THE

OBSERVATORY

A REVIEW OF ASTRONOMY

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MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2025 December 12 at $16^{\mathrm{h}}\,00^{\mathrm{m}}$
in the Geological Society Lecture Theatre, Burlington House

Mike Lockwood, *President*
in the Chair

The President. Good afternoon, everybody. This is a hybrid meeting for those of you who are on-line and using Zoom. Questions will be taken at the end of the lecture, but you'll be muted on Zoom, so please use the Q&A facility. We'll read out your question to the meeting.

For today's programme we start with Dr. Louise Devoy, who's Senior Curator at Royal Observatory Greenwich, our once great Observatory, and you might see a rather wonderful pamphlet and some rather wonderful-looking books that she's going to tell us about, I'm sure. Over the past five years Louise has delved into the archives and museum stores to choose 100 objects and their stories for her book *The Royal Observatory Greenwich: A History in Objects*, published to celebrate the Observatory's 350th anniversary in 2025. Louise has a background in astrophysics and the history of science and has worked at various museums in the UK and abroad. Her research interests encompass astronomical instruments, women in astronomy, and networks of knowledge exchange between historic observatories.

Dr. Louise Devoy. Today, I have been tasked with the seemingly impossible challenge of trying to condense 350 years of astronomy, navigation, and timekeeping at Greenwich into just 20 minutes, so bear with me as I try to make this happen and give you a flavour of this unique site in our special anniversary year.

To help me do that, I'm going use my book, *Royal Observatory Greenwich: A History in Objects*, which came out in 2025 October and has all those narratives in much greater detail. It's based on the stories of 100 objects, mostly from RMG [Royal Museums Greenwich] collections, arranged in chronological order from our origins in 1675, with each object described in around 350 words. I wanted to ensure that it wasn't just the famous clocks and telescopes but a whole range of objects, many of which have never been photographed or displayed before. I hope you will enjoy the diversity of objects, both familiar and new.

As you'd expect, it starts with our founding story, at the height of the so-called 'quest for longitude', which began centuries before the Observatory itself. Astronomers and mathematicians had long realized that we could measure longitude at sea using the Earth's rotation. By comparing local times and their associated longitude differences between locations, mariners could make trade routes quicker, safer, and more profitable. Two key ideas emerged: comparing astronomical events as seen simultaneously from two locations, or else taking a timekeeper to sea and comparing local time against the known time elsewhere. Those two challenges shaped the Observatory's work for the next three centuries and form the backbone narrative of the book as we see how astronomers, mathematicians, clockmakers, and instrument makers persevered to make it work.

I also wanted to show that the Observatory is not just about instruments, it's about people, and so you'll encounter a wide range of characters, from the Astronomer Royal and his family to the assistants, teenage human 'computers', and the wider London community of clock and instrument makers. Their endeavours were made possible by objects such as an insulated observing suit [Fig. 1], calculation templates, a hole punch for assembling papers, and even a fork for extracting spider silk for creating micrometer wires! Many objects also bear witness to the Observatory's involvement with various eclipse and transit-of-Venus expeditions, along with Nevil Maskelyne's pioneering experiment in 1774 to measure the density of the Earth by observing the stars either side of a Scottish mountain.

Another objective in writing this book was to highlight the Observatory's growing remit and widening expertise in the 1800s as it became a research centre for measuring terrestrial magnetism, meteorology, and solar activity. Like many other observatories, Greenwich became part of the movement towards astrophysics with the adoption of spectroscopy in the 1860s, albeit with limited results. In the 1890s, the Observatory became a participant in the global International Astrographic Survey (*Carte du Ciel*) that created the first professional roles for women at Greenwich.

The book also highlights the Observatory's continuing use of new technologies to ensure the distribution of accurate Greenwich Mean Time (GMT). In 1833, Astronomer Royal John Pond installed a roof-top time-ball to provide mariners waiting on the Thames with a visual time signal to rate their chronometers before heading out to sea. In the 1850s, accurate GMT was made more widely available *via* electric impulses from the Observatory's Shepherd Motor Clock [Fig. 2]. Those time signals were transmitted *via* telegraph networks that shadowed the country's growing railway network, making GMT an essential part of daily life. By the 1920s, accurate GMT was made available *via* radio signals, firstly as the BBC's 'six pips' broadcast and later as the 'GBR' long-wave transmission from Rugby in Warwickshire.

On a global scale, the Observatory was becoming increasingly important as a reference for 0 degrees longitude. By the 1880s, politicians and business leaders were calling for consensus among the 11 meridians in use, leading to the International Meridian Conference in October 1884. My object in focus here is the Airy Transit Circle [Fig. 3], which was one of the most advanced instruments at the time and helped sway the decision to adopt the Greenwich Meridian as Prime Meridian of the World and as the starting point of the Universal Day.

As we enter the 1900s, we find the Observatory having to cope with the effects of the First World War, leading to diminished staffing and a focus on military priorities such as increased chronometer testing for the Admiralty and a decrease in astronomical research. The story of a pair of binoculars serves as reminder of the secret testing programme in which Greenwich astronomers restored and tested over 3 000 pairs of donated binoculars for military use.

In the 1920s we return to horology with three objects that chart the technological changes in defining time standards in the 20th Century. We start with the Shortt free-pendulum clock: a two-part system consisting of a primary clock with a pendulum suspended in a partial vacuum tank connected to a secondary pendulum clock that were synchronized *via* electric impulses every 30 seconds. That created a very stable and consistent pendulum swing that revealed tiny variations in the Earth's rotation — previously measured as constant — that heralded the end of our 250-year dependence on pendulum clocks for timekeeping standards. The narrative continues with an early experimental quartz frequency standard to represent the transition away from astronomical to laboratory methods of timekeeping and then culminates with an atomic clock from the 1970s that became a standard feature of many observatories worldwide.

A set of lantern slides depicts the relocation of the Observatory's Magnetic Department to Abinger in Surrey as the London site suffered electrical interference from nearby railway lines. Similarly, a slitless spectrograph that saw limited service on the 36-inch Yapp Tele-

Fig. 1

Trousers and jacket, once belonging to 5th Astronomer Royal Nevil Maskelyne, composed of a silk outer layer with lining from linen and wool and with additional cotton wadding to create a quilted effect. This and other images as well as more information are available at `https://www.rmg.co.uk/collections/objects/rmgc-object-534404`. © National Maritime Museum, Greenwich, London.

Fig. 2

From 1852 to 1893, this motor clock sent time signals *via* telegraph wires to many cities in the British Isles and by 1866 even to Cambridge, Massachusetts, *via* the new transatlantic submarine cable. This and other images as well as more information are available at `https://www.rmg.co.uk/collections/objects/rmgc-object-79636`. © National Maritime Museum, Greenwich, London.

Fig. 3

Airy's transit circle. This and other images as well as more information are available at `https://www.rmg.co.uk/collections/objects/rmgc-object-11153`. © National Maritime Museum, Greenwich, London.

scope during the early 1930s helps us appreciate the deteriorating observing conditions at Greenwich as the astronomers battled against air pollution and vibrations from surrounding industries.

After the Second World War, the rural location of Herstmonceux Castle, East Sussex, was chosen as the new home of the Observatory's departments with the staff and instruments gradually relocated over the course of a decade. The historic site at Greenwich became part of the National Maritime Museum and continues to attract over 600 000 visitors each year. We're proud to celebrate 350 years of pioneering science, incredible engineering, and remarkable people at Greenwich and we're excited for our future project, First Light. Over the next few years, we will transform the site to make those objects and their stories even more accessible and engaging for future generations — come and visit!

Dr. Quentin Stanley. It's a wonderful book and thank you for signing my copy. [Laughter.] The actual honour of manning the last observing run of the Airy Transit Circle fell to the late Fellow of the Society, Gilbert Satterthwaite, and he was very much part of the RO's history there. It was a great loss to the Society when he passed away. The timing ball where the mechanism failed: there was the observer at the time who was using a clock in the city to set the time to drop the ball, and the person in the city was using the timing ball to set the clock so you had this recursive drift in time. What will be the next thing we will see that can bring that back to life for us in the changes you're working on at the moment?

Dr. Devoy. We've had to close the south part of the site at the moment which includes our planetarium and our education centre. The historic north part of the site is still open and hopefully will be for another year or so. Then I think we will have to close the site completely at some point, but we're hoping to re-open around 2028. There will be new galleries, and we will have our usual stories, of course, and our Meridian objects as well. We're trying to weave in new elements to bring the objects to life, whether that's using projection, sounds, or digital effects, because at the moment some of the spaces can feel quite sterile, particularly in the Meridian building. We really want to bring those spaces to life a lot more as well. There is also a general trend across many museums that have slightly fewer objects on display, but to tell their stories in a slightly more interesting way, so we're definitely working on those principles as well.

Mr. Horace Regnart. The tragedy of Admiral Shovell and the development, both financially and controversially, of the Harrison clocks, the best of which was accurate to a second both here and in the Caribbean. Is that outside the ambit of your work?

Dr. Devoy. No, it's very much part of our Longitude gallery. The Shovell disaster less so, but Harrison, absolutely. Harrison is a pivotal moment in the stories. They will still be on display, don't worry.

Mr. Regnart. So another time can you come back and give us a lecture about that?

Dr. Devoy. Potentially.

Mr. Regnart. Please! Thank you.

The President. Sir Cloudesley Shovell reminds me of how far we've come, as does Annie Maunder, because she got her first from Cambridge; she sat the exam but couldn't be given a degree. I'm afraid it's to the shame of this Society that Edward had to present the papers because she wasn't allowed to. It just reminds me how far we've come.

Dr. Devoy. Yes, she had a lot of support as well, and, at least, she had her name on the sunspot catalogue, which is great.

The President. She was a big friend of Everett, wasn't she? One more question please.

Mr. Geraint Day. The National Maritime Museum itself doesn't charge for visitors but the Observatory does which seems to be rather unfortunate. It may not be within your remit, but it could be good idea if it is.

Dr. Devoy. It has always been charging since I've joined but I believe yes, it was free at one point. I think when it was free, there was a question around wear and tear on the site because there were over 1 million people [per year] trying to squeeze through Flamsteed

House. It was doing huge amounts of damage; it's an ancient scheduled monument. It has the the highest status in the land, so it's a difficult balance between trying to make it accessible and engaging for everyone, but also generating some income to pay for the maintenance because there is just literally so much wear and tear on the site. We feel we have to charge, but it's difficult, I agree.

The President. I think we should thank Louise again. [Applause.] The next speaker is Go Murakami. Murakami Sensei is an Assistant Professor working at Institute of Space and Astronautical Science (ISAS) in Japan Aerospace Exploration Agency (JAXA). He is the Project Scientist of the ESA–JAXA joint mission *BepiColombo* for the *Mercury Magnetospheric Orbiter*, *Mio*. His science expertise is solar–terrestrial physics, plasma physics, and planetary atmospheric science. He got his PhD from The University of Tokyo in 2011. Then he worked at JAXA/ISAS as a research fellow between 2011 and 2017 for developments and observations of Japanese ultraviolet space telescope *Hisaki* and the *BepiColombo* mission. In 2017 he got the current position at JAXA/ISAS. The title of his talk is '*BepiColombo* — the ESA-JAXA joint mission to Mercury'.

Dr. Go Murakami. In today's era of intensifying planetary exploration by various nations, Mercury remains a planet shrouded in mystery. Beyond the inherent difficulty of placing a spacecraft into Mercury's orbit, the intense solar radiation experienced in orbit and the powerful albedo and thermal radiation reflected from Mercury's surface make it an extremely challenging planet to explore. Consequently, the only previous orbiter successfully to enter Mercury's orbit was NASA's *Messenger* spacecraft in 2011. *Messenger*'s numerous discoveries fundamentally changed Mercury's status in planetary science, establishing it as a unique observational target. However, limitations on the instruments that could be carried by a single spacecraft and the constraints of an orbit confined to the northern hemisphere left many unresolved questions. The *BepiColombo* mission aims to tackle Mercury's remaining mysteries through comprehensive observations by its two spacecraft *Mio* and *MPO* [*Mercury Planetary Orbiter*]. It seeks to advance our understanding of the Solar System's planets, particularly the terrestrial planets, focussing on their 'origin', 'evolution', and 'environment'.

One of Mercury's most striking features is its massive metallic core, which occupies approximately 80% of the planet's diameter. That is significantly larger than the cores of Earth, Venus, or Mars, which range from 40 to 50%. Furthermore, despite being the closest planet to the Sun, *Messenger* discovered that Mercury's surface mineral composition contains far more volatile elements than expected. While various proposals have been made regarding its unique planetary-formation process, none can explain all those features, leaving them still unexplained. Conversely, that indicates that unravelling the formation process holds a crucial key to understanding planetary formation, including Earth's. Even on Earth, the nature of the original solid rocky material remains unclear. The answer may not lie on Earth, which has been profoundly altered by planetary evolution, but rather on Mercury, which strongly retains traces of its primordial state. By deciphering Mercury's geological and compositional information through *MPO* observations, we can approach the mystery of the origin of terrestrial planets.

Another major feature of Mercury is its magnetic field. Mercury possesses a magnetic field believed to originate from its fluid metallic core, with a strength approximately one-hundredth that of Earth's. Among the terrestrial planets, only Earth and Mercury currently possess intrinsic magnetic fields. Prior to that discovery, the prevailing theory held that "the interior of Mercury, the smallest planet in the Solar System, had long since cooled and solidified, and thus possessed no intrinsic magnetic field like Earth's". Why has Mercury managed to retain its magnetic field? That major mystery in the planet's 'internal' evolution process fundamentally changed the significance of Mercury as an exploration target. Furthermore, *Messenger* observations revealed that the magnetic equator is shifted northward by about 20% of Mercury's radius. However, due to orbital constraints, no data exists for the southern hemisphere, making that a projection based solely on observations from the northern hemisphere. Simultaneous multi-point observations by both *Mio* and *MPO* can eliminate solar-wind–induced disturbance components. Furthermore, their north–south symmetric orbits enable more precise measurements of Mercury's intrinsic magnetic field than *Messenger*, encompassing the southern hemisphere. By capturing the information leaking out from Mercury's interior *via* its magnetic field, we can decipher the evolutionary process of that enigmatic solid planet.

Mercury, the closest planet to the Sun, exposed to intense solar wind and possessing a weak magnetic field, forms the most dynamic magnetosphere in the Solar System. Furthermore, its small size and weak gravity result in a thin atmosphere, creating a stage for complex physical processes unique to Mercury where gases from the solid planetary surface directly interact with outer space. In such an 'enironment' how much does Mercury, which forms a barrier called a magnetosphere, actually suffer from solar-wind effects? That perspective has become a crucial issue not only for traditional magnetosphere and space-plasma physics but also for the search for 'a second Earth' especially now that numerous exoplanets orbiting very close to their stars have been discovered. Japan has consistently led the world in Earth magnetosphere exploration. Applying those observational technologies, the *Mercury Magnetospheric Orbiter (Mio)* is the first spacecraft dedicated specifically to observing the Mercury environment. It has the potential to advance dramatically our understanding of how stellar winds affect planetary environments *via* the magnetosphere.

The President. Thank you very much. Questions?

Professor Kathy Whaler. Thank you, really interesting talk. What's the nominal lifetime of the mission once it's started the science phase?

Dr. Murakami. The nominal science period is one year, after eight years' cruise, but of course, we are already planning to extend it.

Dr. Bob Barber. A question about that diagram that you gave, the core, the outer region of the mantle, and you talked about impact. It seemed that the ratio of the diameter of the core to the outer region, was normal. What was missing was the mantle, which is consistent with an impact.

Dr. Murakami. In order to make such a huge core, if we assume the same origin of the materials as Earth's, then we need also a similar size of the planet as Earth. Then after the generation of the core there should be some kind of impact to remove the amount of surface materials.

Professor John Zarnecki. A comment rather than a question. When *Bepi* was originally selected by ESA, which I think was around 2000, it still had a small lander. It's always painful when I see it like that because I had a small instrument on the lander. Sadly it was for financial and technical reasons that it was de-selected.

Mr. Stewart Coulter. It's often said that a minority of astronomers both professional and amateur have seen Mercury. I saw Mercury a couple of months ago. At an early-morning swimming I saw the pre-separation from Australia very easily. I just wonder if I might add to those anecdotes by inviting the audience to put their hands up if they have ever seen Mercury. [About 65%.] Thank you, and if you have not? [About 35%.] Right. So it is the majority of this audience who have seen it. That's interesting. Thank you very much.

The President. Our next speaker is Dr. Lina Hadid from the Observatoire de Paris. Since 2020, Lina has been an astrophysicist and research scientist at the Laboratory of Plasma Physics (LPP), École Polytechnique / CNRS, in France. Her research focusses on studying the microphysical and macrophysical plasma processes in the solar wind and planetary magnetospheres. She analyzes wave and particle measurements in a variety of planetary environments, including Mercury, Earth, Venus, and Saturn, as well as in the solar wind, adopting a comparative-planetology approach. She is the lead of the *Mass Spectrum Analyzer* (*MSA*) onboard the ESA/JAXA *BepiColombo* mission to Mercury. She is also the PI of the Mars *Mass Spectrum Analyzer* (*MSA*) for ESA's M7 mission *M-MATISSE* (*Mars Magnetospheric ATmosphere Ionosphere and Space-weather SciencE*), a multi-point mission to Mars currently in Phase A (2026). In addition to her role in *BepiColombo* and *M-MATISSE*, she has contributed to several international space missions, including the *Cassini* mission and the *JUICE* and *Solar Orbiter* missions. Lina earned her MSc from Paris-Saclay University in 2013 and her PhD in astrophysics from the Laboratory of Plasma Physics at the École Polytechnique in 2016. She was a postdoctoral research fellow at the Swedish Institute of Space Physics in Uppsala (2019) and later at ESA's European Space Research and Technology Centre (ESTEC) in the Netherlands in 2019, before joining CNRS as a permanent research scientist at LPP in 2020. Lina is going to tell us about 'The ESA/JAXA *Bepi Colombo* mission on its way to Mercury: initial plasma observations during the cruise phase'.

Dr. Lina Hadid. Thank you much for that very nice introduction and thank you as well to the organizing committee for the invitation. I'm very honoured to be here and very happy to share with you some of the initial observations from *BepiColombo* during its cruise phase. I will be focussing mainly on the plasma observations, but also on the ion observations. Of course, the results I will show are results of collaborations among many instrument teams.

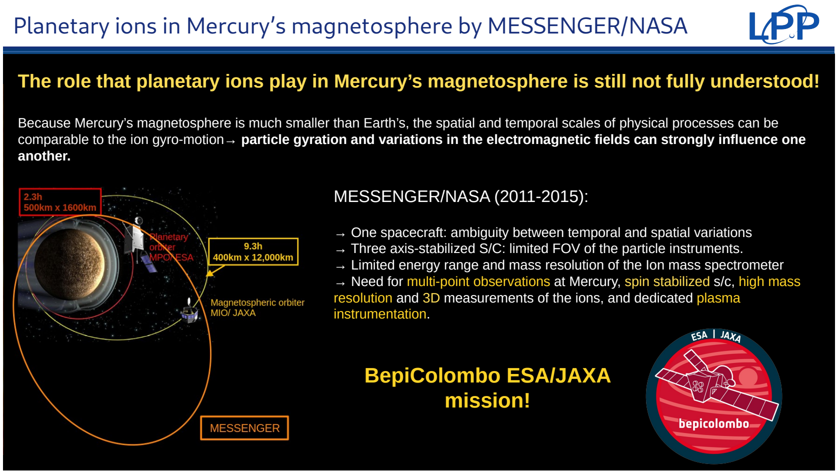
Mercury is the innermost planet in our Solar System, and it's the only planet other than Earth that has an intrinsic magnetic field; however, it's weaker than Earth's but also, unlike Earth, Mercury has an extremely thin exosphere. It is composed mainly of hydrogen, helium, oxygen, sodium, potassium, and other metallic species and originates from the surface of the planet. Those exospheric neutrals get ionized under the effect of the solar EUV radiation, and subsequently they are trapped along the magnetic field around the planet and form those ions that circulate in the magnetosphere of Mercury. Those ions can escape to the solar wind, but some of them return to the surface in the process called ion recycling. The very close proximity of Mercury to the Sun and the weak magnetic field lead to a very dynamical and highly compressed magnetosphere in comparison to Earth, and, in addition, the lack of an atmosphere leads to a much more direct space weathering of the surface, especially under extreme solar-wind conditions. There is very tight coupling between the solar wind, the magnetosphere, the axis, and the surface of the planet.

The first observations of the ion compositions in the magnetosphere of Mercury were performed by the mass spectrometer *FIPS* on board the NASA Orbiter *Messenger* (*MErcury Surface Space EnviroNment GeochEmistry and Ranging*). That identified the presence of light ions, such as protons and He^+, in the magnetosphere, but also the presence of heavier ions, maybe oxygen-group ions and sodium-group ions, and *FIPS* also showed the spatial distributions of those ions. It revealed that the He^+ ions have a more even distribution around the planet, implying probably a much more uniform source of those species *via* evaporation. However, the heavier ions, maybe the sodium-group and the oxygen-group ions, showed a non-uniform distribution around the planet with distinct peaks around the planet.

Despite those very important observations, *FIPS* could not really distinguish the detailed ion composition within those sodium-group ions because of the low mass resolution. So the sodium-group ions included sodium ions, magnesium ions, potassium, and calcium. It was not possible to measure the cold ions below 100 eV per charge.

We still have a lot of unanswered questions and mysteries to solve. For example, the detailed ion composition around Mercury and the link of those ions to the surface, and also the role that those planetary ions play in Mercury's magnetosphere — especially since, as I mentioned, Mercury's magnetosphere is much smaller than Earth's, and so the spatial and the temporal processes at Mercury can be compared to the ion gyro-radius, and the particle gyration and variation in the intermagnetic fields can strongly influence each other.

NASA's first orbiter *Messenger* was only one spacecraft, so it was impossible to disentangle the spatial from the temporal effect. It was also a three-axis stabilized spacecraft, so we have a very limited field of view of the particles, naturally because the spacecraft is not spinning. In order to understand in detail the coupling between the solar wind and this highly dynamical magnetosphere and also to understand the feedback of the surface, we need to have at least two-point measurements. We need to have spin-stabilized spacecraft as well to be able to



Planetary ions in Mercury's magnetosphere by MESSENGER/NASA

The role that planetary ions play in Mercury's magnetosphere is still not fully understood!

Because Mercury's magnetosphere is much smaller than Earth's, the spatial and temporal scales of physical processes can be comparable to the ion gyro-motion→ **particle gyration and variations in the electromagnetic fields can strongly influence one another.**

MESSENGER/NASA (2011-2015):

→ One spacecraft: ambiguity between temporal and spatial variations
→ Three axis-stabilized S/C: limited FOV of the particle instruments.
→ Limited energy range and mass resolution of the Ion mass spectrometer
→ Need for multi-point observations at Mercury, spin stabilized s/c, high mass resolution and 3D measurements of the ions, and dedicated plasma instrumentation.

BepiColombo ESA/JAXA mission!

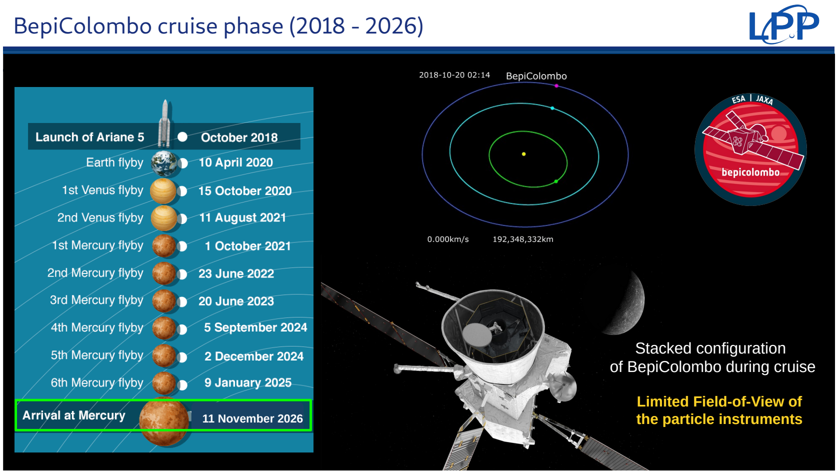
Fig. 4
Orbits of *MPO* and *Mio*.

have a 3-D distribution of the particles and we also need to have high mass resolution for the spectrometer to distinguish the heavy ions from each other, and, of course, we need to have a dedicated plasma instrument to understand in detail the plasma processes in Mercury's magnetosphere and the effect on the atmosphere and the surface, and *vice versa*. That is the goal of the *BepiColombo*, ISAS/JAXA mission.

This is just a sketch here [Fig. 4] showing the orbits of *MPO* (*Mercury Planetary Orbiter*), ESA's contribution, and the magnetospheric orbiter's (*Mio*) contribution. And just for comparison, I added here the *Messenger* orbit, which has a much larger eccentricity, and so with *Messenger* we could observe more closely, for example, the northern pole, but we could not really observe the southern pole and the southern hemisphere.

With those two orbiters, we hope to understand and characterize this coupling between the solar-wind magnetosphere and the surface of the planet. As Go has mentioned, we are currently ending the cruise phase and we are preparing for the orbit insertion in November next year [2026]. During those eight years, *BepiColombo* has performed nine fly-bys, first one around Earth, two around Venus, and six around Mercury, the last one being earlier this year [2025] in January. During that cruise phase the configuration of the spacecraft is very particular: it's in a so-called stacked configuration. So you can see here [Fig. 5] the *Mio* spacecraft inside the *MOSIF* sunshield attached to the planetary orbiter *Mio* and both of them on the *Mercury Transfer Module*; despite that very particular configuration and despite the fact that some of them are not operational, most of them have a lot of opportunities for nominal observations. For example, the particles instrument onboard the magnetospheric orbiter has a field of view which is very limited and we are looking into the sky within just one or two windows. Despite those constraints, we have very interesting observations that give us a preview of the very exciting results that we will get after orbit insertion.

This is just the trajectory of only the Mercury fly-bys here [Fig. 6], in the meridinal x–z plane and in the azimuthal x–y plane. So here you see only five fly-bys — in fact the fifth one actually does not appear here because the closest approach was further away from Mercury. The first three fly-bys were equatorial and they were extremely important for us because in the nominal phase, as I showed earlier, the orbits of *MPO* and *Mio* are polar, so those were



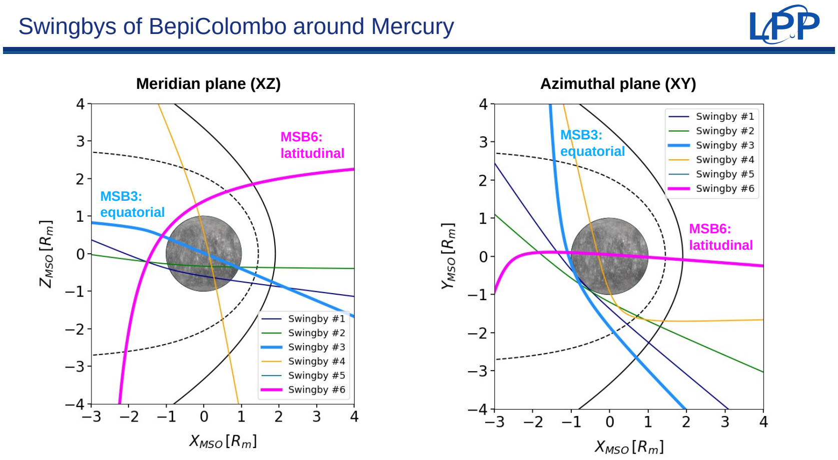
BepiColombo cruise phase (2018 - 2026)

Launch of Ariane 5	October 2018
Earth flyby	10 April 2020
1st Venus flyby	15 October 2020
2nd Venus flyby	11 August 2021
1st Mercury flyby	1 October 2021
2nd Mercury flyby	23 June 2022
3rd Mercury flyby	20 June 2023
4th Mercury flyby	5 September 2024
5th Mercury flyby	2 December 2024
6th Mercury flyby	9 January 2025
Arrival at Mercury	11 November 2026

Stacked configuration
of BepiColombo during cruise

Limited Field-of-View of
the particle instruments

FIG. 5
Configuration during cruise phase.

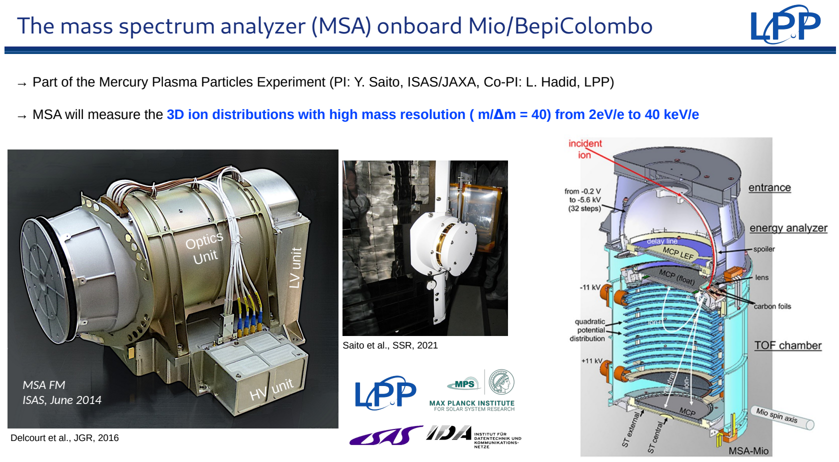


Swingbys of BepiColombo around Mercury

FIG. 6
Swing-bys of *BepiColombo* around Mercury.

the only kind of opportunities that we could have on an azimuthal cut of the magnetosphere of Mercury. On the fourth fly-by and the sixth fly-by, they were highly polar as you can see in the meridian plane, but different. The sixth fly-by, for example, crossed from the day side to the night side. And what I will be showing later are the observations from one equatorial fly-by, the third one, and one highly polar fly-by, the sixth one.

