Astronomers' Universe

Pierre Léna

Astronomy's Quest for Sharp Images

From Blurred Pictures to the Very Large Telescope

Springer

Astronomers' Universe

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Cover illustraton: The full Moon sets at dawn, behind the domes of the Very Large Telescope distributed over the Cerro Paranal platform in the Atacama desert (Chile). The photography is taken 14 km away from Paranal, on the road to the future European-Extremely Large Telescope at Cerro Armazones. Credit: G.Gillet/ESO

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To Sang Shao-Hua
To the memory of Lodewijk and Ulla Woltjer

Preface to the French Edition

We are such stuff as dreams are made on—William Shakespeare, *The Tempest*

I have always been very lucky! Starting out as a professional astronomer at the beginning of the 1960s, my life in research and teaching, which has now reached its end, encountered so many extraordinary developments in astrophysics over the past half-century. There were so many different telescopes to visit and use! So many hi-tech instruments, designed by generations of enthusiastic students and researchers! And so many improvements brought about by the rise of information technologies! I have experienced all that. I have spent many long nights gazing at the sky. I have witnessed magnificent discoveries, thanks to these observatories on Earth or in space. From Europe to America, from Chile to China, I have been able to gauge the universal nature of science and it has been my pleasure to belong to the community of all those curious beings who serve it with such enthusiasm. I have also experienced the potential of a unified Europe and the rich rewards that can spring from it.

The field my own work may have contributed to, and which the work of the students and teams around me certainly did, has become truly immense. It is becoming more productive by the day and now employs hundreds of researchers and engineers. And so it seemed to me important to tell this story of women and men, mirrors, fringes, and stars and to share my inside view as a privileged witness and modest actor.

I am going to tell you a story about blur, a picture book of sorts, but told with words. It is a quest that began with Galileo, one night in Venice to be exact, in 1609, when he pointed his refracting telescope toward the Milky Way, then Jupiter, Saturn, and Venus, and even the Sun itself, discovering everywhere images that no one had ever seen before him. Blurred and imprecise images which immediately brought about a scientific revolution. From that point, astronomers would make constant progress, discerning ever more detail in sharper and sharper images, first peering wide-eyed into refracting and reflecting telescopes, then studying photographic plates, which can show so much more, and finally sending unmanned probes to Mars or Comet 67P/Churyumov–Gerasimenko to photograph these distant bodies at point-blank range.

Between Galileo and the 1960s, which were precisely the years when I began my life as a research scientist, progress was certainly made in the quest for finer detail, some of it very significant. However, this progress did not concern the wavelengths at which stars and planets emit most of their light, namely visible and infrared wavelengths. For these lights, there has been almost no progress! In Arizona, as a young researcher, I was already confronted with the blur in images of the Sun. After some adventures that were as much aeronautic as astronomical, I only returned to the problem of imaging a decade later, inspired by Antoine Labeyrie and also by François Roddier, two exceptional physicists of my own generation. I then had the good fortune to be associated with the design of the Very Large Telescope, now set up in Chile, between 1978 and 2005. Thanks to the trust shown to me by Lodewijk Woltjer, director of the European Southern Observatory (ESO), of which France was a member, I found myself at the heart of a new campaign against the blur in astronomical images.

With hindsight, I am amazed to see how productive those years were. I always felt as though I was making my way through a thick fog, never sure whether I might stumble at the next step. So where did I find the strength to carry out this struggle with myself, with the reluctant instrument, with the sceptic, and with those who would ironise? This book tells that story. I owe much to my family, to friendships and emotions, to a long scientific tradition which I had inherited without even realising it. This story is my way of describing and giving thanks to these legacies.

I am aware of having been just a relay, just another link in the chain. I often mention the young students who joined me on this journey, and I have tried to show how there is a continuity from generation to generation, something I am very conscious of. These are the ones who have made the extraordinary discoveries I describe in this book, who are engaged in still further attempts to reduce the blur, and who are preparing the future.

And of course, this book is also dedicated to them.

Acknowledgements

My thanks go first to Antoine Mérand and Andrés Pino for their invitation to give a talk on the history of the VLT, through my own personal experiences, during a trip to Paranal in 2016. That was where the idea of this book was first formulated, and my wife Sang Shao-Hua was behind it all the way. She deserves the dedicacy. Thérèse and Xavier Perras provided me with precious moments in their 'writing retreat' in Burgundy.

