Cosmic Barcodes

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As it is impossible to travel to, or even send probes to, astronomical objects, we rely to a very large degree on the light we receive to learn about astronomical objects; the advent of cosmic ray, neutrino, and gravitational wave astronomy providing complementary avenues. If one understands the underlying physics and how to interpret it, the light contains a wealth of information. As is well known, Newton used a prism to break the white light of the sun into its component colours, those of the rainbow; its visual spectrum. Later, Wollaston, Fraunhofer, Ångström, and others were able to observe the spectrum at high resolution in its colour, the light's wavelength, and identified dark *spectral lines*, which could be attributed to different elements based on corresponding observations in the laboratory. Quantum theory later was able to explain the lines as transitions between specific quantum states characteristic of the different atoms, absorbing light at particular wavelengths.

With modern spectrographs we can observe the light at very high resolution, as is shown in figure 1 for the sun. When combined with telescopes, spectra of comparable quality can be obtained for bright stars. Very large telescopes now make it possible to obtain spectra of reasonable quality even for individual stars beyond our own Milky Way galaxy. From such spectra, using models of the outer layers of the stars and how the matter and light behaves there to predict how the spectrum looks, we can obtain physical parameters such as age, mass, and chemical composition (i.e. which chemical elements are there and in what proportions), and use the information to study problems such as the evolution of the Milky Way and other galaxies, and the origin of the chemical elements. It is now even possible to obtain spectra of short-lived distant objects such as exploding stars in other galaxies, and of exoplanet atmospheres leaving faint imprints on stellar spectra as they pass in front of the star.

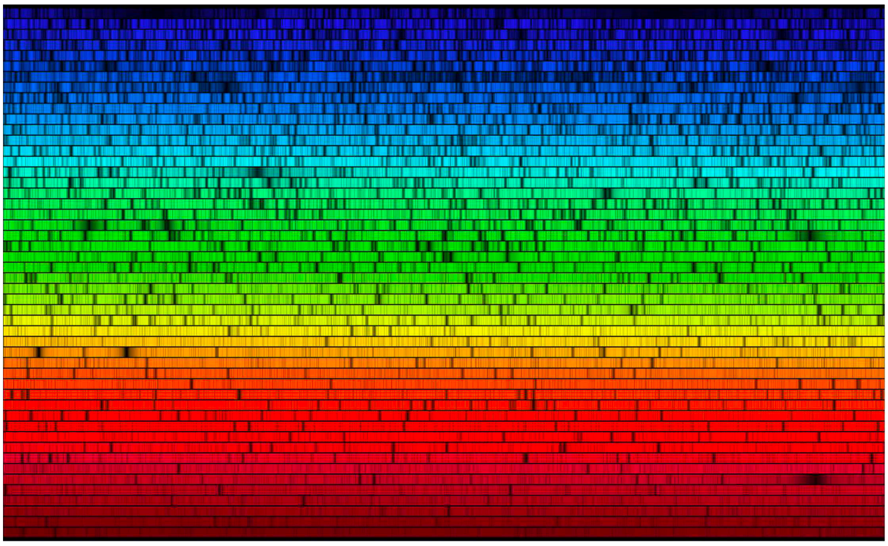

Figure 1: The visual spectrum of the sun, at high resolution, from blue to red. The spectrum shows thousands of dark spectral lines, caused by different chemical elements. For example, the broad dark line in the red to the lower right is caused by hydrogen. The two dark lines on the left at the border between red and yellow are caused by sodium. Some of the dense bands of lines in the blue region are created by molecules containing carbon. Lines of iron are literally everywhere. Credit: Robert Kurucz, Harvard University.