I will show you mainly observations from the *MSA* onboard the magnetostatic orbiter *Mio*. It's part of a particle consortium, and *MSA* is a time-of-flight spectrometer and the goal is



The mass spectrum analyzer (MSA) onboard Mio/BepiColombo

→ Part of the Mercury Plasma Particles Experiment (PI: Y. Saito, ISAS/JAXA, Co-PI: L. Hadid, LPP)

→ MSA will measure the **3D ion distributions with high mass resolution (m/Δm = 40) from 2eV/e to 40 keV/e**

MSA FM
ISAS, June 2014

Delcourt et al., JGR, 2016

Saito et al., SSR, 2021

FIG. 7
The MSA aboard *Mio*/*BepiColombo*.

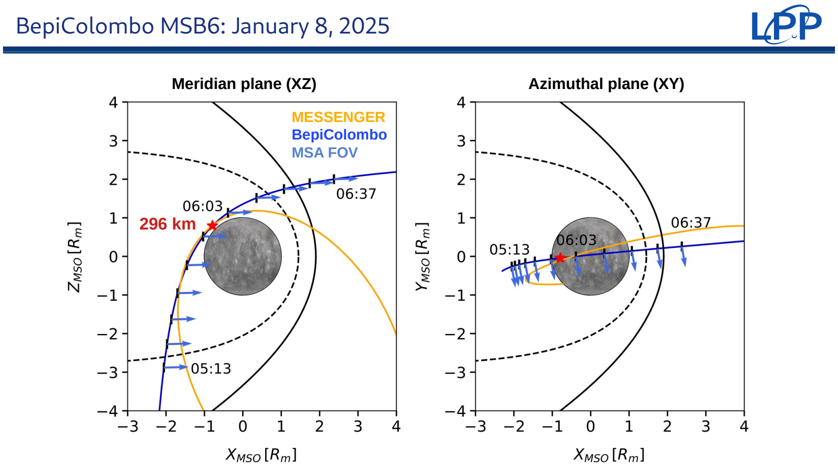
to measure the 3-D distribution functions of the ions with a very high mass resolution and between a few eV and 40 keV; it can actually can be seen as a mini consortium because it's an international collaboration between different institutes. In LPP we have developed the optics unit and then Max Planck Institute provided the high-voltage power supply, ISAS/JAXA provided the detector-electronic units inside the low-voltage box here, whilst IDA provided the DPU.

This is just a sketch [Fig. 7] here showing the cut, and you can see the inside of the optics in it, which consists of an electrostatic analyser that filters the ions with specific energies. And then we have a time-of-light chamber with a very particular design that allow us to have Dirac functions for the ion species and distinguish between sodium and magnesium, for example. We have two electron analysers, one ion analyser, and the mass-spectrum analyser. I will show you observations from those four, but also we have a high-energy–ion detector, a high-energy–electron detector, and an energetically neutral analyser as well. The PI is Yoshifumi Saito from ISAS/JAXA.

The third Mercury fly-by occurred on 2023 June 19. During that fly-by *BepiColombo* crossed the magnetosphere of Mercury from the night side to the day side and from dusk to dawn. And the closest approach was about 235 kilometres. What was particular about that fly-by is that it offers a synoptic view of the large-scale structure and ion composition of Mercury's magnetosphere.

As expected, the energy–time spectrograms for ions and electrons are very similar; then we have the electron observations. I do not have time to go into all the details here, but, by looking at the particle data and the ions, we could distinguish the boundary crossings as *BepiColombo* flew by Mercury. We could actually see the inbound bowshock crossing.

Looking at the very narrow-band signature due to the outgassing of the spacecraft, we could see a small jump at the inbound bowshock crossing. But we also see a clear boundary which is the inbound magnetopause crossing, after which we see a clear dispersion signature in the ions ranging from a few tens of eV per charge up to 40 keV, and we interpreted that region as the low-latitude boundary layer. Then as *BepiColombo* approached Mercury around the closest approach, the ion detectors observed a very clear signature of about 20-keV ions.



BepiColombo MSB6: January 8, 2025

Fig. 8

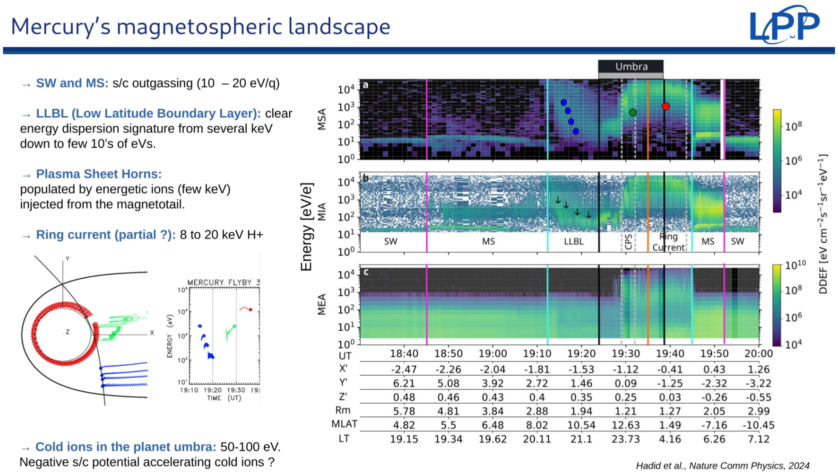
Sixth Mercury fly-by.

We interpreted those as the detection of a partial ring of a ring current; whether it's partial or full, it's very hard to tell, and it is still debated. We need to wait until we get the nominal phase to study that in detail.

Now in addition to this large-scale picture of Mercury's magnetosphere and different regions, the goal of *MSA* we also want to pursue is to characterize the ion composition, but during the cruise phase we are operating in low mode, so we have that information integrated over only about 17 minutes and so we have the information of the ion composition but integrated along six segments.

And along those 17 minutes or so after the low-latitude boundary layer inside the magnetosphere, *MSA* detected cold ions about few 100 eV/e, mainly protons but also alpha particles, and also some signatures of heavier ions including sodium, and a very weak signature of potassium or calcium ions. After this closest approach here the instrument detected signatures of energetic atoms, about a few KeV protons and He^+, but also sodium ions and some heavier ions. Now this was actually for the third fly-by, which was more of an equatorial view of the magnetosphere. Here I want to show you observations from the fly-by which occurred earlier this year in January [Fig. 8]; the trajectory was completely different; it was highly polar. *BepiColombo* crossed dawn to dusk and from night side to day side.

This slide [Fig. 9] shows a latitudinal-cross-section observation of Mercury's magnetosphere, specifically the centre of its plasma-sheet region, where we clearly detected cold protons and ions down to 10 eV per charge for the first time cold potassium and sodium ions very clearly and with distinct distributions along the central plasma-sheet region. But we also see that the plasma is highly dynamic and what I want to show here is that we do observe this kind of dispersion signature in the ion data. In the first panel, we observe heavy elements and protons recorded while *BepiColombo* was connected to closed magnetic-field lines; these specific signatures are consistent with those typically observed at Earth. They represent bouncing ion clusters, so ions that bounce back and forth on the closed magnetic-field line while drifting around the planet. And it's the first time that we could see them at Mercury. So in the end, similar processes are induced in the terrestrial planets and those actually reflect some injections from the tail towards the polar latitudes of the planet.



Mercury's magnetospheric landscape

→ **SW and MS:** s/c outgassing (10 – 20 eV/q)

→ **LLBL (Low Latitude Boundary Layer):** clear energy dispersion signature from several keV down to few 10's of eVs.

→ **Plasma Sheet Horns:** populated by energetic ions (few keV) injected from the magnetotail.

→ **Ring current (partial ?):** 8 to 20 keV H+

→ **Cold ions in the planet umbra:** 50-100 eV. Negative s/c potential accelerating cold ions ?

Hadid et al., Nature Comm Physics, 2024

Fig. 9

Mercury's magnetosphere.

I mentioned ions, but we also have the electron observations. Those are the time spectrograms for all the five. With five different fly-bys, we can say that we have five different magnetospheres.

The *BepiColombo* cruise phase was not limited to the planetary fly-bys; it also it contributed to heliospheric science. And we showed the importance of the cruise science and we could study the evolution of the properties of the solar wind taking advantage of the presence of operational spacecraft in the inner heliosphere with *Parker Solar Probe* (*PSP*) and *Solar Orbiter*. *BepiColombo*, and other L1 probes and so we could study, for example, the evolution of turbulence as a function of the Sun as observed by *BepiColombo* and then *Solar Orbiter*. We had a recent paper, an overview of all the solar energetic-particle events, CME events observed by multiple spacecraft including *BepiColombo* and that's another very important example. It seems that it's the strongest SEP event for the solar cycle 2025 detected by *PSP* and *BepiColombo* and other spacecraft further away from the Sun.

During the cruise phase, we had exciting observations around Earth, Venus, and Mercury. We have at least 50 publications from the fly-bys alone. Not only has *BepiColombo* showed the importance of cruise science to be able to perform measurements in the solar wind when there is no dedicated mission at those distances, and it's important not only for calibration purposes of the instrument, but those observations gave us a tantalizing preview of all the exciting science that could be done during the normal phase, so we are ready now to explore Mercury. Thank you.

The President. Steven, your hand is up before I even ask!

Professor Steve Miller. The light species hydrogen and helium. Are they being captured from the solar wind or are they breakdown of molecules from the surface of Mercury?

Dr. Hadid. It's very difficult to distinguish the origin of the protons, whether it's the solar wind or the surface. We know that there's hydrogen on the surface, but it's very difficult to distinguish the He$^+$; it can evaporate from the surface, but it can come from the interstellar medium.

Professor Monica Grady. Just to follow up on that question from Steve, can you detect deuterium?

Dr. Hadid. I don't think so with *MSA* because we don't distinguish the charges of the ions. We assume it's a singly charged ion.

Professor Grady. But it would have a mass of two. You're measuring ^{2}H then, are you?

Dr. Hadid. Good question!

The President. I wondered if with the cold ions that you see, is the lower limit set by the spacecraft potential?

Dr. Hadid. Yes, actually it will be very challenging for us to observe a few eV per charge. It's a big question.

The President. I just wondered if the appearance of cold ions in certain regions was actually a spacecraft-potential modulation.

Dr. Hadid. In the first fly-by in the shadow region, the spacecraft potential got very low and then it was very interesting because of the change of the potential of the spacecraft; it became negative. So we could actually start tracking. In the end they are accelerated.

The President. Ultimately, I love the boundary-layer dispersion, that there's all sorts of information you can get out of that. Thank you very much indeed. That was lovely. [Applause.]

Our last speaker today is Dr. Paola Pinilla from Mullard Space Science Laboratory. She obtained her BSc and MSc in her country of origin, Colombia. She did a PhD at Heidelberg University in Germany and held several positions before joining UCL, including: a post-doctoral researcher at Leiden Observatory, a NASA Hubble Fellowship at the University of Arizona, and an independent group leader at the Max Planck Institute for Astronomy. Her research interests focus on understanding the first steps of planet formation using theoretical models and observations of young stars. Paola also enjoys working on topics related to equality, diversity, and inclusion. She was recently awarded an ERC starting grant, the 2024 New Horizons in Physics Prize, and the 2025 Royal Astronomical Society Price Medal. So I think you're going to tell us about 'How planets are made of star stuff'. Thank you.

Dr. Paola Pinilla. Thank you so much for the invitation. It's a great honour for me to be here and thank you so much also from the planet-formation community for giving us the Price Medal. Today I'm going to tell you about what I have been working on in 15 years of research since I started my PhD.

It was only three decades ago that the only planets that we knew were those in our Solar System. The Solar System is actually a quite well-organized system; it has the terrestrial planets inside, then the giant planets and the ice giants. It was in 1995 that we discovered the first exoplanet around a solar-type star and that was 51 Pegasi b. That really opened our eyes to a new world because that planet is as massive as Jupiter, but much closer to the star than Mercury to the Sun, so it's a hot Jupiter. We don't have such planets in our Solar System and since then, the number of planets that have been discovered has increased enormously.

In 2009 the campaign was launched with *Kepler*, and by 2016 we already had more than 1000 exoplanets discovered. In 2018 we had the launch of *TESS* (*Transiting Exoplanet Survey Satellite*), another space mission using the transit method to discover exoplanets. Now in 2025, we have more than 6000 exoplanets. Many of those exoplanets don't have a representative in the Solar System, such as hot Jupiters. There are planets like mini-Neptunes and super-Earths that also are very common but we don't have such planets. We believe that, at least in our Galaxy, every star hosts a planet. Nevertheless, we still don't know how planets form. I like to think about planets like like human beings: we are very diverse and our properties and who we are probably depends our infancy. We are trying to do that in the field of planet formation and to understand where they're born, how they are born, and how the properties and the physical processes of those first steps of planet formation impact the diversity that we see in the exoplanets.

Everything starts with a molecular cloud and in those molecular clouds some regions can become very dense and that happens when there is a gravitational collapse, so the molecular cloud cannot be pressure-supported any further. As a result of that collapse, a protostar is formed and in that process, thanks to the conservation of angular momentum, the disc remains around that new star. Those are called protoplanetary discs and it is in those discs we believe planets are formed. The lifetime of that disc is around one to ten million years and after it dissipates we have a planetary system like our Solar System. The star will continue evolving, and eventually, for example, it might end in a supernova explosion that will enrich the interstellar medium and complete the cycle.

We cannot reverse the clock of our Solar System, so to help us to understand our planets and other planets we need to study young stars that are a million years old that have those discs. We believe that initially they have the properties of the interstellar medium, so 99% of it is molecular hydrogen and 1% of that material is dust and it should be cosmic dust. That consists of sub-micron-sized particles that collide and then grow to pebbles, millimetre- then centimetre-sized particles, and then eventually to planetesimals, asteroids, and planets.

That disc dissipates by different mechanisms and observations have shown us that they live between five and ten million years and that the giant planets like Jupiter should form before the disc is gone, so before all the gas is accreted onto the star. Other planets form also within that time, but they still have time to form later after the discs dissipate. Observations have shown us that those discs can have a diverse range of sizes up to 1000 astronomical units (AU) whilst the most common ones are around hundreds of AU and because of that, they span a large range of temperatures, from thousands of kelvins when close to the star to a few kelvins at the edge. Because of that we can observe in a large range of wavelengths from optical to centimetre wavelengths; that's one of the very cool things about the first steps of planet formation, because actually we can see those interstellar dust particles and those dust patterns because the dust dominates the disc opacity and most of the information that we have from planets forming in those days comes from the dust emission.

A disc is shaped like a piece of cheese: it's not completely flat, but it's wedge-shaped. What we believe is that small grains and micron-sized particles are everywhere following the gas. They can be in the surface of the disc because turbulence pushes those grains up to the surface and the light that comes from the star will reach the surface and the particles that are there, that are small, will scatter. We can actually see the distribution of micron-sized particles through the optical wavelengths to the near infrared from scattered-light observations.

Observations of protoplanetary discs with the *Very Large Telescope* with an instrument that is called *SPHERE* (*Spectro-Polarimetric High-contrast Exoplanet Research*) show beautiful structures in these discs such as spiral arms and rings and gaps and some shadows. On the other hand, we can also observe the patterns in the disc. They are expected to be settled to the mid-plane and for that we need to observe the disc at millimetre and centimetre wavelengths and therefore we use radio telescopes. The *Atacama Large Millimeter Array* (*ALMA*) in Chile has revolutionized the field. There are observations with *ALMA* of these protoplanetaries showing that they are not smooth, but they also have quite a lot of sub-structures. Because we can observe those processes of planet formation, those first steps of planet formation from the growth of micron-sized particles to millimetres, we can actually test our models with the observations.

I have been working on modelling: how do particles grow and move in a disc? We model together the transport of the grains and the collisions of those particles, because when particles move in the disc, they can meet other particles, and depending on the relative velocities between particles, they will stick, they will fragment, or they will bounce. There are different physical processes that can move the particles in a disc such as Brownian motion, like here in this room we have small particles that are moving randomly. That happens also in discs but it affects only the very small grains. Then we have turbulence and the grains can move vertically and radially due to that turbulence. We have the effect of gravity that moves the grains towards the mid-plane of the disc and then we have a very important physical phenomenon that is called radial drift. That comes from the fact that the gas is pressure-supported while the dust is not. So while the dust is moving or trying to move in

Keplerian velocity, the gas doesn't move, and as a consequence of that there is a constant head-wind that particles feel and they lose angular momentum and move towards the star.

That was known as the radial-drift barrier in planet formation because the drift time-scales are much faster or they are much shorter than the times that the particles need to grow to pebbles or planetesimals, so we didn't know how planets actually form or how to overcome the radial-disc barrier. And just to show you how that looks, what you will see in this calculation is a particle that starts small in the interstellar medium, 80 AU from the star.

This particle grows due to collisions, it grows in the disc, but once it reaches a certain size, it goes to the star very fast. That was the drift problem and we didn't know how to solve it and in 2012 I was trying to solve that barrier. We propose that the disc, instead of having a smooth pressure gradient, because it's the pressure that changes, that produces variations, we have variations in the pressure that can retain particles, and this is a simulation of gas evolution. It's the grain size and then it's distance from the star, but now we have a lot of grains. So we have a dust density and we have a disc that is not smooth, but it has variations of pressure and in that case, those variations of pressure comes from the interaction of the disc with the magnetic field from the star, and at million-year time scales, we do have grains trapped in those regions of high pressure. We propose that if we have high angular resolution at millimetre and sub-millimetre wavelengths of that type of structure, we will see rings and gaps around the young star, and as I showed you before, that is what we observe now with *ALMA*.

Another thing that can create those pressure pumps is that we have already planets in the disc. If a planet is very massive, it will create a huge gap in the gas surface density. Probably this one is. The planet located at 28 AU is a giant planet and we have a huge gap in the gas surface density that creates a gigantic pressure trap outside. As before, we created synthetic images of that type of simulation and we predicted that if a giant planet was there in the disc we would see a ring-like structure around the star. In observations with *ALMA* one can see how similar they are. We use so-called transition discs that have large cavities to look for baby planets that are forming in those discs.

You can imagine how excited I was in 2018 when we actually discovered the first protoplanet inside a disc and that was in the system called PDS 70. The *ALMA* observation of that disc shows a ring-like structure with two giant planets and emission from a circumplanetary disc. It is at this point where moons are forming. We are still looking for baby planets because they give us the chance to look at planet formation in action.

In summary, what I have explained so far is that we have been focussing on understanding the first steps of planet formation. The initial conditions of the disc are that particles start with micron-sized particles which then collide and grow to bigger objects. We know that we have disruptive collisions and small grains are replenished continuously in the disc and we see from scattered-light observations that we have plenty of small grains in those discs. The ones that grow are expected to drift very quickly toward the star, unless we have a particle trapped in the disc that can come from different regions and we study in detail what those physical phenomena can be that can create those pressure traps. It could be planets, but it could be other phenomena. We came from giant planets by the agglomeration of those objects: if a giant planet is formed, then it can itself be a particle trap because it can create a gap in the disc and help with the formation of the next planet.

I'm going to give you two beautiful examples of that. One comes from recent observations of the *James Webb Space Telescope* and that gives us amazing spectra of the inner regions of protoplanetary discs in the mid-infrared where water emits a different frequency, so we can actually observe the amount of water that is inside the first AU of these protoplanetary discs. One of the amazing results that we have obtained with these data from *JWST* is that there are compact discs that don't have a structure, don't have traps which show high water abundances in the inner disc. That agrees with the fact that if pebbles that are ice-coated are drifting towards the star, once they reach the snow line — that is the region where the water evaporates — they enrich the inner part of the disc with water and we are observing that. On the other hand, discs that show traps and that are extended show low water emission, consistent with the idea that pebbles are being retained in the outer parts of the disc. So those pressure traps have a direct impact on the composition of planets that are forming in regions where the Earth was formed.

Another result is that those traps can also help for the formation of macro-molecules that is very important for matter that is needed for hosting life. What happens is that in those traps fragmentation of particles also happens and those small grains can go to the surface of the disc because they have direct irradiation from the start, they have the right temperature to form those complex molecules. Observations have shown that there is a correlation with the emission of complex molecules and the locations and the existence of those traps. It seems that they really play a role also in the conditions for hosting life.

I'll finish with a short description of a couple of large programmes that I have been involved with in the last years. One is the *ALMA* large programme AGE-PRO which consists of more than 100 observations to trace systematically the evolution of the gas, its mass and size throughout the lifetime of protoplanetary disc. Gas is the main component of discs and is very important for the formation of giant planets, but it's very difficult to observe directly. The reason is because the main component is molecular hydrogen, but it's very difficult to excite at the temperatures of discs and because it lacks a dipole, we cannot really directly observe it. We rely on other molecules that are also abundant like CO_2 to understand how the gas is distributed in the disc, but there are a lot of chemical reactions happening in that disc. We need to observe different molecules to be able to reconstruct how much gas emission there is.

Why is gas so important? Many of the processes that I mentioned before affect the dust; the transport and the collisions depend on the gas distribution because all the dynamics of the particles is dominated by the gas. We need to know how much gas there is in those discs to understand all of those dynamics that I showed you before. In addition, it tells us if we can form gas-giant planets, ice giants, super-Earths, or other type of planets in that disc.

For that we selected 30 protoplanetary discs that are in different star-forming regions that have different ages. We selected ten in Ophiuchus that are younger than one million years, ten in Lupus that are between one and three million years, and ten in Upper Scorpius that are the latest phases of protoplanetary discs. We narrowed the spectral type down to solar-type stars between 0·3 and 0·8 solar masses, so those stars will evolve. We didn't have any binaries in the system to bias our sample. Some young discs in Lupus have masses that are higher than the minimum solar nebula, meaning that they can form systems like our Solar System and several of the Ophiuchus and Lupus areas have masses between Jupiter and the minimum-mass solar nebula, meaning that they have the potential to form planets like Jupiter and also some in Lupus, but they don't have any masses as high as Jupiter.

In this year we got another large programme with *ALMA*. It's called DMOST and is focussed on understanding the discs around M dwarfs as those are very important because they are the most common stars in our Galaxy. The frequency of Earth-sized planets in habitable zones appears to be higher in M dwarfs, so it's very interesting to understand also what are the first steps of planet formation around those objects. What is also very interesting is that some giant planets have been found around those objects, even though it's very difficult to explain the formation from models. In this project we are going to observe 14 protoplanetary discs; that is a small number but it's because they are very small and faint. What we want to do is to measure the gas and dust disc size and compare with models of the vertical structure. That type of information will tell us what kind of planets can also form in that disc. We will also measure the gas mass and are looking forward to getting those observations. We just got the *ALMA* proposal accepted, so it will take some time to get the observations.

The exoplanet field is growing; we have so many space missions that will increase our knowledge about exoplanets. The UK is highly involved with missions like *PLATO* and *Ariel*, and *Gaia* also will give us DR4 next year. That will supply astrometric information and will perhaps be enough to detect thousands of cool giant planets. The future for exoplanets is very bright in the next decade.

We have more than 6000 exoplanets with a large range of properties and so far we really don't know what is the range of that diversity. We want to understand the first steps of planet formation to see if that has an impact on what we observe in exoplanets. One of the main results is that those are not smooth and there is sub-structure and those sub-structures are also diverse. So they can meet even later with the diversity that we see also in exoplanets. Those sub-structures have actually a key impact on the composition of the inner disc where planets like Earth are being formed, and also the origin of micromolecules in discs that are essential for the formation of life.

The President. Questions for Paola?

Dr. Daniel Heyner. I thought the gas at the mid-plane of the protoplanetary disc wouldn't be ionized, so I was surprised to hear that magnetic fields would be responsible creating pressure variations. Could you elaborate on that?

Dr. Paola Pinilla. I know there is no answer to that. It is related also to the dust because the dust can transport ions in the disc, especially very small dust and that can help to reionize the disc. So that's why it's important to understand the fragmentation process of particles because depending on that you have different small grains within the disc that can change the disc ionization. So yes, ionization, especially because of the transport of ions to the small grains, can create pressure variations.

Dr. Ted Parton. Thank you. Excellent talk. Is it possible that you think that between stars there are small gas and dust clouds that are capable of forming planets, the cold planets that we may never see? You know *JWST* has seen some JUMBOs [JUpiter-Mass Binary Objects] which are warm. But is it possible that there's lots of material out there which is never big enough to form a star and so it's never going to get hot enough for us to detect?

Dr. Pinilla. That's an interesting question. That is something that we have observed too, there are free-floating planets with masses of five or ten Jupiters and we believe they form like stars and they can actually be gravitationally bounded to a system. That would be a way to form those very cold giant planets very quickly. They would need to be very massive for that to happen and we don't see in those observations of the gas that the discs are so massive. I would say that, if it's possible, it is likely the same process as star formation by which they form. They are ejected and potentially again bounded to a system.

Professor Richard Ellis. It's possibly a related question. This age programme sounds very exciting, but how accurately are you estimating the ages and what's the method, once you get down to ages of less than two million years? You need very precise ages — are you assuming the age of the star?

Dr. Pinilla. Yes, that's a very important question. So we calculate the ages for each system, but there is a large uncertainty. It could be of the order of a million years but because we observe different star-forming regions and we see the accretion rate of that fraction in that star-forming region changing. So we know that there are young star-forming regions and intermediate star-forming regions — the whole cycle.

Professor Phil Charles. There was one comment in one of the slides which I was intrigued by, which is that you said that Earth-sized planets are more common in the habitable zone in the lower-mass stars, and the implication then is that it's less in the case of higher-mass ones like for instance our own. Would you like to speculate on what might be causing that and why it's so different?

Dr. Pinilla. That's a good question; I would need to think about that. It could be biassed, but I understand that that argument is corrected by completeness. Yes, we are biassed by planets that are closer to the stars by the transit method or the velocity method.

Professor Charles. Just a quick follow-up on the related question. This is not my field at all, but the one thing that I did believe happened is that those gas clouds don't just nicely produce one star with a planetary system, that we see many multiple-star formations and huge interactions with them, and yet you have those lovely systems coming out. Things are a lot more complicated than that, aren't they?

Dr. Pinilla. Observations have shown us that binarity increases with the stellar mass. So we expect multiple systems to be more common for stars that are more massive than our Sun, and less common for solar-type stars and for that reason we try to avoid binaries because they actually affect a lot of planet formation. But it's an interesting topic in itself to try to understand how planets form around circumbinary discs. We do all suspect interactions and when we see what you see here is dust, so you don't see it so clearly, but when we see the gas, we can see a lot of potential interaction with encounters in the star-forming regions. Now with *Gaia* that we know locations and velocities with high precision, we can try to go back in time and see how many interactions have happened in this business.

The President. I look forward to the Pinilla–Charles correction to the Drake equation. [Laughter.] Thank you so much. Just a couple of announcements. The licensing situation is not getting solved but it is close to being. It turns out that all our neighbours in the courtyard have a licence, they just didn't tell us, so we're on it, but it's taking time. The next Open Meeting will be on Friday the 9th of January. You are all welcome to attend. I think we should just end with applause for a wonderful set of talks today. [Applause.] Thank you everybody, I look forward to the next meeting.

THE REORGANIZATION OF THE UK ASTRONOMICAL OBSERVATORIES — 'OBSERVATORY WARS'

By Ian Robson

One of the key events in the history of UK ground-based astronomy was the closure of the Royal Greenwich Observatory (RGO) and the Royal Observatory Edinburgh (ROE), to be replaced by the UK Astronomy Technology Centre (UKATC) located on the site of the ROE on Blackford Hill Edinburgh. Although that took effect in the late 1990s, the discussion surrounding the status of the two Royal Observatories had been raging for over a decade beforehand. This is a personal compilation of the history and the reasoning behind that major upheaval, using archival records of the time where available, open-source data, input from colleagues, and personal involvement. I have striven to ensure it is as accurate as I can determine.

Introduction

As we will see, funding, or lack of it, lies at the heart of all the decision-making regarding current and future astronomy developments and as such, there has always been pressure on financial budgets. My introduction to the management side of supporting UK astronomy was with my appointment to the *United Kingdom Infrared Telescope* (*UKIRT*) Advisory Committee in 1978. That provided advice to the funding agency, SRC (Science Research Council), regarding the construction of the telescope, which was led by the ROE, and its subsequent operation on the Big Island of Hawaii. *UKIRT* opened to the community in 1979 and subsequently I became Chairman of the *UKIRT* Users Committee from 1980–83. That began a long-standing link with the Royal Observatory Edinburgh.

At the same time (1980–83) I was appointed Chairman of the Astronomy II Committee. That funded the astronomy research grants to universities, new projects, and support for the 'establishments' — the two Royal observatories: the RGO and the ROE, the former being situated at Herstmonceux, Sussex. Also funded were small sections of the Rutherford Appleton Laboratory (RAL) at Harwell. In turn, the two Royal Observatories supported the telescopes on their 'island sites', in Hawaii and Australia for the ROE and the Canary Islands (La Palma) for the RGO. The funding was primarily to support the day-to-day operations of the telescopes but additionally, and critically importantly, their new instrumentation. Hawaii hosted the newly commissioned 3·8-m-diameter *UKIRT* infrared telescope, located on the summit of the 14 000-ft dormant volcano of Mauna Kea, while on La Palma, at the much lower-altitude site of the Roque de los Muchachos Observatory, the *Isaac Newton* optical telescope (*INT*) was located. The *INT* had been moved from Herstmonceux in 1979 and as part of the relocation was provided with a new 2·54-m-diameter mirror made of Zerodur (a new material of very low coefficient of thermal expansion) rather than the original 98-inch Pyrex mirror. During that period, Professor Alec Boksenberg was Director of the RGO and Professor Malcolm Longair was Director of the ROE. Malcolm was also Regius Professor of Astronomy at Edinburgh University and Astronomer Royal for Scotland. The La Palma site would be the future home for the new 4·2-m-diameter optical telescope, the *William Herschel Telescope* (*WHT*), which would be commissioned in 1986.