Progress would have been difficult without discussions with the many people who played their own role in this story, including in particular Daniel Bonneau, Vincent Coudé du Foresto, Pierre Cox who invited me to ALMA, Françoise Delplancke, Frank Eisenhauer, Reinhard Genzel, Andreas Glindemann, Daniel Hofstadt for his warm welcome at Rupanco Lake, Pierre Kervella, Bertrand Koehler, Antoine Labeyrie, Anne Lagrange for our meetings in Chartreuse, Denis Mourard at Calern, Norbert Hubin, Thibaut Paumard, and Guy Perrin for reading the manuscript, Yves Quéré, Daniel Rouan, Jean Schneider, Farokh Vakili, and Julien Woillez: I am sincerely grateful to all of them. Thanks also to Pierre Chavel, for supplying me with genuine fringes. Many others are cited, but there just was not time to exchange recollections with everyone. Many thanks also to them.

Using my professional archives at the Paris Observatory, I was able to recover all the necessary information, thanks to the excellent organisation of Nicole Fouquet, who was an invaluable secretary throughout these decades. For the classification of the archives, I owe everything to Marie-Agnès Dubos, while Agnès Fave helped me to access them. I am truly grateful to all three.

Without the encouragement of Sophie Bancquart and the careful editing work of Juliette Thomas, I doubt whether this project would ever have been completed. A huge thank you to my French publisher *Le Pommier*!

Note on the English Edition

I am very happy that Springer accepted to publish this translation of the book which came out under the title *Une Histoire de Flou* in France at the beginning of 2019. I thank Luc Dettwiller for his careful reading and corrections, and the colleagues who provided illustrations. I would particularly like to thank the editor Ramon Khanna for his support and the translator Stephen Lyle for the quality of his work, as well as the editing team in India. My warmest thanks go also to Xavier Barcons, Director General of the European Southern Observatory, for the help with this edition which he agreed immediately.

Since I wrote the book in 2018, adaptive optics and interferometry have been bringing in ever more outstanding results. I have only been able to mention a few of them rather briefly in the present publication, but they confirm the victorious trend up until now in the war on blur, if such was necessary.

I am particularly happy to share this story with all those who may not read French but have taken part in this great adventure over the past half-century or are contributing to it in the present century. I hope I can be forgiven for my deliberately personal account of this, with all its omissions and sometimes personal assessments, for which of course I assume responsibility.

On October 8, at the very moment when this book goes into press, the Nobel prize in physics is given to Reinhard Genzel and Andrea Chez, for their work on the black hole at the galactic center, and jointly to Roger Penrose for his theoretical work on general relativity and black holes. As this is an extraordinary step in the story I have attempted to tell, it should not be omitted here.

Lo and Ulla Woltjer, to whom I owe so much, have both recently departed this world. I dedicate this English edition of the book to them.

Paris, France Pierre Léna
October 2020

Contents

1

One Night in Paranal

> And from that primal night in which two men born blind grope for their ways, the one equipped with the tools of science, the other helped only by the flashes of his imagination, which one returns sooner and more heavily laden with a brief phosphorescence? The answer does not matter. The mystery is common to both.—Saint-John Perse, *Speech upon receiving the Nobel Prize in Literature*[1]

In these latitudes, night falls quickly. At midday, the Atacama desert in Chile, drenched in heat under the almost vertical noonday sun, loses its shadows, its relief, and its colours, only to get them back at the close of day. To the west, a veil of white hugging the horizon has now become a layer of nearby cloud, and beneath this, a few kilometers away but invisible, lies the Pacific Ocean. Far away to the north-east, the peak of the volcano Licancabur (5916 m) and the snow-topped Andes form the horizon, above which the dark shadow of the Earth is now climbing.[2] At an altitude of more than 2600 m, I am alone up here, and I feel totally alone, surrounded by the silence of the desert, as I await the onset of night. Above me, an immense sky turns dark blue and deepens, and the wind has dropped. On the vast horizontal platform that surrounds me stand a group of strange buildings. Four of these, almost standing in a row, are truly gigantic metal structures, catching the last reddening rays of the

[1] www.nobelprize.org/prizes/literature/1960/perse/speech/.

[2] This anti-twilight arch is also known as the Belt of Venus. See Lynch and Livingston (2001).

