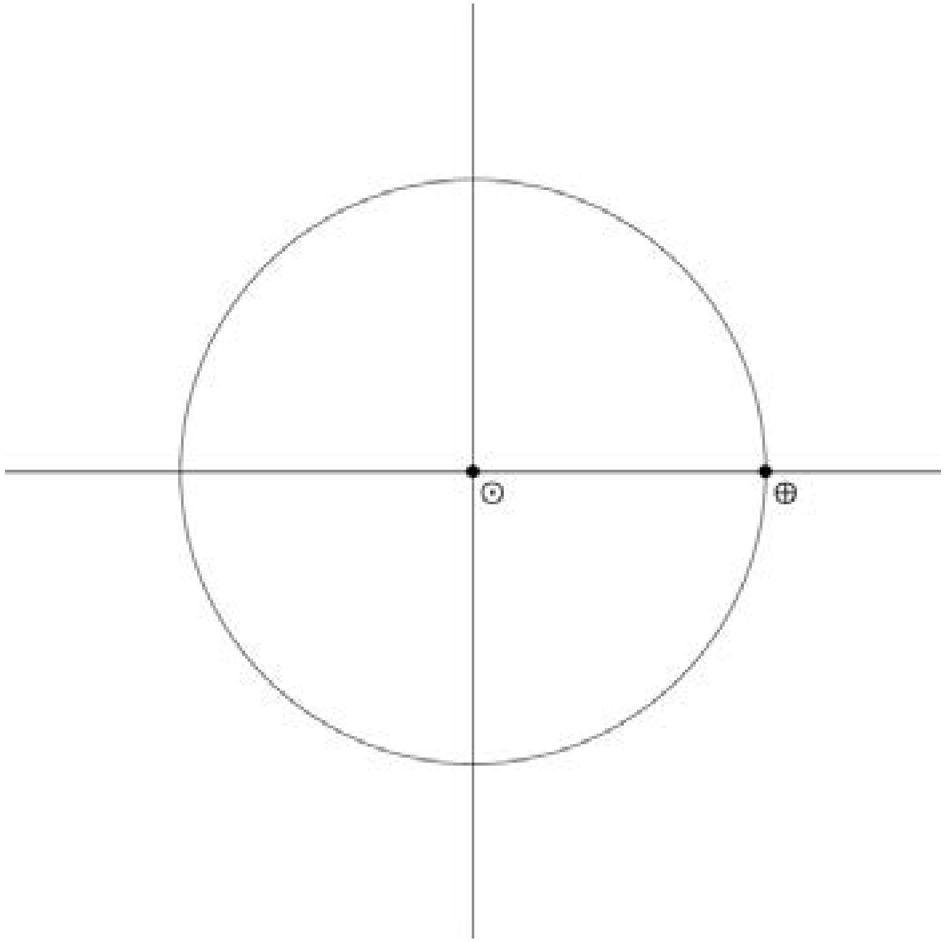
(b) On the answer sheet, mark the positions of the Sun, Earth and Mars at the moments of opposition and quadrature in the heliocentric system and determine the radius of the orbit of Mars in a.u. geometrically, without using Kepler's Laws. Show your method in the answer sheet.

(9 points)

(c) Derive the inclination of the orbit of Mars to the ecliptic. (3 points)

(Total: 20 points)

Answer Sheet



Planetarium Round 3: 'TRAPPIST-1'

Aliens have found out that Earth's astronomers discovered planets in the TRAPPIST-1 system by observing numerous transits. They have used their flying saucer (similar to the one you were in for the observation round) to take you to the 5th planet (designated f) of TRAPPIST-1, and have asked you to show them the methods Earthlings use to uncover the parameters of the system. A clock displaying time in Earth hours will be visible. The whole presentation lasts 520 h (1 s represents 1 h).

(Projection time 10 minutes)

Based on your observations (you can use the space on the last sheet for observing notes),

(a) determine the following quantities for the planet you are on (use Earth hours for the times): (7 points)

i. length of the sidereal day [h]	
ii. orbital period [h]	
iii. length of the 'solar' day [h]	
iv. circular orbit	YES / NO
v. obliquity (axial tilt)	

(b) and the following quantities for each planet b, c, d and e: (16 points)

	b	c	d	e
synodic period [h]				
maximum elongation [°]				

(c) calculate the orbital period in hours and the semi-major axis in *tau* (where 1 tau = "TRAPPIST-1f astronomical unit" = the semi-major axis of the orbit of TRAPPIST-1f) of each planet: (8 points)

	b	c	d	e
orbital period [h]				
semi-major axis [tau]				

(d) The term 'gravitational resonance' is used to describe the phenomenon when ratio of the orbital periods of two planets in a system is close to the ratio of two integers. The table below lists some of the resonances observed in the TRAPPIST-1 system. Find which pair(s) of planets correspond to each of the listed resonances if any.

(4 points)

Resonance	Pair of planets
3:2	
8:5	
5:3	
8:3	
4:1	
6:1	

(Total: 35 points)

Answers

Group Competition Answer Sheet

		A	N	D	
			I	N	D
			C	A	S
		D	O	R	
			L	Y	R
		C	A	M	
		A	U	R	
			S	E	X
			C	Y	G
			O	P	H
	P	U	P		
		T	E	L	
		E	R	I	
	C	V	N		
	L	M	I		
	L	A	C		
			U	M	A
			S	C	U

Group Competition Answer Sheet

A0-2

English (Official)

Arecibo Message

iOAA

Mars retrograde loop

(a) Minimal Earth-Mars distance [au]:

0.51

(b) Duration of retrograde motion [days]:

80

(c) Angular size of loop [°]:

22

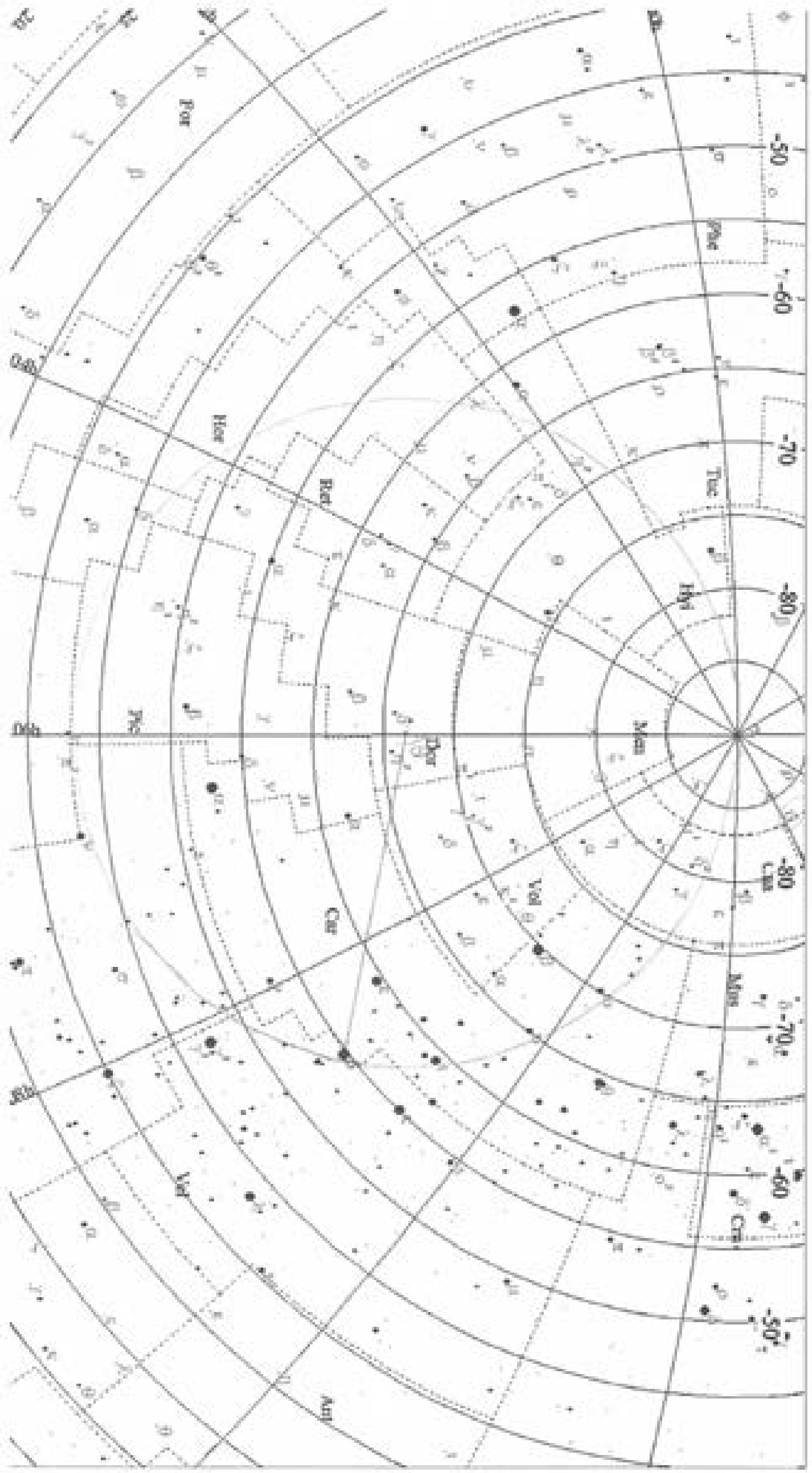
Southern Pole Star

Year: 20585

Saros Lunar eclipse

Date: 1st march, 2025

Hour: 18 UT ~~19 24h~~



Group Competition Answer Sheet

A0-3

English (Official)

Astrolabe: stars

Star	Bayer letter or name	Constellation	Right Ascension [h]	Declination [°]	Distance [ly]	Mark aliens' star
A	Altair	Aql	19.87	9	17.7	
B	Deneb	Cyg	20.73	46	2600	
C	Vega	Lyr	18.67	39	24	X
D	Rasalhague	Oph	17.60	13	49	
E	Enif	Peg	23,07	15	133	
F	Alioth	UMa	13	+50°	83	
G	Pollux	Gem	5,27	56	43	
H	Arcturus	Boo	15,67	26	75	
J	α-Com	Com	14,33	19	37	
K	Aldebaran	Tau	4,67	17	65	
L	Betelgeuse	Ori	5,47	7	250	
M	Alhena	Gem	5.93	8	548	
N	Rigel	Ori	5,20	-8	863	
O	Procyon	CMi	7,67	6	11	
P	Sirius	CMa	6,73	-17	8.6	
R	Spica	Vir	13,47	-10	250	
S	Alphard	Hya	9,53	-9	170	

Group Competition Answer Sheet

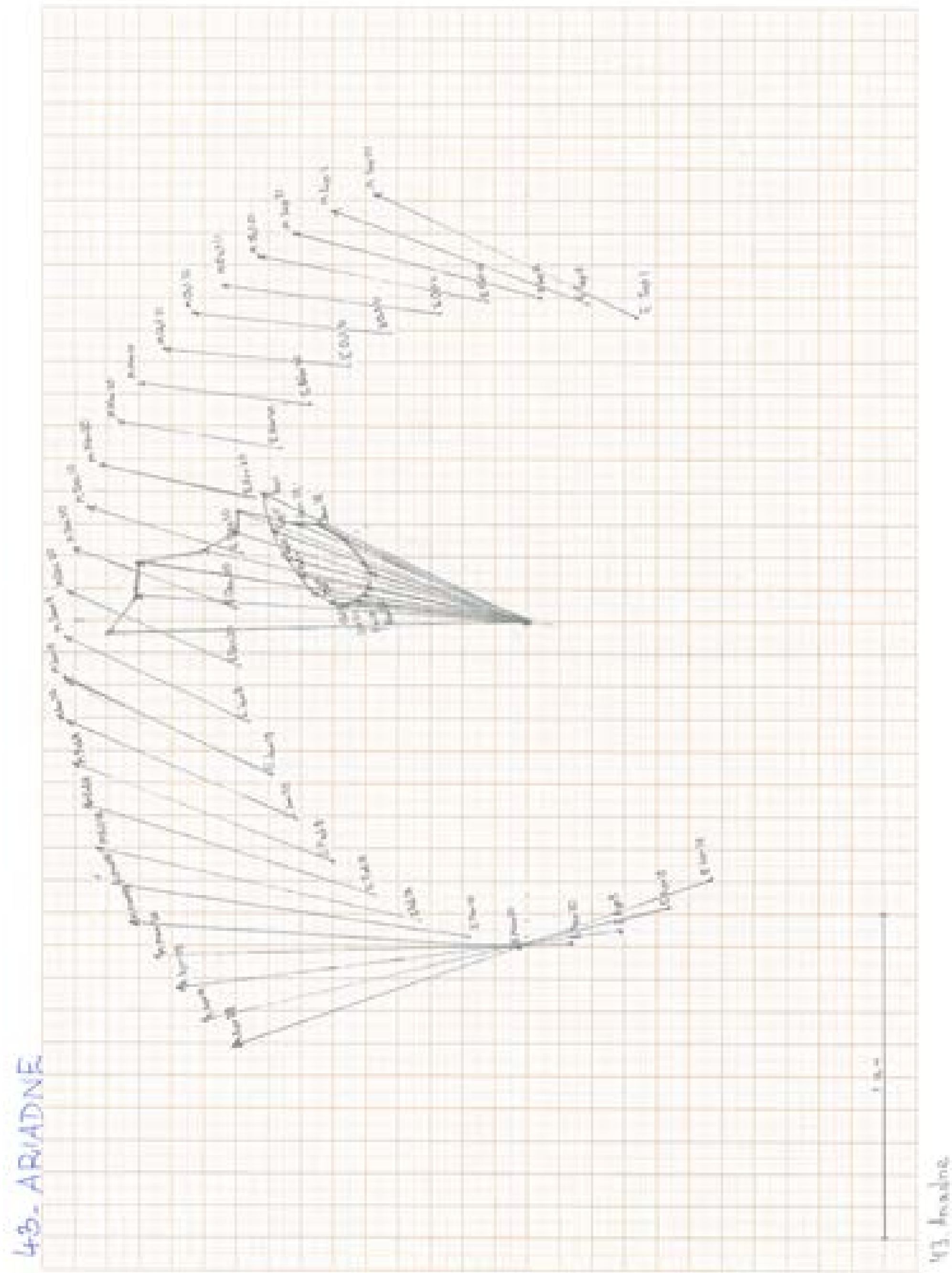
A0-4

English (Official)

Astrolabe: right ascension and declination of Sun, times of sunrise and sunset

	right ascension	declination
coordinates of the Sun	22h	−10°

	time of sunrise	time of sunset
19 February	6	17.2



Neptune

T.1 (6 pt)

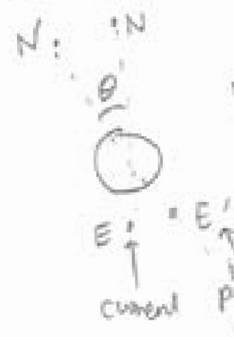
Solution:

We compute synodic period

$T_{neptune}(y) = a^{3/2}_{(AU)} = 164.[illegible]92113$

$T = \left(\frac{1}{T_{\oplus}} - \frac{1}{T_{♆}}\right)^{-1} = \left(\frac{1}{1} - \frac{1}{164.[illegible]}\right)^{-1} = 1.006101571\,y$

angle change (previous vs. current oppositions)



$\frac{1.006101571}{1} \times 360° \equiv 2.19656564° \pmod{360}$

We want a total change of 180° (autumn → spring), which corresponds to

$\frac{180°}{2.19656564°} = 81.94610565\,y \approx \underline{\underline{82}}$

so the year was $2024 - 82 = \boxed{1942}$

Magnetic Field

T.2 (5.0 pt) a) In circular motion of e^-

$$\frac{m_e v^2}{r} = (e)\cdot v\cdot B \Rightarrow r = \frac{m_e v}{eB}$$

frequency of rotation $\Rightarrow f = \frac{v}{2\pi r} = \frac{v\, eB}{2\pi\, m_e v} = \frac{eB}{2\pi m_e}$

frequency of rotation = frequency of emission = $\frac{c}{\lambda}$

$$\frac{eB}{2\pi m_e} = \frac{c}{\lambda} \Rightarrow B = \frac{2\pi m_e c}{\lambda e}$$

$$= 17.85 \times 10^{3}\,T \approx \boxed{2\times 10^{4}\,T}$$

b) plasma ⇒ free H^+ ⇒ $B \sim \frac{2\pi m_p c}{\lambda e}$

$$\lambda' \sim \frac{2\pi m_p c}{Be} \approx \boxed{1\,mm}$$

Theory

SGP-S2

A3-1

English (Official)

Microlensing

T.3 (5.0 pt)

$$I' - I = -2.5\log\left(\frac{F'}{F}\right)$$

$$\frac{F'}{F} = 10^{-\frac{2}{5}(I'-I)} = 10^{-\frac{2}{5}(15.2-20.4)} = 120.23$$

$$F' = 120.23\,F$$

Same quality: Collected light same

$$F' \cdot \pi\frac{D^2}{4} = F\pi\frac{D'^2}{4}$$

$$\frac{F'}{F} = \left(\frac{D'}{D}\right)^2 \qquad D' = \sqrt{\frac{F'}{F}}\,D = \sqrt{120.23} \times 8.2\,\mathrm{m}$$

$$= 89.913\,\mathrm{m}$$

$$= \underline{90\,\mathrm{m}}$$

Theory

CZE-S4

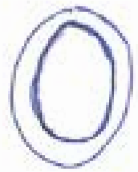
A4-1

Czech (Czechia)

Europa

A.4 (10.0 pt)

assuming $A \approx 1 \Rightarrow I_R \approx 0$



$$W_c = \frac{\lambda S \Delta T}{h}$$

$h = 6\,\mathrm{km}$

$r = 1561\,\mathrm{km}$

$$S = 4\pi r^2$$

$$W_c = \frac{\lambda 4\pi r^2 \Delta T}{h}$$

$$W_c = 2{,}64 \cdot 10^{12}\,\mathrm{W}$$

$6\,\mathrm{km} \ll 1561\,\mathrm{km}$

$\Rightarrow$ $M_i \ll M_E$

$$W_R = W_\oplus \cdot \frac{M_E}{M_\oplus}$$

$$P_\oplus = 70 \cdot 10^{-3}\,\mathrm{W\,m^{-2}}$$

$$W_\oplus = 4\pi r_\oplus^2 P_\oplus$$

$$W_R = 4\pi R_\oplus^2 P_\oplus \frac{M_E}{M_\oplus}$$

$$W_R = \underline{2{,}87 \cdot 10^{11}\,\mathrm{W}}$$

$$W_c \approx 10\,W_R$$

$\Rightarrow$ 90% come from tidal effects

V části (b) vyberte pravděpodobnější zdroj tepla
- RADIOAKTIVNÍ ROZPAD
- SLAPOVÉ SÍLY

Dark Energy

T.5 (12 pt)

Since dark energy is constant, it doesn't scale with redshift.