In 1981, overall funding for astronomy research was provided by the Science and Engineering Research Council (SERC), which was formed out of the Science Research Council. The SERC was a UK governmental, non-departmental public body (NDPB). The astronomy funding was passed down to the Astronomy and Space Research (ASR) Board, which, to a first approximation, split the funding between ground-based and space-based astronomy research. The Astronomy II Committee reported to the ASR Board and as Chairman I was a member of the Board, and my role was essentially to fight for the ground-based astronomy community — and that was always a fight due to lack of funding. In due course, following a management re-organization the ASR Board morphed into the Astronomy and Planetary Sciences (APS) Board, which funded ground-based astronomy through the Ground-Based Programme Committee (GBPC), the Studentships and Fellowships panel, and the Theory and Computational panel.

The role of the two Royal Observatories and the location of the RGO

In the mid 1980s there was severe pressure on budgets across the whole of SERC. Possibilities of relieving that pressure for the ground-based astronomy budgets translated into a number of attempts to merge the two Royal Observatories. In particular, that focussed on what to do with the RGO when it left Herstmonceux, which had become too expensive to maintain and its telescopes were obsolete following the move of the *INT* to La Palma in 1979. Indeed, those budgetary pressures were so serious that SERC even set up a committee under Sir John Kendrew to review the value and cost of CERN membership. That recommended a cut of 25%, which could not be implemented.

In the spring of 1985, SERC set up a Working Group under the Chairmanship of Sir John Kingman. That was to re-evaluate the rationale of having two Royal Observatories for ground-based astronomy and to comment on whether to relocate the RGO to a university or to merge with the ROE, with all options being open for consideration. However, that immediately hit a snag when Professor Donald Lynden-Bell, the President of the Royal Astronomical Society (RAS) at the time, complained that there were no practising optical astronomers on the panel. After some to-ing and fro-ing and concern about being the only active research astronomer on the Group (additional astronomers not being allowed), Professor Richard Ellis agreed to serve, but only as an advisor. The existence of that Working Group caused significant alarm in the UK community and Sir John Kingman asked the RAS President to seek community input, which was received in a number of letters. Both the ROE and Daresbury Laboratories suggested hosting the RGO at their sites. The Working Group's final report was released in 1985 December and was endorsed by SERC Council in 1986 January. The recommendation was that the RGO should be moved from Herstmonceux closer to a university, or be merged with the ROE at Edinburgh with some of the technical and engineering activities going to the RAL, which was already building the *James Clerk Maxwell Telescope* (*JCMT*).

SERC then invited UK university Vice-Chancellors to make bids to host the RGO. Eight bids were received, including from Cambridge, Manchester, Edinburgh, Oxford, and Durham. In 1986 March a shortlist of three bids was selected; Cambridge, Edinburgh (ROE), and Manchester. At about the same time the RAS conducted a Fellowship-wide survey and received the following responses: to move the RGO, yes or no? no (444) yes (242); if it has to move then to where: Cambridge (286), ROE (189), Manchester (164), elsewhere (152). After firstly favouring a merging with the ROE at Edinburgh, apparently very considerable pressure was brought to bear that resulted in SERC Council making the final recommendation in 1986 June that the RGO should move to a new site in Cambridge, with a target date of completion by 1990. That caused a large outcry in the community, letters to the press, and a campaign by Patrick Moore to 'Save the RGO'. However, the die was cast, the RGO would move from Herstmonceux.

The Ground-Based Plan: the future of UK ground-based astronomy

While all that debate was going on the scientific focus was directed towards the next generation of optical telescopes. SERC had set up the Large Telescope Panel, chaired by Professor Richard Ellis. That was charged with making the case for the UK to participate in a large (8-m-class) optical/infrared telescope. Following that review the GBPC set up a Panel under Professor Sir Alan Cook (Chair of the APS Board) to address the strategic long-term funding and opportunities for ground-based astronomy and planetary science. I was a member of the Panel, and it produced a crucial glossy report that was published in 1989 — the Ground-Based Plan. That was far-reaching and recognized that if the UK was to participate in future programmes and new facilities, it was inevitable that given the likely funding situation, current programmes and/or facilities would have to cease. Specifically, the Report recommended that support for new facilities should be focussed on the following: the completion of the second phase of the *MERLIN* radio interferometer — becoming *e-MERLIN* and with the additional large dish at Cambridge; around a 25% share of a Polar Cap (*EISCAT*) incoherent-scatter radar at Svalbard; at least a 25% share of a gravitational-radiation observatory; an 8-m optical/infrared telescope package including at least a 40% share of an 8-m-class telescope. To fund that 15-year strategic plan, the APS Board should set aside £2M each year, to be found from the existing programme if additional funding was not forthcoming. That plan was approved and clearly set out the principle that the UK must plan for access to the next generation of astronomical facilities and that current projects/facilities/activities may have to shrink or even close in order to provide the necessary funding. That was quite revolutionary because at the time the ground-based astronomy community had developed a reputation for always wanting new facilities but not being prepared to terminate existing and possibly life-expired telescopes. The inability to close the small Kottamia optical telescope in Egypt was a prime example that was often used to beat the astronomers around the head.

In 1988 I was appointed Chairman of the GBPC by the SERC Director of Science, Dr. Barry Martin, with a remit to implement the recommendations of the Ground-Based Plan. That position also made me a member of the Astronomy and Planetary Science Board. That was a time of tight budgets but also of future opportunities. Dr. Ian Corbett replaced Barry Martin in late 1989.

The move of the RGO to Cambridge and the future is Gemini

A key event for UK astronomy was the move of the RGO from Herstmonceux to a purpose-built, brand-new facility at the University of Cambridge, adjacent to the Institute of Astronomy (IoA). That began in 1988, and the new location was officially opened by the Duke of Edinburgh on 1990 June 14. With budgets being tight and a growing space-science programme, there was additional scrutiny on the 'fixed costs' within the astronomy programme. That focussed attention on the two Royal Observatories and their significant staff costs, including the support for the operational facilities in Hawaii and La Palma. (The Australian *Anglo–Australian Telescope* and the *UK Schmidt Telescope* are excluded from this narrative although the Schmidt did have an operational activity at Edinburgh in terms of support and a plate-measuring machine — *SuperCOSMOS*.) I remember a heated discussion at a GBPC meeting concerning the support from the RGO for La Palma and that subsequently resulted in an audit of the two observatories by the SERC Director of Science (Dr. Ian Corbett), the senior secretary (David Schildt), the GBPC secretary, Dr. Peter Fletcher (I think), and myself. In 1990 Professor Malcolm Longair left the ROE for the University of Cambridge and Dr. Paul Murdin from the RGO took over as Acting Director in 1991.

One of the key planks of the Ground-Based Plan was a significant share in a future 8-m-class optical/infrared telescope. Two possible options had appeared on the scene: the US-led *Gemini* Telescope Project, and a European Large Telescope, which would be at least 50% Spanish. The *Gemini* project consisted of two identical 8-m optical/infrared telescopes, one situated on Mauna Kea in Hawaii and a second on Cerro Pachon in Chile. The European Large Telescope was to be an 8-m optical/infrared telescope located on La Palma alongside the *WHT* and *INT*. That latter option was heavily supported by the RGO for obvious reasons. In the end a GBPC review panel opted for the *Gemini* proposal, although not without significant disagreement in the community. In the autumn of 1990 that recommendation was presented to the APS Board, which accepted it. The project was formally initiated to progress with further involvement in *Gemini* but without a legal agreement to join. [As a footnote, the 'European' telescope on La Palma was ultimately constructed and became the 10·4-m *GranTeCan*, which started operations in 2009.]

An amusing anecdote to that was that prior to the final decision-making meeting of the APS Board regarding acceptance of the *Gemini* project, Professor Richard Ellis (who was at Durham at the time) and I had agreed to meet up with Ian Corbett and Peter Fletcher at Heathrow airport (as a suitable meeting location that was quite feasible in those days before enhanced airport security). That meeting would entail Richard and me flying down from Newcastle Airport. Unfortunately, we ended up talking too long in his office at Durham, which meant catching our flight from Newcastle airport was looking to be on very shaky grounds. Following a rather hectic and rapid car dash to Newcastle Airport we just made it with Richard being left to check in while I parked up. We were the last people to board the British Airways BAC111 and found ourselves sitting across the aisle from the violinist Nigel Kennedy, who'd been playing at Newcastle University Union (while his Aston Villa football team was being beaten at Newcastle). On arriving at Heathrow and getting my bag down I passed Nigel his violin case (carefully) saying "I think this belongs to you", to which he replied "thanks, and it costs a whole lot of money too". Being a Newcastle supporter I naturally commiserated about the Aston Villa loss. The Heathrow meeting turned out to be very useful in terms of deciding our final strategy for the upcoming Board meeting and

Richard and I flew back to Newcastle later that afternoon.

No sooner had the decision on *Gemini* taken place when SERC was hit with a major funding crisis resulting in a shortfall of £52M. Savings were required from all areas of the programme and the GBPC was faced with planned cuts of £3·6M in FY91/92, £6·8M in 92/93, and £8·0M in FY93/94. Those were savage in-year budget reductions and would require drastic action to achieve them. The university grants were mostly protected, major projects were slowed down or delayed, but there were still broad cuts across the rest of the programme in a salami-slicing round of activity. Inevitably, the funding of the establishments came under further scrutiny and another panel was set up to address that issue. The outcome of that (the Hughes report) was to seek savings of £1M from the RGO and the ROE and to consolidate optical and infrared instrumentation on a single site. While nothing immediately transpired for a variety of reasons, that was essentially the beginning of what came to be known as 'Observatory Wars'.

In 1993, a SERC review of the Observatories' management recommended that the RGO and the ROE (along with the island sites) should come under a single Director of Observatories. That was then implemented with Professor Alec Boksenberg, then Director of the RGO, being appointed to the position. At the same time there was another management change when Dr. Paul Murdin moved from the ROE to SERC to develop UK Space Science at the British National Space Centre in London. At the time I was the Director of the *James Clerk Maxwell Telescope* and the Joint Astronomy Centre in Hawaii and so I reported to Alec. Programmatically, another positive step in implementing the goals of the Ground-Based Plan was achieved when, in the same year, SERC officially signed up to a 25% share in the *Gemini* international optical/infrared observatory project.

And now we are PPARC and 'Prior Options' looms large

1994 April saw another major event take place: the dissolution of the SERC to become PPARC — the Particle Physics and Astronomy Research Council. That slimmed-down but more-focussed Council was now bereft of the RAL work and essentially consisted of a headquarters in Polaris House, Swindon, the two Royal Observatories, and their associated 'island sites', along with other funded facilities, some, like the Anglo-Australian Observatory, overseas. Professor Ken Pounds of the University of Leicester was appointed as the PPARC Chief Executive.

In the meantime, the UK Government, in 1993 May, produced a policy review that would shake the UK science establishment to its core. That came in the form of a science white paper that was entitled 'Realising our potential: A Strategy for Science, Engineering and Technology'. It basically asked the question whether UK government-funded science establishments were necessary in the first place and if so, whether the work could better be delivered through the private sector rather than government — in essence, could they be privatized. The terms of reference for that exercise were announced in 1994 February although the review had already begun in the previous December. The review reported in 1994 June. This process was generically known as 'Prior Options' and although many research establishments had been included (*e.g.*, Rutherford Appleton Laboratories and Daresbury Labs) PPARC was excluded, probably because it had just recently been formed.

The Prior Options review produced a high level of criticism from the length and breadth of the UK science community. The Government's official response to the review recommendations came in 1995 September and although it did not support some of the recommendations, it decided to expand 'Prior Options' to include a wider range of establishments. This time PPARC was included (although the direction of travel had been known to PPARC a couple of months before the official announcement and a great deal of time and effort had been spent in trying to avoid that result given that some of the industry-based PPARC Council members were broadly in favour). So now all the PPARC establishments were subject to review for potential privatization and to be run by 'service providers'. That meant that the Joint Astronomy Centre in Hawaii, of which I was Director, suddenly became part of Prior Options and my focus had to turn away from the science to managing what would turn out to be a huge piece of work in terms of preparing prospectuses and legal aspects. That seriously detracted management from being able to concentrate on science delivery and planning for the future. Prior Options would also have an impact on the on-going saga of the Observatory Wars.

Meanwhile, it was clear that the overall funding situation was becoming even tighter, and the tension between the funding for the 'establishments' (the two Royal Observatories) and funding university grants for astronomy research would increase. That was because the cost of the UK's 25% share in the *Gemini Telescope* operational support would be significant, especially as it would be based overseas in Hawaii and Chile, while at the same time the university astronomy community was rapidly expanding, with new groups being set up in many physics departments. That resulted in an increased demand for research-grant funding. Finally, there was a growing desire on the part of some large university departments to have a significant share of the UK astronomy instrument-building capacity, thereby challenging the near-monopoly position of the two Royal Observatories.

The 'Hough' reviews of the Royal Observatories

In 1994 PPARC management set up a Panel to review the future of optical, infrared, and millimetre astronomy in the UK. That was led by Professor Jim Hough of the University of Hertfordshire. The timing of the review was governed by the international agreement for the operation of the joint UK–Australia Anglo–Australian Observatory (AAO) in Australia and the development of the tri-national (UK, Canada, Netherlands) funded *JCMT* in Hawaii. The inter-governmental agreement covering the AAO meant that if the UK was to withdraw or change contributions it had to give notice by 1996. Likewise, the current *JCMT* Development Fund would expire in 1999 and the *JCMT* Board would need notification during 1995 in order to plan for future telescope and instrument developments beyond that date. The membership of the Panel included an international astronomer, Dr. Reinhard Genzel, and each Royal Observatory Director nominated one person. John Peacock was nominated from the ROE while Robert Laing was nominated from the RGO, and it was Robert who first coined the phrase 'Astronomy Technology Centre' although not in the same format that would eventually be created, as he had envisaged continued support for the island sites rather than just an instrument-building centre.

The Panel reported to the PPARC Director of Science (Dr. Ian Corbett) in 1995 January (the Hough-1 report) and that was presented to PPARC Council on February 16. The Report made a number of far-reaching recommendations, the three key ones being: universities should become more involved in instrument construction; the two Royal Observatories should be merged into a single, smaller unit, which would be known as the UK Astronomy Technology Centre (UKATC); the island sites should be autonomous, reporting to respective Telescope Boards. An obvious conundrum followed: where would a UKATC reside? Or, put another way and as seen by most people, the most obvious solution would be to locate it at one of the two existing Royal Observatories, and in which case, which would remain open and which would close — bring on the 'Observatory Wars'.

The recommendation that the two island sites should be autonomous, receive funding directly from Swindon Office, and be managed by executive boards, was not so much of a difference for the Hawaii site, at least for the *James Clerk Maxwell Telescope*. That had effectively been the position since 1992, when I took over as Director. I reported to the international *JCMT* Board and received funding essentially directly from the three agencies (UK, Canada, and the Netherlands) and the previous managerial link to Edinburgh was reduced. As we will subsequently see, from 1996 April 1, the Joint Astronomy Centre (JAC) in Hilo, Hawaii, which was the management HQ supporting the *JCMT* and *UKIRT*, was supported directly from Swindon Office. The same became true for La Palma, which was jointly funded by the UK and the Netherlands, with a small Spanish interest.

Returning to the Hough-1 Panel, the PPARC Council meeting of 1995 February accepted the general recommendation of autonomy for the island sites but had reservations about the concept of a UKATC. This was for a number of reasons: financial, operational, and political. It was also felt that an adequate cost–benefit analysis had not been undertaken to justify a UKATC. Therefore, PPARC management immediately instigated a second panel to analyse the technical and financial requirements of a UKATC, including its size, skill mix, management structure, and relationship to the island sites. That was also chaired by Professor Jim Hough. Included in the terms of reference of that Panel was the crucial recommendation as to where this new UKATC should be located. That would be a fast-acting panel, reporting to the PPARC Director of Science by the end of 1995 May, in time for the PPARC Council meeting of June 6.

All of that was causing great unease within the astronomical community, especially after Ken Pounds gave a report to the National Astronomy Meeting at Cardiff in 1995 April amid mounting criticism from a variety of sources that there had been a lack of consultation throughout the process. On paper it would appear that in the battle to be the UKATC, the RGO would have the upper hand, being located in a modern, purpose-built facility in Cambridge, the seat of major astronomy research, and the home of the Astronomer Royal (Professor Sir Martin Rees) and the home of the Director of Observatories (Professor Alec Boksenberg). However, within the university astronomy community there was a considerable push for Edinburgh, mainly based on its project-management track record and the future move to infrared astronomy.

While all that was going on Alec Boksenberg announced he would retire and when that took effect the two Observatories would again be split, each having its own Director. Dr. Jasper Wall was appointed to the RGO and Mr. Stuart Pitt to the ROE. That was a key time of flux and it was clear that the future of the observatories had to be fought for. I had known and worked with Dr. Adrian Russell of the ROE since going to the *JCMT*, where Adrian was a support scientist and Head of Instrument Development. He moved back to the ROE to take up the position of UK Project Manager for the *Gemini Observatory* project. Adrian was a great guy in all respects, bright, knowledgeable, and extremely helpful. His only negative was in being a Sheffield United supporter. I was very keen that he should not apply to be ROE Director at that time, although he was the best candidate for a future UKATC Director. I lobbied hard for that solution. My reasoning was that the position of ROE Director would be mired in the politics of the Observatory Wars and he should keep his powder dry on the assumption that when the ROE won the battle, he would not have been smeared in the political infighting at a senior level and would be in a prime position to take on the Directorship of the UKATC (to which he was subsequently appointed in 1998). On the other hand, Stuart Pitt, as head of ROE administration and a terrier of a Scotsman, was the ideal candidate to take the ROE forward through the subsequent battlefield. Indeed, that was the consensus view of the senior staff at the ROE, in effect making Stuart Pitt the only Director of the ROE to ever have been elected by his peers.

The recommendations of the Hough-2 report were profound. They concluded that a UKATC would provide a core of specialist staff for instrument design and construction along with telescope development, that a UKATC should work with the university community in instrument building at an approximately equal share, and that it needed a staff of 45 to fulfil that required remit. Finally, and crucially, it recommended that the UKATC should be based at the ROE Edinburgh, mainly on the basis of the move towards infrared astronomy but also because of the project-management track record at the ROE. It was also noted that there was a considerable synergy between the ROE and the co-located University of Edinburgh astronomy unit, the Institute for Astronomy (IfA). The Panel had also pointedly noted that

that synergy was lacking at Cambridge even though the RGO and IoA were next door to each other. So, there we have it — a UKATC at Edinburgh and the future of the RGO and its staff very uncertain but closure seeming a distinct possibility. However, there would be a lot of water to flow under the bridge before those far-reaching recommendations would become a reality. In looking back, it is worth noting that a potential possible solution could have been to create the UKATC at RAL, but because RAL was then in another Research Council that idea was not seriously considered.

The Hough-2 draft Report and recommendations were circulated to the Astronomy Committee, PPARC Council, and senior members of the UK astronomy community. Alec Boksenberg, as Director of Observatories, wrote a detailed, four-page document on 1995 June 6 (I assume as input to the PPARC Council meeting) effectively arguing against all the recommendations of the Hough report, including autonomy for the island sites. On-going concerns about lack of effective communication between PPARC and the community continued to swirl around on email and in letters. The attitude of the IoA and Cambridge University to the potential closure of the RGO caused some internal tensions and as Richard Ellis, by then Director of the IoA, commented to me that when a senior astronomer at the IoA was asked if the IoA should support the RGO the reply was that "the RGO wasn't Royal, it wasn't at Greenwich and it wasn't an observatory!" That speaks volumes for the degree of antipathy felt towards the RGO by some. It didn't help that another major astronomy arm of Cambridge University, the Cavendish Laboratory, including the radio astronomers from the Mullard Radio Astronomy Observatory, was literally remote from the IoA in terms of both geography and collaboration. Nevertheless, it must be acknowledged that the RGO had considerable support from within the community, especially amongst the traditional optical astronomers.

The 1995 June meeting of PPARC Council again failed to support the plan and with hindsight that was perhaps not surprising. Reading between the lines those recommendations were too much of a bite to take at one go without having 'rolled the pitch' beforehand, something that had been impossible given the short time-scale for the Panel to report. Also, with starkly divergent views amongst senior astronomers in the community, the decision of Council failing to support the recommendations is readily understandable in that such a major recommendation to close the RGO was contentious and of course political. It was, therefore, inevitable that the final decision would take some considerable time. To add to the impasse, the RGO had been in its new building for only some six years, so closing it would not appear to be without criticism from on-high. So, the fight was on to save the RGO and lots of gnashing of teeth within the community ensued. The final Hough-2 Report was sent to Council in July and the final decision was poised for the PPARC Council meeting in 1995 September. A lot of work was undertaken over the summer by Ian Corbett and senior astronomers to try to crystallize the position regarding future ground-based projects, in particular, *Gemini*, given the lack of projected funding.

PPARC becomes subject to Prior Options

However, as we have noted earlier, the process of taking the Hough-2 recommendations forward was effectively put on hold following the announcement on 1995 July 26 by Ian Taylor, the Minister for Science and Technology, that PPARC would be assessed under the Prior Options programme. PPARC focus would be turned away from a decision about forming a UKATC, to one of preparing prospectuses and in the case of the overseas sites, seeking specialist legal advice. PPARC Council set up a small panel to assess the Prior Options progress. That was chaired by Professor Ian Halliday (a member of Council) and included the PPARC CEO Ken Pounds and Adrian Carter of the Office of Science and Technology. The panel would report to Council on December 6 but an interim report to the September Council by Ian Halliday stated: (a) that the principle of PPARC owning telescopes, or being a member of a collaboration that owns telescopes, in order to guarantee secure access for the UK astronomical community, is fully justified; (b) that the PPARC should endeavour to retain and develop telescopes well beyond 2000, and to continue to operate and maintain them efficiently, effectively, and economically; (c) and hence the 'abolition of programme functions' option should be rejected.

The paper went on to outline the possible options as: (a) 'Integrated' — Hawaii + La Palma + RGO + ROE as a single organization — in effect the status quo; (b) 'Separate' — four independent organizations; (c) 'UKATC' — essentially Hough-1; (d) 'RGO' — Hawaii and ROE independent; RGO and La Palma combined as a single organization independent of the others. However, options (b), (c), and (d) resulted in a number of sub-options to consider and the result was a large range of management possibilities. The report then detailed the on-going discussions of costs, management, and potential impact on future activities. One thing was very clear: that was going to be a complex process.

Meanwhile, an obvious up-front question for Prior Options was whether the local UK academic institutions (Cambridge and Edinburgh universities) might be interested in running the two UK sites. On 1995 August 1, Jim Sadlier, the Royal Observatory Secretary, wrote formally to Richard Ellis (Cambridge) and Andy Lawrence (Edinburgh), asking them to begin internal enquiries as to that possibility. Following that letter, Richard Ellis wrote back on August 9 expressing a general enthusiasm and noting that an internal working group had been set up comprising the IoA, the Mullard Radio Astronomy Group (MRAO), and the Department of Applied Mathematics and Theoretical Physics to consider further the possibilities. He also pointed out there could be many difficulties to overcome and that in any case it would need to be considered by the General Board of the University. That was followed up by a letter from the Vice Chancellor of the University of Cambridge to Ian Halliday, again expressing positive views but noting that much would depend on the financial situation and the PPARC future programme.

While all of that upheaval was going on, yet another funding crisis arose for PPARC. In the light of the reduction in planned spend on ground-based telescope developments, the Ground-Based Telescopes Development Panel (the Williams Panel) was reconvened to consider a revised programme and to recommend that to the 1995 December 6 PPARC Council. Clearly, that was going to be a 'busy' Council meeting. Meanwhile, in October the RGO prepared an extensive document entitled 'Our Future: Memorandum to Prior Options', comprising 28 pages of arguments and 9 Appendices. That was followed by a paper from Walter Gear, John Peacock, and Andy Lawrence on behalf of the ROE Management Board entitled 'ROE and the future of UK Astronomy' presenting the ROE view of how best to support ground-based optical-infrared-millimetre astronomy.

A University Consortium?

In 1995 November, a consortium of Cambridge, Durham, and Oxford universities sought to investigate whether a charitable trust could set up a not-for-profit company to manage the astronomy programme and the UKATC, while PPARC retained responsibility for programme policy. That was met with a range of both support and lack of enthusiasm from the university hierarchy. It was also clear that neither Cambridge nor Edinburgh Universities were willing to represent the interests of other universities, which was quite understandable. In 1995 December, PPARC Council approved the proposals from Ian Halliday regarding the way forward for Prior Options along with a revised time-table with an implementation date of 1997 April. Those were then forwarded to the Minister. The key recommendations were: that PPARC should retain ownership of the telescopes on Hawaii and La Palma and seek, through competitive tender, to contract managing organizations to operate them on behalf of the Council and its international partners; that PPARC should invite tenders for the provision, under contract to PPARC, of services, including the procurement of instrumentation and technical support currently provided by the Royal Observatories' UK sites (RGO and ROE). Work then began in earnest in terms of making up prospectuses for potential bidders and refining the 'rules of the game' in terms of what could and could not be disclosed. To oversee the process a steering committee was set up under Ian Halliday and a management committee under the chairmanship of John Love, PPARC Director of Administration. However, it was clear from the start that PPARC lacked knowledge and experience of that type of process, and external advice, including legal advice, would have to be obtained.

Although somewhat isolated in Hawaii, Prior Options caused much additional work. On paper, the Joint Astronomy Centre was the most obvious site to transfer to public as opposed to UK-government operations, especially given the way that many US facilities were operated through a third party (AURA — the Association of Universities for Research in Astronomy) rather than directly by the funding agency, the National Science Foundation (NSF). For the JAC the work involved figuring out the international legalities, especially given the tri-nation *JCMT* funding, the planned expectation of operating closely with the *Gemini-North* facility (to save money), and looking at other innovative means. There was lots of discussion regarding the way forward and about how a JAC might be structured, how it would interact with *Gemini*, possible bidders, rules about in-house and management bids clarified, and interfaces needing attention. That revealed the potential complexity and the dawning realization of the possibility that the management could easily become more complex and costly to administer rather than simpler and cheaper! At the same time *JCMT* operations were completely focussed on the delivery from the ROE and commissioning of the world-beating and world's first submillimetre 'camera', *SCUBA*. As it turned out, that instrument would be the saviour for the *JCMT* in the downstream international review that would be called for later.

On 1996 April 25 a Deptartment of Trade and Industry (DTI) press release was made announcing that the Minister had accepted, in full, the conclusions of the Review of the Royal Observatories (the Halliday Panel). The key recommendation was that management of the UK telescopes and the delivery of the instrumentation programme currently carried out by the Royal Observatories should be subject to competitive tendering by all competent suppliers. That was officially welcomed by Ken Pounds on behalf of PPARC and a bulletin was issued describing the outcome, the process, and the proposed time-table, which we shall return to later.

That announcement stimulated further work, led by Richard Ellis, on the suggestion that a consortium of UK universities might come together to bid. A key aspect seemed to be that any organization wishing to bid must already be in formal existence at the time of the bid. Although it was noted that the consortium should maintain neutrality on the RGO *vs.* ROE UKATC situation, there was clearly support for the RGO to be the main contender in spite of Hough-2. The group of four universities (Cambridge, Durham, Oxford, UCL) decided to leave things across the summer but to resume in September, when the nature of the bidding and rules had become clearer. In the meantime, they would seek to have meetings with representatives of the RGO and the ROE.

As Prior Options work gained pace it became clearer what the JAC was required to produce in terms of quality targets for the assessment of the management of the operation. That would mean a lot of work. To manage the progress, PPARC set up assessment panels to oversee the three tendering processes. For Hawaii, a special Prior Options meeting was convened in Boston (USA) on 1996 May 14. That had very high-level representation comprising Harvey Butcher (NL and *JCMT* Board Chair), Don Morton (Canada and *JCMT* Board), Wilfried Boland (NL and *JCMT* Board), Wayne Van Citters (US, Head of Astronomical Sciences Division NSF), Pat Roche (UK Chairman), Matt Griffin (UK and *JCMT* Board), Jim Hough (UK), as well as the PPARC contingent and myself.

Astronomy and political debate

However, not only was Prior Options causing great angst within the entire UK science community, it became both contentious and political. In the UK parliament there was a major debate on Prior Options on 1996 June 11 brought about by an opposition amendment. That was opened by Dr. Gavin Strang (Labour, Edinburgh East) with the statement: "I beg to move, That this House believes that Government support for science and technology is vital to the United Kingdom's future; recognises the crucial long-term contribution which the public sector research establishments make to the economy and to extending the boundaries of knowledge; regrets the rationalisation and fragmentation of these establishments in recent years and opposes the dogma-driven privatisation objectives of the Prior Options Review." [Spelling, capitalization, and punctuation as in the original.]

That was followed by an Early Day Motion tabled on July 9, which stated: "That this House is deeply concerned at the serious threat to the United Kingdom science base posed by internal disruption and loss of staff morale caused by the Prior Options Programme to privatise Government Scientific research institutes; notes that the timescale for Prior Options is already three months behind the schedule announced in a Government Press release of April 25; understands that the second tranche of institutes to be privatised under Prior Options is likely to incur costs exceeding £100 million; condemns the lack of foresight of the legal minefield requiring huge fees to be paid to United States and European lawyers for the disposal of Particle Physics and Astronomy Research Council sites in Hawaii and La Palma; deplores the fact the transfer into private ownership of overseas observatory sites alone is expected to result in half a million pounds of unanticipated legal costs; regards Prior Options as unviable; and calls upon the Government to halt the process and recognise that the policy represents the worst in Government dogma and is a gross waste of taxpayers' money." [Spelling, capitalization, and punctuation as in the original.]

Alongside that the House of Commons Science and Technology Select Committee had launched an inquiry into the Prior Options Reviews, into which the Royal Society made the following submission in 1996 October, summarized by:

> There are four key points:
>
> - the Government has not provided evidence for the assumptions underpinning the Prior Options process as currently being applied to PSREs (Public Sector Research Establishments)
> - those assumptions need to be set in the context of national strategy for research, both within the Science Base and at Departmental level
> - care is needed to ensure that Prior Options does not damage the highly successful collaboration that has built up between Universities and Research Council Institutes
> - repeated reviews questioning the continued existence of PSREs, over and above the normal reviews undertaken periodically by Research Councils or Departmental owners of PSREs, adversely affect efficiency and productivity.