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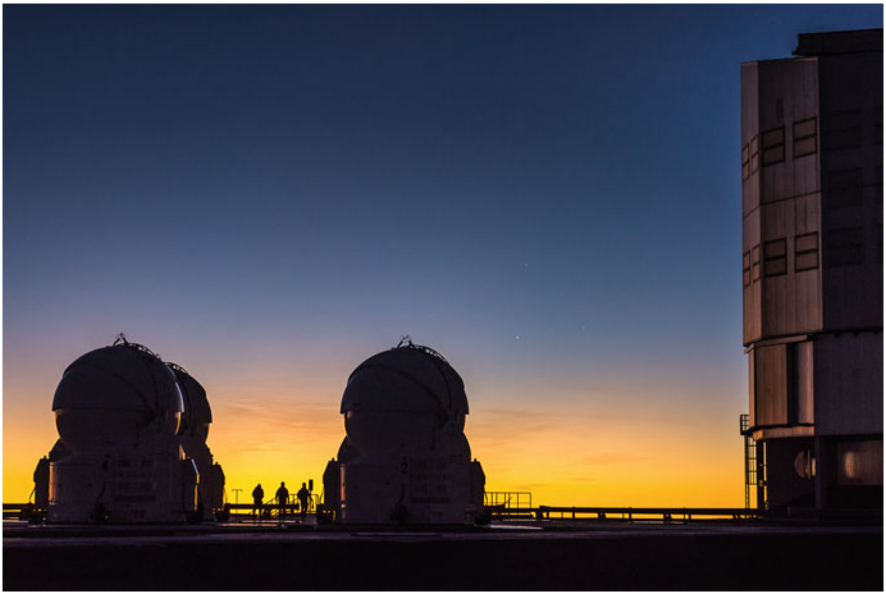

Fig. 1.1 On the VLT platform, looking to the twilight at West, with three egg-cup shaped telescopes and three astronomers preparing for the night. A conjunction of three planets can be made out in the twilight sky, just to the right of the rightmost dome: Jupiter at the top, Venus bottom left, and Mercury bottom right. Credit: ESO/G. Brammer

setting sun. Four others, smaller and painted white, look rather like egg-cups (see Fig. 1.1). They sit on rails that reach across the platform.

There is nothing else to attract our attention. Not a soul in sight.

The Observatory

In 1986, I climbed this mountain for the first time, lost in the middle of one of the most barren deserts on Earth. At that time, the platform we see there today had not yet been built. The peak was just a kind of rocky ridge, almost without any vegetation at all, although I did pick up one rather unusual plant. With its woody stem, it long adorned my office at the Paris Observatory in Meudon. It could survive in these conditions of perfect drought only by absorbing the first dew to form on its leaves at dawn, before the burning sun would climb too high (see Fig. 1.2).

This peak was selected in 1983 by the Swedish astronomer Arne Ardeberg. It was such a promising site that it was made the subject of a systematic

Fig. 1.2 The mountain Cerro Paranal (2680 m), before the installation of the VLT, rises In the middle of nowhere, in the Chilean Atacama Desert. Credit: ESO/M.Sarazin

study. When I first arrived 3 years later, three Chileans—Francisco Gonzalez and his two sons Francisco and Italo—had been camping there for weeks on end to monitor optical and meteorological data. These would determine whether Cerro Paranal would be a suitable place to build the largest optical telescope in the world, a project proposed by a handful of European nations, including my own, France. Very dry weather conditions, a transparent sky, an extremely stable atmosphere, and very low levels of seismic activity were all part of the ruthless examination that Cerro Paranal would have to pass in competition with several other mountain peaks. When it was finally chosen in 1990, the top was levelled off by about 30 m using dynamite to make way for the construction of a platform that could accommodate the telescopes we hoped to build and which today constitute Europe's Very Large Telescope, the VLT, our wonderful telescope.

On this spring evening in 2018, more than 30 years after my first visit, I have returned to Paranal. That event in my youth is blurred and indistinct now in the foggy recesses of my memory. Meanwhile, night has fallen and myriad stars appear, incredibly bright, steady and untwinkling, so stable is the atmosphere, without a hint of turbulence. Their tiny specks of light combine to make the vast sky as bright as the broad expanse of the desert is dark, without village or lights as far as the eye can see. Lower down, a car suddenly breaks the silence of the desert and begins to make its way up the slope. It comes to a halt, parks, and three silhouettes emerge, only to be swallowed up a moment later by an entrance hollowed out of the mountain.