$\rho_{cr} = \rho_{m,0} + \frac{\varepsilon_\Lambda}{c^2}$; using $H_0 = 70\ km/s/Mpc$,

$H_0 = 70 \times 10^3 \frac{m}{s} \times 10^{-6} \frac{1}{pc} = 2.2683 \times 10^{-18} \frac{1}{s}$

$\varepsilon_\Lambda = c^2(\rho_{cr} - \rho_{m,0}) = c^2(9.2034 \times 10^{-27} - 2.8 \times 10^{-27})$

$\varepsilon_\Lambda = 5.7544 4773 3 \times 10^{-10}\ J\ m^{-3}$

$\varepsilon_\Lambda \approx 5.8\ J\,m^{-3}$ (2 s.f.)

Since $\rho_m \propto a^{-3}$ and $\rho_\Lambda = \frac{\varepsilon_\Lambda}{c^2} \propto a^0$ (Λ is constant)

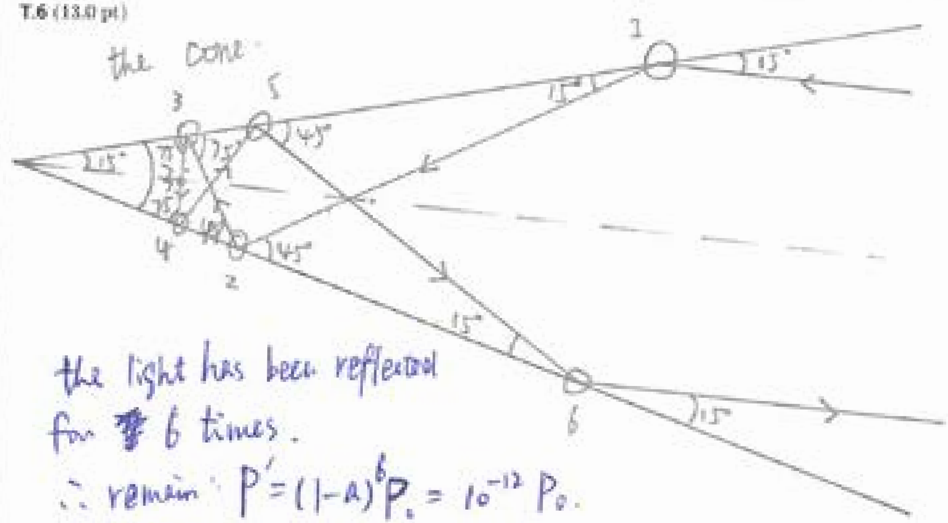
$\rho_m = \rho_{m,0}\, a^{-3} = \frac{\varepsilon_\Lambda}{c^2}$

$a = \sqrt[3]{\frac{\rho_{m,0}\, c^2}{\varepsilon_\Lambda}} = \frac{1}{1+z}$

$\therefore \underline{z = 0.31743} \approx 0.32$

辐射热测量计

T.6 (13.0 pt)



the light has been reflected for 6 times.

$\therefore$ remain: $P' = (1-A)^6 P_0 = 10^{-12} P_0$.

(as $T \approx 0K$)

where $P_0 = \frac{L_\odot}{4\pi R^2} = 340.1\ W/m^2$.

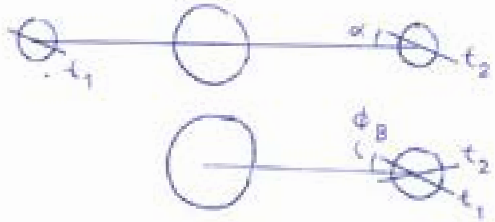
$\therefore P = P' = 3.401 \times 10^{-10}\ W/m^2$.

$\because P = \sigma T^4$

$\therefore T = \sqrt[4]{\frac{P}{\sigma}} = 0.28K$.

T.7 (20.0 pt)

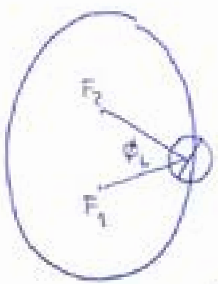
(a)



The equator of the moon can wobble up and down with

$\phi_B = \alpha = 6°41'$ //

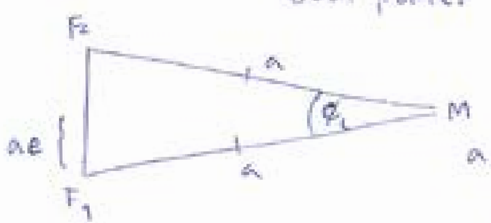
(b)



let observer be at F_1.

The maximum longtitudinal libration, ϕ_L is equal to the largest angle possible between F_1 and F_2.

which happen when e is maximum and moon is at equal distance from both point.



$MF_2 = MF_1 = a$

$$a \sin\frac{\phi_L}{2} = ae_{max}$$

$$\sin\frac{\phi_L}{2} = e_{max}$$

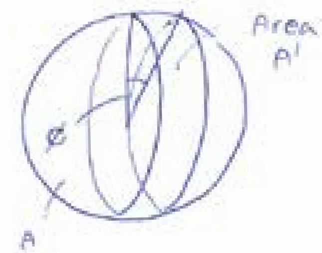
$$\phi_L = 2\sin^{-1} e_{max}$$

$$\phi_L = 2\sin^{-1}(0.064) = 7.3° \text{ //}$$

T.7 (cont.)

(c) approximate the increased area to be a ring with a thickness ϕ for ease of calculation

$$\phi = \frac{\phi_L + \phi_B}{2} = \frac{6°41' + 7.3°}{2} = 6.99 \approx 7.0°$$



Area A'

$$A' = 2\pi r_m \cdot r_m \phi \text{ [rad]}$$

$$= 2\pi r_m^2 \phi \text{ [rad]}$$

$$\cancel{= 2\pi (1737 \times 10^3)^2 \cdot \frac{7\pi}{180}}$$

$$\cancel{= 2.3 \times 10^{12}}$$

~~Frontal Area $A = 2\pi r_m^2$.~~

fraction of Area $f = \left(\frac{1}{2} + \frac{2\pi r_m^2 \phi \text{ [rad]}}{4\pi r_m^2}\right)$

$$= \frac{1}{2} + \frac{\phi \text{ [rad]}}{2}$$

$$= \frac{1}{2} + \frac{7\pi}{2 \cdot 180} = 0.56 \text{ //}$$

T.7 (cont.)

(d) Period

$$\frac{1}{P} = \frac{1}{m_{ano}} - \frac{1}{m_{dra}}$$

$$P = \left(\frac{1}{27.554550} - \frac{1}{27.212221}\right)^{-1} = 2190.35 \text{ days}$$

$$= \frac{2190.35}{27.321661} \text{ months}$$

$$= 80.17 \text{ months}$$

Neutrínók

T.8 (20.0 pt)

M_0 $e^- + p^+ \rightarrow n^0 + \nu$

$\Delta t = 0{,}01 s$

mass of a $^{56}_{26}Fe$ nucleus: $m_0 = 56$ atomic mass unit $= 9{,}3016 \cdot 10^{-26}$ kg

Number of atoms: $N = \frac{M_0}{m_0} = 2{,}1373 \cdot 10^{55}$

1/10 th of it is e^-, ~~the~~ another 1/10 th is p^+

$\Rightarrow$ number of neutrinos: $n = \frac{N}{10} = 2{,}1373 \cdot 10^{54}$

$d = 89 pc$

$$f = \frac{n}{4\pi d^2 \Delta t} = 2{,}7905 \cdot 10^{14} \frac{1}{m^2 s}$$

in the sun: ~~[illegible]~~ ~~[illegible]~~ ~~[illegible]~~

$$4p^+ \rightarrow {}^4_2He + 2e^+ + 2\nu + E$$

$$E = (4m_p c^2) - (m_{He} c^2 + 2m_e c^2) = 4{,}07 \cdot 10^{-12} J$$

(mass of neutrinos is negligible) number of proton-proton cycles

$L_0 = \frac{E}{\Delta t} = \frac{y E}{\Delta t} \Rightarrow y = \frac{L_0 \Delta t}{E} = 9{,}40 \cdot 10^{35} \Rightarrow$ $2y = 1{,}88 \cdot 10^{36} = n_0$

~~[illegible]~~ number of solar neutrinos ~~[illegible]~~

$$f = \frac{n_0}{\Delta t \cdot 4\pi d_0^2} =$$

$d_0 = 1 AU$

Neutrinos

T.8 (cont.)

$1 M_\odot$
$\Delta t = 0{,}01\,s$

$e^- + p^+ \to n^0 + \nu$

mass of ${}^{56}_{26}Fe$ nucleus:

$m_0 = 56 \cdot$ atomic mass unit $= 9{,}3 \cdot 10^{-26}\,kg$

Number of atoms: $n_a = \frac{M_\odot}{m_0} = 2{,}1 \cdot 10^{55}$

Number of ~~electrons~~ protons (26 / atom)

$n_p = 26 \cdot n_a = 5{,}5 \cdot 10^{56}$

number of protons in the end:

n_{p+n} {number of protons & ~~electrons~~ neutrons

$\frac{\text{number of protons \& neutrons}}{9} = n_p'$

$n_{p+n} = 56 \cdot n_a = 1{,}2 \cdot 10^{57} \Rightarrow n_p' \simeq 1{,}3 \cdot 10^{56}$

~~$\Delta n_p = n_p' - n_p$~~ $\Delta n_p = n_p - n_p' \approx 4{,}2 \cdot 10^{56}$

$\Rightarrow$ we got this many neutrinos

$d = 89\,pc$, $f = \frac{n}{\Delta t \cdot 4\pi d^2} = 5{,}5 \cdot 10^{16} \frac{1}{s\,m^2}$

neutrinos from Sun: $4p^+ \to {}^4_2He + 2e^+ + 2\nu + \varepsilon$

$\varepsilon = (4m_p c^2) - (m_{He} c^2 + 2m_e c^2) = 4{,}1 \cdot 10^{-12}\,J$

~~$L_\odot = \ldots$~~ $L_\odot = \frac{y\varepsilon}{\Delta t} \Rightarrow y = 9{,}3 \cdot 10^{35} \Rightarrow n_\odot = 2y = 1{,}9 \cdot 10^{36}$

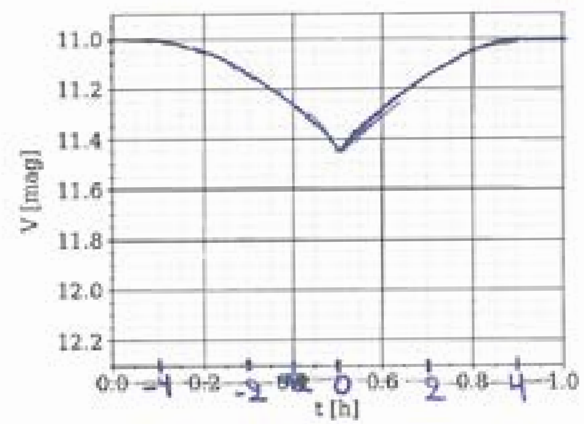
y: number of p-p cycles; $n_\odot$: number of neutrinos from Sun

$f_\odot = \frac{n_\odot}{4\pi d_\odot^2 \Delta t} = 6{,}8 \cdot 10^{14} \frac{1}{m^2 s} \Rightarrow f \approx 10^2 \cdot f_\odot$

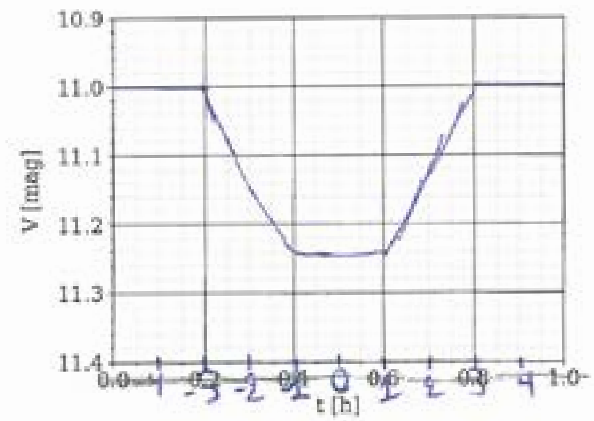
$d_\odot = 1\,AU$

Second eclipse

T.9 (20 pt)



Predicted lightcurve for system Bolek.



Predicted lightcurve for system Lolek.

T.9 (cont.)
Your calculations: In the Bolek system, minimum brightness only lasts for a single moment, so the two stars have the same radius $R=R_1=R_2$. Also, the eclipse lasts for $\Delta t_B = t_{end} - t_{beg} = 4h-(-4h) = 8h$. Let us suppose that the star which passes in front of the other one has an apparent magnitude equal to m_1 and the other one m_2. During the eclipse minimum brightness, the system has apparent magnitude m_1 and apparent brightness L_1, whereas m_{tot} and $L_{tot} = L_1 + L_2$, when both stars are visible. Thus,

$m_1 - m_{tot} = 2{,}5\log\frac{L_{tot}}{L_1} = 2{,}5\log\left(\frac{L_1+L_2}{L_1}\right) \Leftrightarrow 2{,}5\log\left(1+\frac{L_2}{L_1}\right) = 12{,}2 - 11 = 1{,}2 \Leftrightarrow$
$\log\left(1+\frac{L_2}{L_1}\right) = 0{,}48 \Leftrightarrow \frac{L_2}{L_1} = 2{,}02$. ~~Moreover, if both stars have a velocity equal to u_B, then $2u_B = \frac{2R_1+2R_2}{\Delta t_B} \Leftrightarrow \Delta t_B = \frac{R_1+R_2}{u_B} = \frac{2R}{u_B}$~~

In the secondary eclipse, the minimum brightness is L_2, so:
$m_2 - m_{tot} = 2{,}5\log\frac{L_{tot}}{L_2} = 2{,}5\log\left(1+\frac{L_1}{L_2}\right) = 2{,}5\log\left(1+\frac{1}{2{,}02}\right) = 0{,}45 \Leftrightarrow m_2 = 11 + 0{,}45 = 11{,}45$
~~The secondary eclipse also lasts for $\Delta t_B' = \frac{2R_1+2R_2}{2u_B} = \frac{2R}{u_B} = \Delta t_B = 8h$~~
~~Moreover, if both stars have a velocity equal to u_B in both eclipse~~ Moreover, if the stars have linear velocities u_1 and u_2 each one, then, in both eclipses the one star is moving with an apparent velocity of $u_{\sigma\chi} = |u_1 - u_2|$. $(\vec{u}_1 \uparrow\downarrow \vec{u}_2)$
During the primary eclipse, the first star covers a distance of $r = 2R_1 + 2R_2 = 4R$ in relation to the second one, so
$\Delta t_B = \frac{4R}{u_{\sigma\chi}} = \frac{4R}{|u_1-u_2|}$. If the secondary eclipse lasts for $\Delta t_B'$, then, due to the second star covering again a distance of $r = 2R_1 + 2R_2 = 4R$ with a velocity $u_{\sigma\chi} = |u_1 - u_2|$.
Consequently, $\Delta t_B' = \frac{4R}{|u_1-u_2|} = \Delta t_B = 8h$
Moreover, the secondary eclipse minimum brightness lasts again

T.9 (cont.) just for a moment, since the ~~star~~ second star covers the first one again only for a moment, because of $R_1 = R_2 = R$.
In the Lolek system, the eclipse lasts for $\Delta t_1 = 3h - (-3h) = 6h$, whereas the total eclipse $\Delta t_1' = 1h - (-1h) = 2h$
Let us suppose that the star 3 passes in front of the star 4 during the primary eclipse. If they have velocities u_3 and u_4, the star 3 has a velocity $u_{\sigma\chi} = |u_3 - u_4|$ in relation with the star 4. The eclipse lasts for the χρονικό διάστημα it needs to cover a distance equal to $d = 2R_3 + 2R_4$, whereas the total eclipse lasts for the χρονικό διάστημα it needs to cover a distance $d' = 2R_3 - 2R_4$ if it is bigger or $d' = 2R_4 - 2R_3$ in case it is smaller.
In the first case, $u_{\sigma\chi} = \frac{d}{\Delta t_1} = \frac{d'}{\Delta t_1'} \Rightarrow \frac{2(R_3+R_4)}{2(R_3-R_4)} = \frac{6h}{2h} \Leftrightarrow \frac{R_3+R_4}{R_3-R_4} = 3$
~~$\Leftrightarrow 1 + \frac{R_4}{R_3} = 3 \Leftrightarrow R_4 = 2R_3 > R_3$, impossible~~ $R_3 = 2R_4$
Thus, only the second case is acceptable. Thus $u_{\sigma\chi} = \frac{d}{\Delta t} = \frac{d'}{\Delta t'} \Leftrightarrow$
$\frac{2(R_3+R_4)}{2(R_4-R_3)} = \frac{6h}{2h} \Leftrightarrow \frac{R_3+R_4}{R_4-R_3} = 3 \Leftrightarrow R_3 + R_4 = 3R_4 - 3R_3 \Leftrightarrow 2R_4 = 4R_3 \Leftrightarrow$
$R_4 = 2R_3$ (1)
Thus, if m' the maximum apparent magnitude of the system during the eclipse, then: $m' - m_{tot} = 2{,}5\log\frac{L_{tot}}{L'} =$
$= 2{,}5\log\frac{L_3+L_4}{L_3 + \frac{\pi R_4^2 - \pi R_3^2}{\pi R_4^2}\cdot L_4} \overset{(1)}{=} ~~2{,}5\log\frac{L_3+L_4}{L_3+\frac{3}{4}L_4}~~$

T.9 (cont.)

$$= 2,5\log\frac{L_3+L_4}{L_3+\frac{\pi 4R_3^2-\pi R_3^2}{4\pi R_3^2}\cdot L_4} = 2,5\log\frac{L_3+L_4}{L_3+\frac{3}{4}L_4} = 2,5\log\frac{4(L_3+L_4)}{4L_3+3L_4}$$

$$\Leftrightarrow 2,5\log\frac{4L_3+4L_4}{4L_3+3L_4} = 11,24-11 = 0,24 \Leftrightarrow \frac{4L_3+4L_4}{4L_3+3L_4} =$$

$$= 10^{\frac{0,24}{2,5}} = 1,25 \Leftrightarrow 4L_3+4L_4 = 5L_3+3,75L_4 \Leftrightarrow 0,25L_4 = L_3 \Leftrightarrow$$

$$L_4 = 4L_3 \quad (2)$$

Because of $R_4 = 2R_3 > R_3$, during the secondary total eclipse, ~~the appa~~ only the star 4 will be visible and, consequently, the apparent ~~brighten~~ brightness of the system will be equal to $L = L_4$.