Let the bidding begin

Those protests hit a brick wall and at the end of July, Jim Sadlier wrote to interested parties that the *Official Journal of the European Union* (*OJEU*) notice would be issued in early August requesting bidding for the tendering of the work of the Royal Observatories. That was an important milestone because once issued, it sets in train a legal framework for the process, including a time-line. The information pack that went alongside the *OJEU* notice was very extensive and drawn up by legal experts. That triggered a response from the four key universities of Cambridge, Durham, Oxford, and UCL indicating an expression of interest in bidding on behalf of the newly formed UCAR, the University Consortium for Astronomical Research that Richard Ellis had worked so hard to introduce.

Throughout the summer of 1996 there were numerous letters written by astronomers to the press and scientific journals. Martin Rees, in his role as Astronomer Royal and member of the Royal Society, continued to be opposed to the cost reductions and potential closure of the RGO and, more generally, with the way PPARC was handling the issue. I remember visiting the RGO in the summer to discuss the Prior Options process, and during a meeting with Jasper Wall, he noted that he was convinced the UK astronomy community would not let the RGO be closed. I wasn't so sure at all and pointed out that if Ken Pounds offered the choice of retaining the RGO or awarding a postdoc to each university researcher then just how committed would the community be. My feeling was they'd go for the postdoc but he was not convinced and continued to believe that the RGO would, in the end, be the choice for the UKATC, or at least be preserved as an institution.

On 1996 September 4, PPARC issued a news bulletin explaining the proposed implementation of the Prior Options Review. That explained there would be three separate but parallel tendering exercises: to manage the operation and development of *UKIRT* and the *JCMT* on Hawaii and to provide services to *Gemini North* when it came into operation; to manage the operation and development of the ING telescopes on La Palma; to provide the range of services currently provided by the RGO and the ROE. It also promised to provide an update for the community at the Royal Astronomical Society Ordinary Meeting on October 11. The planned time-table was for bids to be received by mid-February 1997 and then be assessed by evaluation panels. It was unclear how long the evaluation might take but hopefully the recommendations would be presented to PPARC Council by 1997 April.

A bidders-briefing conference was subsequently held on 1996 September 6. That included a section on 'pre-qualification'. 24 organizations attended and many questions were put forward for clarification, one being the status and importance of the Miscellaneous Governmental Organization status enjoyed by the JAC. That instrument brings tax and visa benefits to staff at the overseas sites as well as freedom from import duty for new instruments. The answer to the query was that that was being investigated.

Replies from potential bidders to the bidding questionnaire were due by September 20. UCAR followed that up in September noting that they intended to form a charitable trust that would in the future be extended to all UK universities that had a significant stake in observational astronomy and that they had considerable support from the community. Andy Lawrence indicated that Edinburgh would not be joining. A community-wide meeting was organized by UCAR at UCL on 1996 October 8. That was attended by 31 astronomers from 13 universities, not including the original four.

PPARC then selected the bidders felt to be suitable to proceed to the next stage. There were eight bidders for the UK programme, ten for Hawaii and seven for La Palma. In fact, we in Hawaii had been directly contacted only by the US managing agency AURA, and the UK managing agency Serco plc. That had resulted in a single meeting with representatives of each on a purely information-only exchange with strict rules of engagement. It was also known that Serco had formed a 50-50 collaboration with the University of Edinburgh to bid for the UK option.

In the autumn a written parliamentary question asked the President of the Board of Trade to make a statement on the future of the Royal Observatories. On behalf of the Government, the Minister for Science and Technology, Mr. Ian Taylor, replied on 1996 November 5: "The Government accepted the recommendations in the report of the prior options review of the royal observatories which had been endorsed by the council of the Particle Physics and Astronomy Research Council. These were that the management of the overseas telescopes and the provision of the instrumentation programme provided by the royal Greenwich observatory and the royal observatory Edinburgh should be subject to competitive tendering by all competent suppliers. PPARC is currently implementing the recommendations of the review with the intention of an invitation to tender being issued this month." [Capitalization as in the original.] So, in spite of all the protestations from the science community, in early November Prior Options was apparently well and truly up and running politically speaking, and PPARC was expected to be delivering it. But, watch this space!

Things are not going to plan for Prior Options, the beginning of the end

In fact, progress on the project plan for the implementation of Prior Options continued to slip as detailed work by lawyers unearthed a number of issues. Together those meant that the tender document for the Prior Options process could not be agreed and therefore could not be issued on the planned project time-table. Further legal work would need to be undertaken. That resulted in a delay to the invitations to tender (ITT) being announced on November 1, moving the ITT release date to November 14, with a new closing date for bids to be 1997 February 28. However, on November 22 a further delay was announced, this time with no new dates for the ITT or the resulting reply by bidders. Clearly things were not going well behind the scenes.

On November 15, Jasper Wall issued a letter to the community inviting astronomers to join the NAT — the National Astronomy Trust, which would be a non-profit company limited by guarantee with charitable-trust status (CLG). This would be headed up by Jasper Wall, Neil Parker, and Keith Tritton of the RGO. Clearly as an RGO-based organization it was unclear how it would sit with UCAR or the community as a whole. An opening meeting was planned to take place in London on December 4.

However, a bombshell announcement took place on November 29 when Jim Sadlier wrote to potential bidders that PPARC was "unable to proceed with the current tendering exercise for the contracting out of the programme of the Royal Observatories". Quoting from the letter: "in recent weeks PPARC has identified a number of significant pressures on its capacity to fund its current and future programme at the anticipated level and has been advised that there may be new and significant liabilities which need to be investigated further. Without a full analysis of the impact of these changes, in the context of the current 1996 PES (Public Expenditure Settlement) and Allocations, PPARC is not in a position to disclose with sufficient certainty the full nature and extent of its assets and liabilities pertinent to the contracts for which you have been invited to bid. In these circumstances it would be inappropriate to issue the Invitations to Tender which have been prepared. The current estimate is that it will take some months to complete this analysis and it will therefore no longer be possible to adhere to the planned timescale for the award and announcement of contracts. I attach a copy of a UK Government statement which will be made in Parliament today." [Spelling, capitalization, and punctuation as in the original.] The Government statement concludes that that current tendering exercise has been formally terminated.

It remained unclear exactly what precise financial circumstances and liabilities had been unearthed. Speculation focussed on whether the on-going impact of the Prior Options work, which had been unfunded by Government and was effectively taking funds directly from the astronomy programme, would have required much more funding from the astronomy programme than could have been sanctioned. It was also the fact that the new science budget had just been announced, and that had confirmed that there would be no additional funding for the Prior Options processes. Therefore, those costs would directly impact the science research programmes. Another avenue of speculation was that the work by the lawyers had unearthed some interesting aspects, one of which was the status of the Miscellaneous Governmental Organization (MGO) aspect of the JAC that had been raised in the questions at the bidder's forum. The lawyers concluded that if the PPARC staff were moved too close to the RCUH (Research Corporation of the University of Hawaii — the managing agency for the 'local' staff) terms and conditions, and if they were moved to a dollar salary (which was one of the possibilities under consideration), then that would effectively remove the MGO status currently enjoyed by the JAC. Being an MGO gave the JAC particular advantages, such as relief from import duty and special visa status with very extended stays for PPARC staff on secondment from the UK. Without MGO status, the way that the JAC was operated by PPARC would change dramatically and it seemed that PPARC (and I assume Canada and the Netherlands) did not wish to lose those advantages. So, how to treat the MGO status of the JAC was one of the complicating factors for the Hawaii site and was probably one of a number of risks and uncertainties that contributed to PPARC recommending that the current Prior Options tendering action should be terminated.

A subsequent article in *Nature* was very critical of the Government and the Prior Options process for the Royal Observatories and it noted that if the Opposition party (Labour) won the next election, due in spring the following year, it would make its own decision "based on science, not ideology". Both NAT and UCAR continued to proceed with organising themselves into viable bidding bodies. NAT held its community meeting on December 4, which attracted 17 attendees with 10 being separate from the RGO. The next meeting was scheduled for 1997 January 8. It is hard to overstate the amount of effort that went into these meetings and preparations of paperwork and looking into the legal status of charitable trusts and just energizing the UK astronomy community. There is no doubt that those involved in UCAR and NAT worked long and hard to argue for their cause, preserving the importance and capability of UK ground-based astronomy.

In parallel to the Prior Options troubles, PPARC was facing a very serious financial challenge. It informed the Ground Based Facilities Committee (GBFC) meeting in early December that the budget would be short by £2–4M over the coming two financial years and £2M per year thereafter. Reasons given included the cost of Prior Options so far, increases in international subscriptions, increases in university grant overheads, and restructuring costs. PPARC called a meeting of its four Site Directors on December 6. At that meeting each was required to prepare a single proposal that took into account a 30% cut with immediate effect and those would be discussed at the 1997 January 31 meeting of the GBFC. However, the *Gemini* Director, Dr. Matt Mountain, had been assured that his programme was protected from those cuts. As it turned out, Hawaii came out of that cut-back relatively unscathed for the time being compared to other areas. *UKIRT* had a slow-down in new instrumentation and a lack of commitment downstream, while the *JCMT* would be subject to an international review following a couple of years of *SCUBA* observations.

Benchmarking of costed options for the establishment of a UKATC

At the 1997 February 26 meeting of PPARC Council it was stressed that Prior Options was paused rather than cancelled and Council approved the Executive advice to remove the two island sites from the prospectus and leave only the UK domestic option open for future bidding. That was then sent for Ministerial approval. It was noted that because that was under Ministerial review it would be politically very sensitive and that discussion outside of PPARC or its bodies needed to be treated judiciously. It was interesting to note that a number of other government entities had just been released from the Prior Options process, but not PPARC.

In the meantime, PPARC Council had set up an internal panel to benchmark costed options for delivering the astronomy programme, focussing solely on the Royal Observatories. That panel would be made up of mainly Council members and would be chaired by Brian Eyre (AEA Technology). It included Dr. Sue Ion (BNFL) and Professors Enderby (University of Bristol), Hough (University of Hertfordshire), Pounds (PPARC), and Longair (University of Cambridge and non-Council). It would work to a very short time-table, reporting to the

Council meeting of 1997 May 20/21. The terms of reference were: "to consider a range of internally costed models for restructuring the Royal Observatories to deliver PPARC's programme; to assess the cost effectiveness of each of these models; to take account of the downstream effects of such models and any implications for the science programme; to advise Council on the analysis of costed options, and, to recommend the way in which the restructuring should be managed." [Punctuation as in the original.]

The evaluation criteria were listed under the following headings: cost-effective delivery; responsive capacity; interfaces with PPARC, community, and telescope facilities; minimizing PPARC's risks and liabilities; transitional arrangements. Also, it was required that two benchmarking proposals should be submitted; one as a PPARC facility following PPARC rules and procedures and secondly under a different operational model whereby programme delivery and costs may be shared with a third party. The rules of engagement were specified and to ensure a level playing field PPARC (Swindon HQ secretariat) would provide the programmatic information about the future agreed programme. The Observatories would be able to inject additional (non-programme-approved) work they believed would be obtained. It was stressed that that was not a bidding process as in Prior Options but an internal review.

The implication is clearly that that would be the long anticipated 'shoot out': the culmination of Observatory Wars and there would be a single winner and a single loser between the RGO and the ROE. That meant that a considerable amount of work would fall on Swindon Office and the two Observatories over a very short period of time. The specifications, costing tables, and rules of engagement were released on 1997 March 21 and the bids were required by April 21! Those were very tight time-scales.

Jasper Wall promptly wrote to the VC of Cambridge explaining the situation and including a first pass at an RGO submission. That was an extensive document, based on the Company Limited by Guarantee (CLG) proposal of the proposed National Astronomy Trust and it projected that there would be a large positive discrepancy between the future work expected to fall to the RGO compared to the ROE. Meanwhile, the ROE had been talking to Serco about the possibility of them bidding to operate the UKATC. Serco had taken over the NPL in 1995 and had a potential interest and also a connection in that Donald Pettie, the Chief Engineer of the ROE, was a close friend of Serco's Chairman George Gray. That led to discussions between Serco and the University of Edinburgh about the possibility of a joint venture. The final submission to PPARC from the ROE included three options: (*i*) traditional PPARC operation; (*ii*) a progressive partnership with the University of Edinburgh; and (*iii*) a Joint Venture Company owned by the University of Edinburgh and Serco plc. Throughout that, a key argument in the ROE submission was that instrumentation was the key to the future, and the instrumentation expertise was strongest in Edinburgh.

The decision of the Benchmarking Panel was essentially to endorse the Hough-2 recommendations — the UKATC goes to Edinburgh. Those were in turn approved by PPARC Council and forwarded to the Government for final approval in 1997 May. As it turned out, that was just after New Labour had come to power on May 1. The PPARC Council recommendations were subsequently leaked to the press (*Daily Telegraph*) on May 24, which concentrated on the projected closure of the RGO. That sparked a flurry of activity in the community with emails and letters to MPs and Ministers. In particular, Martin Rees and Phil Charles were very vocal in support of the RGO and looked to see if the decision could be reversed by meeting with the Science Minister (John Battle) before the official announcement. Richard Ellis wrote to his local MP, Anne Campbell, on June 9 in which he sought to gain the higher moral ground by urging her not to criticize PPARC in the upcoming meeting with the Minister, because although he was personally disappointed with the decision to favour Edinburgh over Cambridge, the fundamental decision to have only one Observatory was correct and was widely acknowledged in the community. He noted that astronomers needed to work with PPARC rather than against it and attempting to change the Council's benchmarking decision could set things back by one or two years and cause more anguish in the community and the Observatory sites. It would also exacerbate the financial situation for PPARC. To keep things fair, Edinburgh, represented by Andy Lawrence and Professor Michael Rowan-Robinson (QMW) along with two Edinburgh Members of Parliament, also met with John Battle to press their case.

In a separate note Richard Ellis pointed out that for the IoA the decision was serious in terms of accommodation as the rapidly expanding research complement had been partly housed in the RGO building and it looked impossible to re-house the staff in the existing IoA. He proposed that Cambridge University seek to negotiate with PPARC with the aim of retaining the RGO building for astronomy.

Judgement Day — a UKATC at Edinburgh

1997 July 4 was the date of the momentous announcement for UK astronomy by the new Labour Government. In a written parliamentary answer, the Science Minister, John Battle, announced approval to bring together the work of the two Royal Observatories to a single site and that would be known as the UK Astronomy Technology Centre and it would be located at Edinburgh. The same Parliamentary announcement confirmed that following advice from PPARC it would no longer have to adhere to the Prior Options process. At a stroke, that brought to an end the questions of privatization of the operations of the Observatories and island sites. The Hansard record is presented below. [Spelling, capitalization, and punctuation as in the original.]

> Mr. Battle: The Particle Physics and Astronomy Research Council (PPARC) has decided to concentrate the work it funds at the Royal Greenwich Observatory (RGO), which is based at Cambridge, and the Royal Observatory Edinburgh (ROE) in a new UK Astronomy Technology Centre (UKATC) at Edinburgh. This new name will better reflect the fact that the Royal Observatories are now really observatories in name only. Their main function is to provide technological support for the telescopes operated by PPARC on behalf of British astronomers.
>
> A substantial amount of money will be freed up as a result of this decision amounting to £2·4 million per annum over the next four years and at least £4 million per annum thereafter. This sum, which is equivalent to approximately 20 per cent. of the budget for astronomy grants, will be re-invested in basic science. It will fund grants to astronomers doing exciting new science in our universities. In addition, I am confident the new UKATC will benefit greatly from the increased efficiency and better co-operation between scientists which will result from combining the RGO and ROE programmes.
>
> This decision will allow PPARC to reorganise the Royal Observatories in the way which best meets their scientific requirements. I believe that, as the responsible Research Council, they should have the freedom to manage their research facilities efficiently and effectively. PPARC will develop this in consultation with the unions and other interested parties. Under the previous administration, PPARC was bound to implement the conclusions of the 1995 Prior Options Review of the Royal Observatories that the management of the United Kingdom telescopes and the delivery of the instrumentation programme currently provided by the Royal Observatories should be subject to competitive tendering. PPARC have reviewed the situation in the light of developments since then and have advised me to release them from this obligation. I have decided to follow this advice in line with our long-standing opposition to dogmatic privatisation.
>
> The concentration at Edinburgh will take place over some years. The RGO is an historic institution with a great tradition that has already survived two changes of location. I am asking PPARC to explore every possible avenue for keeping the institution alive. Nevertheless, this decision will lead to some job

> losses. Therefore I have asked PPARC to make every effort to help anyone who loses their job to find alternative employment.
>
> I have laid a copy of the report on which PPARC's advice was based and a copy of my letter to the Chairman of PPARC in the Library of the House.

On the same day PPARC announced a press release justifying the decision and given the momentous nature of the decision, that is worth repeating in full.

> The Particle Physics and Astronomy Research Council welcomes the Government's decision today to release it from its obligations under the Prior Options process to review the future arrangements for the Royal Observatories. This allows PPARC to re-organise the Observatories in the way which best meets scientific requirements and protects scientific research in the Universities. PPARC now intends to implement the conclusions of its review panel on the Royal Observatories, which it accepted in full and have now been endorsed by the Government. The recommendations were that:
>
> - the case for continuing to operate the two UK sites (the Royal Greenwich Observatory (RGO) and the Royal Observatory Edinburgh (ROE)) was not sustainable;
> - there should be a single internationally visible UK Astronomy Technology Centre (ATC) to incorporate PPARC-funded activities at RGO and ROE, located at one of the sites;
> - the ATC should be located at Edinburgh for the reasons given in the Panel's report.
>
> These conclusions were consistent with the recommendation of PPARC's earlier reviews of the needs of the UK's ground-based optical, infrared and millimetre-wave astronomy programme; with the key findings of the prior options review and with the broad support of the UK astronomy community as expressed through the Royal Astronomical Society survey, for a move to operation on a single site. PPARC's ability to implement these conclusions will help free an average of £2·4 million per annum over the next four years and at least £4 million per annum thereafter. Without the restructuring now planned, the additional costs of continuing with the present structure and staffing levels would have had to be found at the expense of other parts of the programme — primarily grants to universities. The savings represent approximately 20% of the astronomy research grants. The money will be reinvested in astronomy.
>
> The Decision brings to an end a period of some 15 years uncertainty about the future of the Royal Observatories. The Council's decision to proceed with this internal reorganisation will produce a structure matched to the long-term needs of ground-based astronomy in the UK. PPARC will be able to deliver its plan programme more cost-effectively.
>
> The restructuring will not affect the operation of the existing telescopes on the island sites (on La Palma and Hawaii) nor the UK's contribution to the construction of the two 8-m *Gemini* telescopes being built in Chile and on Hawaii in collaboration with the USA, Canada, and South America. The Council has planned an outstanding future programme of astronomy planetary and space-science research and training, providing access for the UK community to a range of world-class facilities including the new *Gemini* telescopes, with unprecedented image quality, due to start operations in 1999. The other facilities include ground-based telescopes operating across the wavelength spectrum; and a range of current and future space missions. The Minister's decision now will be important in protecting that research.

> The detailed case for the choice of Edinburgh as the UK Astronomy Technology Centre was set out in the report of the Council's review Panel chaired by Dr. Brian Eyre CBE, FEng (Deputy Chairman AEA Technology Plc). The key elements are that the Royal Observatory Edinburgh approach:
>
> - more closely matches the current and future programme requirements for an advanced astronomy technology centre with the necessary skill mix to produce state-of-the-art instrumentation in collaboration with universities and/or overseas partners;
> - to repayment work more closely matches the PPARC mission and objectives at least risk.
>
> Staff of the Observatories have been informed of this decision, as have PPARC's international partners. PPARC is in the process of drawing up an implementation plan in consultation with all the organisations involved, including the trade unions, for the establishment of the ATC and for the delivery of the PPARC programme. The Minister has also asked PPARC to explore every possible avenue for keeping alive the historic institution of the Royal Greenwich Observatory.

As noted above, a major factor in the announcement was that that would, in principle, save a significant amount of money for PPARC. However, and perhaps not surprisingly, the potential cost implications were a major issue for the DTI and Ian Corbett had several tough meetings with DTI and Treasury officials seeking reassurance. Their worry was that SERC had effectively made a loss in moving the RGO from Herstmonceux to Cambridge and they were now about to make a further loss in disposing of the RGO building and staff. In the longer term PPARC would be expected to recoup the initial financial hit, but governments and politics tend to think short-term. However, the ROE had finally won and apparently the end was in sight for the RGO at Cambridge.

The implementation of the Observatory Wars decision

PPARC promptly set up an Implementation Steering Committee to oversee the decision, which also included changes to the management of the island sites. That Committee met on July 17 and had five key objectives, which were: "(a) to create a new PPARC entity — the UK Astronomical Technology Centre (ATC) on the Blackford Hill site in Edinburgh; (b) to divest PPARC of management responsibility for the delivery of non-ATC functions currently carried out by the ROE, and of the ownership of assets and liabilities associated with these functions; (c) to divest PPARC of management responsibility for the delivery of non-ATC functions currently carried out by the RGO, and of the ownership of assets and liabilities associated with these functions; (d) to ensure, in co-operation with other interested parties, the continuation of the ROE and the RGO; (e) to develop the management autonomy of the overseas facilities through increased delegated authority."

Those objectives essentially set the scene for the UKATC and remain today. Likewise, there were a number of important policy issues underlying those objectives. Those were: "(a) the ROE and the RGO, as presently constituted, will cease to be PPARC establishments and will be replaced by a newly constituted PPARC unit, the ATC; (b) the ATC's mission will be narrower and more focussed than that of the ROE and the RGO. It will be to provide technological support to the UK's astronomy instrumentation programme and to the development of PPARC's overseas ground-based facilities; (c) its longer-term viability will depend on its ability to deliver work cost-effectively in collaboration and competition with university groups and other suppliers; (d) the names 'ROE' and 'RGO' will be retained but the organisations to which they will be assigned will be decided by the Monarch advised by PPARC/OST through the Home Office/Scottish Office; (e) subject to negotiations with all interested parties, the name 'ROE' will apply to the range of activities on Blackford Hill; (f) the transfer of non-ATC functions and the assets and liabilities of the RGO and the ROE will be contingent on negotiations with a range of interested parties, and decisions will be subject to rigorous business analysis to satisfy the requirements of public accountability; (g) organisations which require non-ATC functions may, provided they satisfy eligibility criteria, compete for funding through the normal peer-review review processes; (h) the Directors of the overseas facilities will have the authority to negotiate and place contracts with the ATC or other supplier organisations on the basis of cost-effectiveness; (i) the Directors of the ATC the ING and the JAC will have delegated authority to develop and implement distinct personnel policies and systems consistent with their specific business needs." [Spelling, capitalization, and punctuation as in the original.]

The document also covered the Management structure and Delegated Authority for the three sites.

Following that, Jim Sadlier, on behalf of Ken Pounds, issued a letter to PPARC staff updating progress since the July 4 announcement. As well as the expected meetings with the two universities involved, Ken Pounds met with the Standing Committee of Astronomy Professors on July 9, the Directors of the RGO (July 7) and the ROE (July 16), and the trade unions on July 28. Dr. Adrian Russell had been appointed as interim Director ATC and subsequently met with *Gemini* staff at the RGO individually to see how best to protect the *Gemini* work programme during the transition period.

The end is in sight for the RGO

On the assumption it would be closed, there were many issues to be sorted out at the RGO. Those included the library, the RGO archive, and the Starlink node. Staff of the RGO then attempted to organize a 'management buy-out' and Jasper Wall, Neil Parker, and Sue Tritton submitted a detailed 40-page proposal and business plan to PPARC in an attempt to maintain the RGO. That plan continued to be based on a Company Limited by Guarantee (CLG), retained a technology capability, seemed to require a construction programme that was in excess of what PPARC was planning, and would be a competitor to the UKATC. The plan went to the October meeting of PPARC Council but discussion was deferred until the December meeting.

On October 8, Professor Donald Lynden-Bell on behalf of senior staff of the IoA and Richard Hills of the Cavendish Lab wrote to Ken Pounds and PPARC Council pointing out the long history of the RGO and the potential for further work to be undertaken there in spite of the concentration of technology at Edinburgh. That on-going, and mostly PPARC-funded, work was in the fields of wide-field astronomy, astrometry and post-*Hipparcos* missions, astronomical data archiving for the UK, and supporting research. In November, the Cambridge University VC wrote to the Chair of UK Council arguing to retain the RGO along the same lines as Donald Lynden-Bell. Richard Ellis, as a member of the Implementation Steering Committee, also tried to rescue aspects of the RGO along the same lines of focussing on wide-field astronomy, astronomical data archiving, and astrometry (post *Hipparcos*). However, there was the growing recognition that PPARC would not back down and would not support an establishment that wished to retain its technology arm and would therefore be a competitor in some areas to the newly constituted UKATC. The final decision was made at PPARC Council on 1997 December 12, the RGO would be closed and its assets disposed of, and the staff transferred or made redundant. In fact, the RGO would finally close on 1998 October 31, bringing to an end 323 years of operation from its previous sites of Greenwich, Herstmonceux, and, finally, Cambridge. However, the future of the RGO building at Cambridge would now come into the frame.

On replying to the Cambridge's VC letter of November 20, Ken Pounds brought up that question and asked for a Cambridge view on how they would react to a transfer of the RGO building to the proposed RGO CLG, or if the University might be interested in acquiring the building from PPARC for a negotiated sum, some of which might support operation of the CLG for a couple of years. The reply came on 1998 February 6. That was generally non-committal but was positive on the discussions with Ian Corbett regarding the transfer of some RGO staff to Cambridge. It also brought up the matter of the RGO name, which Cambridge would have preferred to retain but now looked likely to transfer to the National Maritime Museum, which was responsible for the operation of the original Observatory at Greenwich. That would satisfy the requirement of the Science Minister and the site at Greenwich would include a public-understanding-of-science aspect as well as being a national museum. However, Martin Rees remained opposed to such a move and wrote to John Battle expressing his dismay. Ken Pounds then wrote to Battle pushing the main reason for the decision to close the RGO (the dire financial situation of PPARC) and supporting the case for the transfer of the name to the museum at Greenwich, something that he noted was strongly supported by PPARC Council and the National Maritime Museum.

The situation now focussed on discussions with Cambridge University on the status of the RGO building, the transfer of some astronomy functions along with selected staff and of redundancy for those who would not have future funded roles. In the discussions it was quickly agreed that three RGO staff members would transfer to Cambridge University with regard to Starlink support and that the post docs would similarly transfer across. The non-staff costs then became a focus of negotiation, specifically the joint library and the RGO building. On 1998 September 10 John Love wrote to the University with a proposal for PPARC to surrender the lease of the building and for the University to then buy it for £2·75M. In exchange, PPARC would pay £750k to the University towards the alterations and extension of the IoA building and would pay 50% of the costs of moving the library from the RGO building to the IoA up to a maximum of £25k. Importantly, the name ‘Royal Greenwich Observatory’ would be excluded from any agreement.

Further staff transfers would be in the astronomy survey group and a small number of research staff. Some PPARC staff would not transfer to the University but would be relocated in the Cavendish building to the south of Madingley Road. Some PPARC staff would transfer to the UKATC in Edinburgh.

As part of the disposal of the assets within the RGO building, I remember a particularly unpleasant experience of visiting in late 1998 along with Colin Cunningham (ROE) and other representatives from La Palma and RAL to determine whether any of the equipment could be relocated to our respective sites. It was very depressing and given that it was not obvious that Hawaii would be a good location, especially given the shipping distance, I left after lunch. I believe the RGO conference-suite table and chairs eventually got transferred to Edinburgh!

The UKATC

So now we have the background to the decision-making process that led to the 1998 closure of both Royal Observatories and the formation of the UKATC at Edinburgh. Although on paper that included the closure of the ‘old’ ROE as it had previously operated at Edinburgh, they were undoubtedly the winners. The closure and dispersal of the RGO resulted in a large loss of staff from Cambridge and the transfer of eight staff to Edinburgh. Those turned out to be of high calibre and would serve the ROE well in the coming years. What is often forgotten is that there was an equivalent process that took place at Edinburgh, with the transfer of ‘ROE’ research staff to the University of Edinburgh (IfA) along with the Wide Field Astronomy Unit, which oversaw the UK Schmidt photographic survey plates and the *SuperCOSMOS* plate-measuring machine. That left the UKATC as a predominantly technology-focussed institution as intended by the Hough reports. The UKATC was officially opened on 1998 October 23 by Lord Sainsbury, the Minister for Science, with Adrian Russell as its first

Director. However, the size of the UKATC was more than double that recommended by Hough-2 and, depending on the work requirement, has fluctuated around or above this figure ever since.

Just to add an end-point to this story, in 2000 the UK announced its intention to join the European Southern Observatory, ESO. That would entail having access to a suite of 8-m telescopes (the four *VLT*s) but, more importantly, to be able to participate in the *Atacama Large Millimetre Array* (*ALMA*) on Cerro Chajnantor in Chile and eventually the next generation of ground-based telescopes, the *Extremely Large Telescope* (*ELT*). The UK finally became a member in 2002 June and as part of the accession fee the UK agreed to provide the *VISTA* wide-field infrared/optical telescope, which was being built by the UKATC. *VISTA* had been put forward by a consortium of UK universities, led by Professor Jim Emerson of QMUL, for government support from a special university infrastructure fund, and secured £35M of funding. The UKATC had contributed important expertise to the proposal and its leadership in its construction was invaluable. After a number of hiccups *VISTA* was eventually delivered to Cerro Paranal in Chile, but that is another story, or rather a saga, in which I became involved as Director UKATC. Hopefully, someone will take up the baton and recount the story as it is intriguing, interesting, and a story well worth telling.