The scene changes now to this half-buried room where I meet the three silhouettes, in fact, three astronomers. It is from this control room that the eight telescopes on the platform are sent their instructions. The work stations are comfortable, each equipped with several screens covered with all kinds of measurement data. These pass on the commands that specify the night's schedule, already fed into the computers. If all goes well, those seated here will stick strictly to the plan, because every minute of observation counts. When the weather conditions are favourable, the night will always be too short to do everything one would have liked. Which way to point which telescope? Which instrument to choose this evening to analyse the light it gathers? Which measurement programme to carry out? For which team of astrophysicists, who will have made their proposal months before, then received acceptance and been allocated a certain number of nights of observation?

The reception tonight is a little out of the ordinary. To probe the depths of the Universe, only two teams will have access to the line-up of eight telescopes—the four giants with their 8.2 m mirrors, and the four others, measuring only 1.8 m, nestling in their white egg-cups. This is indeed unusual, because more often than not, there are half a dozen teams here sharing the instruments mounted on the telescopes, each running their own observation programme. The names of the four giants, whose birth will be recounted here, were suggested in the 1990s by a young schoolgirl, Jorssy Albanez Castilla, following a competition between schools in the Chilean II Region. The names put forward come from the language of the Mapuche people and refer respectively to the telescopes less poetically labelled UT1, UT2, UT3, and UT4, as Antu (the Sun), Kueyen (the Moon), Melipal (the Southern Cross), and Yepun (Venus).[3] We shall use these names here. The mirrors of these giants, each 8.2 m in diameter, place them among the largest optical instruments in the world, even in the present decade from 2010.

[3]The name 'Yepun' was originally taken to refer to the star Sirius, but later research on the language of the Mapuche showed that it actually meant the 'evening star' and referred to the planet Venus: https://www.hq.eso.org/public/teles-instr/paranal-observatory/vlt/vlt-names/yepun/.

A Distant Neighbour, the Black Hole in Sagittarius

The first team is led by Guy Perrin, an astronomer from the Paris Observatory. Tonight he is working with Frank Eisenhauer. Frank comes from one of the Max Planck Institutes in Garching, set in the middle of a superb science campus in the suburbs of Munich, in Baveria.

Guy was born in 1968 and became one of my keenest and most brilliant students, in those far-off days when he was studying physics and astrophysics at the *École polytechnique* and the University of Paris VII. During this account, we shall meet this eminent astronomer on several occasions, and we shall take the time to give a better introduction. This evening, his team has obtained permission to use the four giant telescopes of the VLT simultaneously and for several nights in a row. As surprising as it may seem, these four telescopes can work in concert, bringing together and mixing the light that each has collected. The aim of this observation programme, selected after tough competition between astronomers, is fascinating indeed. The idea is to obtain as precise and detailed an image as possible of what is going on in the immediate neighbourhood of a black hole, in fact, the supermassive black hole which almost certainly sits at the center of our galaxy, the Milky Way.

As astonishing as it may seem, the idea that an object as exotic as a black hole could exist in the Universe is not a new one, since it was first proposed in 1783. It was in that year that an English clergyman, John Michell, raised the possibility of a massive body, so massive that even light—whose speed was by then roughly established—would not be able to escape from its surface, due to the pull of gravity. Michell knew the mass of the Sun. He concluded that a star made from the same matter and of the same density as the Sun, but having five hundred times its radius, would be able to retain all the light emerging at its surface. This would be what he called a dark star.[4] Clearly though, such a star would be invisible to any telescope. But the Reverend Michell, in a stroke of genius, explained that one would nevertheless be able to detect its presence through the effects of its powerful gravitational field, in the ideal case where it formed a binary system with another, normal star.[5] By observing the latter, one should find an oscillatory motion that would reveal the presence of the

[4]On 27 November 1783, John Michell already had the idea of a black hole: www.aps.org/publications/apsnews/200911/upload/November-2009.pdf.

[5]"If the semi-diameter of a sphere of the same density as the Sun in the proportion of five hundred to one, and by supposing light to be attracted by the same force in proportion to its *vis inertiae* [inertial mass] with other bodies, all light emitted from such a body would be made to return towards it, by its own proper gravity."

invisible companion. Many double star systems had already been identified by that time, but nothing was known about how probable such a configuration might be. How likely was one to stumble across a binary object comprising a normal star and a dark star? It is not surprising therefore that there was such a long wait between Michell's suggestion and the date when the first black hole was discovered in 1973, through production of X-ray emission in its vicinity. This was the X-ray source subsequently referred to as Cygnus-X1. But it was a fruitful interlude and we shall return to it in Chap. 7.