The unreasonable importance of the negative hydrogen ion

Most people have heard of hydrogen with one proton and one electron. Far fewer are aware that hydrogen can actually accept a second electron, to form a negatively charged ion, and this ion, though rare has a very important role in shaping the light that eventually comes to us from the sun. In order for the negative ion system of one proton and two electrons to be stable, the second electron can never be close to the first electron. Thus, the second electron is usually very far from the proton, very loosely bound to the atom; that is, it takes very little energy to remove it. When a hydrogen atom encounters an electron, it can be captured relatively easily into this state, with only a small change in energy, and the energy change results in a photon being emitted. In reverse, if such a loosely bound electron is hit by even a quite low energy photon, it can absorb the energy and be ejected from the ion. In more general terms, the negative hydrogen ion interacts very strongly with light with wavelengths corresponding to photons with energies in the visual region of the spectrum.

In an atmosphere of a star like the sun, there are far fewer negative hydrogen ions than normal neutral hydrogen atoms (which are far more abundant than any other atom), but the negative hydrogen ion interacts much more strongly with light at visual wavelengths; neutral hydrogen in its ground state is as clear as glass, with no interaction at all with light at visual wavelengths, while the negative hydrogen ion is opaque. In consequence, the vast majority of photons that one sees coming from the sun, originate in the formation of a negative hydrogen ion. A schematic of this process is shown in figure 2.

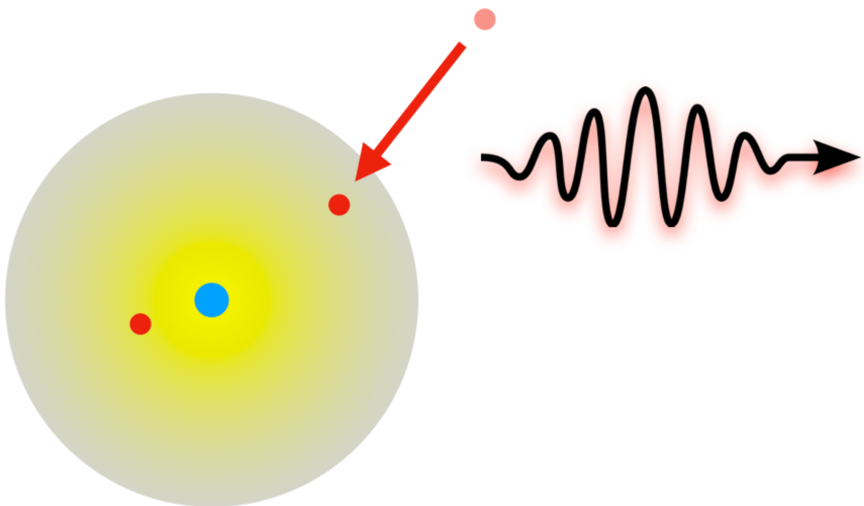

Figure 2: Schematic of the formation of the negative hydrogen ion by capture of a passing electron and emission of a photon. The red dots represent the electrons, the blue dot the proton, and the yellow haze the typical extent of the electron motion in the ion.

The astrophysical importance of the negative hydrogen ion and its interaction with light has been well known for quite some time, roughly a century. More recently, however, we have begun to appreciate the importance of the negative hydrogen ion in its effect on the states of other atoms, and thus on their spectral lines. Because the second electron is loosely bound, and thus the size of the negative hydrogen ion is relatively large compared to neutral atoms or positively charged ions, it rather easily and often can give its electron to positive ions passing by, even if they are quite distant; see figure 3. This process of electron transfer, will first affect the number of neutral and positively charged ions. Further, since the process occurs into particular quantum states of the neutral atom that is then formed, these processes affect which states the atoms are in. As the strength of spectral lines depends on which states the atoms of the gas are in, this process overall affects spectral lines, and thus how we interpret observations to obtain properties of stars, such as the abundance of an element, e.g. lithium, in the atmosphere. It is worth noting that the general importance of electron and other charge (proton) transfer processes in physics, astrophysics, chemistry, material science, and biology, is now broadly recognised.