Regarding the on-going operation of the UKATC, it was becoming clear in the mid-2000s that we were becoming an oddity within PPARC, which was essentially a university grant-awarding and project-awarding body along with supporting the astronomy delivery on the two island sites. The Astronomy Technology Centre was not sitting comfortably within PPARC, especially as it was not a cheap facility and there had already been one attempt to close it, so the possible writing was on the wall for another attack. Therefore, with the blessing of PPARC senior management, as Director I initiated a discussion with RAL to become part of CCLRC [Council for the Central Laboratory of the Research Councils] (Rutherford and Daresbury Laboratories), probably within the Technology Department. However, no sooner had that discussion begun (we had only one meeting but received a positive reception) when, out of the blue in 2007 April, PPARC was, at a stroke, merged with CCLRC to become the Science and Technology Funding Council (STFC). One of the rationales for that merger was that the new body would have an economy of scale and would benefit from PPARC's strategic planning and financial diligence.

However, that merger opened up a major problem with regard to the overall funding; a multi-million pound 'black hole' was discovered in the finances. That would have severe impacts on projects and for the laboratories as a whole. A major casualty was the UK's participation in the *Gemini* Observatory. The *Gemini North* telescope had started operations in 2000 and was followed by the *Gemini South* telescope a couple of years later. However, by 2008 the criticality of the STFC funding situation described above resulted in the UK having to save a significant amount of money and so it was with regret the UK had to 'withdraw' from the *Gemini* operations. But, after a major outcry in the UK, re-admittance followed in December 2009, but, unfortunately, it was to be only a reprieve. Only three years later, in 2012, following on-going STFC financial problems, the UK formally withdrew from the *Gemini* Observatory. This time there would be no way back and that particular strategic aim of the Ground-Based Plan would be taken up through our membership of ESO. However, financial pressures continued and with two further closure threats fought off it was agreed that the UKATC should become a unit of the Technology Department of STFC, which duly took place. And, ending on a positive note, the UKATC continues to play a leading role in supplying world-beating instrumentation for the ESO 8-m telescopes (*VLT*s), the next generation (*ELT*) of ESO's ground-based telescopes, as well as space projects like the *JWST*, *MIRI*, and *LISA*. But that is another story.

With the invaluable benefit of hindsight it is probable that if the original Kingman conclusions of 1985 had been implemented then the current situation, broadly speaking, could have been in place by 1990, and all the resulting angst and expense would have been avoided.

However, the turmoil of Prior Options would probably have been unavoidable.

Acknowledgements

I would like to thank the following for providing input and comments on the text: Professor Jim Hough, Dr. Ian Corbett, Professor Richard Ellis, Professor Andy Lawrence, Dr. Adrian Russell, Professor Phil Charles, Professor John Peacock. I am particularly indebted to Richard Ellis for cataloguing and then digitizing a subset of his extensive archive and providing me with access to those data, without which this project would never have progressed.

REDISCUSSION OF ECLIPSING BINARIES. PAPER 30: THE SLIGHTLY EVOLVED F-TYPE SYSTEM BK PEGASI

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BK Peg is a double-lined detached eclipsing binary containing two late-F stars in an orbit with small eccentricity. We use light-curves from the *Transiting Exoplanet Survey Satellite* (*TESS*) and spectroscopic measurements from previous studies to measure the physical properties of the companions to high precision. We obtain masses of $1{\cdot}411 \pm 0{\cdot}004\,M_{\odot}$ and $1{\cdot}254 \pm 0{\cdot}004\,M_{\odot}$, and radii of $1{\cdot}990 \pm 0{\cdot}004\,R_{\odot}$ and $1{\cdot}460 \pm 0{\cdot}004\,R_{\odot}$, which are among the most precise measurements made for those quantities in normal stars. Those properties match theoretical stellar-evolution models for a solar chemical composition and an age of 2·65 Gyr. We also present an updated ephemeris of the system, as a result of our *TESS* measurements and a collection of mid-eclipse times from previous studies.

Introduction

This study is part of the on-going series[1] in which known detached eclipsing binary systems (dEBs) are re-analysed based on new photometric data, primarily obtained with the NASA *Transiting Exoplanet Survey Satellite*[2] (*TESS*). Our main objective is to exploit space-based observations[3] to refine the measurements of the stellar components' properties and to incorporate those systems into the *Detached Eclipsing Binary Catalogue*[4] (*DEBCat*[*]).

In this work, we present a study of BK Pegasi (Table I), a dEB composed of two late-F stars in a slightly eccentric orbit. The system has the unusual characteristic that its more massive and larger primary component (hereafter star A) has a slightly lower effective temperature than the secondary (star B). That is a consequence of the primary's on-going evolution toward the sub-giant stage on the HR diagram[5].

[*] `https://www.astro.keele.ac.uk/jkt/debcat/`

TABLE I

Basic information on BK Pegasi. The BV magnitudes are each the mean of 94 individual measurements[14] *distributed approximately randomly in orbital phase. The JHK_s magnitudes are from 2MASS*[15] *and were obtained at an orbital phase of* 0·89.

Property	*Value*	*Reference*
Right Ascension (J2000)	$23^{h}47^{m}08^{s}{\cdot}26$	16
Declination (J2000)	$+26^{\circ}33'59''{\cdot}97$	16
Bonner Durchmusterung designation	BD+25 5003	17
Tycho designation	TYC 2254-2563-1	14
Gaia DR3 designation	2852979962499356288	16
Gaia DR3 parallax (mas)	3·2643 ± 0·0177	16
TESS Input Catalogue designation	TIC 269747005	18
B magnitude	10·46	14
V magnitude	10·04	14
G magnitude	9·835	16
J magnitude	8·892	15
H magnitude	8·643	15
K_s magnitude	8·611	15
Spectral type	F8 V + F7 V	10

Hoffmeister[6] originally identified its eclipsing character and classified the system as an Algol-type variable. The first determination of the orbital period was carried out by Lause[7,8], yielding a value of 2·745 days. Later, Popper & Dumont[9] revealed that light-curves of BK Peg contain two eclipse minima of almost identical depth (Fig. 1). They corrected the orbital period value to 5·49 days, which was later refined by Clausen *et al.*[10] (hereafter CL10).

Initial estimates of the absolute dimensions were reported by Popper[11] in his review of stellar masses, followed by spectroscopic analyses and refined determinations of the absolute parameters in a subsequent study[12]. According to those two studies, the masses (1·43 $M_\odot$ and 1·28 $M_\odot$) and luminosities (4·68 $L_\odot$ and 3·09 $L_\odot$) of the components differ significantly. Following that study, Demircan *et al.*[13] obtained UBV light-curves of the system and refined the absolute dimensions, using the radial velocities (RVs) given by Popper[12].

In addition, Demircan *et al.* discussed the evolutionary status of the system using the mass–radius (M–R), mass–luminosity (M–L), and temperature–luminosity (T–L) planes based on stellar-evolution models[19], claiming that the components are still in the core hydrogen-burning phase and best represented by high-metallicity models with an age of about 3·3 Gyr. More recently, CL10 presented high-precision absolute dimensions and spectroscopic chemical abundances for BK Peg, showing that the components have evolved to the upper half of the main-sequence band. Their comparison with scaled solar-evolution models suggested slightly younger ages ($\approx$ 2·5 to 2·8 Gyr), with indications that the amount of convective core overshooting may affect the inferred evolutionary status.

Photometric observations

BK Peg has been observed by *TESS* in two sectors (Sector 57 in 2022 October and Sector 84 in 2024 October). For Sector 57, short-cadence data with 120-s sampling were available, whereas only full-frame images (FFIs) are available for Sector 84. Therefore, our analysis is based solely on the 120-s-cadence data from Sector 57. The data were retrieved from the NASA Mikulski Archive for Space Telescopes (MAST*) *via* the LIGHTKURVE package[20].

For our analysis, we utilized the simple aperture-photometry (SAP) light-curves produced by the SPOC data-reduction pipeline[21], excluding data points flagged as low-quality using the LIGHTKURVE 'hard' quality flag. In Sector 57, the data are not fully continuous and contain

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*`https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html`

gaps. For that reason, portions of the light-curve where the eclipses were poorly sampled or affected by gaps were manually rejected and only the remaining data were retained for further analysis. The entire sector is shown in the top panel of Fig. 1, while the manually trimmed segments are displayed in the bottom panel. The remaining data were converted into differential magnitudes and the median magnitude was subtracted for convenience.

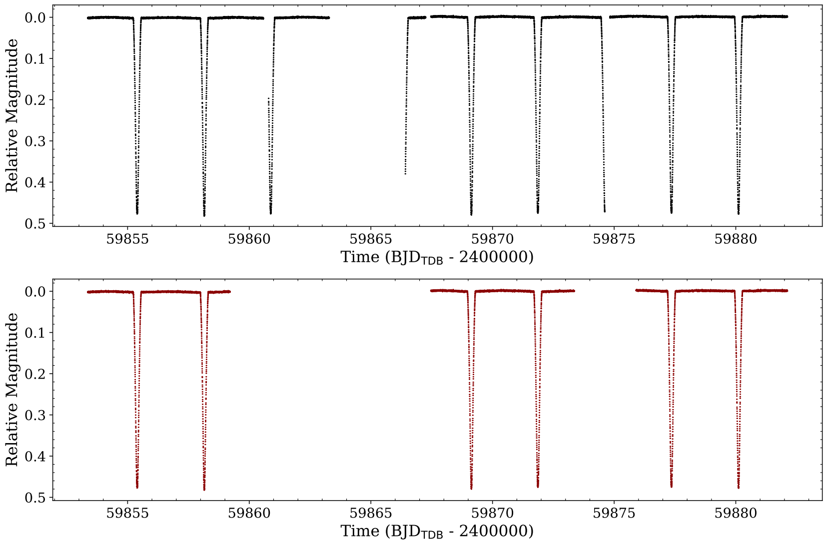

Fig. 1

Top: *TESS* sector 57 photometry of BK Peg. The flux measurements have been converted to magnitude units, and the median was subtracted. Bottom: trimmed light-curves of sector 57 for further analysis.

Light-curve analysis

As shown in Fig. 2, BK Peg is a well-detached binary system with two eclipses of nearly equal depth of approximately 0·5 mag. That makes the system a suitable target for modelling with the JKTEBOP* code[22,23]. Due to the orbital period of the system (≈ 5·5 days) and the duration of the *TESS* sector (≈ 27 days), only five orbital cycles were observed. For each eclipse, all data during the event were extracted from the *TESS* light-curve, along with additional segments immediately before and after the eclipse. Those additional segments cover at least 30 minutes and are useful for setting the out-of-eclipse brightness of the system. Each eclipse was then normalized to zero differential magnitude by fitting and subtracting a straight line to the out-of-eclipse data, thereby removing slow instrumental or astrophysical trends. Subsequently, second-order polynomial fits were independently applied to the out-of-eclipse regions in three separate portions of the *TESS* light-curve to suppress further low-frequency variations and minimize the residuals.

The fitted parameters were the fractional radii of the stars ($r_{\rm A}$ and $r_{\rm B}$), the central-surface-brightness ratio (J), third light (L_3), orbital inclination (i), eccentricity (e), argument of periastron (ω), orbital period (P), and a reference time of primary minimum (T_0). The fractional radii were expressed as their sum ($r_{\rm A} + r_{\rm B}$) and ratio ($k = r_{\rm B}/r_{\rm A}$), and the

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*`http://www.astro.keele.ac.uk/jkt/codes/jktebop.html`

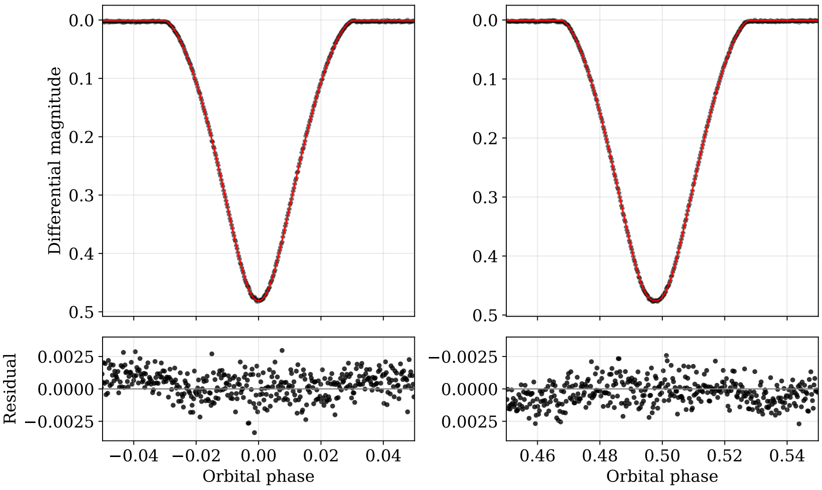

Fig. 2

Best-fit model to the *TESS* sector 57 light-curves of BK Peg for the primary eclipse (left panels) and secondary eclipse (right panels), obtained using JKTEBOP. The observed data are shown as black points, and the model fit is plotted as a red solid line. The residuals are displayed on an enlarged scale in the lower panels.

orbital-shape parameters as the combinations $e\cos\omega$ and $e\sin\omega$ to decrease correlations between parameters. Limb darkening (LD) was implemented using the power-2 law[24–26], with the linear coefficient (c) fitted and the non-linear coefficient (α) fixed at a theoretical value[27,28]. The same LD coefficients were used for both stars due to their almost identical temperature. To ensure that the adopted photometric uncertainties accurately represent the observed scatter, the *TESS* flux-measurement errors were iteratively scaled until the reduced chi-square of the fit, χ^2_ν, reached unity. An example fit is shown in Fig. 2. Our fitted light ratio is in excellent agreement with the spectroscopically-determined value of 0·57 ± 0·04 from CL10.

We calculated uncertainties in the fitted parameter values using 10 000 Monte Carlo simulations. The results of that analysis are provided in Table II with a comparison to the results from y-band light-curves of CL10. We have increased the error bars for $r_{\rm A}$ and $r_{\rm B}$ to 0·2% because it has not yet been demonstrated that light-curve models are reliable beyond that level of precision[29]. Overall, our results are in good agreement with those in CL10. The only noticeable difference is found in the eccentricity, which is lower in our solution by approximately 20%. Although the formal errors for e and ω in our table are very small, they primarily reflect the statistical precision of the fit rather than physical certainty. As a consequence of the very small eccentricity, the argument of periastron ω is highly subject to model degeneracies, and such an apparent difference between our value of ω and that reported by CL10 is probably dominated by model degeneracies rather than a physically significant change in the orbit. We leave the discussion of apsidal motion to future study, emphasizing the necessity of on-going measurements of times of primary and secondary eclipse.

TABLE II

Photometric parameters of BK Peg measured using JKTEBOP *from the TESS light-curves. The error bars are 1-σ standard errors obtained from the Monte Carlo simulations applied to sector-57 data. Also, we provide the results from the y-filter light-curves in CL10 for comparison.*

Parameter	*Value*	*CL10 (y)*
Fitted parameters:		
Orbital inclination (°)	88·14 ± 0·17	88·02 ± 0·05
Sum of the fractional radii	0·19001 ± 0·00009	0·1898 ± 0·0005
Ratio of the radii	0·733 ± 0·094	0·7379 ± 0·0050
Central-surface-brightness ratio	1·0432 ± 0·0038	1·0444 ± 0·0031
Third light	0·01 ± 0·10	0·0 (fixed)
$e \cos \omega$	−0·00356 ± 0·00001	−0·00364 ± 0·00006
$e \sin \omega$	−0·0010 ± 0·0022	0·00283 ± 0·00181
LD coefficient c	0·614 ± 0·009	
LD coefficient α	0·515 (fixed)	
Derived parameters:		
Fractional radius of star A	0·1096 ± 0·0002	0·1092
Fractional radius of star B	0·0804 ± 0·0002	0·0806
Light ratio $\ell_{\rm B}/\ell_{\rm A}$	0·5608 ± 0·0009	0·5670
Orbital eccentricity	0·00368 ± 0·00004	0·0046
Argument of periastron (°)	195·15 ± 0·12	142·1

Orbital ephemeris

This work includes only one sector of *TESS* data, which consists of three intervals of photometric observations (Fig. 1). We modelled each interval individually with JKTEBOP and determined the mid-times of primary eclipses. As those three intervals span only 25 d, we collected three times of primary minimum from previous studies[13,30] and eight times of minimum from the *VarAstro* portal of Variable Star and Exoplanet Section of the Czech Astronomical Society*. All primary minimum times are presented in Table III.

We fitted a linear ephemeris to those minimum times with PYTHON's SCIPY package[31], obtaining

$$\text{Min I} = \text{BJD}_{\text{DB}} 2450706{\cdot}46975(20) + 5{\cdot}48991130(12)E \qquad (1)$$

where E corresponds to the number of cycles since a reference time of minimum, and the numbers in parentheses show the uncertainties in the final significant figure of the corresponding measurement. The root-mean-square of the residuals is 61 s which is higher than most of the error bars suggest, and the reduced χ^2 is $\chi^2_\nu = 4{\cdot}32$. The uncertainties in the ephemeris have been multiplied by $\sqrt{\chi^2_\nu}$ to account for that high χ^2_ν.

Popper & Etzel[33] and Demircan *et al.*[13] also noted the variability of individual light-curves and suggested that one of the components of BK Peg might be a pulsating star. We checked the *TESS* data for the presence of pulsations using the PERIOD04 code[34]. We found no significant pulsation signal, to a limit of 0·2 mmag, but we see hints of starspot activity. Such activity could affect the fit of the light-curve and the times of minimum obtained from it.

Due to its slight eccentricity, BK Peg is expected to experience slow apsidal motion which could also increase the scatter when attempting to fit a linear ephemeris. However, we see no hint of that effect in Fig. 3. We leave an analysis of apsidal motion to future work.

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*`https://var.astro.cz/en/`

TABLE III

Times of mid-eclipse for BK Peg and their residuals versus the fitted ephemeris.

Orbital cycle	*Eclipse time (BJD$_{TDB}$)*	*Uncertainty (d)*	*Residual (d)*	*Source*
−329·0	2448900·28904	0·00056	0·00106	Demircan *et al.*[13]
0·0	2450706·47007	0·00030	0·00106	Ak *et al.*[30]
63·0	2451052·33246	0·00070	−0·00100	Ak *et al.*[30]
751·0	2454829·39325	0·00070	0·00037	Hübscher *et al.*[32]
931·0	2455817·57785	0·00001	0·00081	*VarAstro*
990·0	2456141·48076	0·00001	−0·00107	*VarAstro*
1004·0	2456218·34064	0·00001	0·00003	*VarAstro*
1398·0	2458381·36621	0·00001	0·00029	*VarAstro*
1531·0	2459111·52508	0·00001	0·00087	*VarAstro*
1543·0	2459177·40241	0·00001	−0·00073	*VarAstro*
1667·0	2459858·15185	0·00002	−0·00038	*TESS* sector 57
1669·0	2459869·13184	0·00008	−0·00021	*TESS* sector 57
1671·0	2459880·11153	0·00002	−0·00035	*TESS* sector 57

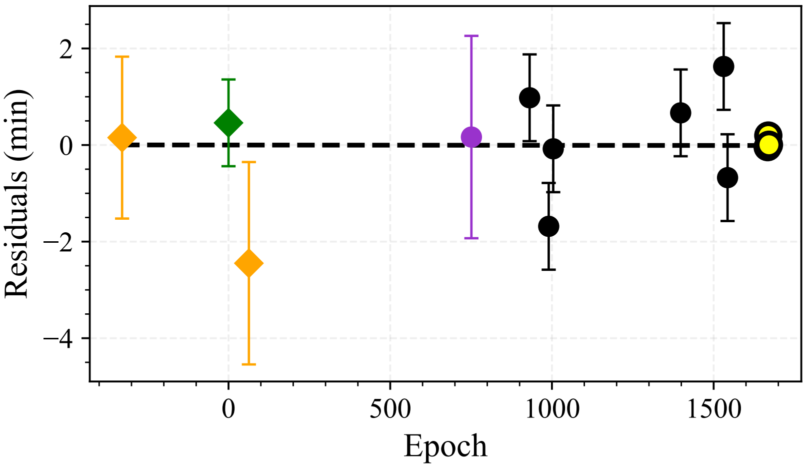

FIG. 3

Residuals of the primary minimum times from Demircan *et al.*[13] (green), Ak *et al.*[30] (orange), Hübscher *et al.*[32] (purple), *VarAstro* (black), and *TESS* (yellow), as listed in Table III. The dashed black line represents the residuals of zero according to the linear ephemeris. Diamonds represent the photoelectric observations, while circles denote the CCD observations.

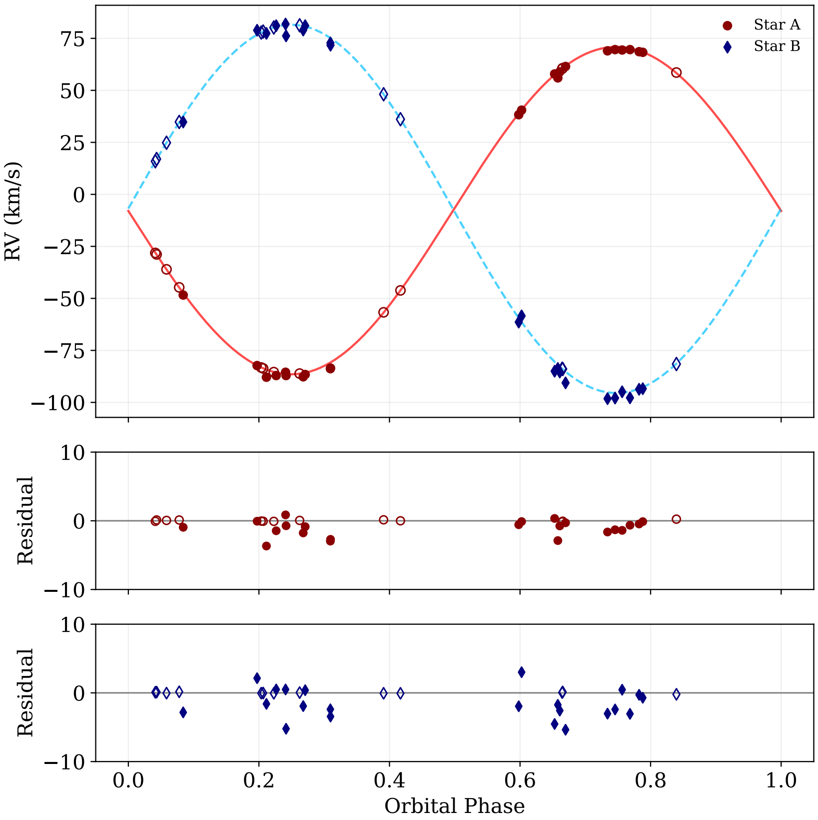

Fig. 4

RVs of BK Peg compared to the best fit from JKTEBOP (solid red and dashed blue lines). The RVs for star A are shown with dark-red colour, and for star B with blue colour. The residuals are given in the lower panels separately for the two components. RVs from Popper[12] are shown with closed circles and diamonds, and those from CL10 with open circles and diamonds.

Radial-velocity analysis

BK Peg has been the subject of two previous spectroscopic studies: Popper[12] and CL10. The former obtained 22 RV measurements for each star from photographic spectra obtained at Lick Observatory, whereas the latter provided 13 RV measurements per star from the *FIES* échelle spectrograph at the *Nordic Optical Telescope*[35]. CL10 compared their results with Popper and concluded that they are in a good agreement within errors, although the systemic velocities ($V_{\gamma,A}, V_{\gamma,B}$) differ by about 1 km s^{-1}.

In this study, four different analyses were performed based on the RV data source: Popper only, CL10 only, the combined RV data set with separate V_γ values for the two stars, and the combined RV data set with the same V_γ for the stars. In each case, we fitted the RV data using JKTEBOP with a fixed P but allowing for a shift in T_0. The other fitted parameters were $K_{\rm A}$, $K_{\rm B}$, $V_{\gamma,A}$, and $V_{\gamma,B}$. We kept $e\cos\omega$ and $e\sin\omega$ fixed at the photometric values provided at Table II. We present our results in Table IV and the phase-folded RV measurements from both sources, along with their model residuals, are shown in Fig. 4. In all instances, the error bars were calculated from 5000 Monte Carlo simulations. We conclude that all solutions are in agreement with the previous results of Popper and CL10 within the error bars. For our final result we took the average of the $K_{\rm A}$ and $K_{\rm B}$ values from our two fits to the combined data, but added the difference between the values for the two fits to the quoted uncertainties. That provided an additional uncertainty on the results stemming from our choice of which model to apply.

Physical properties and distance to BK Peg

Physical properties of BK Peg were calculated using the JKTABSDIM code[37] with the photometric properties from Table II and the spectroscopic properties from Table IV. We adopted the effective temperatures $T_{\rm eff,A} = 6265 \pm 85$ K and $T_{\rm eff,B} = 6320 \pm 90$ K from CL10. We present our results in Table V. We have achieved a precision of 0·3% in both mass and radius, and our measurements also agree with those from CL10 and Popper.

We measured the distance to BK Peg using the BV magnitudes from Tycho[14], JHK_s magnitudes from 2MASS[15] corrected onto the Johnson system, and the surface-brightness calibrations of Kervella *et al.*[38] We adopted an interstellar reddening of 0·04 ± 0·02 mag to equalize the distance measurements in optical and infrared passbands. As a result, our best distance estimate, in the K_s band, is 301·2 ± 3·6 pc. That is slightly lower than the distance of 306·3 ± 1·7 pc from the inverse of the *Gaia* DR3 parallax[16].

Comparison with theoretical models

We compared the measured properties of BK Peg to theoretical predictions from the PARSEC 1.2 stellar-evolution models[39]. We initially set the fractional metal abundance by mass to be $Z = 0{\cdot}014$ to match the mildly sub-solar metallicity found by CL10 in their spectroscopic chemical-abundance analysis. In that case, an age of 2500 ± 50 Myr fits the masses and radii of the stars, but both are significantly cooler than the models predict. Increasing the Z improves the match with the temperatures of the stars: for $Z = 0{\cdot}017$ we obtain good agreement in mass, radius, and $T_{\rm eff}$ for an age of 2650 ± 50 Myr.

In Fig. 5 we compare the properties of BK Peg to the predictions of the PARSEC models in a Hertzsprung–Russell diagram. That shows that both components are on the main sequence, although star A is nearing the end of its main-sequence lifetime.

Summary and Conclusions

BK Peg is a dEB containing two late-F–type stars in a slightly eccentric orbit of period 5·49 days. We used the light-curves from *TESS* sector 57 and RV data from Popper and CL10

TABLE IV

Spectroscopic orbits for BK Peg from the literature and from the current work. All quantities are given in km s^{-1}. The error bars are 1-σ standard errors obtained from the Monte Carlo simulations.

Source	$K_{\rm A}$	$K_{\rm B}$	$V_{\gamma,{\rm A}}$	$V_{\gamma,{\rm B}}$	$\sigma_{\rm A}$	$\sigma_{\rm B}$
Popper[12]	79·14 ± 0·33	88·86 ± 0·56	−8·51 ± 0·30	−8·35 ± 0·51	1·36	2·30
CL10	78·77 ± 0·11	88·59 ± 0·21	−7·39 ± 0·08	−7·20 ± 0·15	0·26	0·50
This work (Popper RVs)	79·02 ± 0·26	88·86 ± 0·49	−8·59 ± 0·24	−8·93 ± 0·45	1·08	2·13
This work (CL10 RVs)	78·70 ± 0·04	88·51 ± 0·04	−7·47 ± 0·03	−7·29 ± 0·03	0·11	0·09
This work (all RVs, separate V_γ)	78·70 ± 0·06	88·51 ± 0·05	−7·49 ± 0·04	−7·30 ± 0·03	1·00	2·14
This work (all RVs, common V_γ)	78·75 ± 0·06	88·55 ± 0·04	−7·37 ± 0·03	−7·37 ± 0·03	1·31	2·11
Adopted spectroscopic orbit	78·72 ± 0·11	88·53 ± 0·09	−7·43 ± 0·16	−7·34 ± 0·10	1·00	2·14

TABLE V

Physical properties of BK Peg defined using the nominal solar units given by IAU 2015 Resolution B3 (ref. 36).

Parameter	*Star A*	*Star B*
Mass ratio $M_{\rm B}/M_{\rm A}$	0·8892 ± 0·0015	
Semimajor axis of relative orbit ($\mathcal{R}^{\rm N}_{\odot}$)	18·158 ± 0·016	
Mass ($\mathcal{M}^{\rm N}_{\odot}$)	1·4109 ± 0·0035	1·2545 ± 0·0037
Radius ($\mathcal{R}^{\rm N}_{\odot}$)	1·9901 ± 0·0040	1·4599 ± 0·0038
Surface gravity (log[cgs])	3·9898 ± 0·0016	4·2079 ± 0·0022
Density ($\rho_{\odot}$)	0·1790 ± 0·0010	0·4032 ± 0·0030
Synchronous rotational velocity (km s^{-1})	18·340 ± 0·036	13·454 ± 0·036
Effective temperature (K)	6265 ± 85	6320 ± 90
Luminosity $\log(L/\mathcal{L}^{\rm N}_{\odot})$	0·740 ± 0·024	0·486 ± 0·025
$M_{\rm bol}$ (mag)	2·890 ± 0·059	3·524 ± 0·062
Interstellar reddening $E(B-V)$ (mag)	0·04 ± 0·02	
Distance (pc)	301·2 ± 3·6	

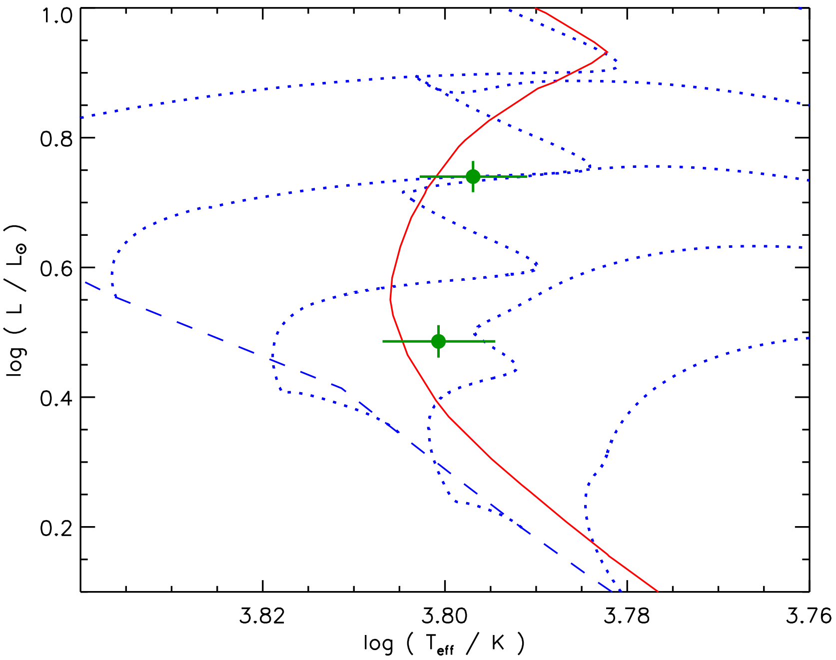

FIG. 5

Hertzsprung–Russell diagram for the components of BK Peg (filled green circles) and the predictions of the PARSEC 1·2 models [39]. The dashed blue line shows the zero-age main sequence for $Z = 0{\cdot}0170$. The dotted blue lines show evolutionary tracks for $Z = 0{\cdot}017$ and masses of 1·1 $M_{\odot}$ to 1·5 $M_{\odot}$ in steps of 0·1 $M_{\odot}$ (from bottom-right to top-left). The solid red line shows an isochrone for $Z = 0{\cdot}017$ and an age of 2650 Myr; it is not a perfect match in this diagram because it was chosen as the best fit to the masses and radii of the components of BK Peg.

to measure the mass and radii of the companions. We measured the distance to the system using published $T_{\rm eff}$ values and surface-brightness calibrations, finding a value close to but slightly shorter than the *Gaia* DR3 parallax distance.