Exactly in the center of our Galaxy—and here we use a capital letter, because this is the home of the Sun and its system of planets—, there sits an object some 26,000 light-years away with a mass about four million times the mass of the Sun. This is the only entity with such a high mass concentration in the Galaxy, and it has gradually become accepted that it is probably a black hole. We call it Sagittarius A*, because it sits in the beautiful constellation of Sagittarius, so glorious in the summer sky. The A* indicates that it is a source of light waves emitted at radio frequencies, and indeed, this is how it was discovered. Our German colleague Reinhard Genzel and his team began exploring the neighbourhood of this source in the 1990s. They launched the idea, which every further observation has since supported, that there is a supermassive black hole there, so close to us in space, just as it is in time for the light to travel to us—only 26,000 years, barely more than the time that separates us from the Neolithic. There are other black holes out there, but they are lost in space, a thousand times further away or more. This makes SgrA* a first rate laboratory, so much more accessible than all the others. From our vantage point on Earth, we can observe there some of the phenomena predicted by the general theory of relativity when the gravitational field becomes unbelievably strong. Sagittarius A* will therefore be one of the heros of our story.

This evening, the team seated at the control station will be coordinated by Frank from Bavaria, a colleague of Reinhard's, and Guy, two astrophysicists well-versed in their line of work. Each of the four operators, the only ones allowed to set their telescope in motion, will carry out the night's observing programme, passing on instructions to the corresponding computers. The latter will then obediently point the four telescopes Antu, Kueyen, Melipal, and Yepun toward the constellation of Sagittarius. They must follow the apparent motion of the stars in the sky, due to the steady rotation of the Earth on its axis during the night. Using carefully arranged mirrors, the light gathered by the four giant mirrors is then channeled to an underground room containing the impressive GRAVITY instrument built in the laboratories of Frank, Guy, and several others. Activated remotely by the control panels, this instrument can then receive, measure, and analyse the light which left the central region of the Galaxy some 26,000 years earlier, when Europe was still largely covered by ice. This light brings astronomers much crucial information. Carefully prepared computer programs are able to represent the results in the form of graphs, figures, curves, and numbers which will keep Frank and Guy busy throughout the night, along with half a dozen collaborators, scrutinizing the details of this complex celestial process (see Fig. 1.3).

The ultimate aim, doggedly pursued now for over a decade, is an extremely ambitious one. The idea is to distinguish each individual star within very close range of the black hole, held captive by the incredibly strong gravitational field it produces and hence orbiting around it at tremendous speeds. Tonight, the team are thus using the GRAVITY instrument to produce an unbelievably sharp image, sharper than any yet obtained in this region of the infrared light spectrum. Night after night, it is used to determine the changing position of one of these stars, called S2. The distance between S2 and SgrA*, as measured tonight, is only about fourteen light-hours. The sharpness of the image, which has to be good enough to distinguish the black hole from the star S2, is thus

Fig. 1.3 In the control room of the VLT and its interferometric mode (VLTI), French and German astronomers Guy Perrin and Odele Straub observe the center of the Galaxy with the GRAVITY instrument. Credit: Guy Perrin

simply characterised by an angle, namely, the angle between the direction of S2 and the direction of SgrA*, as viewed from the Earth. This angle is found as the ratio of two lengths, viz., fourteen light-hours divided by twenty-six light-years. This gives

$$\frac{14}{26{,}000 \times 365 \times 24} \sim 50 \times 10^{-9},$$

or fifty billionths of a radian,[6] which is about twelve thousandths of a second of arc, or twelve milliarcseconds. Put another way, the sharpness of the image obtained would be good enough to make out the silhouette of a rocket standing on the Moon! So this is the task undertaken by Guy, Frank, and the ninety-seven other researchers making up the GRAVITY team, the rest of whom will be eagerly awaiting news from the previous night, as they open their electronic mailboxes back in Europe the following morning. Because tonight, the measurements obtained with this unique instrument represent the culmination of a long and painstaking investigation which began 26 years ago. A few weeks later, a paper entitled "Detection of the gravitational redshift in the orbit of the star S2 near the Galactic center massive black hole" will inform the scientific community that, for the first time, one of Albert Einstein's most important predictions regarding the effects of a very strong gravitational field have been firmly supported.[7] Later, we shall see how they reached this point.

