New space simulator imitates the universe

SRON will develop a space simulator with the financial support of the research council NWO. In the simulator, which simulates the darkness and extremely low temperatures in space, the space research institute will subject its space instruments to intensive tests. The first candidate is the infrared spectrometer SAFARI.

The Japanese space telescope SPIR, which is due to carry SAFARI into space in 2018, will have an actively cooled mirror. This means that astronomers’ observations will soon no longer be affected by the heat radiation emitted by the space telescope itself. SAFARI will therefore be able to detect extremely weak infrared sources that could not previously be seen as well as taking ‘pictures’ of the cosmos in three adjacent wavelength ranges. SAFARI will be equipped with ultrasensitive infrared detectors to pick up the weak signals received by the telescope. These Transition Edge Sensors are being developed by SRON. However, the new technology places far higher requirements on the calibration of the instruments and on the test facilities on the ground, which must be extremely light proof. The space simulator SAFARI is now developing with financial support from NWO (about 900,000 euros) satisfies all of those requirements. The total costs are about €1.2 million euros; the simulator must be operational by the end of 2012.

China wants SPEX for Mars mission

The China Academy of Space Technology (CAST) is seriously interested in the SPEX instrument, the spectropolarimeter currently being developed by SRON, in collaboration with the Astronomical Institute of Utrecht University and other Dutch parties. SPEX should be placed on the first Mars mission that is being developed completely under the leadership of China.

SPEX (Spectropolarimeter for Planetary EXploration) has been selected by CAST because its exceptional technology makes groundbreaking science possible with a very small instrument. SPEX measures the degree of polarization of sunlight that is scattered by particles in a planet’s atmosphere and that is reflected by the planet’s surface. From these measurements, unique properties of the particles and the surface can be derived. On Mars, SPEX will focus on the crystals that form the ice clouds and the dust particles that race over the surface in storms. The degree of polarization of the sunlight that is scattered by these particles provides detailed information about the microphysical properties (chemical composition, size and shape) of the particles.

This will give scientists more insight into how ice clouds and dust influence the Martian climate, and might reveal how dust storms on Mars develop and sometimes evolve into the infamous planet encircling events.

In March, a meeting was held in Beijing to further explore the details of the collaboration between CAST and SRON. This meeting, completely supervised by the Netherlands Office for Science and Technology of the Dutch Embassy in China, proved to be successful. CAST and SRON declared their intention to reach a long-term collaboration in the fields of planetary research and earth observation using spectropolarimetry.
SME goes into space

The development of long-term relationships, the use of each other’s specializations and increasing the involvement of SMEs. These are a few of the action points discussed during the network event organized by NWO, SRON and Samenwerkingsverband Noord-Nederland (SNW) in March for the high-tech SMEs in the north of the Netherlands. The theme of the meeting was the European space instrument SAFARI, which is being developed under the leadership of SRON.

During several sessions in the laboratories of SRON Groningen, SRON presented the groundbreaking technology that is being developed for SAFARI. The demonstrations about SAFARI’s cryogenic test facilities, the mechanical design of its detector casing, and its electronics, software and cryomechanisms gave a glimpse behind the scenes at SRON and facilitated lively discussions about possible leads for SMEs.

The infrared connection: from HIFI to SAFARI

Measurements made during the first half of 2010 by SRON’s molecule hunter HIFI – one of the three instruments onboard ESA’s space telescope Herschel – have led to more than 50 scientific publications. To celebrate that, SRON presented a special edition of the European Journal Astronomy & Astrophysics to SRON's specialisms and increasing the involvement of SMEs. These are a few of the action points discussed during the network event organized by NWO, SRON and Samenwerkingsverband Noord-Nederland (SNW) in March for the high-tech SMEs in the north of the Netherlands. The theme of the meeting was the European space instrument SAFARI, which is being developed under the leadership of SRON.