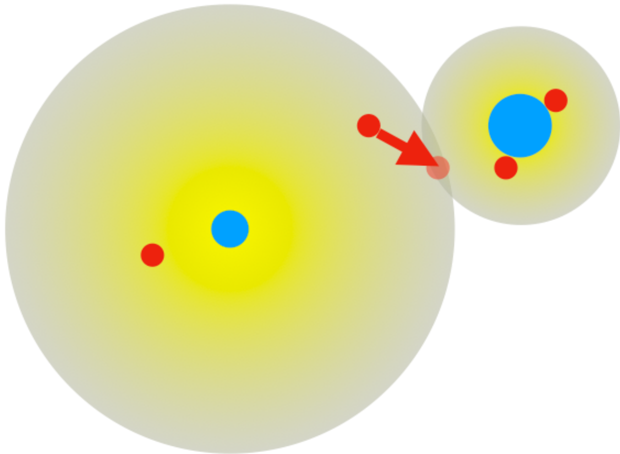

Figure 3: Schematic of the transfer of an electron from the negative hydrogen ion to, for example, a positive lithium ion, as they pass each other in a collision. The lithium nucleus has 3 protons (blue) and 3 units of positive charge (also usually 4 neutrons), and thus the lithium ion with two closely bound electrons starts with one unit of charge in total. The positive ion accepts an additional electron to become a neutral lithium atom, but in a specific excited state. Note the negative hydrogen ion has a much larger extent in terms of its electron cloud, due to the presence of the first electron.

To model stellar spectra accurately, we need to understand such processes quantitatively, that is, which states are populated and with what probabilities. These characteristics depend on the speed and distance between the two particles, and thus the overall rate for electron transfer depends on temperature and pressure in the gas. In practice, we obtain complementary information on these processes from theoretical calculations, and from experiments. From a theoretical point of view, as the system is at the atomic level, and the physics is described by the laws of quantum mechanics, this means to solve Schrödinger's equation. Solving Schrödinger's equation for any system with more than two particles, can in general not be achieved analytically, and thus computational methods must be used. For example, the system described above of a negative hydrogen ion and a lithium ion contains two nuclei and four electrons. Such solution is possible only with approximations, and thus experiments are needed to test the calculations. We have been able to do this for some elements of astrophysical interest such as lithium, sodium, magnesium, carbon, and oxygen at the DESIREE facility (Double ElectroStatic Ion Ring ExpEriment; see figure 4), a national infrastructure at Stockholm University.

Figure 4: DESIREE (Double ElectroStatic Ion Ring ExpEriment) at Stockholm University. Ions are stored moving in two oblong rings (circumference 8.6 m each), and brought together to collide with each other in the common central section. The particles moving in the same direction to have low relative speeds, typical of stellar atmospheres. The experiment is kept at about 13 degrees Kelvin, or minus 260 degrees Celsius, to reduce background signals. Credit: DESIREE, Stockholm University.

Experiments and their interpretation are more time consuming (and expensive) than calculations, and cannot provide all the information needed for modelling. In addition, experiments currently cannot be carried out for heavy elements such as iron, which is of particular astrophysical importance, as spectral lines of iron are ubiquitous in stellar spectra, and iron is often used a proxy for the total amount of heavy elements in stars. Thus, theory and experiment are complementary, and the experiments are vital feedback on the calculations. The results of the calculations are used in models of stellar spectra, which are then compared with observations, to derive properties of the star. Below I discuss just one example of how the data has been useful, enabling accurate and reliable interpretation of stellar spectra.

Where is all the lithium?

During the "Big Bang" at the beginning of our universe, the elements hydrogen and helium were produced, along with a small amount of lithium. Naively we expect that in the oldest stars in our galaxy, the ratio of lithium to hydrogen will reflect the ratio produced in the early universe. However, this is not what has been observed, roughly only half of the lithium relative to hydrogen that was expected to be produced in the Big Bang, is seen in the oldest stars.