Exoplanets: Other Worlds So Close

In the vast room, silence reigns as everyone concentrates on the task at hand. For a second team, led this evening by Anne, is getting ready for the following night. Today, in the hours leading up to dusk, Anne has been carefully testing the instrument known as Sphere, set up at one of the focal points of the telescope Melipal. Her own laboratory contributed to its design and construction. When she has finished, she will hand over the use of Melipal to the GRAVITY team, but tomorrow night the telescope will be left to her, so she is doing a final check that Sphere will be able to carry out the intended programme (see Fig. 1.4).

[6] One radian is a unit of angle equal to the angle subtended at the center of a circle of unit radius by an arc of length π on the circumference of that circle. It is equal to $(180/\pi)$ degrees, or about 60°.

[7] This wonderful observation was published at the end of 2018 in the journal Astronomy & Astrophysics: Gravity Collaboration (2018).

Fig. 1.4 While the Sun is setting, Anne Lagrange relaxes before her observing night at Paranal. Credit: A. Lagrange

I first met Anne-Marie Lagrange—we shall call her Anne—when she was a young student at the *École polytechnique*, still trying to decide what path to follow in the world of science. Eventually, she opted for astrophysics and so it was that each week her keen gaze and determined face could be made out among the students following the master's lectures.[8] At the time, I was teaching at the University of Paris VII. Anne is another of the main characters in our story. After obtaining her doctorate between 1985 and 1988, when the European project was still in its infancy, Anne became interested in a star surrounded by dust, thought to have comets, like our

[8] What is now called a Master 2 in France was then a *Diplôme d'études approfondies* or DEA.

own star, the Sun. Now, whenever there is dust and comet formation, there may also be planet formation? The star β Pictoris and its ring are located in the southern constellation of Pictor. Like several other constellations in the southern hemisphere, this one was named after the voyages of Magellan, by the French astronomer Nicolas-Louis Lacaille around 1750. The star Beta Pictoris would become a springboard for Anne's amazing career. She would go from one discovery to the next, never losing her charm and simplicity, until in 2011 she was designated *Femme scientifique de l'année* in France.

Anne's research project is quite different from Guy's. Her quest is not to explore the mysterious and tumultuous environment of a distant black hole more than twenty thousand light-years from the Earth, but to prove the existence of a planet in orbit around another star only a few light-years away, and then establish its characteristics. Anne is an internationally recognised and respected expert on the subject of other worlds, or exoplanets. So why is this subject so important in the present story?

In Ancient Greece, Democritus invented the idea of the atom by pure intuition, more than 2000 years before Jean Perrin proved its existence and thereby obtained the Nobel Prize for Physics in 1926. Democritus was also interested in the existence of other worlds in the Universe. This was pure speculation, once again, but it is well worth quoting:[9]

> There are innumerable worlds of different sizes. In some there is neither a Sun nor Moon, in others they are larger than ours and others have more than one. These worlds are at irregular distances, more in one direction and less than another, and some are flourishing and some are declining. Here they come into being, there they die, and they are destroyed by collision with one another. Some of the worlds have no animal or plant life nor any water.

As the text makes so clear, these hypothetical other worlds are very different from the one associated with our own star. The analogies mentioned compare them with the Earth, but distinguish them by their diversity. Speculation about their existence has been going on for more than twenty-three centuries, continuing with *Conversations on the Plurality of Worlds* (1686) by Bernard Le Bouyer de Fontenelle, who was the permanent secretary of the Royal Academy of Sciences in Paris, or again the proposed existence of channels that the Italian astronomer Giovanni Schiarapelli thought he had found on Mars in 1877, and later still, the little green men I myself discovered in the comic strips of my youth.

[9]Democritus, lost text, quoted by Hippolytus in the third century AD.

At the beginning of the nineteenth century, the astronomer Pierre-Simon de Laplace suggested that the Solar System could have been formed from a cloud of gas, which he called the "primitive nebula". This meant that the Sun and planets actually shared a common history, and this mechanism could then apply elsewhere, not just to our own Solar System. Right through the twentieth century, Laplace's nebular hypothesis continued to guide research on what remained an enigma, the formation of the planets around our own star. Astronomers began to look more closely at nearby stars to see whether they too might have planetary systems whose existence could be proved by careful telescope observation. But unfortunately, the challenge was too great, because it was impossible to detect the faint light from these planets. They were just too far away to be able to make out on a photograph taken behind a telescope. In Chap. 6, we shall describe some of the stories that make up this century-long investigation, which remained fruitless.