The physical properties of the companions match theoretical models for a slightly super-solar metallicity and an age of 2650 Myr. That conflicts with the spectroscopic metallicity measurement of $[{\rm Fe/H}] = -0{\cdot}12 \pm 0{\cdot}07$ given by CL10.

Since there were only three mid-eclipse-time measurements available from the *TESS* data, we also collected mid-eclipse times from previous literature works or open databases such as the *VarAstro* portal. The eclipse times have an excess scatter around our fitted ephemeris. We conclude that further times of eclipse should be obtained to refine the ephemeris and measure its apsidal-motion period.

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The Editors congratulate David E. Holmgren (first author of the following article) on having an asteroid named after him this year: (587299) Holmgren = 2005 WJ_{209} (see the IAU WGSBN (Working Group on Small Bodies Nomenclature) Bulletin **6**, #2, 2026 February 2, p. 12).

LONG-TERM STUDIES OF EARLY-TYPE BINARY STARS: THE SPECTROSCOPIC ORBIT OF NY CEPHEI

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A new spectroscopic orbit and set of absolute dimensions are presented for the early-type eclipsing binary system NY Cephei. Those results are based on 30 years of CCD spectral data obtained at the Dominion Astrophysical Observatory (DAO). A search for apsidal motion was also attempted by combining those data with older Reticon data to extend the time-base to 40 years. We present a tentative detection of apsidal motion with a period of 13 500 yr.

Introduction

NY Cephei (HD 217312, BD+62 2147) is an eclipsing binary system with components of spectral types B0·5V and B2V, in an eccentric orbit having a period of ≈ 15·3 d. It is well known for showing only one eclipse due to the combined effects of the orbital inclination and eccentricity. It has been studied previously by Tkachenko *et al.*[1], Albrecht *et al.*[2], Ahn[3], Holmgren *et al.*[4], and Heard & Fernie[5]. Moffatt[6] also proposed the system as a test of non-symmetric gravity theory, predicting a regression of the line of apsides. The search for apsidal motion is taken up further in this paper, building upon the work of Holmgren *et al.*[4]

After presenting the new CCD spectra in the next section, the measurement of radial velocities for the component stars is discussed. An initial spectroscopic orbit based on those measurements is presented. That is followed by a presentation of the component line profiles and spectroscopic orbit recovered from spectrum disentangling. Following that, the absolute dimensions and search for apsidal motion are discussed. The search for apsidal motion presented here is unique in that digital spectra covering a time interval of over 40 years are used. Finally, estimates of the projected rotational velocities are presented, based on the disentangled helium-line profiles.

Observations and reductions

The spectra presented here were obtained with the 1·2-m telescope and *McKellar* spectrograph of the Dominion Astrophysical Observatory between 1996 and 2025. The 32121H configuration of the spectrograph was used (32-inch-focal-length camera, 1200 line/mm grating, first-order diffraction, central wavelength of 660·0 nm), with the UBC-1, SITe-4, and Fletcher CCD detectors. The reciprocal dispersion was 1 nm/mm at Hα. Fig. 1 shows a typical CCD spectrum of NY Cephei. The older Reticon spectra used here in the search for apsidal motion (p. 162) were obtained with the same telescope and the 3261 configuration of the *McKellar* spectrograph (32-inch camera, 600 line/mm grating, first order, central wavelength of 420·0 nm). Those data are described in more detail by Holmgren *et al.*[4] The detectors used, and the number of spectra obtained with each, are summarized in Table I.

The red spectral region used to obtain the new spectra was chosen as that takes advantage of the higher quantum efficiency of the CCD detectors in that region. Also, for a given radial velocity the step in wavelength is larger than at shorter wavelengths. Further, the presence of telluric lines in the Hα region can help to stabilize disentangling solutions using that line.

The CCD spectra of NY Cep presented here were obtained as part of a much larger programme of monitoring early-type binary systems for Hα emission and non-radial pulsation. There are stellar lines in the 630·0–690·0 nm region that are quite suitable for radial-velocity measurement and spectral-type estimation. Specifically, lines of neutral helium, singly-ionized oxygen, and singly-ionized carbon are present.

Table I

Detectors used in this work.

Detector	*Number of pixels*	*Pixel size (μm)*	*Wavelength region (nm)*	*Number of spectra*
Reticon	1872	15	397·0–451·0	25
UBC-1	4096	15	630·0–690·0	8
SITe-4	4096	15	630·0–690·0	88
Fletcher	4604	13·5	630·0–690·0	2

All reductions of the CCD data were done using the IRAF processing system[7,8]. Continuum rectification of the spectra was done using a program written in GNU DATA LANGUAGE (GDL

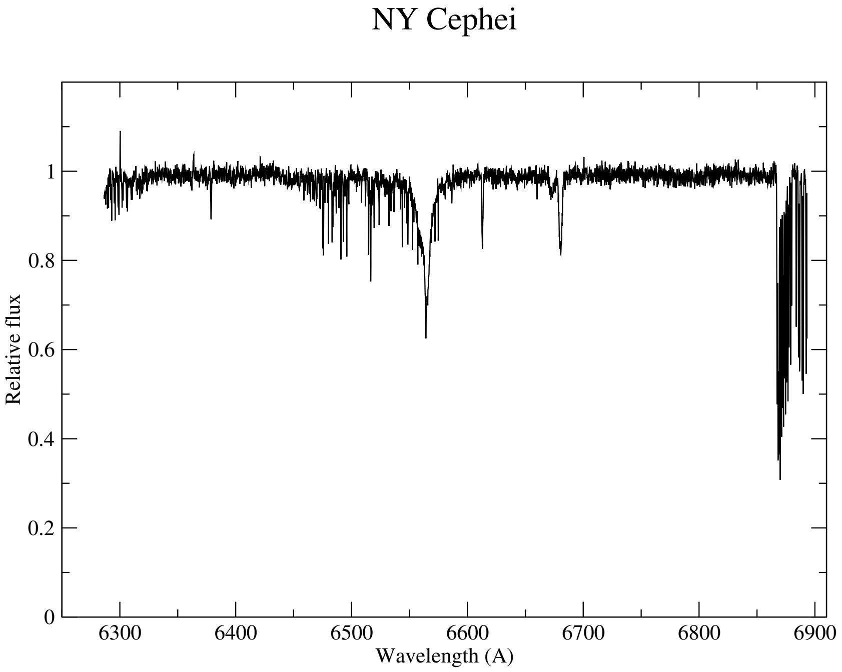

Fig. 1

A wavelength-calibrated and rectified spectrum of NY Cephei at the orbital phase corresponding to maximum radial-velocity separation.

— *e.g.*, Coulais *et al.*[9]). Heliocentric-radial-velocity corrections were done using GDL and routines from the IDL Astro library[10].

Stellar-spectrum exposures were interspersed with those of a thorium–argon arc for the wavelength calibrations. Flat-field and bias frames were also obtained on each night.

Radial-velocity measurement

Cross-correlation-function (CCF) radial-velocity measurements were done using the He I 667·8-nm region (666·5 nm–669·0 nm) and a synthetic Gaussian template with σ = 25 km/s. Using a synthetic template had the added benefit of reducing the noise in the line profiles. A typical CCF is shown in Fig. 2. The cross-correlation methodology used here follows that described by Tonry & Davis[11].

To obtain an estimate of the precision of those radial velocities, wavelength measurements of an atmospheric O_2 line (Fig. 3) on several spectra were made, and then compared to the rest wavelength from the *HITRAN* database[12]. The corresponding radial-velocity offsets are shown in Fig. 4. The standard deviation in those offset measurements is about ±1 km/s; that is an estimate of the internal error in those CCF radial velocities.

Spectroscopic orbit

A subset of the spectra was used to compute an initial spectroscopic orbit, which allowed a mass ratio to be defined. That mass ratio was then used as a constraint in the disentangling solutions, described in the next section. Only 35 spectra on which both components were

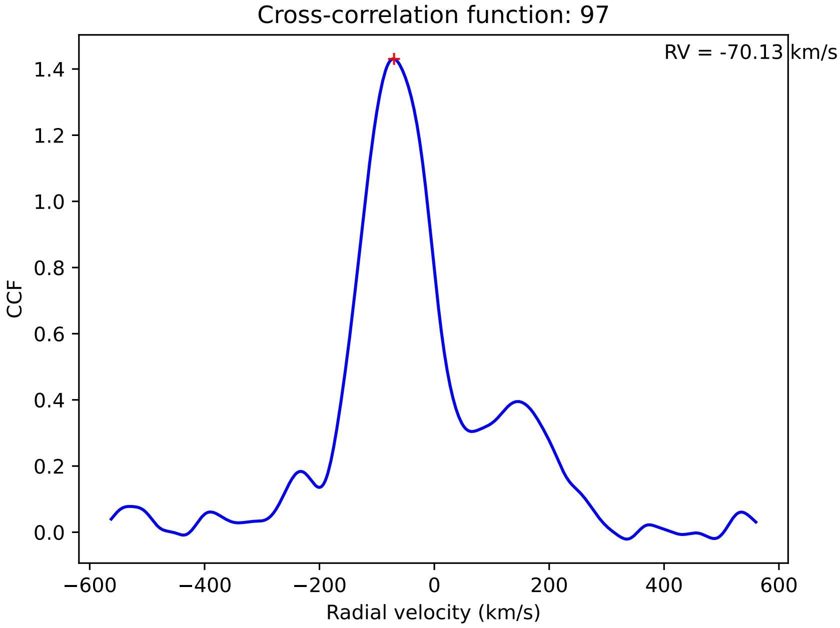

Fig. 2

An NY Cep cross-correlation function near the maximum radial-velocity separation.

visible and relatively unblended were used. A least-squares orbital solution using those data is shown in Table II. The orbital period was included in the solution as a check on previously published values. The computed value found here agrees with those presented by Ahn[3] and Albrecht *et al.*[2]

A plot of the data and fit is shown in Fig. 5. We therefore have an estimated mass ratio (P/S) of $q = 1{\cdot}282 \pm 0{\cdot}017$.

Table II

Spectroscopic orbit solution.

Parameter	*Value*
V_{01} (km/s)	$-14{\cdot}0 \pm 1{\cdot}2$
V_{02} (km/s)	$-7{\cdot}63 \pm 1{\cdot}50$
K_1 (km/s)	$113{\cdot}5 \pm 1{\cdot}1$
K_2 (km/s)	$145{\cdot}6 \pm 1{\cdot}4$
$q = K_2/K_1$	$1{\cdot}282 \pm 0{\cdot}017$
e	$0{\cdot}435 \pm 0{\cdot}008$
ω_0 (deg)	$53{\cdot}8 \pm 1{\cdot}8$
$T_{\rm peri} - 2400000$ (HJD)	$55116{\cdot}613 \pm 0{\cdot}056$
P (d)	$15{\cdot}27578 \pm 0{\cdot}00012$
$\sigma_{1,\rm p}$ (km/s)	$\pm 4{\cdot}10$
$\sigma_{1,\rm s}$ (km/s)	$\pm 7{\cdot}83$

The minimum masses and projected semi-major axes based on that orbit are:

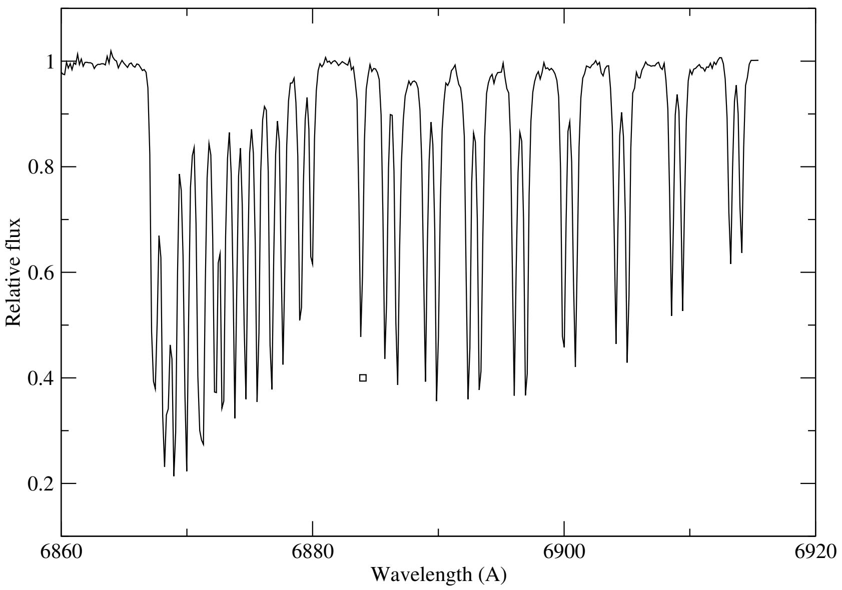

Fig. 3

A wavelength-calibrated and rectified spectrum of NY Cephei showing the O_2 line used (indicated by the square) for radial-velocity offset measurement.

$$\begin{aligned} M_1 \sin^3 i &= 11{\cdot}3 \pm 0{\cdot}3\, M_\odot \\ M_2 \sin^3 i &= 8{\cdot}8 \pm 0{\cdot}3\, M_\odot \\ a_1 \sin i &= 30{\cdot}9 \pm 0{\cdot}4\, R_\odot \\ a_2 \sin i &= 39{\cdot}6 \pm 0{\cdot}5\, R_\odot \end{aligned}$$

Disentangling

Spectrum disentangling in the frequency domain[13] was used to recover the line profiles and spectroscopic orbital elements for the primary and secondary of NY Cep. That technique was implemented in the PYTHON programming language, and a more detailed description will be the subject of a forthcoming paper. A two-component version was used with the He I 667·8-nm-line data, and a three-component version with the Hα data, since it was necessary to separate out the telluric-line contribution. As spectrum disentangling does not address the Rossiter–McLaughlin (rotation) effect, spectra near the eclipse were given zero weight in the solution for the orbital parameters and line profiles. Flux factors $s_{1,2}$ were computed at all phases to account for brightness variations as a function of orbital phase. The flux factors are regarded as a fundamental quantity, since calculation of their ratio $z = s_1/s_2$ can result in the magnification of small errors, rendering that ratio of limited use. Hadrava[14] describes the flux factors in detail, and their relative values ensure that the observed line profile at any phase is reconstructed correctly. Prior to computing the disentangling solutions, all line-profile data were linearized using cubic-spline interpolation onto a radial-velocity scale with a constant sampling interval.

Each disentangling iteration involves a nonlinear simplex minimization over the orbital elements, including a linear least-squares solution for the Fourier components of the line profiles. That is followed by a linear least-squares solution for the flux factors, and the whole procedure is iterated until convergence. The disentangling-solution parameters used

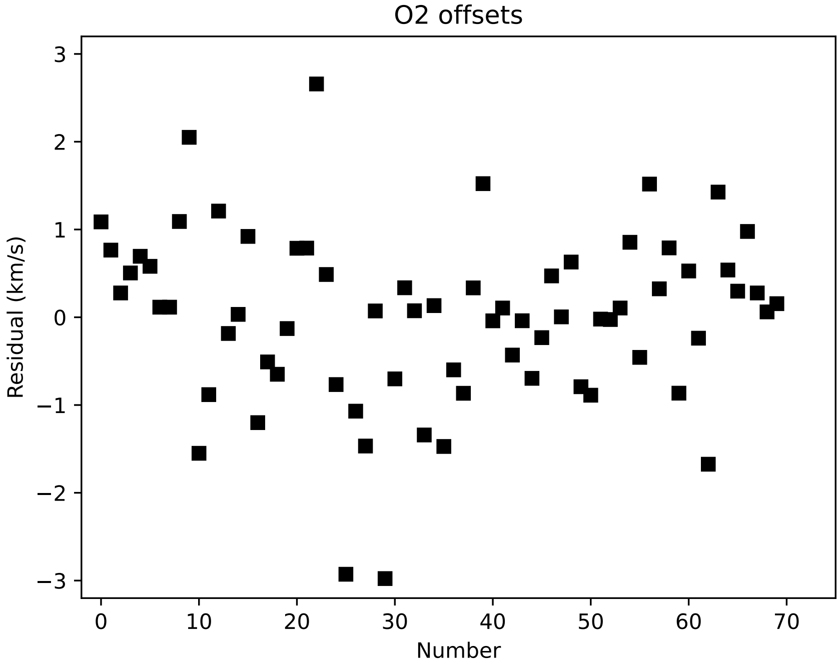

Fig. 4

The measured radial-velocity offsets in the O_2 telluric line.

in this paper are summarized in Table III. The telluric parameters were used only in the Hα solution. The function being minimized is the sum of squared residuals between the observed and computed line-profile Fourier components. That sum of squares is scaled to be a reduced chi-squared, so that its value is ≈ 1·0. The nonlinear minimization allows for the orbital parameters to be fixed or varied over a specified range. For the three-component Hα solution, the heliocentric-radial-velocity corrections $V_\odot$ are used as a constraint on the

Table III

Disentangling-solution parameters.

Parameter	*Unit*	*Meaning*
K_1	km/s	Primary radial-velocity semi-amplitude
K_2	km/s	Secondary radial-velocity semi-amplitude
$q = K_2/K_1$		Mass ratio (P/S)
e		Orbital eccentricity
ω_0	deg	Longitude of periastron
$\dot{\omega}$	deg/d	Apsidal-motion rate
$T_{\rm peri}$	HJD	Time of periastron passage
K_3	km/s	Telluric radial-velocity semi-amplitude
e_3		Telluric orbital eccentricity
ω_3	deg	Telluric longitude of periastron
$T_{{\rm max},3}$	HJD	Time of maximum positive velocity (telluric orbit)

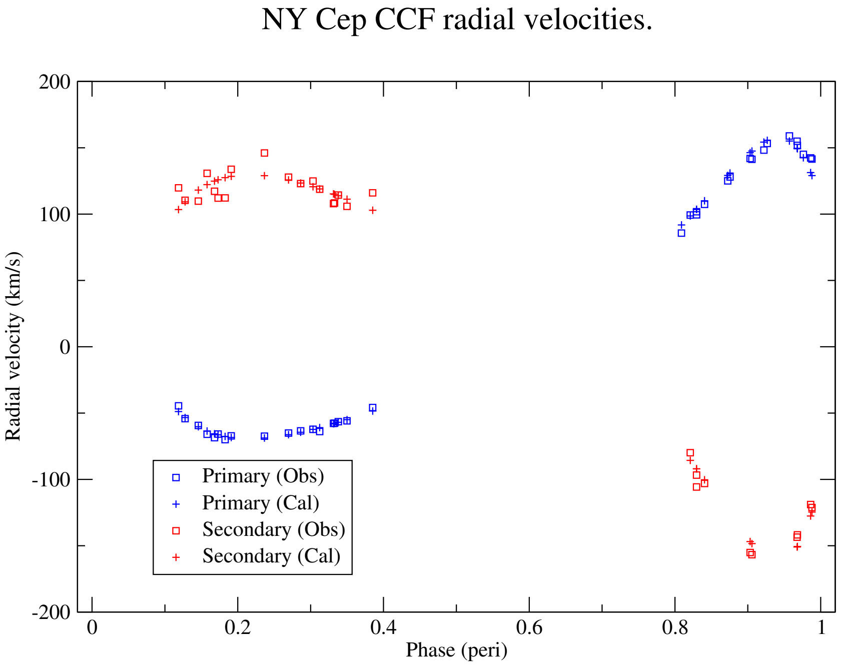

Fig. 5

The measured CCF radial velocities (squares) and computed orbit (plus signs).

telluric parameters. That part of the fit is indicative of the solution quality for K_3, $T_{\mathrm{max},3}$ and ω_3. Also, $T_{\mathrm{max},3}$ is used due to the small eccentricity of the Earth's orbit, following Sterne's recommendation[15,16].

At the end of each disentangling iteration, the computed flux factors $s_{1,2}$ are used in a minimization to recover a value of the light ratio[14]. The uncertainty in the light ratio may be computed by measuring the noise levels in the recovered profiles and then using error propagation.

After converging a disentangling solution, radial velocities were measured from the line-profile data by sliding and scaling the recovered component line profiles to fit the observed profiles. The computed flux factors were used for the scaling. Also, the mass ratio was used as a constraint on the measured radial velocities.

The He I 667·8-nm line-profile data set is shown in Fig. 6. Certain very noisy profiles were given zero weight in the disentangling solution. For that solution, the radial-velocity sampling interval was 2·5 km/s. Weights were assigned to each profile according to its signal-to-noise ratio.

The orbital period was fixed at $P = 15{\cdot}27566$ d, following Ahn[3] and Albrecht *et al.*[2] That same value of the period was also used in the Hα solution.

The final orbital parameters derived from He I 667·8 nm are shown in Table IV. Errors in the orbital parameters were computed by examining the variation in the sum of squares of residuals as a function of each parameter independently. A parabolic fit to the minimum then gave an estimate of the parameter error. Note that that method does not account for inter-parameter correlations. That approach to error calculation was found to be more effective than inverting the Hessian matrix at the solution point.

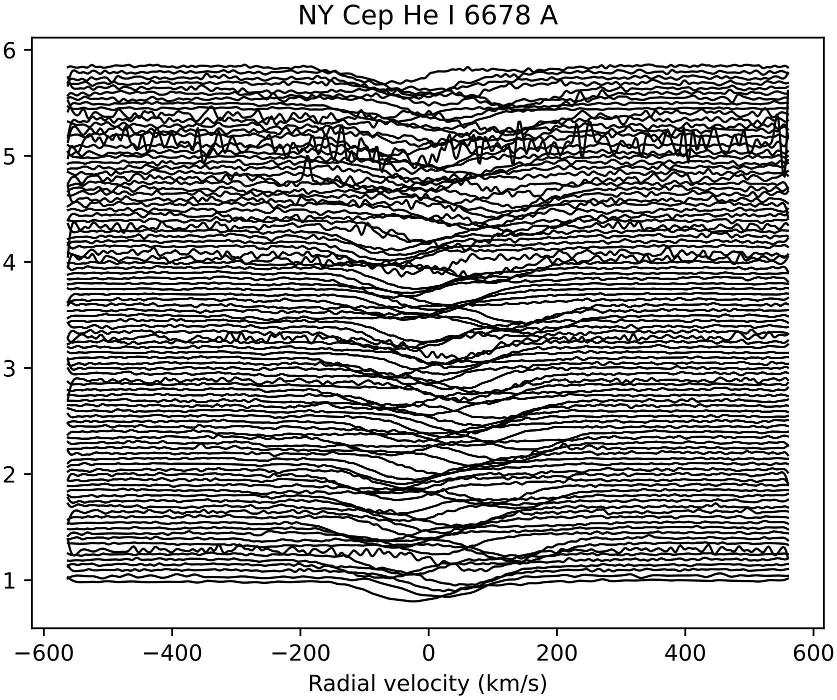

Fig. 6

The line-profile data for He I 667·8 nm in NY Cep. The spectra are ordered with the earliest at the bottom and the most recent at the top of the plot.

The final component line profiles are shown in Fig. 7, the measured and computed radial velocities in Fig. 8, and the flux factors in Fig. 9. The r.m.s. errors for the measured radial velocities were ±1·24 km/s and ±1·80 km/s for the primary and secondary, respectively.

The measured flux factors were used to recover the light ratio, indicating $l(\mathrm{P/S}) = 4{\cdot}08 \pm 0{\cdot}10$.

Table IV

Orbital elements from He I 667·8 nm.

Parameter	*Value*
K_1 (km/s)	113·9 ± 0·5
q	1·241 ± 0·069
K_2 (km/s)	141·4 ± 0·5
e	0·4391 ± 0·0008
ω_0 (deg)	57·5 ± 1·1
T_{peri} − 240000 (HJD)	55116·751 ± 0·067

The flux factors indicate quite clearly the presence of the primary eclipse near phase 0·63. Also, near phase 0·05, there is a hint of a secondary eclipse. However, that could also be interpreted as the rotation (Rossiter–McLaughlin) effect.

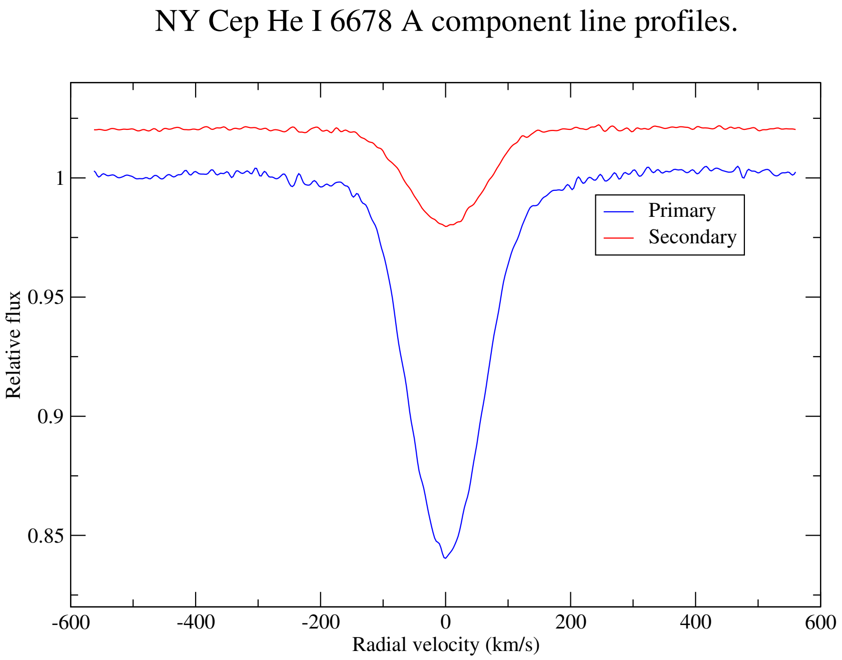

FIG. 7

The primary (bottom) and secondary (top) line profiles for He I 667·8 nm in NY Cep. The secondary profile has been displaced upward for clarity.

The solution for the Hα-profile data is shown in Table V and Fig. 10, Fig. 11, & Fig. 12. That solution converged in 80 iterations. The line-profile data used in that solution are shown in Fig. 13. Once again, weights proportional to the signal-to-noise for each spectrum were used. The r.m.s. errors of the radial velocities measured from the Hα profiles were ±0·73 km/s for the primary and ±0·90 km/s for the secondary.

A radial-velocity sampling interval of 6 km/s was used for the Hα solution. The eccentricity and period for the telluric orbit were held fixed at 0·0167301 and 365·2422 d, respectively. Once again, the flux factors show the presence of the primary eclipse and possible secondary eclipse or rotation effect. However, the noise level in those is much greater than that in the solution of the He I 667·8-nm data set.

The heliocentric velocity corrections $V_{\odot}$ were used to constrain the telluric parameters. That part of the fit is shown in Fig. 14.

Due to the high declination of NY Cep, the telluric radial velocities cover a range of only about ±15 km/s, which is slightly larger than two radial-velocity sampling bins. That and unavoidable small rectification errors limited the solution quality for the telluric line profile. To some extent, it is possible to fix that using band-pass filtering once the Fourier components of the line profiles have converged.

The telluric line profile shows the rotational lines of the H_2O molecule.

The light ratio (P/S) measured from the depths of the recovered primary and secondary line profiles is l = 3·74 ± 0·10.

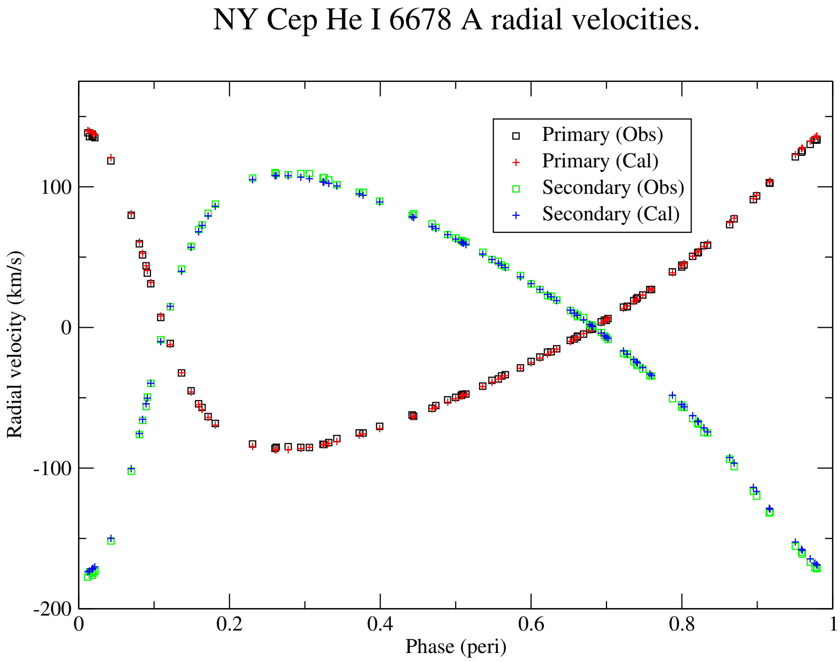

Fig. 8

The measured and computed radial velocities for He I 667·8 nm in NY Cep.