A possible solution has been suggested by looking at the amounts of different chemical elements in different types of stars in the old globular cluster NGC 6397 (See figure 5). In such a cluster, it can be expected that all of the stars formed at roughly (astronomically speaking) the same time, and formed from the same cloud of gas with the same relative amounts of chemical elements. In a study led by Andreas Korn at Uppsala University, spectra of eighteen stars were observed with the European Southern Observatory's Very Large Telescope (ESO VLT), a telescope with a mirror of 8-metre diameter and one of the largest in the world, and the amounts of elements lithium, magnesium, calcium, titanium and iron relative to hydrogen were derived precisely. The first result was that the amounts measured were not the same in all stars, but varied with the type of star; as the stars are of the same age, the type of star is connected with the star's mass and thus how quickly it has evolved. Through detailed analysis of the trends and comparison with models, one could conclude that the amount of a given element in the observable atmosphere of the star, does not always reflect the amount in the star as a whole, or the amount at the time it was formed. The results pointed to that, over the roughly 13.5 billion years that the stars have evolved since their formation, elements such as lithium have "settled" or fallen into the star, and thus now there is less lithium in the observable atmosphere than the star started with.

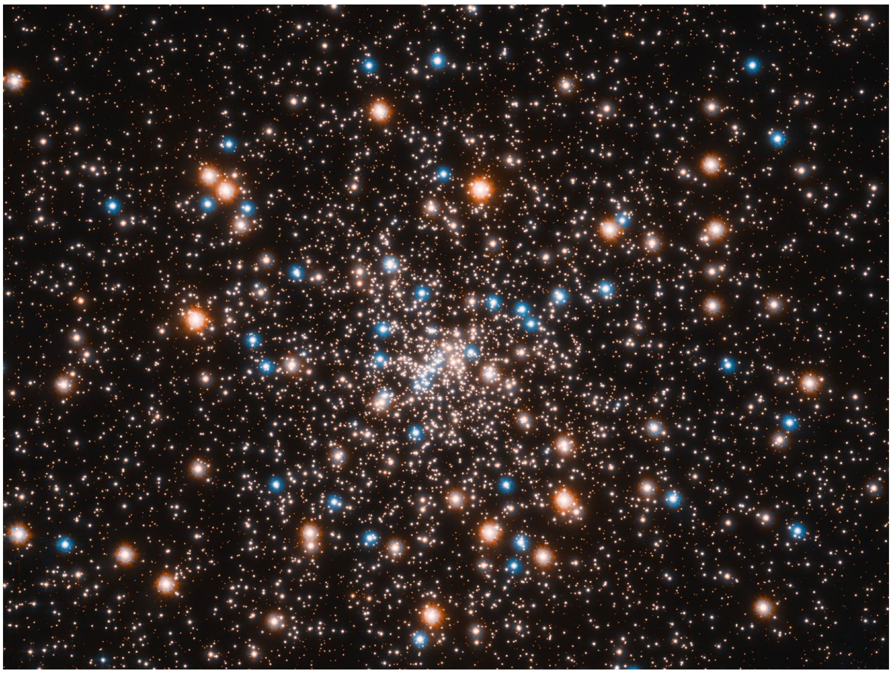

Figure 5: The old globular cluster NGC 6397. Credit: Hubble Space Telescope, NASA/ESA.

Current frontiers

There are currently three main frontiers in the study of astronomical spectra, driven predominantly by observational technology, including the possibility now to observe gravitational waves. The first is purely number of spectra we can obtain. The second is the detection of very weak signals. The third is spectra of short-lived transient events.

Millions and millions of spectra

The Milky Way galaxy is estimated to contain between 100 and 400 billion stars. Just a few decades ago, stellar spectra could only be observed one at a time, and with the sizes of telescopes available, one could reasonably obtain good quality spectra for tens or perhaps hundreds of stars. This is now changing rapidly with the advent of dedicated survey telescopes and multi-object spectrographs fed by optical fibres, that can observe hundreds or thousands of stars *simultaneously.*

One example is ESO's 4-metre Multi-Object Survey Telescope (4MOST), shown in figure 6, and expected to start operations in 2024. The fibre positioner is shown, which can place each of 2436 fibres on the image of different objects (stars, galaxies), feeding the light to a spectrograph that can record all the spectra. 4MOST plans to obtain roughly 18 million spectra of stars during the first five years of operations, of order ten thousand spectra per night. A large effort will be dedicated to analysing these spectra as well as possible, including the chemical composition of stars, which tells us something about where the star was born. With the information obtained sampling various parts of the Milky Way galaxy, and combining it with the information on stellar motions from the Gaia satellite, we can essentially obtain a map of the motions and chemical compositions of stars. From this information we expect to obtain new insights into how our galaxy, the Milky Way, came to be as it is today, including how the various structures comprising it were created.