After a series of somewhat hesitant announcements, there was a spectacular turn of events on 6 October 1995, when two Swiss astronomers at the Geneva Observatory, Michel Mayor and his student Didier Queloz, revealed the presence of a planet which would come to be known as 51 Peg b, with a similar mass to Jupiter. This planet orbits a nearby star rather like our own, 51 Pegasi, in the constellation Pegasus, visible to us in the northern hemisphere. Detection was indirect, since the planet is not actually visible on any image. What is detected are the gravitational effects of its presence on the motion of the star 51 Peg, revealed by a very high resolution spectrograph designed at the Marseilles Observatory by André Baranne. This discovery put an end to the suspense first sparked by Democritus and began a new era in astrophysics. As so often happens, the ground is prepared for a discovery, the question matures over a long period, and then one day the fruit falls from the tree. In 1992, the word 'exoplanet' was used for the first time. Today it refers to planets more or less like those in our own Solar System but orbiting other stars.

Thousands of exoplanets have been discovered in the Galaxy since 1995, and the current feeling among astronomers is that the majority of stars in our Galaxy probably possess one or more exoplanets, whence it is likely that the same will be true in the billions of other galaxies. This is an awe-inspiring prospect and indeed a major scientific revolution, providing a wonderful field of investigation for young scientists in the twenty-first century.

At the end of the day, the telescope Melipal, one of the four telescopes making up Europe's Very Large Telescope, is no more than a gigantic camera in which the objective is a mirror rather than a lens. A set of secondary then tertiary mirrors transmits the image formed at one of the focal points located to the side of the telescope. The millions of pixels of the light detector placed there, which uses precisely the same physical principles as the detectors in an ordinary camera, sends this digitised image to the computer screens in the control room. Anne has chosen the colour, that is, the wavelength of the infrared light she wishes to analyse, along with a host of other parameters that will be needed for her observations. The extraordinarily difficult challenge that Anne hopes to meet tomorrow night is to distinguish a tiny exoplanet which appears right next to its star and which is a million times fainter than that star, then form an image and analyse the light coming from it. Besides the need for an extremely sharp image, comparable to the sharpness obtained by the GRAVITY instrument, the problem is also to handle the radically different brightness of the star and its planet. This is more difficult than detecting a tiny mosquito flying around a distant lighthouse by the feeble light it scatters from the lighthouse lamp.

Thanks to her discoveries, Anne has become an internationally recognised specialist on exoplanets. The programme to be carried out by the Sphere instrument was designed by a team of a hundred and twenty-five scientists from all over the world, a group with which Anne is closely associated. The aim is to study a specific star called V1032 Centauri, or PDS 70, in the southern constellation Centaurus. This star is slightly cooler than the Sun and very young, being only about 5 million years old. It thus formed just a little before the birth of Lucy, the Australopithecus whose fossil was found in Ethiopia by the palaeontologist Yves Coppens and his colleagues. It has been known for about 15 years that this star is surrounded by an interesting disk of gas and dust which might have given rise to a planet. Could we then distinguish such a planet with absolute certainty, providing firm evidence for this relationship between disks of this kind and the formation of exoplanets? We shall discuss this relationship in more detail in Chap. 6. Thanks to the extremely sharp image produced by the Sphere instrument, the observations to be made over the coming nights will be combined with others acquired at Paranal over the last 4 years, and images from other telescopes, to try to confirm the suspicion that an exoplanet sits within this disk. This conclusion can then be further corroborated by observing the orbital motion of the planet in images taken at intervals of several months (see Fig. 1.5).

Anne tells me that this result would be the most beautiful among all those obtained by herself and her colleagues over the past decade.