Table V

Orbital elements from Hα.

Parameter	*Value*
K_1 (km/s)	106·4 ± 4·6
$q = K_2/K_1$	1·33 ± 0·10
K_2 (km/s)	141·9 ± 12·8
e	0·430 ± 0·024
ω_0 (deg)	51·8 ± 3·1
$T_{\mathrm{peri}} - 240000$ (HJD)	55116·725 ± 0·059
K_3 (km/s)	14·89
ω_3 (deg)	166·74
$T_{\mathrm{max},3} - 240000$ (HJD)	55034·5

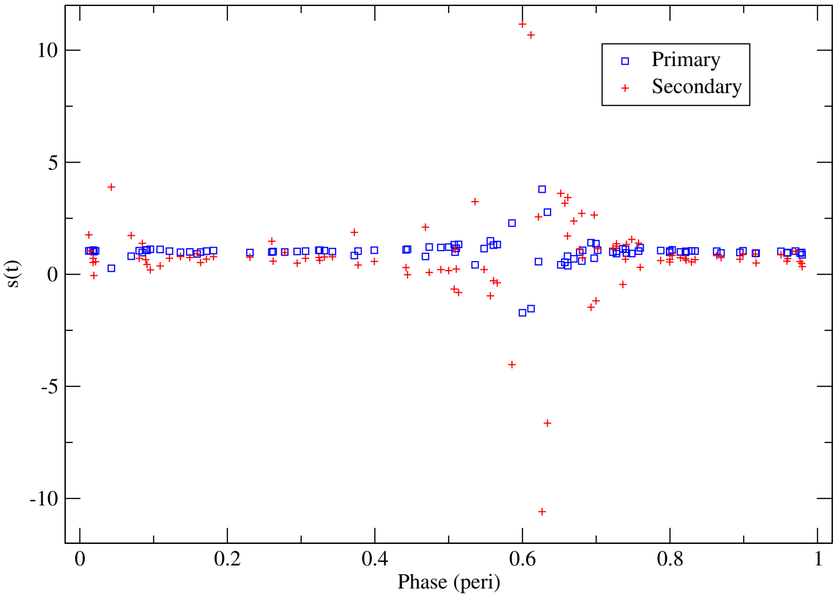

Fig. 9

Flux factors for He I 667·8 nm in NY Cep. Squares denote the primary, plus signs the secondary.

Search for apsidal motion

A search for apsidal motion was done by computing a disentangling solution which combined the new He I 667·8-nm data with the older He I 447·1-nm–Mg II 448·1-nm Reticon data from Holmgren *et al.*[4] As with the other disentangling solutions, the Reticon data were given weights proportional to the signal-to-noise of each spectrum. Also, since the Reticon data were obtained at a resolution approximately half of that of the CCD data, they were given half the weight in the disentangling solution for the combined data set.

The computed solution is shown in Table VI. Note that the apsidal-motion rate $\dot{\omega}$ is included, and that it has a large uncertainty due to the relatively short time interval used to estimate it.

Table VI

Orbital elements from the combined solution.

Parameter	*Value*
K_1 (km/s)	$111{\cdot}70 \pm 0{\cdot}1$
$q = K_2/K_1$	$1{\cdot}29 \pm 0{\cdot}02$
K_2 (km/s)	$144{\cdot}1 \pm 0{\cdot}1$
e	$0{\cdot}4435 \pm 0{\cdot}0006$
ω_0 (deg)	$60{\cdot}9 \pm 0{\cdot}2$
$T_{\rm peri} - 240000$ (HJD)	$55116{\cdot}853 \pm 0{\cdot}049$
$\dot{\omega}$ (rad/d)	$1{\cdot}28 \times 10^{-6}$
U (yr)	13500

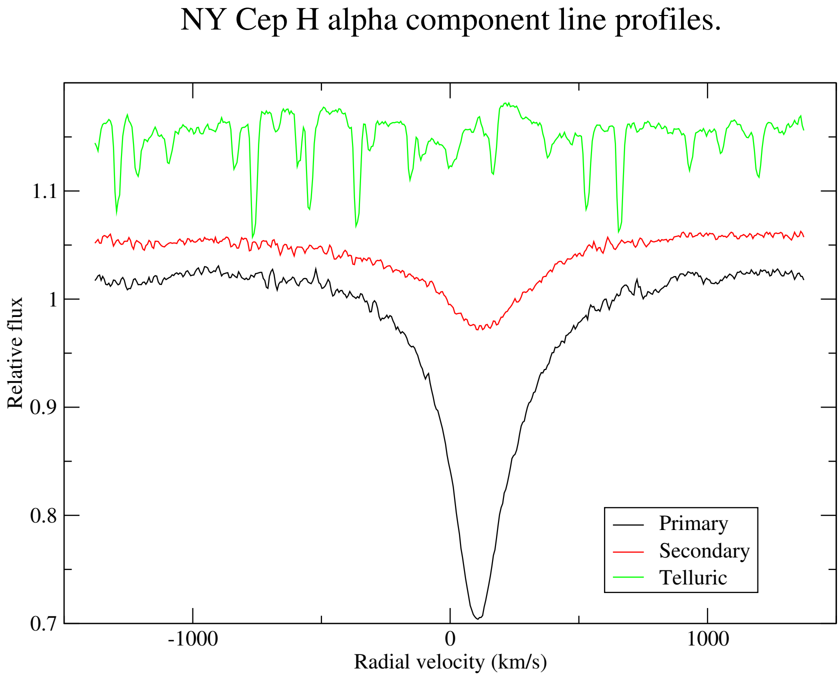

Fig. 10

The primary (bottom) and secondary (middle) and telluric (top) line profiles for Hα in NY Cep. The secondary and telluric profiles have been displaced upward for clarity.

The theoretical apsidal-motion period[16,17], including both classical and relativistic contributions, is 4445 yr. That is discussed in more detail in the section on absolute dimensions. The difference between the observed and theoretical rates is not unexpected given the relatively short time-base used to estimate the former. Future observations should allow that observed apsidal period to be refined.

The recovered He I 667·8-nm profiles are shown in Fig. 15, and the flux factors in Fig. 16. The profiles show good agreement with those obtained from the solution of the CCD data alone.

The recovered He I 447·1-nm and Mg II 448·1-nm profiles are shown in Fig. 17, and the flux factors for that region in Fig. 18. The flux factors for that region indicate the presence of the primary eclipse, and a possible secondary eclipse or rotation effect. We note the good inter-agreement between the two sets of flux factors.

The computed light ratio (P/S) for the He I 667·8-nm region was 4·43 ± 0·07 and that for the He I 447·1-nm–Mg II 448·1-nm region was 2·38 ± 0·07. The former light ratio shows good agreement with that found from the measured equivalent widths.

Spectrophotometry

The disentangled He I 667·8-nm line profiles from the combined solution were measured for equivalent width. Integration of the profiles gave $EW_p = 0{\cdot}0549$ nm and $EW_s = 0{\cdot}0115$ nm. Those then give a light ratio (P/S) of $l = 4{\cdot}76$.

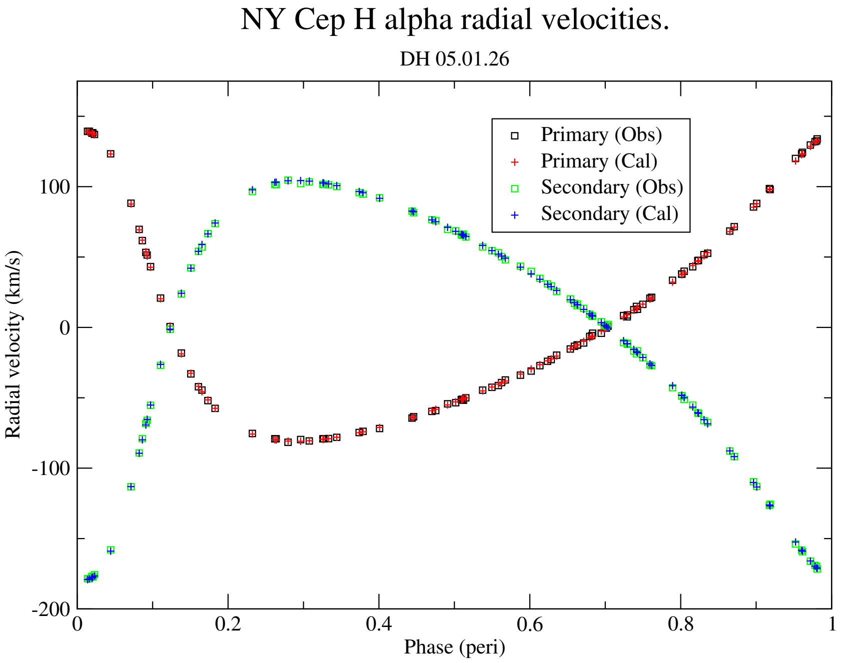

FIG. 11
The measured and computed radial velocities for Hα in NY Cep.

Synthetic spectra from the *POLLUX* database[18] were used to estimate the projected rotational velocities of the components. Using the He I 667·8-nm line, a NLTE model with $T_{\rm eff}$ = 28 000 K and log g = 4·0, when convolved with a rotational line profile having $v \sin i$ = 80 km/s, produced a satisfactory fit for the primary. Similarly, a model with $T_{\rm eff}$ = 23 000 K, log g = 4·0, and $v \sin i$ = 100 km/s gave a satisfactory fit for the secondary. Those fits also include a Gaussian instrumental profile having a FWHM of 12 km/s, estimated from the widths of relatively unblended telluric O_2 lines. No attempt was made to fit those profiles in a least-squares sense due to the coarse nature of the model-atmosphere grid. Prior to the fitting, each profile was corrected according to the light ratio. Those results for the projected rotational velocities are in agreement with those from Holmgren *et al.*[4] and Albrecht *et al.*[2]

Absolute dimensions

The minimum masses and projected semi-major axes computed using the different orbital solutions are compared in Table VII. Note that the last line in that table refers to the combined solution used to search for apsidal motion.

The minimum masses and projected semi-major axes from the different solutions are in good agreement. However, the errors for the Hα line are larger than those for the other solutions. In particular, the disentangling solution for the combined data sets and the orbit based on the CCF radial velocities are in excellent agreement. We therefore adopt the results from the combined disentangling solution, which are in good agreement with those from Albrecht *et al.*[2]

Using the minimum masses, projected semi-major axes, and the mean fractional radii from

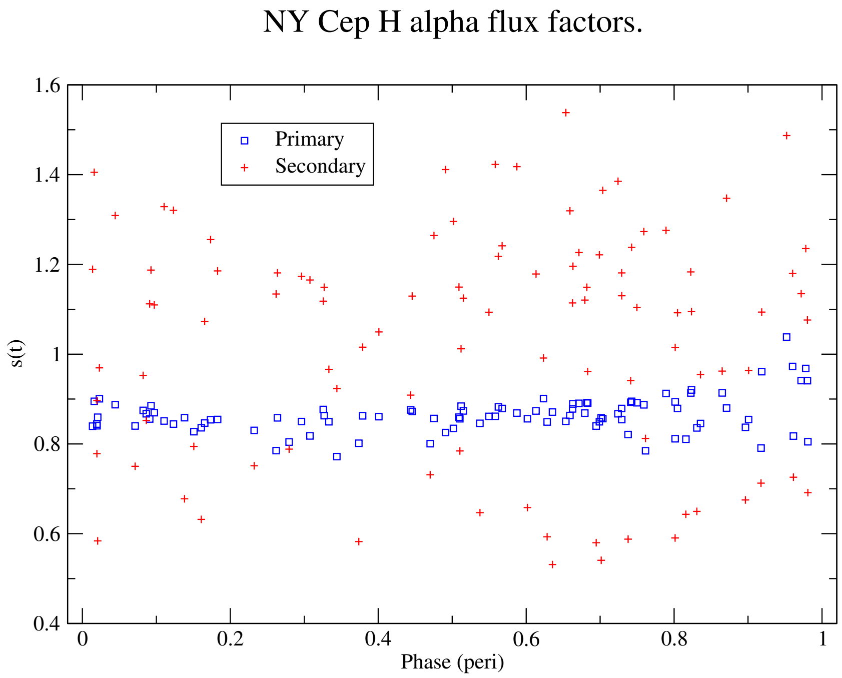

Fig. 12

Flux factors for Hα in NY Cep. Squares denote the primary, plus signs the secondary.

Table VII

Comparison of minimum masses and projected semi-major axes.

Method	$M_1 \sin^3 i$ ($M_\odot$)	$M_2 \sin^3 i$ ($M_\odot$)	$a_1 \sin i$ ($R_\odot$)	$a_2 \sin i$ ($R_\odot$)
CCF	11·3 ± 0·3	8·8 ± 0·3	30·9 ± 0·4	39·6 ± 0·5
He I 6678	10·6 ± 0·7	8·5 ± 0·7	30·9 ± 0·1	38·4 ± 2·1
Hα	10·2 ± 1·4	7·6 ± 1·2	29·0 ± 1·5	38·7 ± 3·6
Combined soln.	11·7 ± 0·3	8·7 ± 0·2	30·23 ± 0·03	40·5 ± 0·8

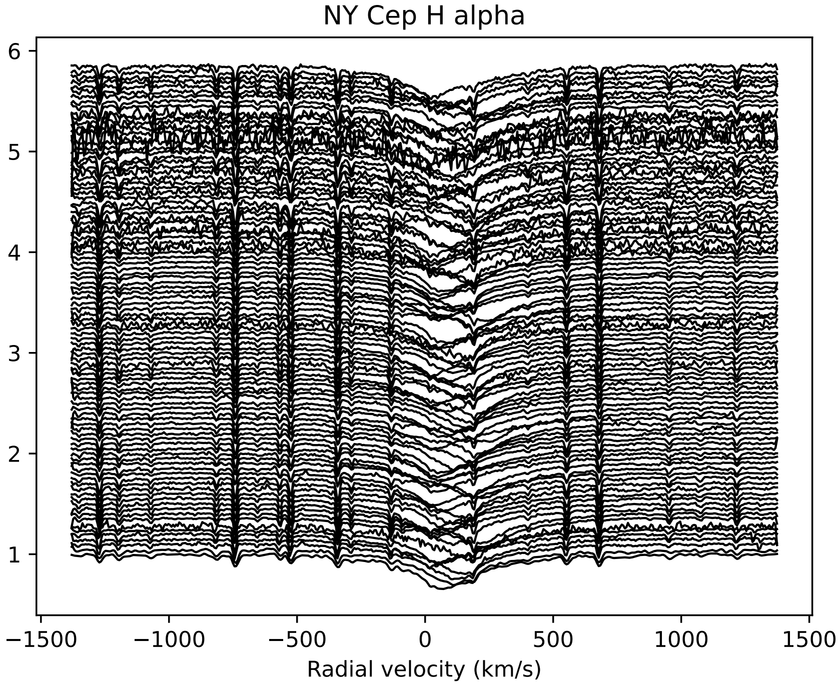

Fig. 13

The Hα-line-profile data for NY Cep. The spectra are ordered with the earliest at the bottom and the most recent at the top of the plot.

Ahn[3], we find the following absolute masses and radii:

$$\begin{aligned} M_1 &= 12{\cdot}1 \pm 0{\cdot}3\, M_\odot \\ M_2 &= 9{\cdot}4 \pm 0{\cdot}3\, M_\odot \\ R_1 &= 6{\cdot}8 \pm 0{\cdot}5\, R_\odot \\ R_2 &= 5{\cdot}7 \pm 0{\cdot}5\, R_\odot \end{aligned}$$

Those are quite similar to the results found by Holmgren *et al.*[4] and slightly larger than those from Albrecht *et al.*[2]

From the estimated projected rotational velocities, orbital period, and inclination, we find that the primary and secondary components rotate faster than the Keplerian rate at periastron by factors of 3·6 and 5·4 respectively.

Using the absolute dimensions, the orbital eccentricity from the combined disentangling solution, and internal structure constants $\log_{10} k_2$ from Claret[19], a theoretical apsidal period of 4445 yr is found. From Claret's[19] tables, for the primary $\log_{10} k_2 = -2{\cdot}193$ and for the secondary $\log_{10} k_2 = -2{\cdot}234$. The corresponding system age is $\approx 10^7$ yr.

The classical and relativistic contributions to P/U are[17]:

$$\begin{aligned} [P/U]_{\rm cl} &= 7{\cdot}044 \times 10^{-6} \\ [P/U]_{\rm rel} &= 2{\cdot}364 \times 10^{-6} \end{aligned}$$

Those show that the relativistic contribution is about a factor of three smaller than the classical part.

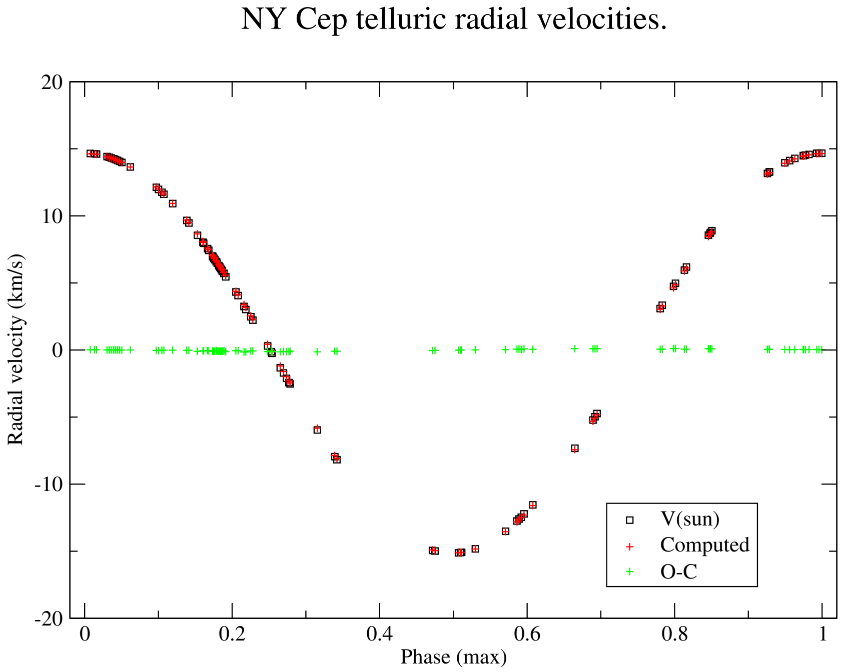

Fig. 14

Telluric-line radial velocities from the Hα solution. Squares denote $V_{\odot}$ values, plus signs denote computed radial velocities, and crosses denote fit residuals.

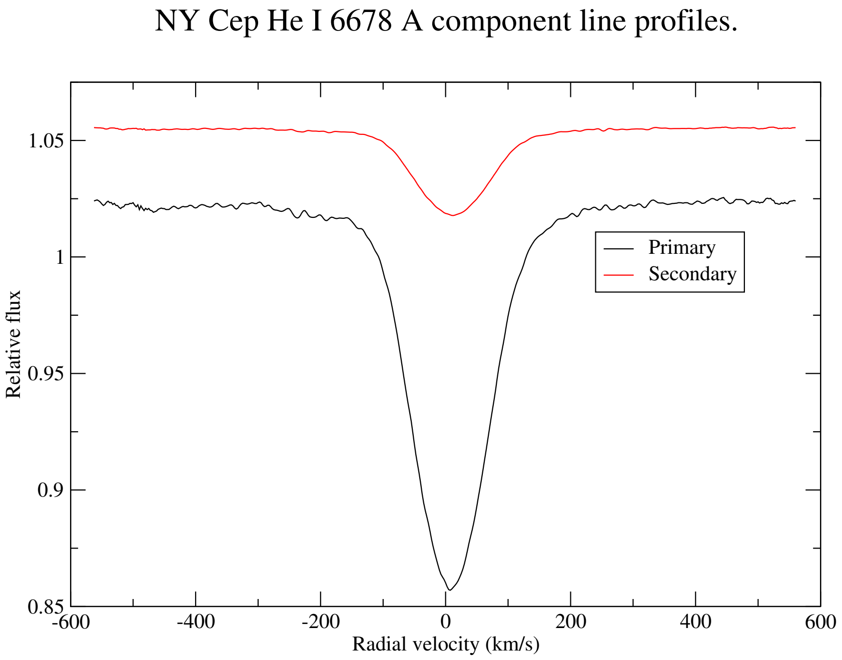

Fig. 15

The recovered He I 667·8-nm line profiles for the primary (bottom) and secondary (top) using both CCD and Reticon data.

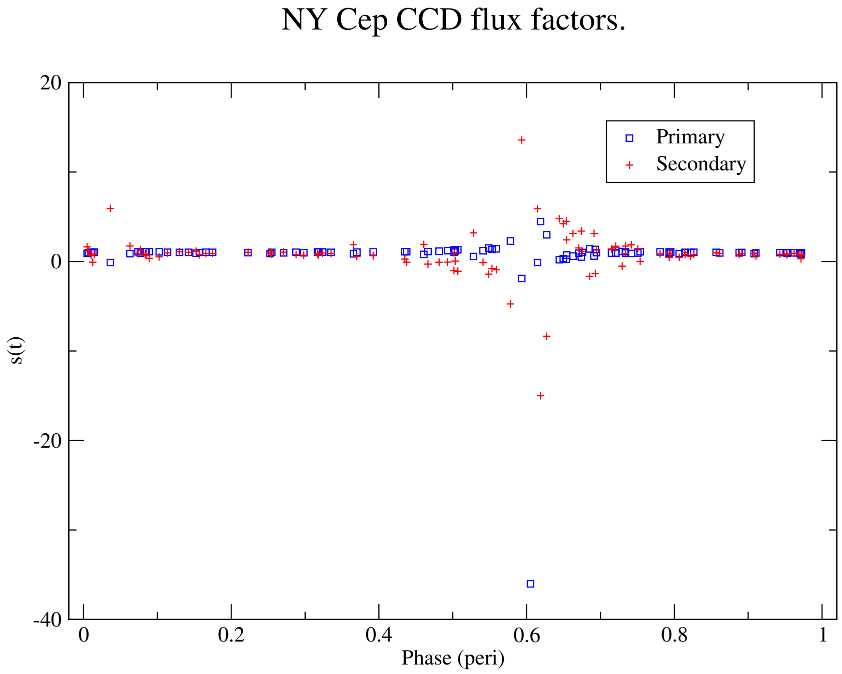

FIG. 16

The flux factors for the He I 667·8-nm region. Squares denote the primary, plus signs the secondary. Both CCD and Reticon data were used.

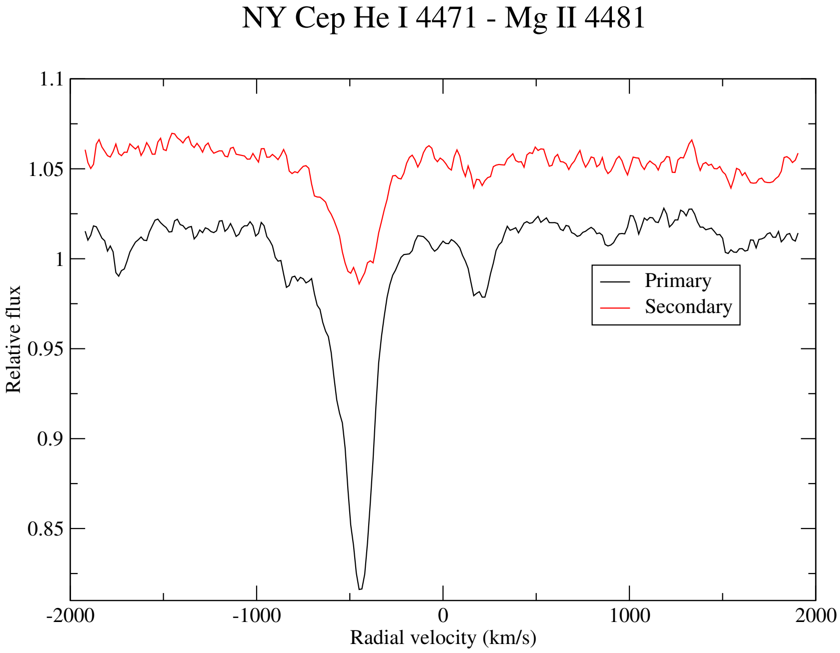

Fig. 17

The recovered He I 447.1 nm–Mg II 448.1 nm line profiles for the primary (bottom) and secondary (top) using both CCD and Reticon data.

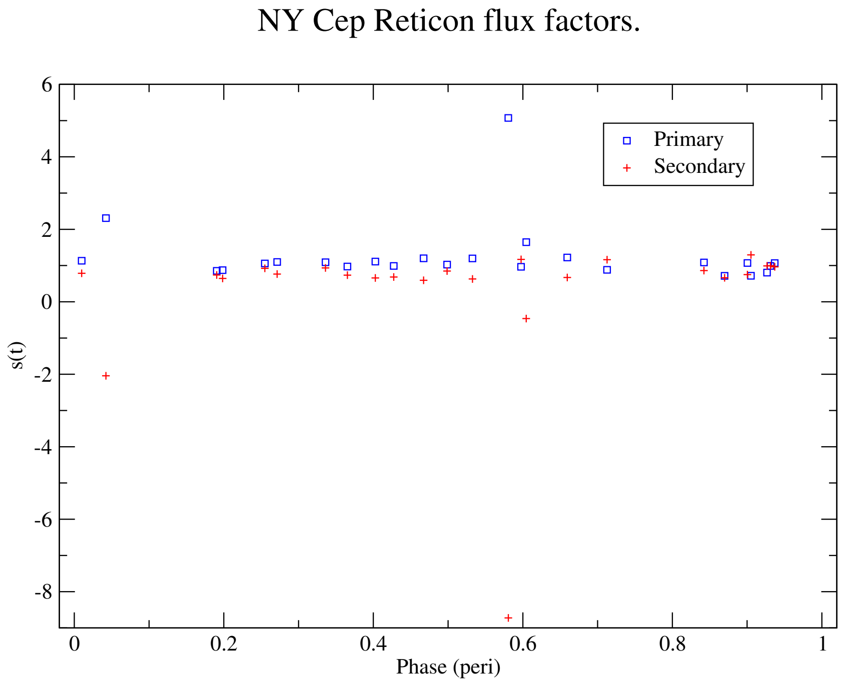

Fig. 18

The flux factors for the He I 447.1 nm–Mg II 448.1 nm region. Squares denote the primary, plus signs the secondary. Both CCD and Reticon data were used.

Radial-velocity measurements.

TABLE VIII

NY Cep He I 667·8-nm radial velocities.