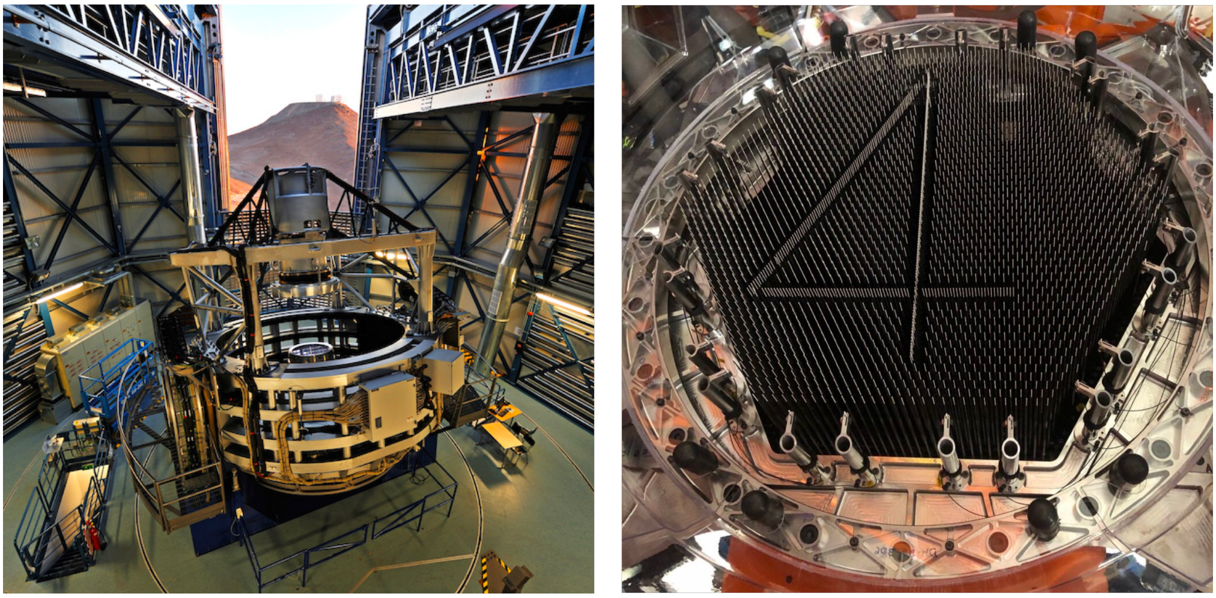

Figure 6. 4MOST on the left, and the fibre-positioning system for 2436 optical fibres on the right. Credit: ESO, 4MOST.

Spectra of habitable planets around other stars

Recent surveys such as with the Kepler space telescope, have told us that practically all stars have planets around them, and thus there are more than 100 billion planets in the Milky Way. In recent years with the world's largest telescopes (8 to 10 metres in diameter) and the Hubble Space Telescope, spectra of the atmospheres of planets around other stars, so-called exoplanets, could be obtained, and various elements identified. The spectra are obtained as the planet passes in front of the star, and the weak imprint left by the planet's atmosphere extracted from the total observed spectrum. The James Webb Space Telescope (JWST) has opened up particular parts of the infrared region of the spectrum needed to observe molecules of interest such as carbon dioxide, which was observed in the atmosphere of an exoplanet for the first time in 2022 in a project led by Natalie Batalha from University of California at Santa Cruz.