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This issue of SRON Spectrum is dedicated to SPICA/SAFARI, the Japanese-European mission planned for launch in 2018. To the reader that might sound a long way off but insiders know that in space research we work with long timeframes. And there are major interests at stake for Dutch space research, the prospects are particularly inspiring, and preparations within SRON – as principal investigator for SAFARI – are in full swing. Why has such an enormously complex project already been started on if the predecessor HIFI has scarcely been in space for 18 months? The answer is very simple. SPICA/SAFARI is the worthy successor of ISO, Spitzer and Herschel. Of course I’m really proud that so soon after HIFI, SRON may once again lead the development of a groundbreaking space instrument. For me it is a confirmation that SRON, with its powerful combination of scientific research and instrument development, is still in the Champions League of space research. I am proud of our technicians and instrument developers who know exactly what we can achieve with space technology. And I enjoy the enthusiasm of our astronomers whose efforts provide us with first-hand knowledge of the scientific harvest from the space instruments. Driven by curiosity, we can together explore our living environment – the universe – and try to find an answer to the ultimate question: What is the origin of the universe, our solar system and life on Earth?

It is difficult to say what our holy grail is in this very broad research area. Perhaps we will be confronted with complete surprises that force us to rethink our picture of the cosmos. Hopefully our observations will shed new light, for example, on the relationship between the process of planet formation – the cleaning up of the protoplanetary disks and the cooling of dust grains – and the presence of gas and dust in the disc. Ultimately, we want to know what stage a disc is at in the formation of planets. And we will almost certainly discover where water is located in the dust clouds stars are born from.

Now with Herschel/HIFI we can only see part of the water in the incubators of stars and planets, namely water vapor. The hypothesis is that the rest of the water is stored in a frozen form, as water ice. That is interesting because only a part of a young solar system is cold enough to allow water to freeze. This means we can indirectly establish where in the gas cloud the water must be located. Yet we can only confirm this hypothesis with SPICA/SAFARI, simply because we cannot observe the water ice with Herschel/HIFI. Is the water indeed located where we expect it? What does this say about the chemistry in planetary systems? Does the water ice tell us something about the origins of our own solar system?

Herschel, shows a large incubator in which new stars are continuously being born. This image of our Milky Way, made by PACS & SPIRE。(ESA)

Due to its large cooled mirror SPICA is extremely sensitive, suitable for a wavelength range of 30-210 microns. That makes it possible to determine the physical and chemical composition of objects in space. Soon, the annoyance of overlapping infrared sources, something which still bothers astronomers using Herschel despite its fantastic performance, will soon be a thing of the past. In effect, this makes SPICA/SAFARI the cosmicological dream machine.

SAFARI, the European nerves center of the SPICA space telescope, is an infrared spectrometer which can also make images of the cosmos. That has enormous advantages. Measuring the red shift allows us to resolve the overlap between sources so that these can be observed distinctly from each other. Spectral information can therefore be used to increase the sharpness of our images of the cosmos. This will provide us with a better understanding of the evolution of stars in the universe. Together with the James Webb Space Telescope and the ALMA telescope in Chile, we will soon be able to do fantastic things, as the missions complement each other in the infrared range. ALMA (from the end of 2012) will focus on the complex chemistry between the stars, including organic molecules. The James Webb Space Telescope (from 2016) will focus on the conditions of extreme red-shifted stars: the light from the first stars in our universe. The photo shows the first six flight-ready components of the main mirror en route to the last cryogenic tests. (C. Gunn)

The James Webb Space Telescope (operational in 2016) will focus on the conditions of extreme red-shifted stars: the light from the first stars in our universe. The photo shows the first six flight-ready components of the main mirror en route to the last cryogenic tests. (C. Gunn)

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The SPICA satellite planned for launch in 2018 is extremely sensitive due to its large cooled mirror. It will therefore be able to determine the physical and chemical composition of objects in space in considerable detail. And that we efficiently use SPICA/SAFARI the cosmicological dream machine.