Thus, $m_{max} - m_{tot} = 2,5\log\frac{L_{tot}}{L_4} = 2,5\log\frac{L_4+L_3}{L_4} = 2,5\log\left(1+\frac{L_3}{L_4}\right) \overset{(2)}{=}$

$= 2,5\log\left(1+\frac{1}{4}\right) = 2,5\log 1,25 = 0,24 \Leftrightarrow m_{max} = 11,24\ m$.

However, this time, the total eclipse will last for $\Delta t_2' = \frac{2L}{u_x}$

Aldebaran

T.10 (25 pt)

a) $\theta = \frac{\left(\frac{31.5}{2} - 0.52\right)\cdot 60}{206265}$ $\quad d_{\oplus - e} = 0.27R_{\oplus}$

$\phi = 44.44 + \Delta\phi$

$\Delta\phi = \sin^{-1}(0.27 + \sin 22.07) - 22.07° = 20.08°$

$\therefore \phi_1 \approx 64.52°$

b) $T = \frac{2R_e}{\left(\frac{2\pi d_{\oplus - e}}{T_e} - \frac{2\pi R_{\oplus}}{T_{ord}}\right)} = 1.18$ hours

c) $\omega = \frac{v_{relative}}{d}$, $d = 380200$ from → 384400

→ $\omega = 26.07$ arcmin/hour

d) From triangle inequality, $|v_{rel}| < |v_{moon}| + |-v_{observer}|$,
$|v_{rel}| > ||v_{moon}| - |v_{observer}||$

$\therefore v_{rel} \in ((1023.16 - 203.26), (1023.16 + 203.26))$

$\omega_{min} = 26.07$ '/hour from before

Variation of d negligible compared to v, so ignore

$d_{max} = \sqrt{384400^2 + 6378^2 - 2\times 384400\times 6378\cos 131.5611} = 388661$ km

→ $\omega_{max} = 39.1$ arcmin/h

X-ray emission from galaxy clusters

T.11 (30.0 pt)

a) $n_e = \frac{M}{(m_{He}+10m_H)} \times (2+10)$

$n_H = \frac{M}{(m_{He}+10m_H)} \times 10$

$n_{He} = \frac{M}{(m_{He}+10m_H)} \times 1$

$N = \frac{n}{V}$

$L_H + L_{He} = 6\times10^{-41} N_e T^{\frac{1}{2}} V (N_H Z_H^2 + N_{He} Z_{He}^2)$

$= 6\times10^{-41} \frac{n_e}{V} T^{\frac{1}{2}} \cancel{V} \left(\frac{n_H}{\cancel{V}} Z_H^2 + \frac{n_{He}}{\cancel{V}} Z_{He}^2\right)$

$= 6\times10^{-41} \frac{T^{\frac{1}{2}}}{V} n_e (n_H Z_H^2 + n_{He} Z_{He}^2)$

$= 6\times10^{-41} \frac{T^{\frac{1}{2}}}{V} \left(\frac{M}{(m_{He}+10m_H)}\right)^2 (2+10)$
$(10\times1^2 + 1\times2^2)$

$= L_{tot}$

T.11 (cont.)

$\left(\frac{M}{(m_{He}+10m_H)}\right)^2 = \frac{L_{tot} V}{6\times10^{-41} T^{\frac{1}{2}} \times 168}$

$M = \sqrt{\frac{L_{tot}\cdot\frac{4}{3}\pi R^3}{6\times10^{-41} T^{\frac{1}{2}} \times 168}} \times (m_{He}+10m_H)$

$= 3.05\times10^{43}$ kg

$= 1.54\times10^{13} M_\odot$

b) $d_{mfp} = \frac{1}{N_e \cdot \sigma}$

$= \frac{1}{\frac{M\times(2+10)}{(m_{He}+10m_H)} / \left(\frac{4}{3}\pi R^3\right) \cdot 6.65\times10^{-29}}$

$= 1.48\times10^{25}$

$= 478$ Mpc

Theory

CAN-S2

A11-3

English (Official)

T.11 (cont.)

c) $E = 3k_B T$

$= 3(1.38)\times10^{-23})(2.73)$

$= 1.13\times10^{-22}$ J

d) $V_{rms} = \sqrt{\frac{3k_B T}{m_e}}$ m_e = mass of electron

$T = 80\times10^{6}$ K

$= 6.03\times10^{7}$ m/s

$E' = E\,\frac{(1+\frac{V_{rms}}{c})}{(1-\frac{V_{rms}}{c})}$

$= 1.50E$

$= 1.70\times10^{-22}$ J

Theory

TUR-S4

A12-1

Turkish (Türkiye)

DART

T.12 (40.0 pt)

(a)

$m_s v_s = (m_s + m)|\Delta v|$

$\Delta v = -8.228\times10^{-4}$ m/s

orbital velocity of Dimorphos $v = \sqrt{\frac{GM}{r}}$

$v - \Delta v = \sqrt{\frac{GM}{r'}}$ $r' = r + \Delta r = \frac{GM}{(v-\Delta v)^2}$

$P = \frac{2\pi r}{v} = 2\pi\sqrt{\frac{r^3}{GM}}$ $\frac{P^2}{r^3} = \frac{4\pi^2}{GM}$

$v = \frac{2\pi r}{P} = \frac{2\pi}{P}\left(\frac{P^2 GM}{4\pi^2}\right)^{1/3}$

$v = 0.176$ m/s

$P' = 2\pi\sqrt{\frac{r'^3}{GM}}$

$\frac{1}{(v-\Delta v)^3} \approx \frac{1}{v^3}\left(1+\frac{3\Delta v}{v}\right)$

$P' - P = \frac{2\pi}{\sqrt{GM}}\left(r'^{3/2} - r^{3/2}\right)$

$\frac{GM^{3/2}}{(v-\Delta v)^3} - \frac{GM^{3/2}}{v^3} = \frac{3\Delta v}{v^4}GM^{3/2}$

$\Delta P = 2\pi GM \times \frac{3\Delta v}{v^4} = -10$ min //

(b)

$\Delta P' = 2\pi GM \times \frac{3\Delta v'}{v^4} = -33$ min $\Delta v' = \Delta v \times 3.3$

$m_s v_s = -p + \underbrace{(m_s' + m)}_{\approx m}|\Delta v|$

$p = -m_s v_s + m|\Delta v'| = 8.1\times10^{6}$ kg $\frac{m}{s}$

$\frac{p}{p_{Di}} = \frac{p}{mv} = 0.01$

(c) $\Delta v' = 3.3\Delta v = -2.7$ mm s^{-1} //

Theory

PER-S2

A13-1

Spanish PER (Peru)

LISA

T.13 (45.0 pt)

$D = 2{,}34\ Kpc = 7{,}22124 \cdot 10^{16}\ m$

$P = 414{,}79\,s \rightarrow f = \frac{2}{P} = 4{,}82147 \cdot 10^{-3}$ ✓

3ra ley de kepler: $M_T = M_1 + M_2$

$$\frac{P^2}{a^3} = \frac{4\pi^2}{GM_T} \rightarrow P^2 = \frac{4\pi^2}{GM_T} a^3$$

$$\rightarrow 2P\frac{dP}{dt} = \frac{12a^2\pi^2}{GM_T}\underbrace{\frac{da}{dt}}_{-\frac{64}{5}\frac{G^3}{c^5}\frac{M_1M_2(M_1+M_2)}{a^3}}$$

$$\rightarrow P\frac{dP}{dt} = \frac{6\pi^2}{GM_T}\cdot\left(-\frac{64}{5}\frac{G^3}{c^5}\frac{M_1M_2(M_1+M_2)}{a}\right)$$

:

Theory

PER-S2

A13-2

Spanish PER (Peru)

T.13 (cont.)

$$\frac{dP}{dt} = \frac{-384\pi^2 G^2 M_1M_2}{5c^5 a P} \ ; \ a = \sqrt[3]{\frac{P^2 GM}{4\pi^2}} = \frac{P^{2/3}\cdot G^{1/3}M^{1/3}}{2^{2/3}\cdot\pi^{2/3}}$$

$$\rightarrow \underbrace{\frac{dP}{dt}}_{-7{,}49\cdot10^{-4}\,s/año \;\; -2{,}3734\cdot10^{-14}} = \underbrace{\frac{-384\pi^{8/3}G^{5/3}\cdot 2^{2/3}}{5\cdot P^{5/3}\cdot c^5}}_{-5{,}07247\cdot10^{-61}\,kg^{-5/3}}\cdot\underbrace{\frac{M_1M_2}{M_T^{1/3}}}_{M^{5/3}}$$

$$\rightarrow M^{5/3} = 4{,}679\cdot10^{49}\ kg^{5/3}$$

$$\boxed{M = 6{,}34\cdot10^{29}\ kg}$$ ✓

Theory

PER-S2

A13-3

Spanish PER (Peru)

T.13 (cont.)

$$\rightarrow h = \frac{2(GM)^{5/3}(\pi f)^{2/3}}{c^4 D}$$

$$\rightarrow h = 1{,}0784 \cdot 10^{-22}$$

$$f = 4{,}822 \cdot 10^{-3}\ Hz$$

$$T_{obs} = 1{,}262 \cdot 10^{8}\ s$$

$$S = h\sqrt{f\,T_{obs}}$$

$$\therefore S = 8{,}41345 \cdot 10^{-20}$$

$$S_{min}(f = 4{,}822 \cdot 10^{-3}) \in [10^{-21};\ 2 \cdot 10^{-21}]$$

$$\rightarrow S > S_{min} \therefore$$

→ a) Yes; it's possible

Theory

PER-S2

A13-4

Spanish PER (Peru)

T.13 (cont.)

$$\frac{P^2}{a^3} = \frac{4\pi^2}{GM_T} \ ; \ M_T = \frac{(M_1 M_2)^3}{M^5}$$

$$\rightarrow \frac{P^2 \cdot G \cdot M^{-5}}{4\pi^2} = a^3/(M_1^3 M_2^3) \ ; \ a = \frac{R_1}{0{,}139}$$

from the graph 1:

$$\rightarrow R_1 = 0{,}015 M_1 + 7{,}2 \cdot 10^{-3} \quad \left(\begin{matrix} R_1 : R_\odot \\ M_1 : M_\odot \end{matrix}\right)$$

in International Sistem:

$$R_1 = 5{,}249 \cdot 10^{-24}\ \frac{m}{kg} M_1 + 5{,}009 \cdot 10^{6}\ m$$

$$\rightarrow a/(M_1 \cdot M_2) = 1{,}416 \cdot 10^{-52}\ m \cdot kg^{-2}$$

$$\rightarrow \frac{3{,}776 \cdot 10^{-23}}{M_2} + \frac{3{,}604 \cdot 10^{7}}{M_1 M_2} = 1{,}416 \cdot 10^{-52}$$

T.13 (cont.)

$$\left.\begin{aligned} 3{,}776\cdot10^{23} &= A \\ 3{,}604\cdot10^{7} &= B \\ 1{,}416\cdot10^{-32} &= F \end{aligned}\right\} \quad \frac{A}{M_2} + \frac{B}{M_1 M_2} = F$$

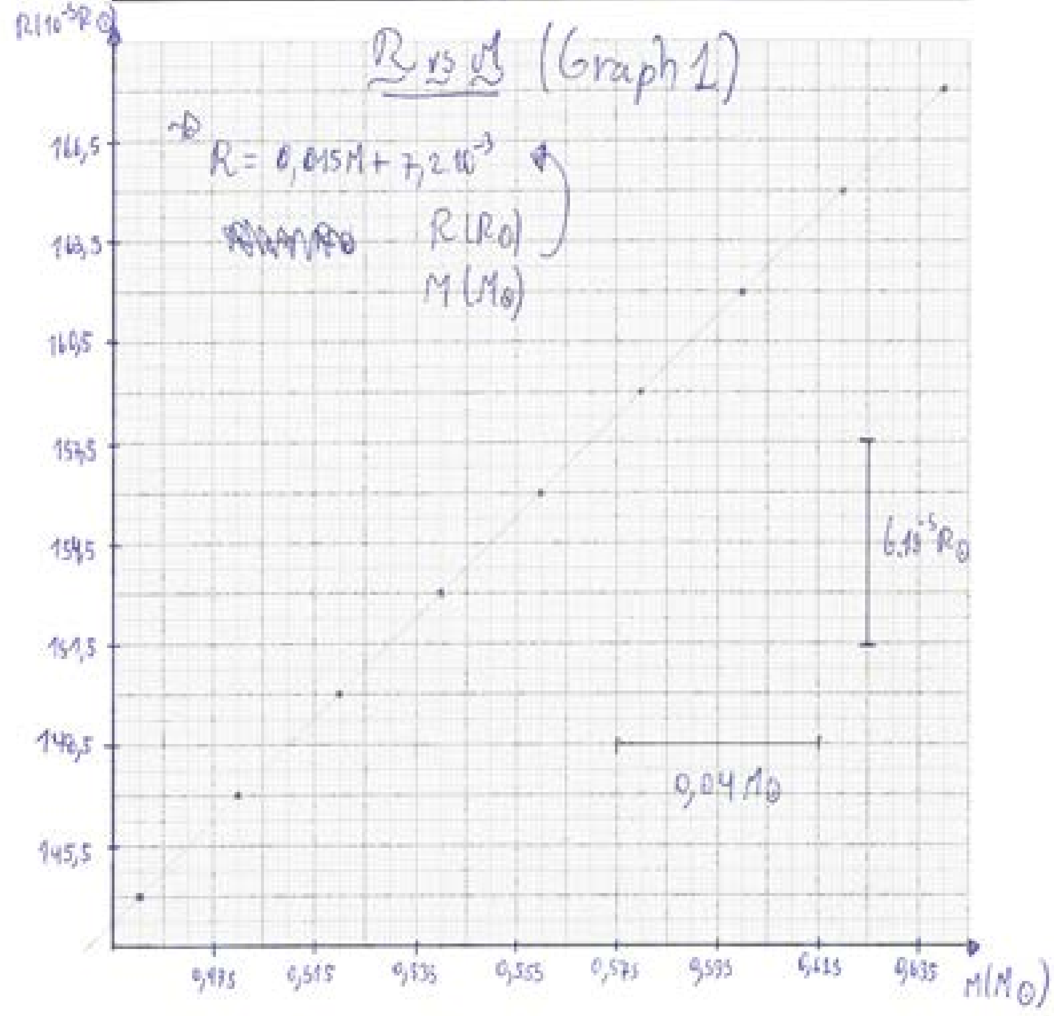
$$\rightarrow A + \frac{B}{M_1} = F \cdot M_2 \rightarrow M_2 = \frac{A}{F} + \frac{B}{F M_1}$$

$$\rightarrow M_1 \cdot M_2 = \frac{A M_1}{F} + \frac{B}{F} \; ; M_1 + M_2 = M_1 + \frac{A}{F} + \frac{B}{F M_1}$$