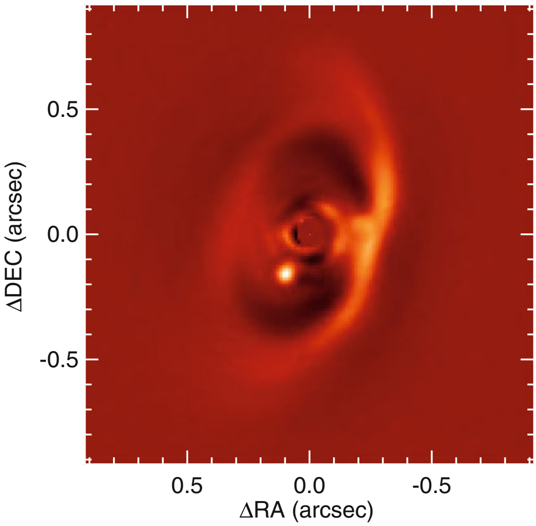

Fig. 1.5 The exoplanet PDS 70 b, discovered in 2018. In this small region (about one second of arc as seen from the Earth), with the instrument SPHERE on the VLT to suppress the blur, the planet shows up in the near infrared. Seen almost face on, the protoplanetary disc appears, with a dark zone where the material has gone to build the planet. The central star has been artificially masked to avoid overexposing the image. The orbit size is about 22 astronomical units (1 AU = distance from the Earth to the Sun). Figure from Müller et al. (2018)

Blurred Images

Using these huge telescopes, Frank, Guy, Anne, and the many astronomers making up their teams detect infrared light and obtain unbelievably sharp images, able to reveal the secrets of exoplanets and black holes. In the images produced by their instruments, displayed on their computer screens and analysed with considerable help from dedicated computer programs in their laboratories, they can make out the kind of detail that few would have even dreamt of 50 years ago. And when their discoveries are published, they are acclaimed the world over. In 40 years, and with the Very Large Telescope set up at the top of Cerro Paranal, Europe has succeeded in meeting a tremendous challenge, and been the first to get there.

So what exactly was this challenge? Fifty years ago, astronomical images, even those produced by the best telescopes of the day, equipped with large and perfectly polished mirrors, were afflicted by an inescapable blurring. What was the cause of this fuzziness, this lack of sharpness in the details? Was there something absolutely unavoidable that would forever limit what we could learn of distant objects when we tried to form their image?

This evening, at the top of Cerro Paranal, Guy and Anne have taken up the long and fascinating story of light which began several centuries ago, enacted by great scientists such as Huygens, Rømer, Newton, Young, Fresnel, Arago, Fizeau, Maxwell, Hertz, Planck, Einstein, and Feynman. Throughout this story, French scientists have played a major role, including several winners of the Nobel Prize in Physics, namely, Alfred Kastler (1966), Claude Cohen-Tannoudji (1997), Serge Haroche (2012), and Gérard Mourou (2018), all pioneers in the exploration of light.[10] This tale of lenses and mirrors takes us right up to the sophisticated instruments installed at Paranal. The astonishing discoveries made about black holes and exoplanets attest to the great successes of the past few decades in the relentless struggle to remove this blurring from our images. I chose to mention these discoveries at the very beginning of my account so that the reader would grasp the importance of this struggle. The black holes and exoplanets deserve more discussion, of course, and we shall return to them at length at the end of our story, once the victory over blurring has been secured.

So here, dear reader, in the following chapters, are a few episodes of this 50 year quest: the amazing story of our bid to beat the blur.

[10] Albert Fert, born in 1938 and a student of Jacques Friedel, obtained the Nobel Prize in Physics in 2007 for his work on solid state physics, another area where French physicists excel.

2

From the Dawn of Time

As for the future, your task is not to foresee it, but to enable it.—Antoine de Saint-Exupéry, *Citadelle*

The story of blurred images begins with the story of imaging, and this got under way 600 million years ago with the long history of the evolution of the eye in living creatures. It continued when the first lenses were made to improve people's vision, followed by the *camera obscura* or pinhole camera, used by Renaissance painters. Then came Galileo, who stood on the hills of Florence in 1609 and pointed the first astronomical telescope toward the sky. It was equipped with lenses and brought images to his eyes that no one had ever yet seen.

Before the invention of this refracting telescope with its lenses, it had long been known that, by simply making a small hole in the wall of a darkened room, the *camera obscura*, an image of the scenery outside could be formed on a screen inside the room. This extremely simple camera was described by Mo Zi in China in the fourth century BC, then by Aristotle. It was used by Leonardo da Vinci and Johannes Vermeer to study perspective. Maybe even by our ancestors in the neolithic. In the darkness of their cave, did they ever notice the rays of light entering by a small opening and forming an inverted image of the sunlit landscape on the wall at the back of the cave? As a distant echo of this idea, which I somewhat hesitantly put forward, I recall the pride of the physicist Yves Rocard during the explosion of the first French atomic bomb at Reggane in the Sahara on 13 February 1960. He amazed the high ranking officers seated around him in the bunker not far from the site of the

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