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Rens Waters
Science Director SRON

This image of our Milky Way, made by Herschel, shows a large incubator in which new stars are continuously being born. (ESA, PACS & SPIRE)
The molecular universe

Over the past 20 years, it has become increasingly clear that we live in a molecular universe. A universe with a rich chemistry in which organic compounds are widespread and in which molecules play an important evolutionary role. SAFARI offers new possibilities to study these molecules and their influence on the evolution of the universe.

The existence and evolution of life in the universe is connected to the presence of molecules. Over about 100 years, we have known about the presence of molecules in space because we could see electronic transitions of diatomic radials in absorption spectra of light from distant stars. Since the 1960s, rotational transitions of molecules in the microwave range have led to the identification of about 150 different molecules. These are largely simple molecules, such as water, ammonia, formaldehyde and carbon monoxide, which are mostly found in so-called molecular clouds in space. Carbon atoms (shown here in green) are arranged in hexagonal structures; hydrogen atoms (yellow) decorate the edges of these disk-like molecules.

Fingerprints

With the opening up of the infrared wavelength range – by means of satellites – we have also discovered the vibrational transitions of molecules, and that has led to major surprises. The mid-infrared emission of virtually all objects is dominated by strong bands of polystylic aromatic hydrocarbons (PAHs). These large, highly stable molecules are very important for astronomers. For example, they influence the energy budget and ionization balance of the gas in space. They also influence the thermal characteristics of the gas and the linking of gas and magnetic fields, thereby playing an important role in the star formation process and, consequently, in the evolution of stars and galaxies. In addition to this, they are an important source of organic molecules, especially in areas of star and planet formation. Under the influence of energetic photons and cosmic particles, PAHs exhibit a rich chemistry that results in a diverse organic ‘soup’ from which – with the correct substrate – life could have evolved anywhere.

Finally, PAHs absorb ultraviolet photons from young and massive stars and convert these very efficiently into infrared photons. PAHs are therefore good ‘coloring agents’ that we can use to study the interaction of massive stars with their surroundings in detail. PAHs provide a sensitive measure for the presence of UV photons and therefore ‘count’ short-lived massive stars.

Highly resilient to its harsh conditions, PAHs account for some 10% of carbon in the universe. These large molecules are very important for astronomers. For example, they influence the energy budget and ionization balance of the gas in space. They also influence the thermal characteristics of the gas and the linking of gas and magnetic fields, thereby playing an important role in the star formation process and, consequently, in the evolution of stars and galaxies. In addition to this, they are an important source of organic molecules, especially in areas of star and planet formation. Under the influence of energetic photons and cosmic particles, PAHs exhibit a rich chemistry that results in diverse organic ‘soup’ from which life could possibly evolve.

Measure for UV photons

The SAFARI instrument on the SPICA satellite offers new opportunities to study these molecules and their influence on the evolution of the universe. SAFARI will soon be able to make detailed measurements of the far infrared spectrum of many sources in our galaxy. During previous studies of PAHs in space, the emphasis has always been on the mid-infrared spectrum. The bands in this part of the spectrum are good for indicating that PAHs are very widely spread as a class of chemicals. Unfortunately, these bands are not very molecule specific and identifying the specific molecules present in space has not proved possible. However, the bands in the far infrared are molecule specific and these characteristics form ideal ‘fingerprints’.

SAFARI can measure PAHs over red shifts up to five, therefore in the galaxies situated furthest from us in the expanding universe. PAHs are also ideal for measuring the star-forming activity in an area. PAHs provide a sensitive measure for the presence of UV photons and therefore ‘count’ short-lived massive stars. SAFARI can measure the PAHs over red shifts up to five, therefore to the galaxies situated furthest from us in the expanding universe. With this the instrument throws new light on the star-forming activity in an important period in the evolution of the universe, during which the majority of stars were formed and galaxies came together.