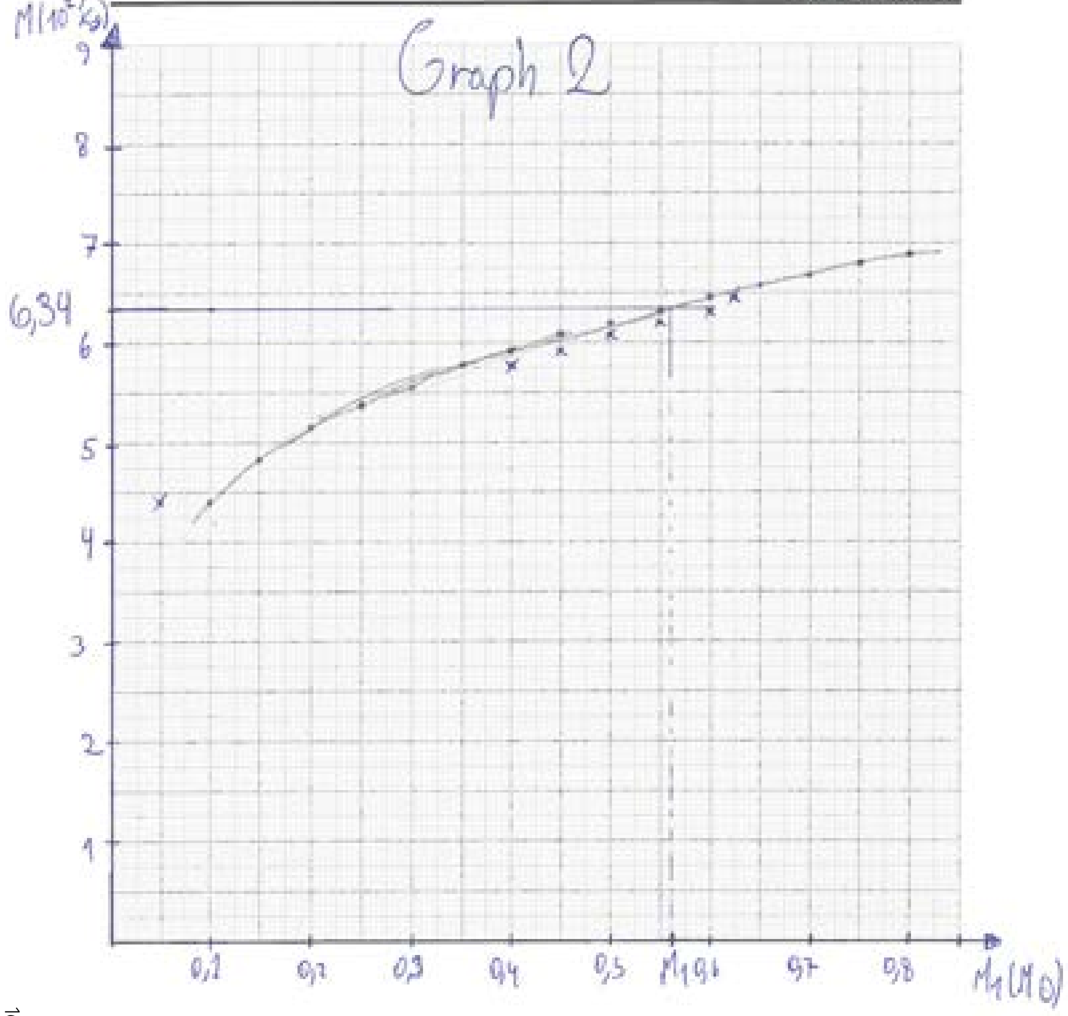
$$\rightarrow M = \frac{\left(\frac{A M_1}{F} + \frac{B}{F}\right)^{3/5}}{\left(M_1 + \frac{A}{F} + \frac{B}{F M_1}\right)^{1/5}}$$; from the graph 2:

C

$$\boxed{\begin{aligned} M_1 &= 0{,}56\, M_\odot = 1{,}11\cdot10^{30}\,\mathrm{Kg} \\ \rightarrow M_2 &= 0{,}249\, M_\odot = 4{,}95\cdot10^{29}\,\mathrm{Kg} \end{aligned}}$$



Mass



Zákryt planetky (15 bodů)

Výpočty založené na obrbitálních elementech předpovídají, že planetka zakryje hvězdu HD 163390 po dobů 21 s, přičemž maximum zákrytu (střed času, co hvězdu nevidíme) nastane ve 23:03:32 UT. Efemeridy však nejsou dokonalé a předpověď se může mýlit až o 20 s v čase a o 10 s v době trvání.

Na základě svých pozorování zjistěte skutečný čas středu zákrytu a dobu trvání zákrytu. K identifikaci hvězdy použijte mapu 1 a následující souřadnice:

HD 163390 RA: $17^h\ 58^m\ 05^s$ DEC: $-18°\ 50'\ 46.14''$

Mapa a obloha jsou ve stejné epoše.

A.1 (15 pt)

Čas středu zákrytu	± nejistota	Celkové trvání zákrytu	± nejistota
$23^h\,03^m\,39,8^s$	$\pm 0,1^s$	16,9 s	± 0,1 s

Start $23^h : 3' : 31,36''$
End 23 3 47,20 ⇒ Duration 16,9 → my media time is approximately ±0,1 s ⇒ error is in my case 0,1 s
→ Middle :

استارلینک (۱۵ نمره)

در یک میدان دید مشابه با سوال ۱، یک 'قطار' از ماهواره‌های استارلینک نزدیک به نصف النهار $17^h\ 59^m$ و در حدود ساعت $23:05\ UT$ ظاهر می‌شود. گذر آنها حدود ۳ دقیقه طول می‌کشد.

می‌توانید فرض کنید که مرکز میدان دید در ارتفاع 20° قرار دارد و فاصله ماهواره‌ها از سطح زمین $400\ km$ است. مدار ماهواره‌ها دایروی و فاصله آنها از یکدیگر مساوی است. می‌توانید فرض کنید مسیر ماهواره‌ها عمود بر افق است.

(a) سرعت زاویه‌ای هر ماهواره در آسمان شبیه سازی شده را از دید ناظر به دست آورید.

(b) اختلاف زمان عبور دو ماهواره متوالی را بدست آورید. مسیر عبور ماهواره‌ها را روی شکل نقشه ۱ مشخص کنید.

(c) سرعت زاویه ای ماهواره ها را از دید ناظر با استفاده از روابط تئوری و اطلاعات داده شده در سوال به دست آورید.

(d) فاصله بین دو ماهواره متوالی را بر حسب کیلومتر تخمین بزنید.

ثوابت:

$$R_\oplus = 6378\ km\ \ M_\oplus = 5.972 \times 10^{24}\ kg\ \ G = 6.674 \times 10^{-11} m^3 kg^{-1} s^{-2}$$

(15 pt.) **A.2**

a) The angle between two satelite is : $0^\circ 25'$

time to travel this angle: 2^s

$$\rightarrow \dot{a} = \frac{-0^\circ 25'}{2^s} = 0{,}2083\ \frac{deg}{s}$$

b) about 2 seconds.

Observation Round

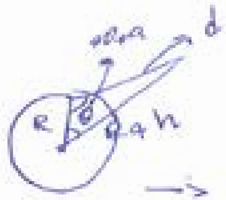
IRI-S1

A2-3

Persian (Iran)

(cont.) A.2

c)



$$\frac{Cs\,a}{R+h} = \frac{Cs\,(a+\theta)}{R}$$

$$\rightarrow Cs(a+\theta) = \frac{R}{R+h} Cs\,a$$

$$\rightarrow \theta = 7{,}84^\circ$$

$$\rightarrow -(\dot{a}+\dot{\theta})\,\mathrm{Sin}(a+\theta) = \frac{-R}{R+h}\,\dot{a}\,\mathrm{Sin}\,a$$

$$\rightarrow \dot{\theta}\,\mathrm{Sin}\,(a+\theta) = \dot{a}\left(\frac{R\,\mathrm{Sin}\,a}{R+h} - \mathrm{Sin}\,(a+\theta)\right)$$

$$\rightarrow \dot{a} = \frac{\dot{\theta}\,\mathrm{Sin}\,(a+\theta)}{\frac{R\,\mathrm{Sin}\,a}{R+h} - \mathrm{Sin}(a+\theta)}$$

$$\dot{\theta} = \sqrt{\frac{GM}{(R+h)^3}} \rightarrow \dot{a} = -0{,}2085\ \frac{deg}{s}$$

Observation Round

IRI-S1

A2-4

Persian (Iran)

(cont.) A.2

d) angular seperation of two satelite in observator's sky := α

$$\alpha = |\dot{a}|\Delta t \quad , \quad |\dot{a}| = 0{,}2085\ \frac{deg}{s}$$
$$\Delta t = 2\ sec$$

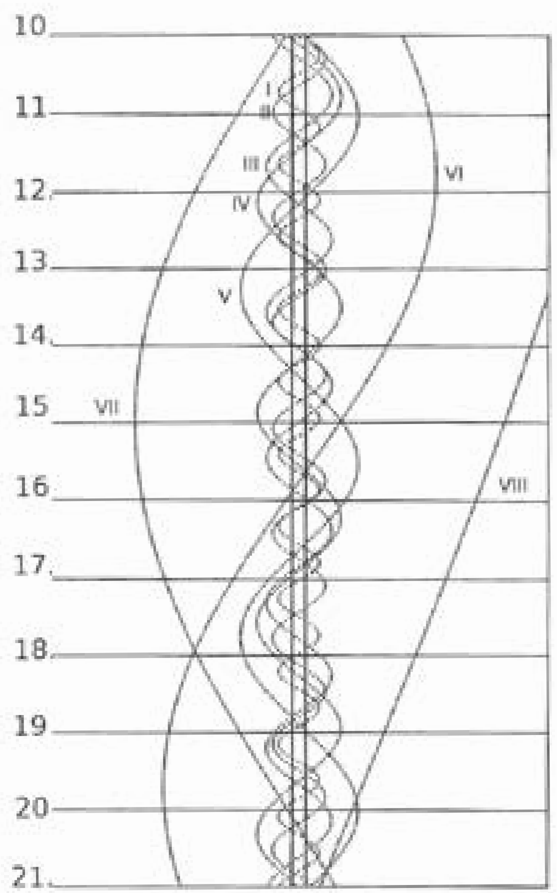
$$\rightarrow \alpha = 0{,}417\ deg$$

$$\rightarrow d = \left(R^2 + (R+h)^2 - 2R(R+h)\,Cs\,\theta\right)^{1/2}$$
$$= 9{,}839 \times 10^3\ m$$

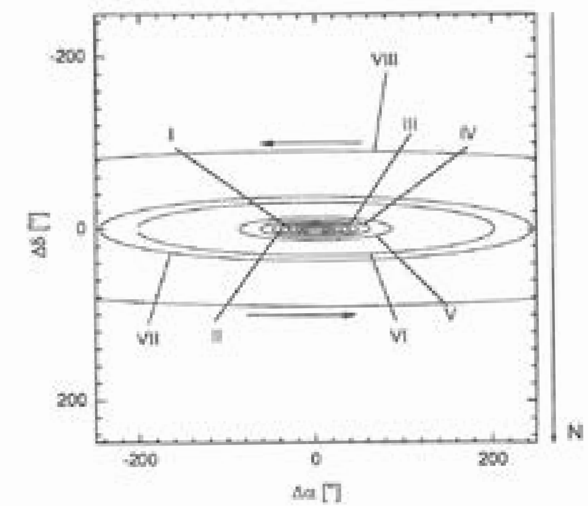
$$\rightarrow l = \alpha d = 7{,}16\ km$$

Các Mặt trăng của hành tinh (10 điểm)

Màn hình sẽ hiển thị hình ảnh của một trong các hành tinh của Hệ Mặt trời. Xác định các mặt trăng và đánh dấu chúng trên phiếu trả lời (bạn có thể sử dụng biểu đồ vị trí của mặt trăng).



Biểu đồ vị trí mặt trăng. Các số bên trái cho biết các ngày của tháng 8 năm 2023 (lúc nửa đêm theo giờ UT).



Biểu đồ vị trí mặt trăng: số mặt trăng (I, II,...) như trên.

Số	Tên	Cấp sao
I	Mimas	13.0
II	Enceladus	11.8
III	Tethys	10.4
IV	Dione	10.6
V	Rhea	9.9
VI	Titan	8.5
VII	Hyperion	14.4
VIII	Japetus	11.0

A.3 (10 pt)
Đánh dấu vị trí của 5 mặt trăng bất kỳ bằng một dấu chấm và ký hiệu chúng bằng số của chúng (I, II, ...)

Supernova (10 poin)

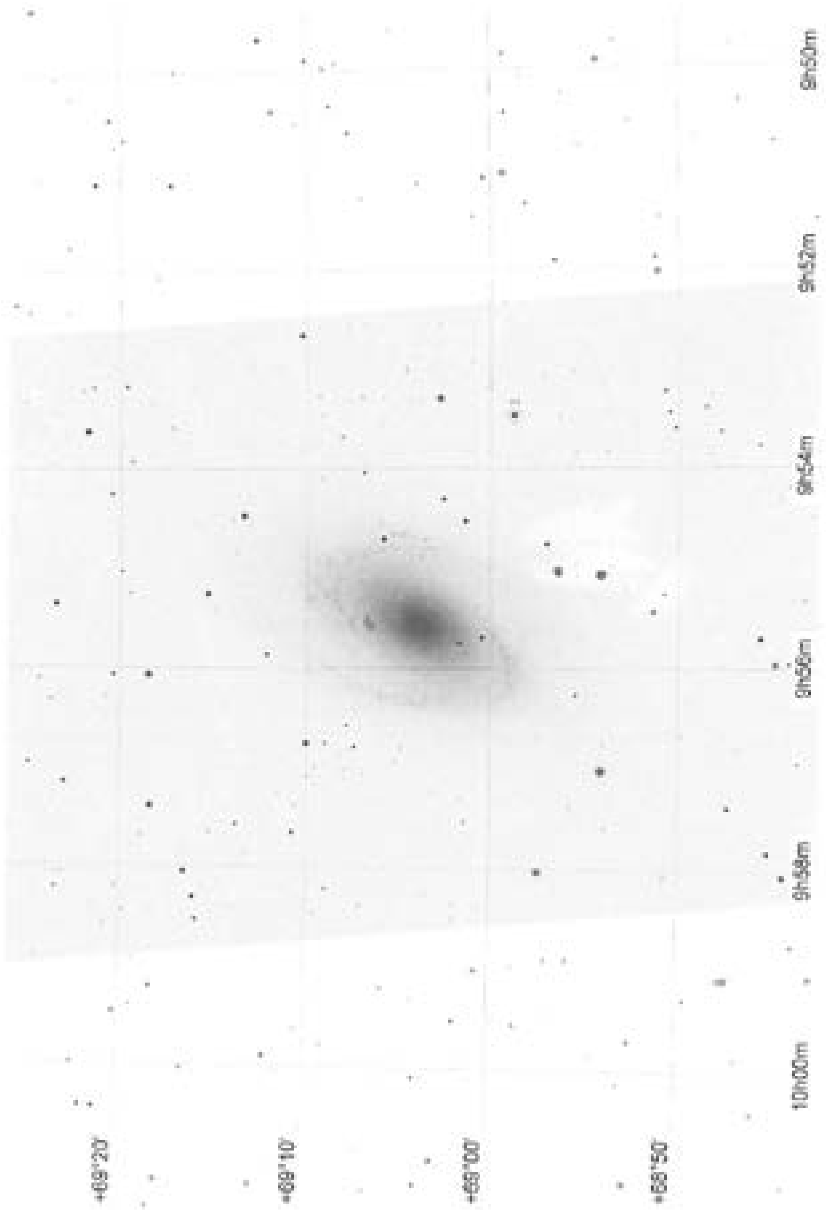
Layar lain akan menyajikan sebuah galaksi dan nova terang (mag < 11) yang sebelumnya tidak tampak. Perkirakanlah koordinat asensio rekta (RA) dan deklinasi (DEC) Nova ini, dan perkirakan magnitudonya. Kamu boleh gunakan Map no 2 yang dilengkapi koordinat bintang dan magnitudonya.