This discovery was made for a so-called "hot Jupiter", a gas giant planet similar in size to Jupiter, but much nearer its star than Jupiter in our solar system. Such a planet cannot be expected to host life as we know it. Habitable planets will necessarily be smaller, rocky planets, either further from the star or orbiting less bright stars, and thus leave an even weaker imprint on the spectrum. To be able to detect such weak spectra, and in infrared regions accessible from the ground, will require the next generation of 40-metre class telescopes and high-resolution spectrographs, such as the ESO Extremely Large Telescope (ELT), expected to start operations in 2028. It is hoped that the relative amounts of various molecules will give indications of the presence of vegetation, and eventually insight into the frequency of such life on exoplanets (see figure 7).

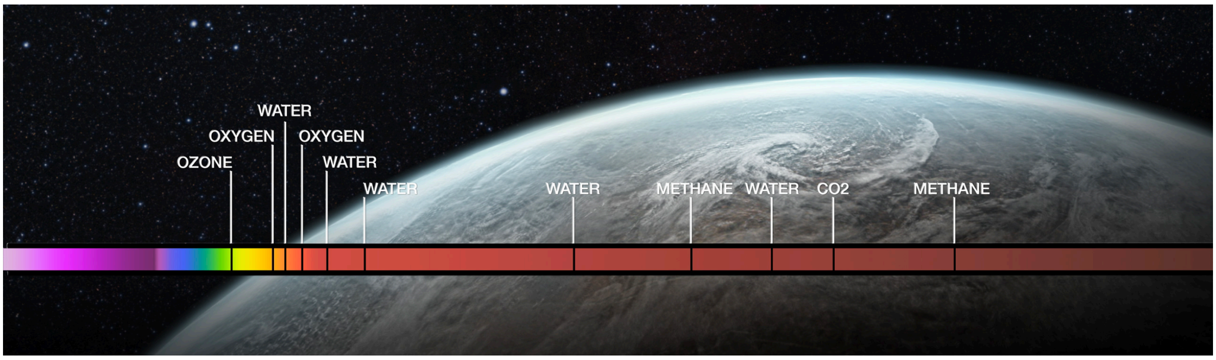

Figure 7. Upper panel: ESO's ELT. Lower panel: Schematic of the spectrum of an exoplanet atmosphere. Note carbon dioxide (CO_2) in the infrared. Credit: ESO.

Spectra of colliding neutron stars

The detection of gravitational waves from the Laser Interferometer Gravitational-Wave Observatory (LIGO) opened the possibility to detect and pinpoint in the sky, rare, short-lived transient events. A particularly striking example was the detection in 2017 of two colliding neutron stars, producing a so-called "kilonova", an explosion visible to our telescopes if we know where to look. Such an event, labelled AT2017gfo, was discovered in a distant galaxy and the optical light and spectra measured over a period of weeks until the explosion became too faint to any longer detect (see figure 8).