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PAHs provide a sensitive measure for the presence of UV photons and therefore ‘count’ short-lived massive stars.
Protoplanetary discs: incubators for planetary systems

We are currently in a fantastic period for this research because with telescopes such as Spitzer and Herschel we have two infrared missions that are providing an incredible amount of new data about such systems. The SAFARI instrument on the planned Japanese space telescope SPICA will be 100 times more sensitive still, as the mirror of SPICA will be actively cooled, and SAFARI contains a new generation of extremely sensitive detectors. SAFARI also has a higher spectral resolution than the previous missions and can therefore more accurately map the presence and quantities of simple molecules, such as water and OH, in protoplanetary discs. These molecules can scarcely be studied from the ground because the Earth's atmosphere contains large quantities of such molecules.

Our current knowledge about protoplanetary discs has mostly derived from observations of the thermal radiation from small dust grains that are heated up by starlight. Detailed observations at the millimeter wavelength made in the 1990s have already shown that such discs contain 1-10% of the stellar mass and have a size of about 100–1000 AU (an astronomical unit is the distance from the earth to the sun). More recent observations in the mid-infrared with both ISO and Spitzer have revealed that the dust grains in these discs had already grown considerably compared to the dust grains from which the star and disc originally evolved. The typical size of these dust grains varies from a few micrometers to several centimeters. We think that the growth process observed here is the first step towards the birth of planets. However, before we reach that stage, the grains need to grow by a further eight orders of magnitude (28 orders of magnitude in terms of mass).

Protoplanetary discs

Based on a large number of the aforementioned infrared measurements, the following image arose of a protoplanetary disc: the inside of the disc is determined by dynamic effects at the point where the disc and the star have exactly the same orbiting time, or by the smallest distance the dust grains can come to the star before they evaporate. The luminosity of the star heats up the disc and - under the influence of gravitation from the star - gives rise to different structures. For some discs the thickness increases with a greater distance from the star and the surface absorbs a large proportion of the total energy emitted by the star. Other discs are completely flat and therefore far colder.

We now have a good general idea of how planets are formed from protoplanetary discs, but the details are still missing from our observations. We still do not know exactly how the dust coagulates and how planets 100 km in size can form from small dust particles. Infrared observations suggest that the small dust grains only coagulate after several millions of years, although it could be the case that the growth process occurs more quickly close to the star. With its higher spectral resolution, SAFARI will enable us to gain more insight into this area, as SAFARI can detect less prevalent molecules, we will also be able to study the chemistry in the incubators of Earth-like planets for the first time.

We think that the growth process of dust grains in protoplanetary discs is the first step in the process of planet formation.

Memory

In our solar system, the oldest objects such as comets and meteorites contain a ‘memory’ of the evolutionary process of our solar system. However, in order to learn something about planet formation during this process we can also look at the composition and structure of protoplanetary discs.
Since the end of the 1990s, astronomers have successfully observed the CO molecule in several prominent discs. They did that using radio telescopes such as the IRAM telescope in France (30m) and later the James Clerk Maxwell Telescope on Hawaii (JCMT, 15m). These observations of molecular gas were crucial for confirming that the material (gas and dust) is indeed located in a thin rotating disk around the young star. As we observe, we see the CO emission red-shifted in the part of the disc that moves away from us and blue-shifted in the opposite half that moves towards us. As we have only just achieved a greater sensitivity with the ALMA (Atacama Large Millimeter Array in Chile) only a dozen protoplanetary discs have been studied in this manner to date.

It is also a confirmation of our idea that the radiation from the star heats up the gas in the disc and that this process is mainly influenced by ultraviolet radiation and X-rays.

Coagulation

Therefore over the past 20 years we have only managed to gain a global impression of the structure and composition of the material in these discs. The basic process of how planets form has now been confirmed by our observations. However, our observations still lack the necessary details because it is almost impossible to obtain distinct images of protoplanetary discs. We want to know exactly how the dust coagulates and how planets 1000 km in diameter are formed from dust particles of just a few micrometers in diameter. Infrared observations indicate that the small dust grains coagulate within several million years, and it might well be the case that the growth process occurs far faster closer to the star than at greater distances from it. Does the quantity of gas also change in this time period? How does the chemical composition change over time?