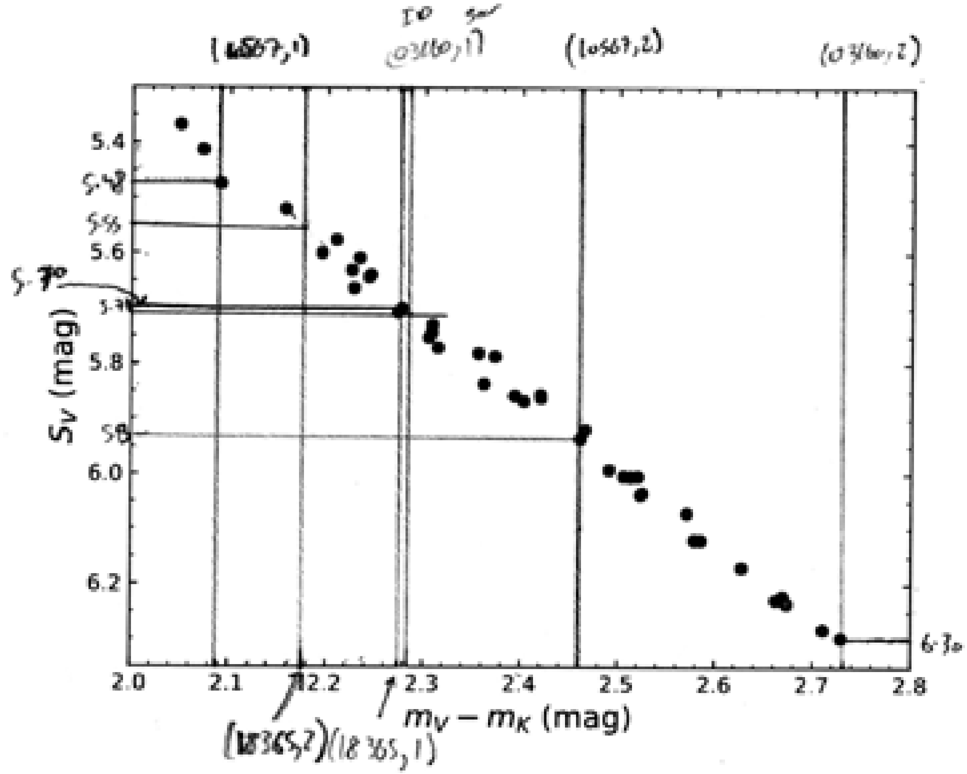
A.4 (10 pt)

Asensio Rekta	Deklinasi	Perkiraan magnitudo
$9^h55^m33^s$	$+69°4'50''$	10.2

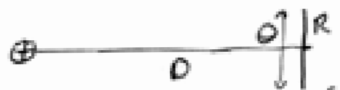
	Star	RA J2000			DEC J2000			mag
		h	m	s	deg	m	s	
1	BD+69 541	9	55	2.7	68	56	22	10.3715
2	Gaia DR2 1070097015969362560	9	53	27.9	68	58	43	11.2281
3	Gaia DR2 1070144329329069568	9	53	17.7	69	2	48	10.0785
4	Gaia DR2 1070453463896461952	9	57	0.8	68	54	6	8.9146
5	Gaia DR2 1070455010084791680	9	55	25.9	68	51	21	11.4722
6	Gaia DR2 1070459408131195776	9	58	1.6	68	57	24	10.20[illegible]
7	Gaia DR2 1070467070352960512	9	55	4.4	68	54	5	9.1615
8	Gaia DR2 1070467379590606976	9	55	1	68	56	22	10.4605
9	Gaia DR2 1070468169864590208	9	54	45.3	68	58	59	12.2087
10	Gaia DR2 1070469475534553728	9	55	41.4	69	0	30	11.7856
11	Gaia DR2 1070470265808536448	9	55	45	69	1	46	11.2905
12	Gaia DR2 1070470609404512512	9	55	33.2	69	3	55	13.3020
13	Gaia DR2 1070472293033168640	9	54	53.2	69	3	48	14.2845
14	Gaia DR2 1070473186386370176	9	54	42.3	69	5	52	11.6033
15	Gaia DR2 1070476794158817152	9	57	38.8	69	10	44	12.6348
16	Gaia DR2 1070476858581360384	9	56	47.1	69	7	27	12.7259
17	Gaia DR2 1070476897238038272	9	56	34.4	69	7	51	13.6578
18	Gaia DR2 1070477240835421440	9	56	44.8	69	9	1	13.7626
19	Gaia DR2 1070477305257957888	9	56	45.1	69	10	1	11.4495
20	Gaia DR2 1070522934990509312	9	55	15.4	69	15	19	12.0436
21	Gaia DR2 1070523111086221568	9	54	26.6	69	13	22	11.0704
22	HD85458	9	55	4	68	54	6	9.1615

Map 2


9h50m
9h52m
9h54m
9h56m
9h58m
10h00m
+69°20'
+69°10'
+69°00'
+68°50'


(10567,2)
5.48
5.56
5.70
5.8
6.30
(18365,2)
(18365,1)
5.4
5.6
5.8
6.0
6.2
S_V (mag)
2.0
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
$m_V - m_K$ (mag)

DA.1 (50.0 pt)



$\theta = \dfrac{2R}{D}.$

Star in LMC radius R

D = distance to LMC.

To find M_V and M_K of each star in binary:

$L_{2V}/L_{1V} = \gamma_{LV}$ (given in table).

$L_{2V} = \gamma_{LV} L_{1V}$

$L_{1+2V} = L_{1V}(1+\gamma_{LV})$ and $L_{1+2} = L_2\left(1+\frac{1}{\gamma_{LV}}\right)$

$10^{-0.4(V_{1+2}-V_1)} = \dfrac{L_{1+2V}}{L_{1V}} = \underline{1+\gamma_{LV}}$

$-2.5\log_{10}(1+\gamma_{LV}) = V_{1+2} - V_1$

$\underline{V_1 = V_{1+2} + 2.5\log_{10}(1+\gamma_{LV}) = M_{V1}}$

$V_2 = V_{1+2} + 2.5\log_{10}\left(\dfrac{L_{1+2}}{L_2}\right) = \underline{V_{1+2} + 2.5\log_{10}\left(1+\dfrac{1}{\gamma_{LV}}\right)} = M_{V2}$

Likewise:

$K_1 = K_{1+2} + 2.5\log_{10}(1+\gamma_{LK}) = M_{K1}$

$\underline{K_2 = K_{1+2} + 2.5\log_{10}\left(1+\dfrac{1}{\gamma_{LK}}\right)} = M_{K2}$

DA.1 (cont.) Then: find S_V from $M_V - M_K$ for each star.

$S_V = M_V + 5\log_{10}(\theta_{mas})$: θ_{mas} is angular diameter in mas.

$\dfrac{S_V - M_V}{5} = \log_{10}(\theta_{mas})$

$\underline{\theta_{mas} = 10^{\frac{S_V - M_V}{5}}}$ from which $\underline{\theta_{rad} = \dfrac{\theta_{mas}(\pi)}{1000 \times 3600 \times 180} = \dfrac{2R}{D}}$

For ID: OGLE-LMC-ECL-03160:

$\gamma_{LV} = 2.80$ $\gamma_{LK} = 4.23$ $V_{1+2} = 16.73$ $K_{1+2} = 14.10$

$M_{V1} = 16.73 + 2.5\log_{10}(1+2.80) = \underline{18.179}$

$M_{V2} = 16.73 + 2.5\log_{10}\left(1+\frac{1}{2.8}\right) = \underline{17.062}$

$\underline{M_{K1} = 15.896}$

$\underline{M_{K2} = 14.330}$ (similarly).

$(M_V - M_K)_1 = 18.179 - 15.896 = \underline{2.283}$

$\underline{S_{V1} = 5.71 \pm 0.8\%}$

$(M_V - M_K)_2 = 17.062 - 14.330 = \underline{2.732}$

$\underline{S_{V2} = 6.30 \pm 0.8\%}$

$\theta_{mas1} = 10^{\frac{5.71 - 18.179}{5}} = \underline{3.21 \times 10^{-3}\ \text{mas}}$

DA.1 (cont.)

$error_1 = \frac{d}{dS_v}\left(10^{\frac{S_v - m_v}{5}}\right) \times \frac{S_v \times 0.8}{500}$

$= 10^{\frac{S_v - m_v}{5}} \frac{\ln 10}{5} \, S_v \times \frac{0.8}{500}$

$= 10^{\frac{S_v - m_v}{5}} \frac{S_v (0.8) \ln 10}{500}$

$error_1 = 3.71 \times 10^{-3} \times \frac{5.71 \times 0.8 \times \ln 10}{500} = \underline{6.75 \times 10^{-5}\,\text{mas}}$

$\theta_1 = \frac{\pi}{6.48 \times 10^8} \theta_{mas_1} = 1.55 \times 10^{-11}\,\text{rad} \pm \frac{6.75 \times 10^{-5} \pi}{6.48 \times 10^8}$

$= \underline{(1.55 \times 10^{-11} \pm 3.27 \times 10^{-13})\,\text{rad}}$

$R_1 = 17.03 R_\odot$, $\theta_{rad} = \frac{2R}{D}$ $\quad \sigma_x = error\ in\ x$

$D = \frac{2R}{\theta_{rad}}$

$\sigma_D = \sigma_\theta \left|\frac{d}{d\theta}\left(\frac{2R}{\theta}\right)\right|$

$= \sigma_\theta \left(\frac{2R}{\theta^2}\right)$

$D_1 = \frac{37.06 R_\odot}{1.55 \times 10^{-11}} = \underline{49.5\,\text{kpc}}$

$\sigma_{D_1} = \pm 1.05\,\text{kpc} \Rightarrow D_1 = \underline{49.54 \pm 1.05\,\text{kpc}}$

DA.1 (cont.) $\theta_{mas2} = 10^{\frac{6.3 - (7.44)}{5}} = 7.04 \times 10^{-3}\,\text{mas}$

$\sigma_{\theta_2} = \theta_{mas2} \times \frac{0.8 \ln 10\, S_v}{500} = \pm 1.63 \times 10^{-7}\,\text{mas}$

$\theta_2 = (3.41 \times 10^{-11} \pm 7.92 \times 10^{-13})\,\text{rad}$

$R_2 = 37.42 R_\odot$

$D_2 = \frac{2(37.42) R_\odot}{(3.41 \times 10^{-11})(2.08 \times 10^{19})} = \underline{49.47\,\text{kpc} \pm 1.15\,\text{kpc}}$

For ID: 10567 $\quad V_{l2} = 16.15 \quad K_{l2} = 13.83 \quad \sigma_{lv} = 1.41 \quad \sigma_{lK} = 1.49$

$m_{v1} = 16.15 + 2.5 \log_{10}(1 + 1.41) = \underline{17.105}$

$m_{v2} = \underline{16.732} \quad m_{K1} = \underline{15.019} \quad m_{K2} = \underline{14.272}$

$(m_v - m_K)_1 = \underline{2.086} \quad (m_v - m_K)_2 = \underline{2.460}$

$S_{v1} = \underline{5.48} \quad S_{v2} = \underline{5.93}$

$\theta_{mas1} = \underline{4.73 \times 10^{-3} \pm 9.55 \times 10^{-5}}$ $\quad \theta_{mas2} = \underline{6.91 \times 10^{-3} \pm 1.51 \times 10^{-4}}$

$\theta_1 = 2.29 \times 10^{-11}\,\text{rad} \quad \theta_2 = 3.35 \times 10^{-11}\,\text{rad}$ and $\sigma_D = \underline{D \frac{\sigma_\theta}{\theta}}$

$R_1 = 24.6 R_\odot \quad R_2 = 36.64 R_\odot$

$D_1 = \underline{48.43 \pm 0.98\,\text{kpc}} \quad D_2 = \underline{49.31 \pm 1.08\,\text{kpc}}$

ID 18365: $\quad V_{l2} = 16.27 \quad K_{l2} = 14.01 \quad \sigma_{lv} = 0.266 \quad \sigma_{lK} = 0.188$

$m_{v1} = \underline{16.473} \quad m_{K1} = \underline{14.197} \Rightarrow m_{v1} - m_{K1} = \underline{2.276}$

$m_{v2} = \underline{18.189} \quad m_{K2} = \underline{16.012} \quad m_{v2} - m_{K2} = \underline{2.177}$

DA.1 (cont.) $S_{v1} = 5.70$ $\qquad$ $S_{v2} = 5.55$

$\theta_{mas1} = 7.00\times10^{-3} \pm 1.47\times10^{-4}$ mas $\qquad$ $\theta_{mas2} = 2.97\times10^{-3} \pm 6.06\times10^{-5}$ mas

$\theta_1 = 3.39\times10^{-11}$ rad $\qquad$ $\theta_2 = 1.44\times10^{-11}$ rad

$R_1 = 37.30 R_\odot$ $\qquad$ $R_2 = 15.94 R_\odot$

$D_1 = 49.61 \pm 1.04$ kpc $\qquad$ $D_2 = 49.91 \pm 1.02$ kpc

Weighting D by variance σ_D^2.

$$\langle D\rangle = \frac{\left(\frac{D_1}{\sigma_{D1}^2} + \frac{D_2}{\sigma_{D2}^2} + \dots + \frac{D_N}{\sigma_{DN}^2}\right)}{\left(\frac{1}{\sigma_{D1}^2} + \frac{1}{\sigma_{D2}^2} + \frac{1}{\sigma_{D3}^2} + \dots + \frac{1}{\sigma_{DN}^2}\right)}$$

$$\langle D\rangle = \frac{\left(\frac{49.54}{1.05^2} + \frac{49.47}{1.15^2} + \frac{48.43}{0.98^2} + \frac{49.31}{1.08^2} + \frac{49.61}{1.04^2} + \frac{49.91}{1.02^2}\right)}{\left(\frac{1}{1.05^2} + \frac{1}{1.15^2} + \frac{1}{0.98^2} + \frac{1}{1.08^2} + \frac{1}{1.04^2} + \frac{1}{1.02^2}\right)}$$

$\langle D\rangle = 49.36\,\text{kpc} \pm \sigma_D$: $\sigma_D = \frac{1}{N}\sqrt{\frac{1}{\sigma_1^2} + \frac{1}{\sigma_2^2} - \frac{1}{\sigma_N^2}} = 0.39$ kpc

$\langle D\rangle = (49.36 \pm 0.39)$ kpc

Isolated black hole

DA.2 (75 pt)

(a)

$$\sqrt{\frac{4GM}{c^2}\frac{D_S - D_L}{D_S D_L}} = \boxed{1.294\times10^{-8}\ \text{rad}}$$

$$= \boxed{2.669\ \text{mas}}$$

(b)

$$\theta_c = \frac{A_+\theta_+ + A_-\theta_-}{A_+ + A_-}$$

$$= \frac{\frac{1}{4}\left(\frac{u^2+2}{u\sqrt{u^2+4}} + 1\right)\left(u + \sqrt{u^2+4}\right) + \ -\ -\ \theta_E}{\frac{u^2+2}{u\sqrt{u^2+4}}}$$

$$= \frac{\theta_E}{4}\left[\frac{2(u^2+2)u}{u\sqrt{u^2+4}} + 2\sqrt{u^2+4}\right]\left(\ \right)^{-1}$$

$$= \frac{\theta_E}{2}\left(\cancel{2}u + \frac{u(u^2+4)}{u^2+2}\right) = \frac{\theta_E}{2}\left(\frac{2u^3+6u}{u^2+2}\right)$$

DA.2 (cont.)

Thus,

$$\theta_c = \boxed{\theta_E\left(\frac{u^3+3u}{u^2+2}\right)}$$

(c)

$$\Delta\theta = \theta_c - u\theta_E = \theta_E\left(\frac{u^3+3u}{u^2+2} - u\right)$$

$$= \boxed{\theta_E\left(\frac{u}{u^2+2}\right)}$$

At $\boxed{u=0,\ \Delta\theta = 0}$ as expected.

(d) see A2-7

(e) Applying linear reg.

$$\nu_E = -6.304\times10^{-3}\ \text{mas/day}$$

and $\delta\nu_E = \dfrac{\nu_E}{r}\sqrt{\dfrac{1-r^2}{n-2}} = 1.6\times10^{-4}$ mas/day

Similarly $\nu_N = -9.713\times10^{-3}$ mas/day

$$\delta\nu_N = 3.4\times10^{-4}\ \text{mas/day}$$

DA.2 (cont.)

So, $\boxed{\nu_E = -2.30\pm0.06\ \text{mas/yr}}$

and $\boxed{\nu_N = -3.55\pm0.12\ \text{mas/yr}}$

(e) Looking at the plot, it is more linear for the last ~~3~~6 data points as it is past the characteristic time while it is within θ_E. So, we apply linear reg w/ the last ~~3~~6 points. We get

(w/ 6 points) $\nu_E = -6.53\times10^{-3}$ mas/day

$$\delta\nu_E = \frac{\nu_N}{r}\sqrt{\frac{1-r^2}{n-2}} = 1.3\times10^{-4}\ \text{mas/day}$$

And (w/ 3 points)

$$\nu_N = -9.19\times10^{-3}\ \text{mas/day}$$

$$\delta\nu_N = 1.7\times10^{-4}\ \text{mas/day}$$

DA.2 (cont.)

Conversely,

$$\boxed{\begin{aligned} v_E &= -2.38 \pm 0.05 \text{ mas/yr} \\ v_N &= -3.45 \pm 0.06 \text{ mas/yr} \end{aligned}}$$

(f) We have

$$\theta(t) = v_{prop} t + \Delta\theta(t) + \theta_0$$

So,

$$\theta_0 + \Delta\theta(t) = \theta(t) - v_{prop} t$$

u	HJD-2450000	E pos (mas)	N pos (mas)
0.0089	5765.2	2.59 ± 0.13	7.31 ± 0.16
0.414	5885.2	2.99 ± 0.12	6.39 ± 0.24
1.687	6179.7	3.18 ± 0.14	5.45 ± 0.18
1.752	6195.8	3.71 ± 0.36	5.54 ± 0.77
2.655	6426.2	3.31 ± 0.21	5.15 ± 0.12
3.339	6587.7	3.35 ± 0.07	5.70 ± 0.40
4.832	6956.6	3.25 ± 0.25	[illegible] ± 0.27
9.037	7795.2	3.44 ± 0.12	6.06 ± 0.17

See A2-8 for plot

DA.2 (cont.)

(g) We have

$$u(t) = \frac{1}{247 \text{ days}}(t - 2455763)$$

And

$$\theta_{shifted} = \theta_E\left(\frac{u}{u^2+2}\right) + \theta_0$$

So we graph do lin reg for

$$\theta_{shifted} \text{ vs. } \frac{u}{u^2+2}$$

(f) cont'd We also shift the data so that the first val is approx 0, and square

$u/(u^2+2)$	u	$\Delta\theta + \theta_0$
0.004		0
0.191		1.00 ± 0.2
0.348		1.95 ± 0.3
0.346		2.09 ± 0.8
0.292		2.28 ± 0.2
0.254		1.78 ± 0.4
0.191		1.65 ± 0.5
0.108		1.51 ± 0.2

DA.2 (cont.)