Filename	*HJD − 2400000·0*	*Phase (peri)*	*V_1(Obs)*	*(O-C)$_1$*	*V_2(Obs)*	*(O-C)$_2$*	*Weight*
6279	51381·9671	0·5024	−47·72	−0·19	64·41	0·24	1·19
6448	51384·8660	0·6921	5·22	0·00	−7·06	−0·01	0·72
13066	51461·0044	0·6764	0·13	−0·00	−0·19	−0·02	1·34
13397	51461·8926	0·7346	19·91	0·05	−26·89	−0·07	1·21
11577	51437·9386	0·1665	−61·95	−0·13	83·57	0·10	1·44
12577	51451·9574	0·0842	47·30	0·10	−63·82	−0·10	1·40
2053	51599·6789	0·7546	27·35	0·09	−36·91	−0·10	0·31
11679	53587·9145	0·9117	99·95	0·04	−134·96	−0·05	1·60
12059	53588·8244	0·9712	128·98	0·05	−174·23	−0·14	1·53
12405	53589·8375	0·0375	118·46	0·14	−159·88	−0·11	1·30
12756	53590·8472	0·1036	12·13	0·02	−16·38	−0·04	1·69
13153	53591·9521	0·1760	−67·67	−0·09	91·36	0·11	1·18
12523	53949·8686	0·6065	−20·84	−0·09	28·13	0·12	1·16
12874	53950·9199	0·6753	−0·23	0·00	0·37	0·06	0·71
13184	53951·9536	0·7430	23·08	0·15	−31·18	−0·21	0·87
18117	54003·0192	0·0859	44·16	0·19	−59·63	−0·27	1·10
17633	54400·8789	0·1313	−28·97	−0·09	39·08	0·08	1·47
15683	54367·9168	0·9734	129·75	0·04	−175·27	−0·12	1·34
408	54490·7398	0·0139	132·87	0·00	−179·40	0·00	1·19
10250	54659·9413	0·0904	35·78	0·10	−48·28	−0·11	1·61
10647	54660·9817	0·1585	−56·21	−0·10	75·89	0·13	0·90
1129	54862·7489	0·3669	−75·36	−0·03	101·76	0·04	1·05
15558	55031·8836	0·4391	−61·68	−0·05	83·34	0·13	1·41
16241	55032·9411	0·5083	−46·23	−0·12	62·43	0·17	1·58
4627	54912·0579	0·5949	−24·13	−0·16	32·53	0·17	1·13
7683	54960·9367	0·7947	43·38	0·13	−58·54	−0·13	1·34
8369	54961·9076	0·8582	72·33	0·12	−97·63	−0·12	1·71
30517	55149·7321	0·1539	−52·49	−0·15	70·86	0·18	1·35
23719	55100·8429	0·9534	121·58	0·14	−164·11	−0·14	1·91
24272	55101·8009	0·0161	132·13	−0·01	−178·42	−0·00	1·41
24845	55102·7048	0·0753	63·55	0·11	−85·80	−0·14	1·19
3163	55248·6399	0·6288	−14·50	−0·11	19·53	0·10	1·45
3706	55249·6451	0·6946	6·01	−0·01	−8·11	0·01	1·57
996	55219·6501	0·7310	18·61	0·05	−25·13	−0·06	0·98
1505	55220·6215	0·7946	43·28	0·06	−58·48	−0·13	1·09
19605	55499·7061	0·0645	82·43	0·06	−111·33	−0·09	1·43
19988	55500·9190	0·1439	−43·11	−0·08	58·24	0·13	1·11
17148	55464·8449	0·7823	38·29	0·13	−51·67	−0·15	1·54
10032	55769·9002	0·7523	26·54	0·12	−35·82	−0·14	0·51
10405	55770·8698	0·8158	52·49	0·12	−70·90	−0·19	1·28
7914	55738·8907	0·7223	15·52	0·02	−20·91	0·02	1·15
16449	55857·7535	0·5035	−47·35	−0·10	63·89	0·10	1·16
15135	55823·9310	0·2894	−85·04	−0·04	114·88	0·11	1·04
13715	56165·7258	0·6645	−3·66	−0·04	4·92	0·03	1·81
14231	56166·8150	0·7358	20·38	0·07	−27·53	−0·10	1·14
6795	56073·9411	0·6560	−6·27	−0·00	8·45	−0·01	0·77
7362	56074·9567	0·7224	15·58	0·05	−21·02	−0·05	0·43
20927	56220·8426	0·2727	−85·87	−0·06	115·97	0·10	0·87
17601	56193·6859	0·4949	−49·37	−0·10	66·65	0·12	0·80
18066	56194·6909	0·5607	−33·15	−0·06	44·81	0·13	1·60

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Filename	*HJD – 2400000·0*	*Phase (peri)*	V_1*(Obs)*	*(O-C)*$_1$	V_2*(Obs)*	*(O-C)*$_2$	*Weight*
3772	56384·0150	0·9545	122·03	0·09	−164·79	−0·13	1·31
2614	56382·0216	0·8240	56·13	0·09	−75·76	−0·09	1·01
3161	56383·0241	0·8897	88·30	0·07	−119·23	−0·10	1·17
14880	56558·7609	0·3940	−70·67	−0·12	95·47	0·20	1·09
11893	56927·6512	0·5429	−37·73	−0·10	50·94	0·13	1·59
12307	56928·7774	0·6166	−17·91	−0·03	24·18	0·04	1·19
12812	56929·6309	0·6725	−1·12	−0·00	1·59	0·09	1·60
11819	57291·6573	0·3721	−74·35	0·12	100·26	−0·29	1·26
12455	57292·6497	0·4370	−62·26	−0·20	83·91	0·11	1·55
13032	57293·6905	0·5052	−46·99	−0·13	63·44	0·17	1·42
10972	57649·7896	0·8167	52·87	0·11	−71·39	−0·15	0·98
8673	57942·9329	0·0069	134·37	0·01	−181·43	−0·01	0·33
9658	57949·9838	0·4685	−55·39	−0·11	74·75	0·11	0·32
4545	57900·9241	0·2569	−86·00	−0·07	116·16	0·13	0·97
5286	57901·8892	0·3201	−82·12	−0·02	110·91	0·05	0·85
19234	58054·9081	0·3372	−79·97	−0·08	108·00	0·13	0·60
9926	58390·6919	0·3189	−82·28	−0·04	111·13	0·08	0·90
10667	58747·8054	0·6968	6·75	−0·02	−9·12	0·02	0·39
10070	59478·8799	0·5556	−34·51	−0·11	46·60	0·14	0·86
8164	59820·8982	0·9453	117·68	0·14	−158·86	−0·16	0·60
8277	59821·8736	0·0092	134·01	0·02	−180·86	0·06	0·54
1335	59633·6570	0·6878	3·79	−0·02	−5·11	0·04	0·59
92	59589·6828	0·8091	49·54	0·11	−66·88	−0·13	0·35
11230	59864·9467	0·8289	58·38	0·11	−78·85	−0·17	0·58
11359	59865·9399	0·8939	90·53	0·05	−122·28	−0·11	0·64
9581	59847·9677	0·7174	13·86	0·09	−18·70	−0·10	0·50
867	60004·6447	0·9740	130·07	0·15	−175·60	−0·17	0·37
5781	60131·8417	0·3008	−84·12	−0·02	113·67	0·11	0·55
5061	60120·8407	0·5807	−27·94	−0·12	37·68	0·11	0·70
5152	60121·8515	0·6468	−8·93	0·11	12·06	−0·15	0·52
11220	60249·6464	0·0127	133·27	0·08	−179·95	−0·11	0·74
11768	60271·8057	0·4634	−56·55	−0·13	76·29	0·12	0·52
11911	60272·8336	0·5307	−40·78	−0·09	55·05	0·11	0·56
10206	60222·7974	0·2551	−86·03	−0·13	116·15	0·17	0·07
10326	60223·8865	0·3264	−81·45	−0·12	109·93	0·12	0·48
1238	60432·9564	0·0129	133·16	0·01	−179·88	−0·10	0·33
1356	60433·9744	0·0795	55·89	0·12	−75·45	−0·15	0·43
1650	60444·9462	0·7978	44·70	0·13	−60·33	−0·16	0·40
1733	60445·9598	0·8641	75·17	0·03	−101·50	−0·04	0·33
3201	60503·8891	0·6564	−6·12	0·02	8·26	−0·02	1·34
5661	60556·7413	0·1163	−8·13	0·17	11·00	−0·21	1·21
1480	60686·6642	0·6215	−13·62	2·86	18·27	−3·99	0·69
169	60721·6341	0·9108	99·46	0·02	−134·31	−0·04	0·74
4975	60859·9437	0·9650	126·59	0·05	−170·88	−0·02	0·75
6693	60900·9947	0·6524	−7·35	0·02	9·91	−0·03	0·74
7504	60928·9772	0·4842	−51·88	−0·14	70·04	0·18	0·77
7596	60930·0041	0·5514	−35·64	−0·17	48·08	0·18	0·80
8787	60970·8513	0·2254	−83·54	−0·03	112·88	0·12	0·70

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TABLE IX

NY Cep Hα radial velocities.

Filename	*HJD − 2400000·0*	*Phase (peri)*	*V_1(Obs)*	*$(O\text{-}C)_1$*	*V_2(Obs)*	*$(O\text{-}C)_2$*	*Weight*
6279	51381·9671	0·5092	−51·31	0·02	65·71	−0·50	1·19
6448	51384·8660	0·6990	0·90	2·12	1·34	−0·23	0·72
13066	51461·0044	0·6833	−4·15	2·10	7·80	−0·25	1·34
13397	51461·8926	0·7414	14·91	1·48	−18·78	−1·45	1·21
11577	51437·9386	0·1733	−51·99	−0·52	66·67	0·27	1·44
12577	51451·9574	0·0910	53·27	−0·47	−68·30	1·02	1·40
2053	51599·6789	0·7614	21·36	0·42	−27·21	−0·19	0·31
11679	53587·9145	0·9185	97·96	−0·35	−125·55	1·27	1·60
12059	53588·8244	0·9781	131·97	0·49	−169·07	0·54	1·53
12405	53589·8375	0·0444	123·34	0·12	−158·03	0·92	1·30
12756	53590·8472	0·1105	20·86	0·51	−26·99	−0·73	1·69
13153	53591·9521	0·1828	−57·52	−0·03	73·71	−0·45	1·18
12523	53949·8686	0·6133	−27·19	−0·71	34·84	0·69	1·16
12874	53950·9199	0·6821	−5·84	0·76	8·18	−0·33	0·71
13184	53951·9536	0·7498	16·38	−0·16	−21·56	−0·22	0·87
18117	54003·0192	0·0928	51·45	0·79	−65·94	−0·59	1·10
17633	54400·8789	0·1381	−18·22	0·58	23·69	−0·55	1·47
15683	54367·9168	0·9803	132·52	0·10	−169·80	1·02	1·34
408	54490·7398	0·0207	138·29	0·73	−177·31	0·14	1·19
10250	54659·9413	0·0973	43·15	0·40	−55·38	−0·23	1·61
10647	54660·9817	0·1654	−44·54	1·09	57·07	−1·80	0·90
1129	54862·7489	0·3738	−74·67	0·14	95·74	−0·77	1·05
15558	55031·8836	0·4459	−63·45	0·24	81·45	−0·72	1·41
16241	55032·9411	0·5152	−50·04	0·01	64·17	−0·40	1·58
4627	54912·0579	0·6017	−31·02	−1·48	39·78	1·68	1·13
7683	54960·9367	0·8015	37·98	0·58	−48·82	−0·58	1·34
8369	54961·9076	0·8651	68·49	0·48	−87·81	−0·09	1·71
30517	55149·7321	0·1607	−42·13	−0·29	54·07	0·09	1·35
23719	55100·8429	0·9603	123·43	0·73	−158·18	0·10	1·91
24272	55101·8009	0·0230	137·11	0·24	−175·72	0·84	1·41
24845	55102·7048	0·0822	69·64	0·31	−89·18	0·25	1·19
3163	55248·6399	0·6356	−19·72	0·66	25·44	−0·86	1·45
3706	55249·6451	0·7014	−0·54	−0·11	0·91	0·37	1·57
996	55219·6501	0·7378	12·61	0·49	−16·85	−1·20	0·98
1505	55220·6215	0·8014	37·84	0·48	−48·48	−0·29	1·09
19605	55499·7061	0·0713	88·23	0·55	−113·22	−0·10	1·43
19988	55500·9190	0·1507	−33·02	−0·42	42·23	0·18	1·11
17148	55464·8449	0·7892	33·48	1·36	−42·86	−1·42	1·54
10032	55769·9002	0·7592	20·76	0·67	−26·66	−0·75	0·51
10405	55770·8698	0·8227	47·40	0·48	−60·77	−0·24	1·28
7914	55738·8907	0·7292	7·50	−1·54	−11·23	0·43	1·15
16449	55857·7535	0·5104	−51·02	0·06	65·40	−0·49	1·16
15135	55823·9310	0·2962	−79·68	1·16	102·20	−2·07	1·04
13715	56165·7258	0·6714	−11·09	−1·17	13·48	0·68	1·81
14231	56166·8150	0·7427	12·88	−1·01	−16·66	1·25	1·14
6795	56073·9411	0·6628	−12·41	0·10	15·37	−0·77	0·77
7362	56074·9567	0·7293	8·85	−0·22	−12·06	−0·35	0·43
20927	56220·8426	0·2795	−81·61	−0·86	104·63	0·47	0·87
17601	56193·6859	0·5017	−53·48	−0·59	68·56	0·32	0·80
18066	56194·6909	0·5675	−37·35	0·76	48·01	−1·15	1·60
3772	56384·0150	0·9614	124·41	1·13	−159·40	−0·36	1·31
2614	56382·0216	0·8309	51·71	0·92	−66·28	−0·76	1·01
3161	56383·0241	0·8965	85·58	0·18	−109·65	0·51	1·17

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Filename	*HJD − 2400000·0*	*Phase (peri)*	$V_1(Obs)$	$(O\text{-}C)_1$	$V_2(Obs)$	$(O\text{-}C)_2$	*Weight*
14880	56558·7609	0·4009	−71·83	−0·73	92·10	0·39	1·09
11893	56927·6512	0·5498	−42·56	−0·24	54·47	−0·11	1·59
12307	56928·7774	0·6235	−24·11	−0·37	30·90	0·28	1·19
12812	56929·6309	0·6794	−6·41	1·05	9·36	−0·27	1·60
11819	57291·6573	0·3789	−73·84	0·31	94·63	−1·03	1·26
12455	57292·6497	0·4439	−64·42	−0·36	82·61	−0·03	1·55
13032	57293·6905	0·5120	−51·71	−0·98	66·29	0·85	1·42
10972	57649·7896	0·8235	47·63	0·29	−61·05	0·01	0·98
8673	57942·9329	0·0138	139·27	0·40	−178·52	0·62	0·33
9658	57949·9838	0·4753	−59·08	−0·87	75·77	0·68	0·32
4545	57900·9241	0·2637	−79·11	0·87	101·32	−1·85	0·97
5286	57901·8892	0·3269	−79·13	0·36	101·47	−1·08	0·85
19234	58054·9081	0·3441	−78·10	−0·02	100·04	−0·69	0·60
9926	58390·6919	0·3257	−79·16	0·42	101·57	−1·08	0·90
10667	58747·8054	0·7036	0·83	0·52	2·10	2·50	0·39
10070	59478·8799	0·5624	−39·19	0·14	50·21	−0·53	0·86
8164	59820·8982	0·9522	119·99	1·79	−153·87	−1·40	0·60
8277	59821·8736	0·0160	139·34	0·78	−178·64	0·11	0·54
1335	59633·6570	0·6947	−4·15	−1·54	4·00	0·63	0·59
92	59589·6828	0·8160	43·09	−0·75	−55·25	1·31	0·35
11230	59864·9467	0·8357	52·68	−0·46	−67·54	1·01	0·58
11359	59865·9399	0·9008	88·06	0·19	−112·99	0·36	0·64
9581	59847·9677	0·7242	8·39	1·08	−10·81	−1·38	0·50
867	60004·6447	0·9809	133·93	1·26	−171·70	−0·56	0·37
5781	60131·8417	0·3077	−80·66	−0·12	103·33	−0·56	0·55
5061	60120·8407	0·5875	−33·94	−0·77	43·49	0·69	0·70
5152	60121·8515	0·6537	−15·34	−0·13	20·25	0·63	0·52
11220	60249·6464	0·0196	137·95	0·10	−176·86	0·98	0·74
11768	60271·8057	0·4702	−59·65	−0·45	76·45	0·08	0·52
11911	60272·8336	0·5375	−44·54	0·58	57·10	−1·11	0·56
10206	60222·7974	0·2619	−79·15	0·69	101·46	−1·54	0·07
10326	60223·8865	0·3332	−78·98	0·04	101·24	−0·69	0·48
1238	60432·9564	0·0197	138·27	0·45	−177·23	0·55	0·33
1356	60433·9744	0·0864	61·68	−0·27	−79·00	0·91	0·43
1650	60444·9462	0·8046	39·89	1·12	−51·19	−1·19	0·40
1733	60445·9598	0·8710	71·58	0·42	−91·79	0·01	0·33
3201	60503·8891	0·6632	−12·58	−0·19	16·61	0·64	1·34
5661	60556·7413	0·1231	0·53	−0·42	−1·37	−0·14	1·21
169	60686·6642	0·6284	−22·88	−0·49	29·45	0·56	0·69
1480	60721·6341	0·9176	98·62	0·84	−126·44	−0·31	0·74
4975	60859·9437	0·9719	129·58	0·93	−166·11	−0·16	0·75
6693	60900·9947	0·6592	−13·42	0·16	17·07	−0·45	0·74
7504	60928·9772	0·4910	−54·28	0·81	69·61	−1·46	0·77
7596	60930·0041	0·5583	−41·30	−0·98	53·04	1·03	0·80
8787	60970·8513	0·2323	−75·34	0·43	96·50	−1·25	0·70

(continued from previous page)

Summary and conclusions

We have presented a new spectroscopic orbit for NY Cep based on cross-correlation and spectrum disentangling. The latter also provided component line profiles for He I 667·8 nm and Hα. Combining that new solution for the helium line with older Reticon data has allowed us to estimate a provisional apsidal period of about 13500 yr. Further spectra should allow that period to be refined. Updated absolute dimensions and projected rotational velocities are also presented.

Acknowledgements

This study was based on observations obtained at the Dominion Astrophysical Observatory, Herzberg Astronomy and Astrophysics Research Centre, National Research Council of Canada.

The authors would like to thank the staff and directors of the Dominion Astrophysical Observatory for generous allocations of observing time over the many years during which this project took place. They would also like to thank the DAO technical staff for their set-up of and assistance with the telescope, spectrographs, and detectors. The authors are also grateful to an anonymous referee for comments which helped improve both the content and presentation of the paper.

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REVIEWS

General Relativity: A Graduate Course, by Horaţiu Năstase (Cambridge University Press), 2025. Pp. 401, 29 × 18·5 cm. Price £18·5 (hardbound; ISBN 978 1 009 57575 1).

The author describes the mathematics in the book as "physics-friendly" and "not exaggerated in its use". While both might be true, it is one of the most mathematical books I've read. I assign it a relativity-book signature of 0+−++−.* The assumptions and lack of derivations

*The characters indicate maths-first or physics-first, breadth, depth, level, amount of maths, mathematical detail shown. With regard to the first, this book falls neatly into neither category. Although Chapter 2 provides some mathematical background, in general the necessary maths is introduced with each topic. Thus, the book allow the author to present "various topics that many, if not most, textbooks consider too advanced, despite their being around for some time and being much used in current research" and "more modern topics that one cannot find in the standard, but now somewhat dated, books of Landau and Lifshitz; Misner, Thorne, and Wheeler; and Wald". On the other hand, the description of General Relativity (GR) is self-contained in that little or nothing about it is assumed, but little time is spent on the foundations compared to the applications. The author, originally from Romania, is a researcher and tenured asistant professor at the Institute for Theoretical Physcis of São Paulo State University, where he has been since 2010. This book corresponds to his one-semester graduate course.

With 33 chapters, the number of topics is greater than in most GR books I've read, but only the essentials of each are presented. Each chapter ends with a list of 'Important concepts to remember' followed by 'References and further reading' and a few problems (without solutions). This is not a book to learn GR from the ground up, at least not for most readers; rather, it is more like a detailed formula collection where one can quickly find the important details and a bit of context. In that sense, it is like a longer version of another book[1] reviewed[2] in these pages, though that book has less breadth and more depth than this one (as well as very detailed solutions to the problems) and makes the common mistake, avoided here, of calling the Lorenz gauge the Lorentz gauge.

Though brief, the discussion of various forms of the Robertson–Walker metric is useful and helpful for avoiding confusion; there is a similar discussion in another book[3] reviewed[4] in these pages. Of course, there are many cases of confusion where the same things are denoted by different terms or the same terms denote different things, but in cosmology that seems to lead more often to lasting misconceptions than in other fields.

I do have to point out some inaccuracies with regard to cosmology, but at least this time I now have a suspicion about the source of one type of confusion. Something similar to the following can be found in many cosmology books.

> Space then expands uniformly throughout the Universe, which leads to the "Hubble Law", that because of this expansion, the velocity of the receding away of a *nearby* point (a fixed star) is proportional to the distance r to the point, $v = Hr$. [Emphasis in the original.]
>
> To picture this, we imagine a two-dimensional closed Universe like a balloon, and filling it up with air, so that it expands. Then every point moves away from every other point, and the relative speed is proportional to the distance between the two points, as in Fig. 27.1.

Of course, as the terms are usually used, a fixed star does not partake of the Hubble flow, but that is a harmless minor point. More serious is the obvious contradiction between the two paragraphs. The second gives an essentially correct picture. In particular, the law holds for all distances and all velocities. However, the first paragraph claims that it holds only for small r. (Red herring: Could the difference be due to the fact that the speeds of dots on the balloon are small compared to the speed of light, whereas that is true in cosmology only for 'nearby' objects? That is a (wrong) claim which is often made (with the 'not even wrong' solution that one should use the relativistic Doppler formula), but that is not the problem here.) The distance r has not yet been defined, but one would naturally assume that it corresponds to the distance between the dots along the surface of the balloon, the so-called proper distance D^{P} (which is the main distance used in GR). However, on the next couple of

covers a wide range of topics, but not in great detail (about 10 pages per chapter and topic; one could write, and indeed many have written, very thick books about most or all of the topics); the level is relatively advanced ("[a]ssuming knowledge of classical mechanics and electrodynamics at an advanced undergraduate level . . . something like Goldstein's book. . . the full 2 volumes of J. D. Jackson's book. . . a classical field theory course as well"; some familiarity with tensor calculus is also required); the presentation is very mathematical; the focus is on results rather than derivations.

pages, in the (very good) discussion of the Robertson–Walker metric, r is used to indicate what in the case of the balloon is the perpendicular distance from a dot on the surface to a diameter of the three-dimensional balloon. We have $r = R \sin \chi$, where $\chi = D^{\mathrm{P}}/R$, R being the (three-dimensional) radius of the balloon. Of course, $r \approx D^{\mathrm{P}}$ only for small r, so if the Hubble law holds exactly for D^{P} and its derivative with respect to cosmic time v, then obviously in general it doesn't hold exactly for r and v. Note that r is the more important distance in observational cosmology: r is the proper-motion distance, $r/(1+z)$ is the angular-size distance (z is the redshift), $r(1+z)$ is the luminosity distance, and so on.* The idea that the Hubble Law holds only in the limit of small distances (or velocities) might, in some cases, come from thinking that it applies to r and not to D^{P}. (The misconception regarding the relativistic Doppler formula is, however, certainly responsible for a large part of the confusion. See ref. 6 for more on the redshift–distance and velocity–distance laws.) On the other hand, separated only by two pages of Christoffel symbols and Ricci tensors, H is *correctly* defined as $\dot{a}/a$, where the scale factor $a = R/R_0$, which is equivalent to the formulation with D^{P} above since χ is constant for co-moving objects. (He also points out that it is called the Hubble constant because it is constant in space (at a given time), not, in general, constant in time — it's thus not a misnomer and if one would prefer to call it the Hubble parameter that is not a valid reason.) But there is more confusion on the very next page:

> Note that only for small distances, where $H(t) \approx$ constant as light traverses the distance from a star (or galaxy, etc.) to get to us, is
>
> $$v = \dot{a}r = H(ar) \approx H_0(ar)\cdot$$

However, as in the definition $H = \dot{a}/a$ and as explained well by Harrison[6], v refers to the *instantaneous* velocity (in the sense of the derivative of D^{P} with respect to cosmic time), rather than some sort of average.

Another common statement is that the static cosmological model which Einstein put forward in the first paper on relativistic cosmology[7] is unstable, as pointed out by Eddington[8], but also that the Einstein–de Sitter model[9] is an appealing model because slightly different models are unstable, and it is only due to observations that the Einstein–de Sitter model is ruled out. Mathematically, both are unstable in the same sense.† As idealized cosmological models, that is a non-issue, because there is no way to disturb them. If one sees them as approximations, then both are unstable in exactly the same sense. As far as I know, during the time that many considered the Einstein–de Sitter model to be a good approximation to our Universe no-one raised Eddington's objection (which applies just as much to the Einstein–de Sitter model as to the Einstein static model) against it.

Note that the chapter on classical cosmology (*i.e.*, Friedmann–Robertson–Walker (FRW) models) is only a dozen pages, almost just a footnote to the book, and my complaints refer to just a couple of pages; the density of confused or confusing passages in the rest of the book is much lower, essentially zero. As I've remarked in other reviews in these pages, certain misconceptions in cosmology tend to be repeated.

I have fewer complaints than usual about typos, matters of style, editing, and diction; it is a well-written book. There are only a few figures, most of them Penrose diagrams. (The only real goof is that the caption for figure 28.1 mistakenly repeats that of figure 22.6.) There are no footnotes. The main text is followed by six pages of 106 references; some are mentioned in the main text, but mainly they correspond to sources mentioned in 'References and further

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*For more on distance definitions, see ref. 5.

†Both are unstable fixed points (and moreover repulsors) in the dynamical-systems parameter space of the normalized cosmological constant $\lambda = \Lambda/(3H^2)$ and the density parameter $\Omega = 8\pi G\rho/(3H^2)$ (where ρ is the usual physical density of nonrelativistic matter — 'dust' to cosmologists).

reading'. (Unusual is that if a reference is cited in more than one chapter, then it gets an additional entry in the reference list, so actually there are fewer than 106.) A four-and-one-half-page index ends the book. The book is well produced with a design familiar from other CUP textbooks; my only serious complaint is that the wide margins, which some readers might find useful, are always on the left, thus the inside margin on odd pages, which is not very practical. The even-page headers contain the chapter, the odd-page headers the section; that should be the case for all books. (Despite that difference, the layout of the headers is the same, with the page number always at the upper left, above the wide margin; here also it would sit better on the right on odd pages, at the outside edge.)

This could be a useful book for those who want a concise mathematical description of many topics in GR. — Phillip Helbig.

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The Royal Observatory, Greenwich, 1881–1939, by Lee T. Macdonald (UCL Press), 2026. Pp. 321, 23 × 15·5 cm. Price £40 (paperback; ISBN 978 1 80665 0449).

Having worked for several years at the Royal Greenwich Observatory at Herstmonceux in Sussex, I always had the fond notion that my spiritual home was the Royal Observatory at Greenwich, founded in 1675 by order of King Charles II for the practical purpose of helping British mariners to determine their longitude at sea. While we have all heard stories about Astronomers Royal from long ago — Flamsteed, Halley, *et al.* — much less was ever heard about those in more recent times. The present book does much to redress the balance, giving copious and well-researched (and well-referenced) details about the work done under William Christie, Frank Dyson, and Harold Spencer Jones in that period between the retirement of George Airy and the start of the Second World War. The records have been scoured for details of the staffing of the Observatory with emphasis on the work of Chief Assistants, Assistants, and 'computers' of various types in the numerous departments which greatly increased in number during this period. While the 'bread and butter' work for navigation — the provision of accurate time and the *Nautical Almanac* — was of high priority, other work blossomed beside it in the Solar Department, the Magnetic and Meteorological Department, and in the nascent astrophysical studies permitted by a range of newer and larger telescopes. International collaboration was always important, such as the *Carte du Ciel* project, and various solar-eclipse expeditions were mounted, including the famous 1919 'relativity' one. Ultimately, of course, the unstoppable growth of London (Cobbett's Geat Wen) put paid to the Royal Observatory, and after the period covered by this book the work was transferred to the wonderful location of Herstmonceux. It was fascinating to read of several personalities who worked at Greenwich and who were still busy in Sussex when I arrived (including Alan Hunter, Donald Sadler, and Humphry Smith).

This is a fine account of the 'official' work of the Royal Observatory but I was disappointed not to learn more about the personalities of those who worked there. Certainly we discover the special interests of the Astronomers Royal, but little about their characters. Similarly, I suppose, we discover little about the part this *Magazine* played, despite the fact that it was founded at Greenwich in 1877 and was based there until the move to Sussex, and many of the Editors came from the Observatory staff. And now for the future. Well, there is now a fine museum at Greenwich but of the 'real' Observatory, just read Ian Robson's fascinating account of the 'Observatory Wars' in this issue to see that the shambles that is British science has lost one of its great institutions. — David Stickland.

Discovering Quarks: Remembering Feynman, Gell-Mann, and Tollestrup, by George Zweig (Cambridge University Press), 2025. Pp. 201, 26 × 21 cm. Price £39·99 (hardbound; ISBN 978 1 009 47350 7).

This is a fascinating book that charts the history of the discovery of quarks, written by one of their co-discoverers. It is a rich and multi-faceted work, approaching the subject from many different angles. Part autobiography and part a history of the field, it offers numerous insights into the main characters in the story, illuminated by a fair bit of physics along the way. Zweig studied with Richard Feynman and Alvin Tollestrup, and the book includes chapters devoted to each of them, along with a chapter on Murray Gell-Mann. Richly adorned with quotations, personal reminiscences, and anecdotes, it provides a vivid sense of their personalities, the very different ways in which they worked, and how the community viewed the emerging ideas at the time. The book also touches on questions of recognition and whether some of the less-well-known figures received the credit they deserved. Zweig himself, although now widely regarded as a co-discoverer of quarks alongside Gell-Mann, has not received the same level of recognition. I would not say that that issue is the main focus of the book, as its scope is much broader, but it does offer some insight into possible reasons. Among those are the fact that Zweig's work initially appeared as a CERN report (reproduced helpfully in an appendix) rather than in a regular journal, the apparent lack of support from some senior figures at the time, and perhaps also the simple fact that the term 'quark' caught on, whereas Zweig's 'aces' did not. The book also contains a substantial amount of physics, which helps the reader appreciate how particle physics developed during the 1960s and 1970s, with some false starts, and it offers insights into the ways of thinking and influence of some of the field's major personalities. Students of physics, as well as readers interested in the history of science, will find it a fascinating and rewarding read. — Alan Heavens.

Probability Theory for Quantitative Scientists, by L. Leuzzi, E. Marinari & G. Parisi (Cambridge University Press), 2025. Pp. 412, 26 × 18·5 cm. Price £54·99 (hardbound; ISBN 978 1 009 58069 4).

This book grows out of a long-running course on probability theory at the University of Rome La Sapienza. It is readable, accessible, and sufficiently deep to satisfy a scientist who wants to understand the mathematical foundations of probability without going all the way to measure theory. In that sense, the title is an accurate description of what the book delivers.

The treatment is grounded in mathematics, but enriched with many examples and perspectives drawn from physics. In particular, it highlights connections with statistical mechanics and introduces topics that are rarely encountered in standard texts. Large-deviation theory, for example, appears surprisingly early and serves as a good illustration of the book's willingness to explore less conventional but important ideas.

One of the strengths of the book is the way it interweaves applications with fundamental theory, and mathematical development with physical insight. The scope is quite varied: some topics are treated in considerable depth, while others are covered more briefly, giving a sense of a guided tour through the subject. The final chapter provides a useful synthesis, drawing together themes introduced earlier.

Overall, it is clearly written and engaging, and will reward both students and researchers in the quantitative sciences. For readers who want to move beyond simply applying probabilistic techniques to understanding where they come from and how they connect to broader ideas, this is an excellent and illuminating resource. — Alan Heavens.

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(1) G. H. Darwin, *The Observatory*, **1**, 13, 1877.
(2) D. Mihalas, *Stellar Atmospheres (2nd Edn.)* (Freeman, San Francisco), 1978.
(3) R. Kudritzki *et al*., in C. Leitherer *et al*. (eds.), *Massive Stars in Starbursts* (Cambridge University Press), 1991, p. 59.

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