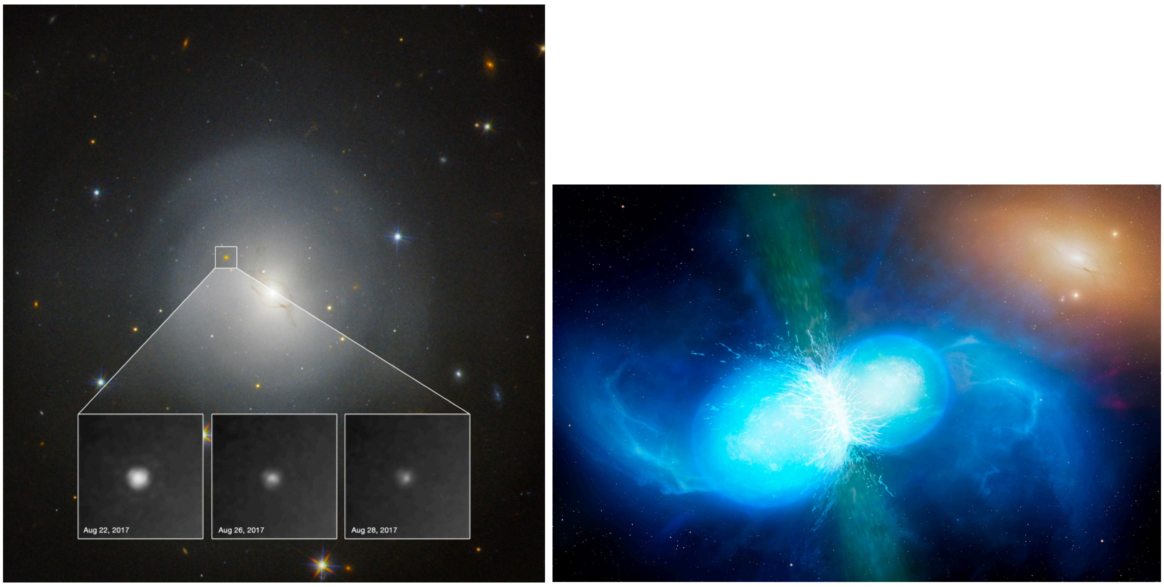

Figure 8. Left panel: The explosion created by the merging of two neutron stars, a "kilonova", in a distant galaxy, and its evolution with time. Credit: Hubble Space Telescope (NASA, ESA). Right panel: Artist's impression of a neutron star merger. Credit: Mark Garlick, University of Warwick.

The merging of neutron stars has long been suspected as a main site for the production of very heavy elements; that is elements heavier than iron, such as silver, platinum, gold, neodymium, gadolinium, and uranium. Analysis of the evolution of the brightness of AT2017gf has indicated that the ejected material must be dominated by very heavy elements, and the signatures of particular very heavy elements such as strontium and cerium have been detected directly in the spectrum. Thus, though not detected directly, it seems very likely that elements such as gold and silver are produced in neutron star mergers.

It remains an open question if there are other possible sites in the universe where such elements are also produced, and if so what the relative contributions to the total production are. Due to over two years of upgrade work, LIGO was not observing in recent years, but this year started an 18-month observing campaign, a much longer run than previous campaigns, also with increased sensitivity. There is reason to be optimistic that this will lead to additional kilonova detections, with corresponding observation of spectra, which will tell us more about this particular site of very heavy element production, such as the dependence on the masses of the neutron stars involved. From a physics perspective, we have the remarkable situation that the light at visual wavelengths from a kilonova is dominated by emission from elements such as samarium and neodymium, rather rare elements on earth. For example, samarium has 62 protons and at the temperatures of interest here usually 61 electrons. This positively charged ion has a very complex electronic structure leading to many different ways it can interact with light, through millions of spectral lines.

Physics to match observations

New observational technology, in the form of larger and more efficient ground- and space-based telescopes (both traditional and gravitational wave), along with better instruments, will in the coming decade provide us with amounts of spectra, and of faint and rare objects, that we could have only dreamed of a few decades ago. It is important that the span and quality of the physical understanding and models used to interpret these new observations keep pace, to ensure that we extract the maximum scientific return from these huge infrastructure investments. This will depend on theoretical and experimental developments, often collected under the umbrella of the field "Laboratory Astrophysics".

When all combined, state-of-the-art observations with the best physically motivated models, it is very likely in coming decades that can we get answers to some very far-reaching questions. The ELT should allow some partial, limited, answers regarding the question of how common plant life is on potentially habitable planets around other stars. The 4MOST survey, building on the information from the Gaia satellite, should allow us to answer in detail how our Milky Way galaxy became as it is today, and why it has the structure it does, potentially also saying something about how galaxies are formed in general. Gravitational wave observatories such as LIGO, and in future the space-based LISA, will help us understand with more certainty and in greater detail how the very heavy elements, such as gold and silver, were produced in nature. A related major advance not mentioned earlier is the advent of large-scale imaging survey telescopes, covering very large fractions of the whole sky on timescales of weeks or even days, such as the Rubin Observatory's Large Synoptic Survey Telescope (LSST). Such surveys will further expand the possibility to find transient events such as kilonovae and supernovae. And with all of the above, we can no doubt expect unplanned discoveries.