(g) cont'd. We apply linear regression, and get

$$\theta_E = 5.35$$

$$\delta\theta_E = \frac{\theta_E}{r}\sqrt{\frac{1-r^2}{N-2}} = 1.2$$

$$\boxed{\theta_E = 5.3 \pm 1.2 \text{ mas}}$$

(h)

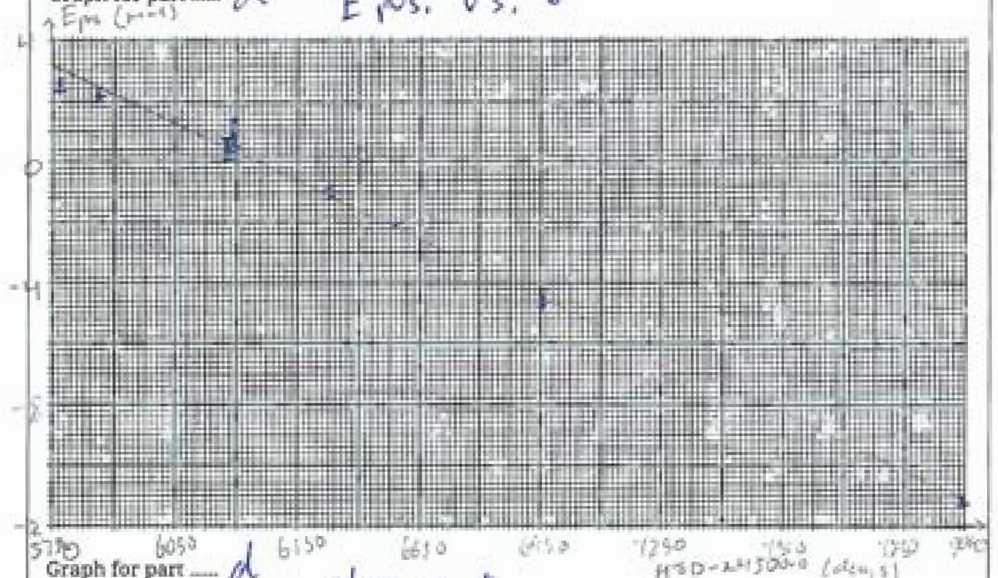
$$\theta_E = \sqrt{\frac{4GM}{c^2}\left(\frac{1}{D_l} - \frac{1}{D_s}\right)}$$

$$= \sqrt{\frac{4GM}{c^2}\left(\pi_l - \pi_s\right)}$$

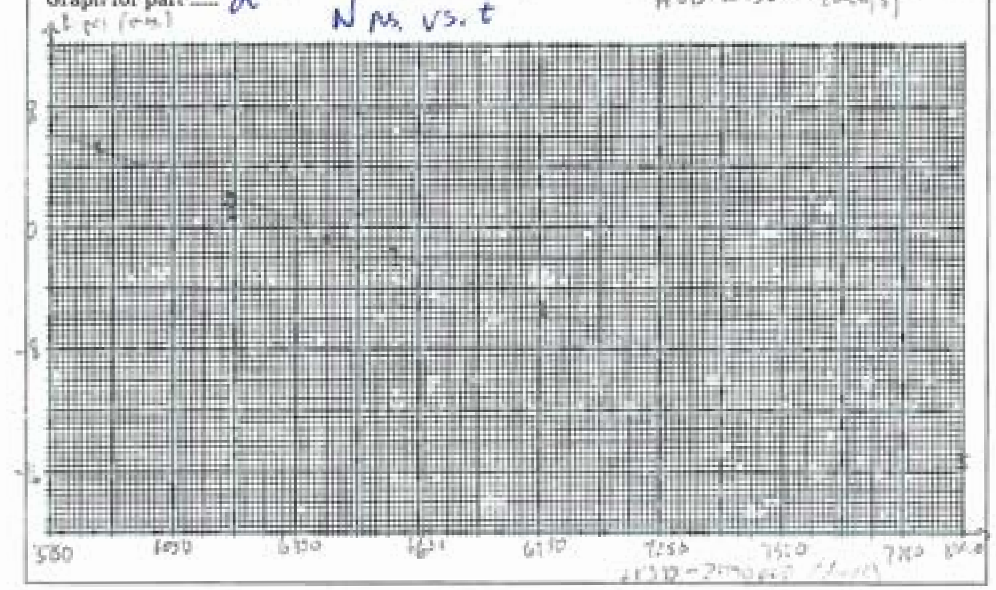
$$\Rightarrow \frac{4GM}{c^2}(\pi_l - \pi_s) = \theta_E^2 \frac{\pi_l - \pi_s}{\pi_E}$$

So, $M = \frac{c^2}{4G}\frac{\theta_E}{\pi_E} = \boxed{(9.1 \pm 1.8)\times 10^{19}\text{ kg}}$

Graph for part ...... d   E pos. vs. t



Graph for part ...... d   N pos. vs. t



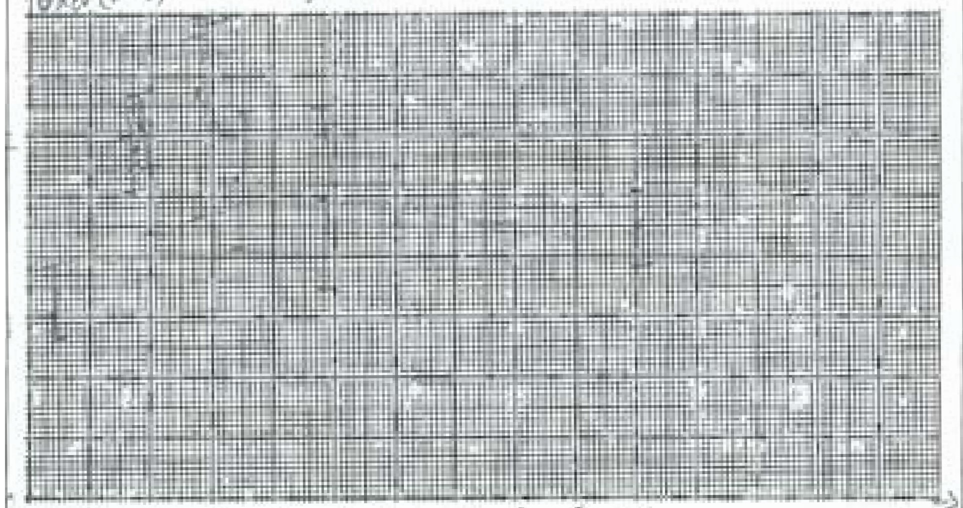
Data Analysis

USA-S3

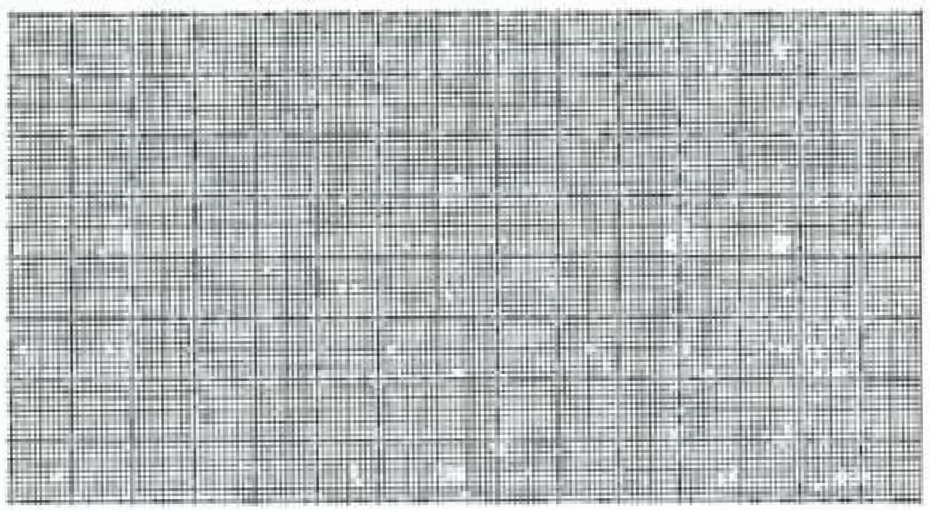
A2-8

English (Official)

Graph for part ...... (5) Δθ vs. u



Graph for part ......



Planetarium Round

BRA-S2

A1-1

Brazilian Portuguese (Brazil)

Conhecimento do Céu (20 pontos)

O projetor irá apresentar o céu visto próximo do equador (0°N, 19°L). A rotação do céu será interrompida por cerca de 2 minutos para a parte (a), depois começará a rodar para as partes (b) e (c). Os objetos para as partes (b) e (c) irão ser projetados simultaneamente.

(a) Uma chuva de meteoros será visível no céu. Determine a constelação do radiante e estime as suas coordenadas de ascensão reta e declinação.

1.a (3 pt)

Constelação	ascensão reta	declinação
Aquarius	23h	−10°

(b) Identifique quais das seguintes estrelas variáveis visíveis no céu estão em estado de brilho baixo (escreva 'DIM') ou alto (escreva 'BRIGHT'). A magnitude média mostrada no atlas e a faixa de magnitude são fornecidas para cada estrela.

1.b (8 pt)

Nome	mag. atlas	faixa de mag.	DIM / BRIGHT
γ Cas (*Cih*) √	2	1.6 — 3.0	Bright
δ Cep √	4	3.5 — 4.4	Bright
μ Cep (*Erakis*) √	4	3.4 — 5.1	Bright
β Per (*Algol*) √	2	2.2 — 3.4	Bright
o Cet (*Mira*)	3.5	2.0 - 10.1	Bright
χ Cyg	4.5	3.3 - 14.1	Bright
L_2 Pup	4.5	2.6 — 6	Bright
δ Sco (*Dschubba*)	2	1.6 — 2.3	Dim

(c) Identifique as constelações cujas bordas estão marcadas e dê suas abreviaturas IAU.

Planetarium Round

BRA-S2

A1-2

Brazilian Portuguese (Brazil)

1.c (9 pt)

Cet, Mus, Sct, CrA, Tuc, Hor, CrA

Planetarium Round

ROU-S5

A2-1

Romanian (Romania)

Marte retrograd

Proiectorul va afişa planeta Marte în mişcare faţă de stelele fixe pe parcursul unui sezon de vizibilitate (1.5 ani), pornind de la răsăritul heliacal, ales astfel încât Marte să fie la latitudinea ecliptică maximă la opoziţie.

De asemenea, ecliptica va fi afişată, marcată cu poziţiile Soarelui pe parcursul unui an şi cu data curentă. Soarele va fi mereu sub orizont.

Perioada sinodică a lui Marte = 780 de ani

(timp de proiecţie: 10 minute)

(a) Găseşte următoarele mărimi fizice:

2.a (8 pt)

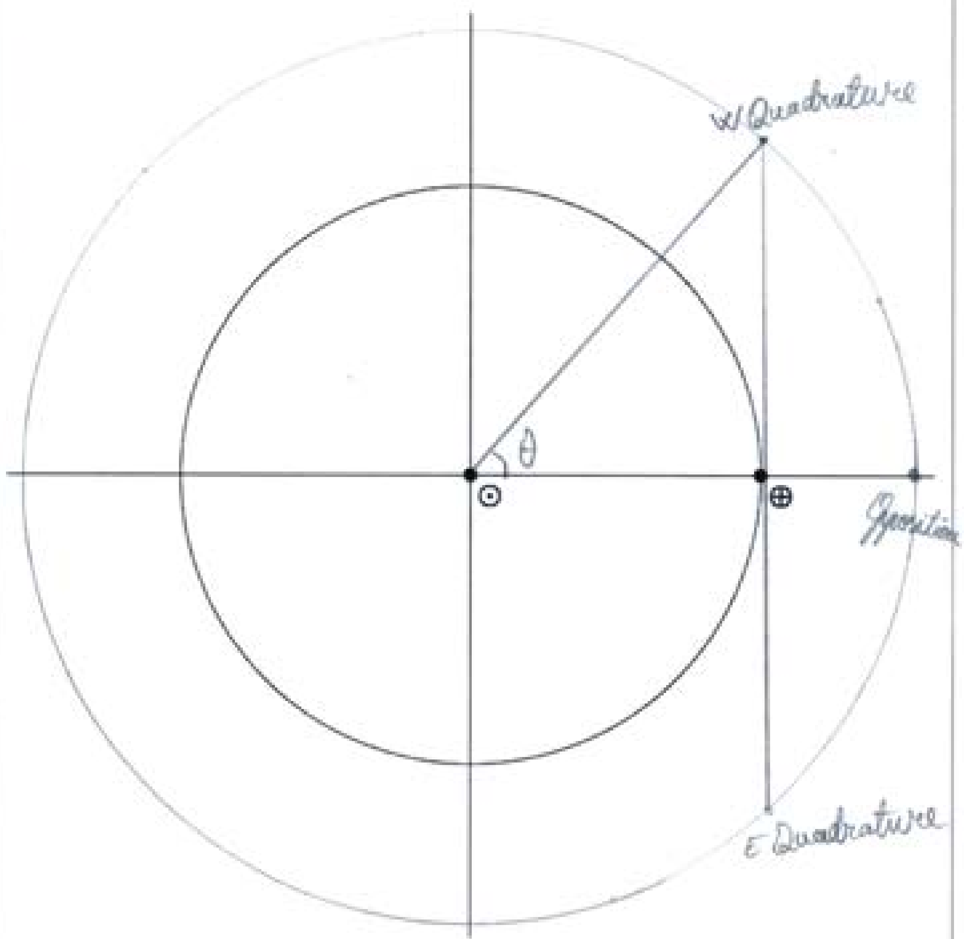
i.	datele cuadraturilor (când elongaţia lui Marte este de 90 °)	
		~~10 Jun 1916~~
ii.	începutul mişcării retrograde	14
	finalul mişcării retrograde	10 Jun 1916
iii.	data opoziţiei	12 February 1916
iv.	latitudinea ecliptică la opoziţie	5°
v.	lungimea intervalului de valori pe care le ia longitudinea planetei în timpul efectuării buclei	240°

Bazându-te pe observaţiile astronomice pe care le-ai făcut şi presupunând că orbitele Pământului şi Marte sunt circulare:

(b) Pe foaia de răspuns, marchează poziţiile Soarelui, Pământului şi a lui Marte în momentele opoziţiei şi ale cuadraturii în sistemul heliocentric şi determină raza orbitei lui Marte în u.a. , printr-o metodă geometrică, fără a folosi Legile lui Kepler. Prezintă-ţi metoda pe foaia de răspuns. (9 puncte)

(c) Găseşte înclinarea orbitei lui Marte faţă de ecliptică (3 puncte)

2.b (9.0 pt)



pagina următoare ⟹

(c) Determină raza orbitei lui Marte:

2.b (cont.)

$$\theta = \frac{360^\circ}{P} \cdot \left(t_{W\,quadrature} - t_{opposition}\right) = 49^\circ$$

$$\left.\begin{array}{l} r = \dfrac{r_0}{\cos\theta} \\ r_0 = 1\,au \end{array}\right\} \Rightarrow r = 1{,}52\,au$$

(d) Determină înclinarea orbitei lui Marte relativ la ecliptică.

2.c (3 pt)

$$\frac{r}{\sin\psi} = \frac{r_0}{\sin(\psi - i)} \Rightarrow$$

$$\Rightarrow \frac{r}{\psi} \simeq \frac{r_0}{\psi - i} \Rightarrow$$

$$\Rightarrow i = \psi \frac{r - r_0}{r}$$

$$i \simeq 1{,}42^\circ \simeq 1^\circ 43'$$

Opposition:

TRAPPIST-1 (35 точки)

Извънземни са установили, че земните астрономи са открили планети в системата TRAPPIST-1, чрез наблюдения на голям брой пасажи.

Те са използвали тяхната летяща чиния (подобна на тази, в която Вие бяхте по време на наблюдателния тур), за да Ви заведат на петата планета (означена с *f*) от системата TRAPPIST-1, и са Ви помолили да им обясните какви методи се използват от земляните за изучаване на параметрите на системата.

Часовник, който показва времето в земни часове ще бъде видим. Цялата презентация ще продължи 520 часа (1 s съответства на 1 час).

Използвайки Вашите наблюдения (Вие можете да използвате мястото на последния лист за бележки от наблюденията),

(a) определете следните параметри на за планетата, на която се намирате (изразете в земни часове всички интервали от време):

3.a (7 pt)

i.	продължителността на звездното денонощие [h]	225h
ii.	продължителността на орбиталния период [h]	225h
iii.	продължителността на 'слънчевото' денонощие [h]	~~[illegible]~~ →∞
iv.	Дали орбитата е кръгова?	YES / NO
v.	Наклон на оста на планетата [°]	0°

(b) и следните параметри за всяка от планетите *b*, *c*, *d* и *e*:

3.b (16 pt)

	b	*c*	*d*	*e*
синодичен период [h]	42h	80h	189h	450
максималната елонгация [°]	17°	25°	36°	49,5°

Planetarium Round

BUL-S3

A3-3

Bulgarian (Bulgaria)

(c) пресметнете продължителността на орбиталния период в часове и голямата полуос в *tau* (където 1 tau = " астрономическата единица за TRAPPIST-1/" = голямата полуос на орбитата на TRAPPIST-1 f) за всяка една от планетите:

3.c (8 pt)

	b	*c*	*d*	*e*
орбитален период [h]	5,4^h	59,0^h	102,7^h	150
голяма полуос на орбитата [tau]	0,29	0,42	0,59	0,76

(d) Терминът 'гравитационен резонанс' се използва когато отношението на орбиталните периоди на две планети в една планетна система е много близо до отношението на две цели числа. В таблицата по-долу са дадени някои от резонансните отношения на периодите, наблюдавани в системата TRAPPIST-1. Намерете периодите на кои двойки планети съответстват на дадените резонансни отношения, ако има такива.

3.d (4 pt)

Резонансно отношение	Двойка планети
3:2	f, e/e,d
8:5	
5:3	e,c
8:3	
4:1	c,f
6:1	b,f

Results

OVERALL WINNER
Peter Andolšek → Slovenia

BEST IN THEORY ROUND
Andrei - Darius Dragomir → Romania

BEST IN OBSERVATION
Peter Andolšek → Slovenia

BEST IN DATA ANALYSIS
Peter Andolšek → Slovenia

BEST INTERNATIONAL TEAM — EX AEQUO

(5)_Astraea
Teo Alvånger → Sweden
Moiz Muddassir → Pakistan
Artavazd Harutyunyan → Armenia
Dzaky Rafiansyah → Indonesia
Vladimir Milanov → Bulgaria

(12)_Victoria
Prodromos Fotiadis → Greece
Paulo H. dos Santos Silva → Brazil
Bryan Herdianto → Indonesia
Boyu Wang → China
Maksymilian Wdowiarz - Bilski → Poland


CONGRATULATIONS!


CONGRATULATIONS!


CONGRATULATIONS!

Gold Medals		
Name	Student Code	Overall score
Peter Andolšek	SLO-S1	411
Evan Kim	USA-S3	382,9
Taichi Shimokobe	JPN-S3	378,2
Andrei-Darius Dragomir	ROU-S1	376,5
Benjamin Woodrow	GBR-S5	374,6
Rajdeep Mishra	IND-S3	365,2
Murilo De Andrade Porfirio	BRA-S1	362,2
Tejeswar Koduru	IND-S2	361,05
Mahdi Ostadmohammadi	IRI-S4	359,15
Ryan Lin	GBR-S2	358,9
Paulo Henrique Dos Santos Silva	BRA-S2	355,7
David Lee	USA-S4	351,5
Hakjin Lee	KOR-S3	344,5
Zander Li	CAN-S2	340,95
Md Sahil Akhtar	IND-S1	338,1
Charlotte Stevenson	GBR-S3	336,4
Kai Wen Teo	SGP-S4	333,35
Amir Mahdi Esmaeili Taheri	IRI-S1	331,65
Akarsh Raj Sahay	IND-S5	330,8
Bayan Gechev	BUL-S2	328,9
Arvin Rasulzadeh	IRI-S5	326,4
Frederick Weir	GBR-S4	322,6
Ara Mahdessian	CYP-S3	321,4
Maksymilian Wdowiarz-Bilski	POL-S5	321
David Bálek	CZE-S1	316,4
James Kennedy	GBR-S1	313,3
Diana Zazubyk	UKR-S5	313,2
Zhi Zheng Ong	MAS-S3	312,8

Silver Medals		
Name	Student Code	Overall score
Teofil Voicu	ROU-S5	309,7
Paulo Otavio Portela Santana	BRA-S5	307
Mihail Bankov	BUL-S1	306,4
Kittiphat Pongarunotai	THA-S3	304,7
Adhitya Chandra	USA-S1	303,3
Lora Lukmanova	BUL-S4	302,2
Cheng Ian Lim	SGP-S3	299,6
Wongwaran Upawong	THA-S5	297,9
Hongyi Huang	CAN-S1	297
Boyu Wang	CHN-S4	291,8
David Zhang	USA-S5	290,7
Jiahang Chen	CHN-S1	290,3
Mohammad Nur Casib	PHI-S2	290
Dorottya Elekes	HUN-S1	288,2
Gabriel Hemetrio De Menezes	BRA-S3	285,8
The Minh Pham	VIE-S3	285,4
Kane Kiat Leng	SGP-S2	284,2
Seyed Amir Hossein Moosavifard	IRI-S3	282,6
Sungwon Bae	KOR-S1	282,2
Ciocârlan Mihai-Bogdan	ROU-S3	281,5
Manuel Mario Nadir Gilvonio Saez	PER-S2	279,3
Hritom Sarker Oyon	BAN-S4	278,9
Mendel Emanuel Mendelsohn	ROU-S2	278,9
Sainavaneet Mukund	IND-S4	278,1
Lasse Paul Blum	GER-S1	277,7
Jakub Hadač	CZE-S2	277,2
Thai Vu Tran	VIE-S5	268,2
Žan Ambrožič	SLO-S4	267,7

Austin Chen	USA-S2	266,5
Adnan Bin Alamgir	BAN-S1	264,85
Yi Xuan Tong	SGP-S5	261,9
Vyacheslav Petrosyan	ARM-S4	260,7
Vladimir Milanov	BUL-S5	260,15
Christian Vogel	GER-S5	259,7
Illia Garbazhii-Romanchenko	UKR-S1	259
Dzaky Rafiansyah	INA-S4	258,8
Miha Brvar	SLO-S3	258,1
Tuna Tülümen	TUR-S4	255,1
Akhmajon Tabarov	KAZ-S3	254
Sarina Farzadnasab	IRI-S2	253
Olita Anastasija Zadoroznaja	LAT-S5	249,5

Bronze Medals

Name	Student Code	Overall score
Ralf Robert Paabo	EST-S3	249
Luise Köhler	GER-S3	245,9
Viktor Vuković	CRO-S5	245,3
Tian Pu	CAN-S4	245,2
Zahran Nizar Fadhlan	INA-S1	244,1
Maximilian Kirchner	GER-S2	243,4
Prodromos Fotiadis	GRE-S1	242,4
Jinwoo Park	KOR-S4	241,85
Minkyu Song	KOR-S5	240,7
Anton Nüske	GER-S4	240,4
Martin Kudrna	CZE-S3	240,1
Vladimir George Necula	ROU-S4	238,35
Žan Arsov	SLO-S2	238,3
Tomáš Patsch	CZE-S5	238,2
Krzysztof Król	POL-S4	237,45
Saskia Põldmaa	EST-S4	234,15
Zehan Huang	SGP-S1	231,4
Ferdinand Ferdinand	INA-S2	230,1
Phanuphat Srisukhawasu	THA-S4	229,8
Eduard Palant	UKR-S2	229,3
Andria Manjavidze	GEO-S2	228,8
Konstantin Krastev	BUL-S3	228,3
Egemen Saritekin	TUR-S3	227,7
Sutthawish Phonglorpisit	THA-S2	227,55
Md Bayezid Bostami	BAN-S2	227,5
Mehmet Öztürk	TUR-S2	224
Philip Wetterberg	SWE-S5	223,3
Ba Linh Nguyen	VIE-S1	222,1
Michał Jagodziński	POL-S2	221,4
Matouš Mišta	CZE-S4	221,2
Piotr Jędrzejczyk	POL-S3	217,4
Dachi Tchotashvili	GEO-S3	217,1
Andrii Zahika	UKR-S4	214,2
Supakorn Paisancharoen	THA-S1	213,6
Indra Rhamadan	INA-S5	212,3
Gniewosz Armista	POL-S1	211,55
Viesturs Streļčs	LAT-S4	211,5
Bekassyl Yelubay	KAZ-S4	209,8
Zhi Qi Tan	MAS-S4	209,3
Luka Tvalavadze	GEO-S4	208,3
Dohyun Kwon	KOR-S2	207,1
Blanka Schmercz	HUN-S4	206,1
Bryan Herdianto	INA-S3	204,8
Ondrej Juhás	SVK-S3	204,3
Artavazd Harutyunyan	ARM-S3	202,8
Yiğit Karaca	TUR-S1	200
Mihailo Radovanović	SRB-S4	199
Ngoc Phuong Anh Nguyen	VIE-S2	199
Rion Fuchigami	JPN-S1	195,9
Youmo Lai	CHN-S2	193,6
Jokūbas Viršilas	LTU-S4	191,6

Statistical summary

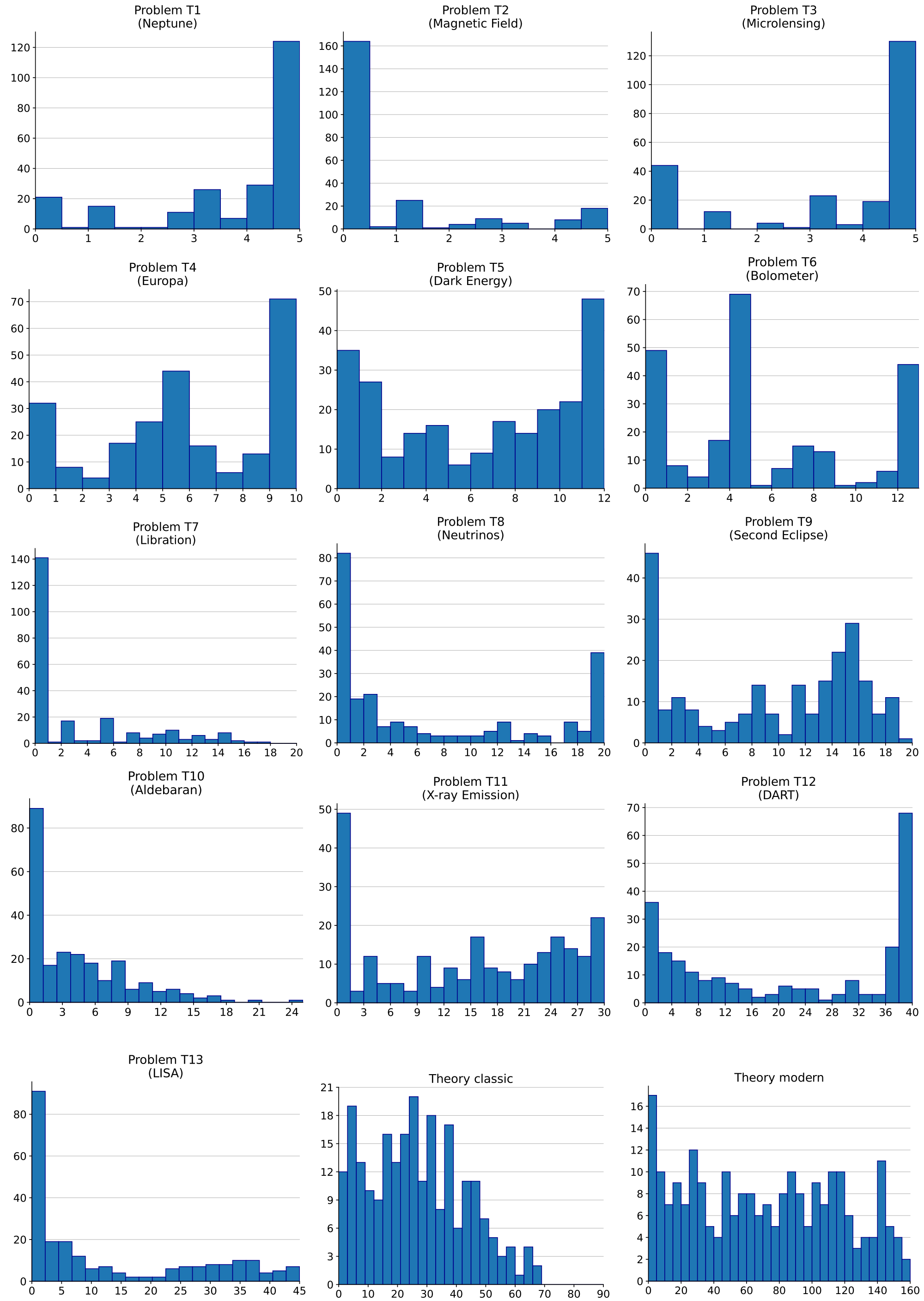
Difficulty of the Problems

The Academic Committee devised a set of problems that encompasses virtually all topics covered in the IOAA Syllabus. A statistical analysis of the participant's scores reveals which topics are the most conceptually difficult for students and which topics were mastered by participants. Figure 1 presents histograms of the scores for each problem, and the median and mean scores are shown in Table 1. None of the distributions looks like a Gaussian.

The spherical and geometric astronomy problems, T7 “Libration” (mean score 0.156) and T10 “Aldebaran” (0.170), were among the most difficult problems. The problem T2 “Magnetic Field” (mean score 0.165) also caused a lot of trouble for the participants, although it was deemed quite easy by the Academic Committee. The data analysis problem DA2 “Isolated Black Hole” (mean score 0.206) was also quite challenging for the students. Here, the greatest difficulty was related to realizing that the smallest astrometric deflection is observed at the peak of the analyzed microlensing event. In the observational round, two problems requiring the use of the stopwatch had the lowest scores: O1 “Asteroid Occultation” (mean score 0.167), and O2 “Starlink’ (0.169)’.

Problem		Median	Mean	Median/Total	Mean/Total
T1	Neptune	4.60	3.73	0.920	0.746
T2	Magnetic Field	0.00	0.82	0.000	0.165
T3	Microlensing	5.00	3.50	1.000	0.700
T4	Europa	5.00	5.61	0.500	0.561
T5	Dark Energy	7.00	6.36	0.583	0.530
T6	Bolometer	4.00	5.35	0.308	0.411
T7	Libration	0.00	3.13	0.000	0.156
T8	Neutrinos	2.00	6.68	0.100	0.334
T9	Second Eclipse	11.15	9.28	0.557	0.464
T10	Aldebaran	3.00	4.24	0.120	0.170
T11	X-ray Emission	15.50	14.65	0.517	0.488
T12	DART	21.00	20.73	0.525	0.518
T13	LISA	5.00	12.99	0.111	0.289
DA1	Distance to the LMC	36.70	29.98	0.734	0.600
DA2	Isolated Black Hole	13.40	15.45	0.179	0.206
O1	Asteroid Occultation	2.00	2.51	0.133	0.167
O2	Starlink	2.00	2.54	0.133	0.169
O3	Planetary Moons	6.00	5.61	0.600	0.561
O4	Supernova	4.00	4.58	0.400	0.458
P1	Knowledge of the Sky	8.00	8.14	0.400	0.407
P2	Retrograde Mars	8.00	8.81	0.400	0.440
P3	TRAPPIST-1	15.00	15.07	0.429	0.431

Tabela 1: Mean and median scores for each IOAA 2023 problem.



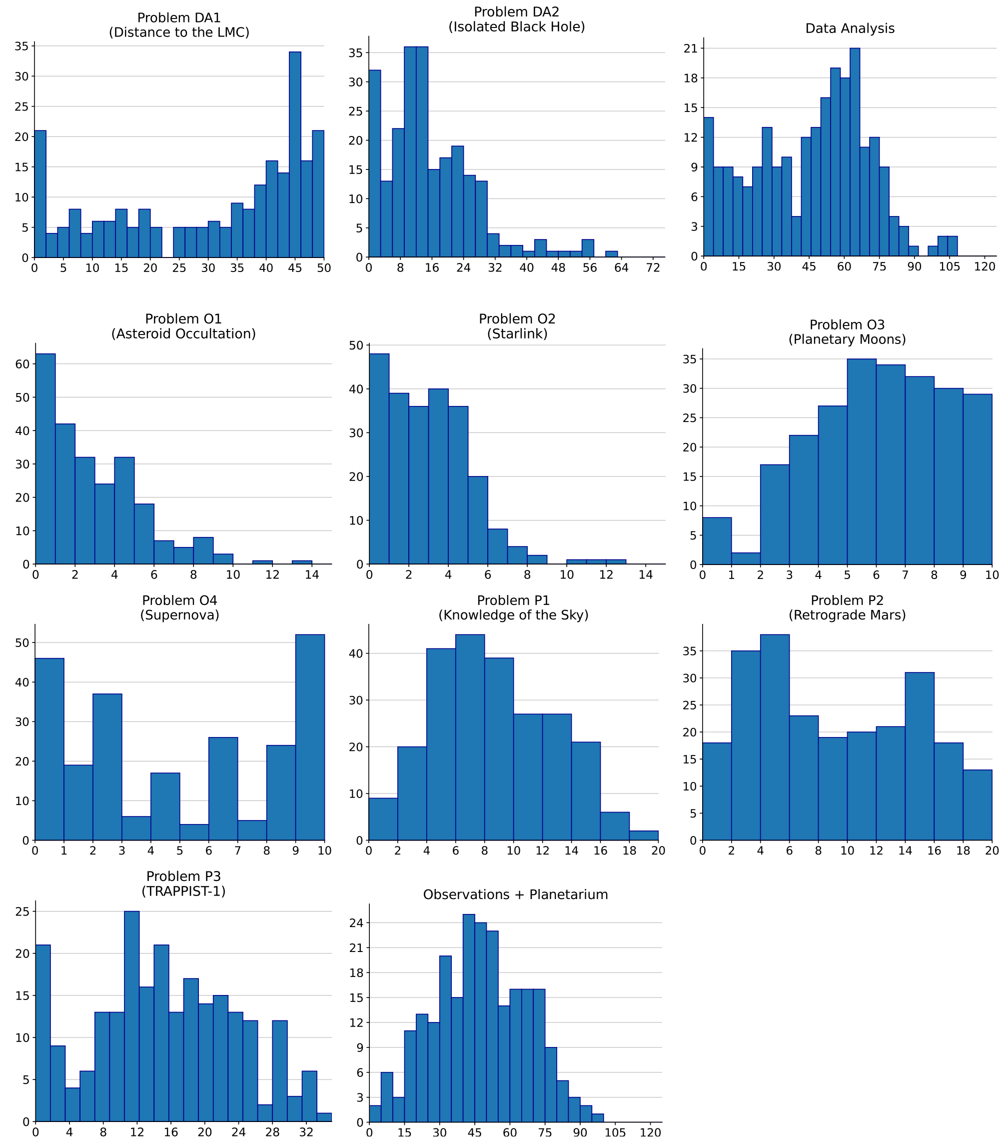


Figure 1: Histograms of the scores for each IOAA 2023 problem.

Summary

Minutes of the International Board Meeting held on 14th August 2023

1. Title of Overall Winner
A change of wording in the Statues from "Absolute Winner" to the more neutral "Overall Winner" was proposed and approved unanimously.

2. Use of calculus
The use of calculus in questions was once again discussed, and a draft proposal for changes to the Syllabus, based on the current syllabus used in the International Physics Olympiad, was presented for discussion.

The proposal consisted removing the marked sections from the text of the Syllabus:

Preamble
Basic concepts in physics and mathematics at high school level are required in solving the problems. Standard solutions should not involve use of calculus and/or the use of complex numbers and/or solving differential equations.

Data Analysis part
The data analysis section focuses on the calculation and analysis of the astronomical data provided in the problems. Additional requirements are as follows:
Proper identification of error sources, calculation of errors, and estimation of their influence on the final results.
Proper use of graph papers with different scales, e.g., polar and logarithmic papers. Transformation of the data to get a linear plot and finding the "Best Fit" line approximately.
Basic statistical analysis of the observational data.
Knowledge of the most common experimental techniques for measuring physical quantities mentioned in Part A.

and adding the following table section:

Mathematical Methods and tools

Numerical Methods	Linearisation of equations and expressions, Iterative solving of functions, estimating area under a curve by graphical method and/or by integration and/or by numerical approximations, Taylor series approximations of common functions
Basic Calculus	Derivatives of elementary functions, their sums, products, quotients, and nested functions. Integration as the inverse procedure to differentiation. Finding definite and indefinite integrals for elementary functions, and sums of functions. Geometric interpretation of derivatives and integrals. Finding constants of integration using initial conditions.
Vectors	Basic properties of vector sums, dot and cross products, Geometrical interpretation of a time derivative of a vector quantity
Geometric Instruments	Use of geometric compass and protractor
Statistics & Error Analysis	Mean, Median, Mode, percentiles, box plots, Standard deviation, basic probabilities, relative errors, error estimation using maximum error and/or standard error

Finally, the proposal included the addition of a general regulation that "the use of the mathematical techniques listed above is for ease of modelling an astrophysical system. Testing expertise in these techniques should never be the primary focus of any problem in IOAA." This regulation would be part of academic guidelines provided to each host.

A number of leaders remarked, calculus is either not on the school curriculum at all or appears only in the final year, and thus the presence of calculus in the problem may scare students. Other leaders noted that the students see calculus and further mathematics in the training camps. It was noted that the boundaries of what [mathematics] is allowed should be defined. Other suggestions included: providing a list of elementary functions; providing linear regression formulae; dividing the [Syllabus] into mandatory and optional parts. The leaders were asked to send further comments and suggestions to the EC by email. No further action was taken.

3. Defining valid calculator types

Even basic calculators now available in most countries include integral function and iterative solving and finding calculators without these functions is becoming increasingly difficult. Thus the EC proposed to expand the list of allowed calculators to include those with such in-built functions. Calculators with customised storage of constants, programmable formulae, AI, and graphing options would still not be allowed. The proposal to allow more functions and enlarge the list of allowed calculators was approved unanimously following a discussion.

4. Composition of International Board

A proposal was presented for changes to the Statutes to clarify the structure of the International Board, following previous discussions during the IOAA 2021 in Colombia. The proposed changes are as follows:

Current text:

Statute #4 para 4:

- The team leaders each become equal and independent members of the International Board for the period until the beginning of the next competition.

Statute #15 para 1:

- The International Board is chaired by a representative of the organising country.

Proposed Change:

Statute #4 para 4:

- The team leaders each become equal and independent members of the International Board.

Statute #15 para 1:

- For the duration of the event, the International Board is chaired by a representative of the organising country.

Statute #17 (add bullet points at the end):

- The term of the international board is defined to be from the start of one competition till the start of the next competition.
- Individual members may choose to opt out of the international board, by nominating their replacement from the same country. Requests for such replacements may be approved by IOAA EC after due consideration.
- From the time of conclusion of one IOAA till the start of the next IOAA, the international board is chaired by the IOAA president.
- IOAA EC members are ex-officio members of the international board.

During discussion it was noted that the appointed host country representative must agree to be the IBM chair. Voting on the proposal will take place after at least 3 months in accordance with the Statutes.

5. Guidelines for hosts, in case they are unable to accommodate all registration requests

Hosts are obligated to make every possible effort to include all the countries which have participated in IOAA in the last 3 years. In addition, it is expected that hosts will also accommodate requests of participation from countries which have participated sometime in the past as well as new countries. However, at the same time, it is understood that in some cases the hosts may be forced to put a limit on the number of participants for logistical reasons beyond their control (e.g. number of rooms in hotel / hostel or availability of jury or telescope examiners). A draft procedure was outlined by the EC as follows:

Protocol for accommodating maximum teams during IOAA

	Criteria	Plan A	Plan B	Plan C	Plan D
1	Host countries of last 10 years + committed hosts for next 5 years	5+2	5+2	5+2	5+2
2	All remaining past hosts + all committed future hosts	5+2	5+2	5+2	35+12
3	All other countries in attending all 3 IOAAs in last 3 years	5+2	3+1	3+1	3+1
4	All other countries attending at least 1 IOAA within last 3 years	5+2	3+1	3+1	3+1
5	All other past participants	5+2	3+1	2+1	Obs.
6	All new countries	5+2	3+1	2+1	Obs.
7	Guest teams	5+2	3+1	2+1	NA

Teams in any given category cannot be included under a better plan than teams in the higher category. All teams in the same category must be treated equally.

E.g. if teams in category 4 are included only under plan B, then teams in categories 5/6/7 cannot be offered plan A. They can be offered either plan B or C or D. Guest teams only after all others.

During discussion the following points were made:

- All teams in the same category must be treated equally.
- Differences in team sizes create imbalances.
- The timescale of future hosts needed to be defined.
- It might difficult to explain to national funding agencies that a team might not be able to send a 5-student team in the future.
- The proposal prioritises traditional teams and might not encourage new teams. but there is no better plan. Observers/guest teams should be limited instead to maximise students.
- Budget is not the only limiting factor, e.g. physical space for tests, students hotel, etc. (However some of these factors can be solved with a large enough budget.)
- rows 1 and 2 should be merged, and 5 and 6 should be swapped.
- We need to retain the new countries we invite.
- Small countries with small budgets will be more impacted. Equal number of participants would be more fair.
- Countries must declare when they will be hosts after 5 years of participation, and this is not being observed.
- Smaller neighbouring countries can collaborate amongst themselves. Co-hosting by 2 countries should be encouraged.

The proposal was remanded for further review by the EC.

6. Defining observer fees and guest team fees

The EC made a proposal to revise the structure and amount of observer and guest fees, noting that the fees applied at IOAA were inadequate to cover rising costs and much less than other Olympiads. It was also proposed that the hosts recognise non-scientific members of the delegation (spouses / family members of scientific mentors, parents of students, etc.) as 'visitors' and may offer additional excursions / activities for them on some of the IBM days.

During discussion it was noted that part of the fees should be made available for use by the EC, and that the exact amounts perhaps should be at the discretion of the host. Nevertheless, in the final vote, an Observer/Guest team member fee of 1600 EUR was approved unanimously, and a Visitor category with a fee of 2000 EUR was approved unanimously. Both fees may be revised after 5 years.

7. Introducing fee for the main team

Given the rising costs of hosting and a participation fee for the main teams was proposed. Of the other olympiads, only the International Mathematics Olympiad and the International Olympiad on Informatics have either zero or very modest fee, however both have multi-year sponsorship deals with major software firms. All other Olympiads charge a participation fee. The following fee structure was proposed.

Default participation fee for IOAA each year from 2027 will be 1900 EUR per team. In the intermediate years, we propose a gradual increase in the participation fee. In 2024, there will be no participation fee, in 2025 it will be 600 EUR per team, and in 2026 it will be 1200 EUR per team.
For delegations smaller than 5 persons (students+leaders), fees will be charged instead at the rate of 400 EUR per person.
The countries which have hosted IOAAs in the past, without charging any participation fee, will be exempt from the participation fee until 10 years after their hosting.
The host country may choose to offer additional discounts for the teams willing to pay the participation fee a few months in advance.
The participation fee amount may be reconsidered by the IOAA board every five years.

During discussion the following points were made:

- Fees adds strength to negotiations with government; on the other hand, fees are small part of total [host] budget.
- Proposal favours well-established countries and discourages small countries.
- We need to know where the fees will be used (90% - 95% to host country organisation, and the rest to a common pool to fund calculators, proceedings etc). Transparency is essential. Need to set up a company/organisation/bank account etc.
- Some countries [with small annual local budgets] will not be able to cover the additional costs; different countries have different costs of organisation. Hard to find funding for astronomy. IOAA may become a private event,
- Fee for newcomers should be low or zero.
- Free for all is not possible anymore.
- Fees would be too high to Latin American countries; however fees can be discussed with and adjusted by hosts.
- Fees only work if they are flat [i.e. equal].

The final vote on this will be conducted after 3 months in accordance with the Statutes.

8. Future hosting

Brazil confirmed hosting of the 17th IOAA between 17–26 August 2024. Potential future hosts (to be confirmed) are:

2025 - Iran or Kyrgyzstan
2026 - Malaysia
2027 - Germany
2028 - Türkiye
2029 - S. Korea

In addition Nepal expressed an interest in hosting IOAA Jr in 2024 and Thailand confirmed hosting IOAA Jr in 2026.

9. Other matters

Cristian Pirghie (ROM) presented a report about the first IOAA Jr (2022). Loukas Zachella (GRE) talked about the next IOAA Jr (2023).

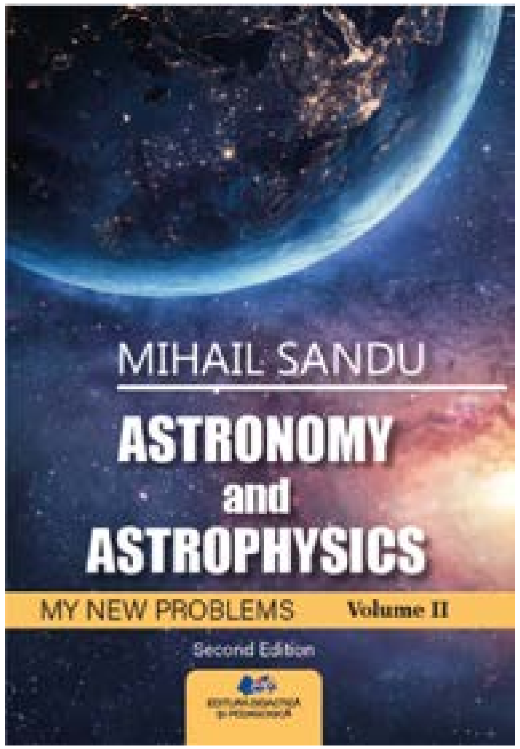
Posters and media

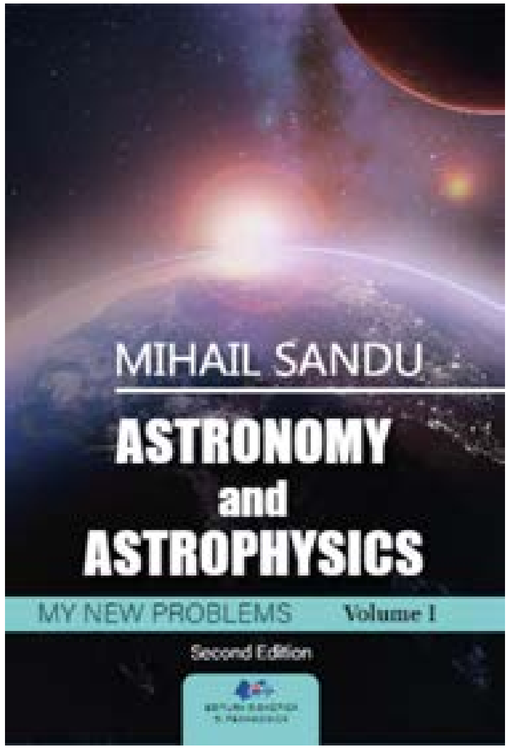
Audience Award Winner

Best poster Winner

See all posters online

Selected posters (Brazil, Czechia, Germany, Malaysia, Portugal, Chile) presenting the scientific results of valuable observations were presented at the Congress of the Polish Astronomical Society (Toruń 2023) and will be published in the conference materials.





The organizers of the 16th International Olympiad on Astronomy and Astrophysics would like to thank Professor Mihail Sandu.

For over a dozen years, Professor Sandu has been preparing IOAA task studies, which are provided free of charge to the Olympiad participants. This is an excellent source of knowledge for training and Olympic preparations.

Professor Sandu graduated from the University of Bucharest and the Tourism Technological Highschool in Călimăneşti. For many years, he has been teaching physics to primary and secondary school students and has also organized extracurricular activities for students with talent for science.

He is the author of physics books for students, he wrote and published tens of physics exercises (problems) books, targeting mainly the high performance goal, as well as physics books for highschool teachers, preparing them in obtaining the degrees in teaching. He also hel university courses for the participating students and teachers to the International Physics Olympiads.

He is a member of the National Committee of Physics of the Ministry of Education and Research in Romania. In 1996, at his proposal, the National Physics Olympiad was held at Calimanesti and Ramnicu Valcea. He was author of the tasks for the Olympiad.

His books were distributed free of charge among participants of the International Astronomy and Astrophysics Olympiad in the years 2014—2023.

The Morning Star

Headlines

„16th International Olympiad on Astronomy and Astrophysics begins! 250 students from 50 countries will compete in Katowice and Chorzów."

naszemiasto.pl

"For the next 10 days the Silesian Voivodeship will be one of the most important places on the world's astronomy map."

TVP Nauka

"Katowice: Polish student among the gold medalists of the International Olympiad on Astronomy and Astrophysics!"

Wnp.pl – Economic Portal

The International Olympiad on Astronomy and Astrophysics returns to Chorzów and Katowice. „I'm glad to be here again, after twelve years"

Slązag.pl

"250 of the best young astronomers from as many as 50 countries took part in the 16th International Olympiad on Astronomy and Astrophysics on August 10-20 in Chorzów and Katowice. Five-person teams of winners of national olympiads solved numerous theoretical and data analysis tasks at the International Congress Center in Katowice and the Silesian Planetarium (Silesian Science Park)."

Urania.edu.pl

We have a lot in common. You are looking for stars in the sky. We are also a kind of constellation, composed of as many as 41 stars - cities and towns that creates the Upper Silesian-Zagłębie Metropolis. We have over 2 million inhabitants. If we were one star - we were the brightest star in the Polish sky - the largest Polish city. I join in the wishes and congratulations. I wish you satisfaction from your scientific achievments. I hope that after them you will also find time to get to know our Metropolis. - said Kazimierz Karolczak, chairman of the Metropolis, during the opening of the event.

metropoliagzm.pl

I congratulate not only the winners, but also each of the teams taking part in this amazing, truly cosmic competition, the real stake of which is to constantly expand knowledge about the universe - astrophysics and astronomy. In fact everyone is a winner. We are honored that the Silesian Voivodeship hosted this international scientific competition. I hope that all its participants felt at home with us, and one day, perhaps in the near future, you will come back to us with your families or friends to show them our region and, of course, the Silesian Planetarium to see millions of stars. Thank you for participating in the Olympiad and come visit us again - the voivodeship marshal, Jakub Chełstowski during the closing ceremony of the 16th IOAA.

Slaskie.pl

Photo gallery







NASA

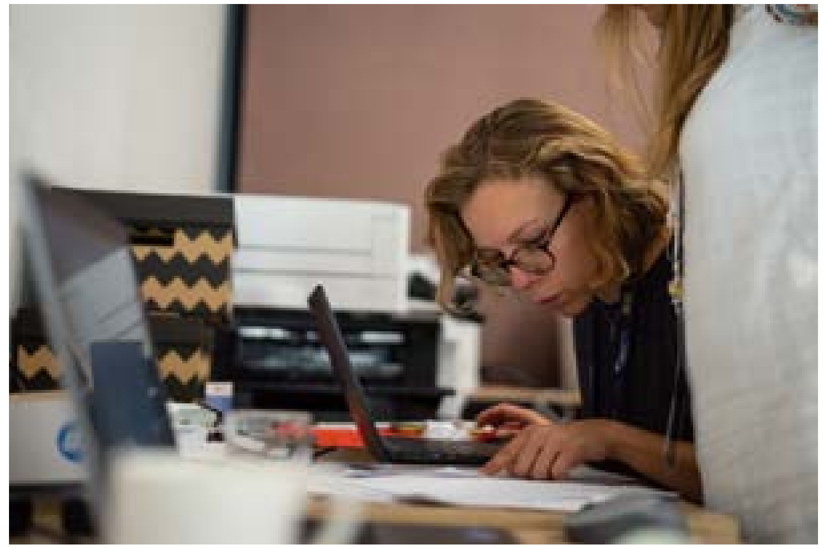


18:18:08



IOAA


Behind the scenes



The team responsible for "Proceedings of the 16th International Olympiad on Astronomy and Astrophysics 2023" had met on October 6-8, 2023 in Wisła to determine the structure and content of this publication. During the meeting, a night sky observation zone was created, thanks to which it was possible to thoroughly verify the information contained in this book.

Proccedings of the 16th International Olympiad on Astronomy and Astrophysics (IOAA) Silesia, Poland

Edited by:
Jarosław Juszkiewicz

Co-editors:
Damian Jabłeka
Waldemar Ogłoza
Anna Skrzypecka

Illustration photos:
Damian Jabłeka

Photographs:
Paweł Mikołaczyk— PAMEDIA
Piotr Margraf — PAMEDIA

DTP:
Marcin Kasperek — KlarStudio.pl

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