The answers to these questions have important consequences, not only for planet formation but also for our understanding of how the dust coagulates and how planets many kilometers in size are formed from colliding small dust grains. We assume that ice and small dust grains originate from colliding with each other. The relative quantity of iron in certain minerals, the relative composition of the ice (water, CO, CO2) and also the intrinsic structure, for example crystalline versus amorphous. And because we assume that ice and small dust grains originate from colliding with each other, it will also teach us something about the composition of the blocks of rocks that will form the planets and their atmospheres.

Over the past year, the Herschel satellite has made important new contributions to resolving these problems. Within the key programmed GASPS (Gas Evolution in Protoplanetary Systems, PI: B. Dent) the PACS instrument is making measurements in the far infrared to study the gas in a sample of 240 discs, aged between 0.3 and 30 million years and located in the closest star-forming regions. The strength of the gas emission lines allows important conclusions with respect to the heating of the disc. The data reveal that discs around stars with a low mass (0.5-1 solar masses) are more strongly heated by an extra component of ultraviolet radiation or X-rays, whereas discs around stars with a large mass (25 solar masses) are only heated by the photosphere of the star. The gas temperature determines the vertical scale of the disc, therefore the height to which the material is dispersed. However, it is also a confirmation of our idea that the radiation from the star heats up the gas in the disc, and that this process is mainly influenced by ultraviolet radiation and X-rays.

Evolutionary stages

Detailed computer simulations of sources with an age of 1-3 million years have revealed that in these stages of disc formation the gas to dust ratio is far lower than in the birth stages of the discs. However, as the discs get older the gas emission becomes weaker which means that the older sources can scarcely be detected. The resolution of the PACS instrument is often not enough to observe the emission of molecules, except for the stronger sources around stars with a large mass or in the earliest stages of their evolution. This has also been confirmed by results from other key programs such as DIGIT (Dust, Ice and Gas in Tomography, PI: N. Evans) and WISH (Water in Star Forming Regions with Herschel, PI: E. van Dishoeck).

The higher spectral resolution of SAFARI will enable the first studies of the chemistry in regions where Earth-like planets form.

Furthermore, we will be able to see details in the profile of dust and ice bands (which could provide important conclusions about the relative quantity of iron in certain minerals), the relative composition of the ice (water, CO, CO2) and also the intrinsic structure, for example crystalline versus amorphous. And because we assume that ice and small dust grains originate from colliding planets many kilometers in size, it will also teach us something about the composition of the blocks of rocks that will form the planets and their atmospheres.

Inga Kamp
Kapteyn Institute, University of Groningen

It is expected that the SAFARI instrument will lead to a major breakthrough thanks to its extreme sensitivity, which is 100 times greater than that of the current generation of space instruments. With SAFARI we will not only be able to expand research into older stars, and therefore the last stages of planet formation, but we will also be able to map far more star-forming regions, which will enable us to see if there are differences in the efficiency of planet formation. The higher spectral resolution of the instrument will also make it possible to detect less widely spread molecules. This will lead to the first studies of the chemistry in regions where Earth-like planets form.
Puzzling connection
However, further research into the evolution of galaxies is needed, says Van derWerf. We especially need to quantitatively separate the frequently coinciding effects of the formation of young stars and the development of a black hole. To do this, we need to determine exactly how much energy comes from a black hole and how much energy from star formation. Van der Werf: 'I think that with Herschel, we will be able to force a breakthrough in this area, which we could then develop further with SPICA/SAFARI. As it is such a sensitive instrument, we can use SAFARI to observe how this process took place in the early universe.'

'First of all, the research is relevant because the calculations must be correct,' says Van der Werf. ‘If you want to know where the star populations we see originate from, then from the infrared light you must be able to determine how many stars have formed, and then you must not mistake the formation of a black hole for the formation of stars. That would lead to a miscalculation. But what intrigues me far more, is the exact connection between the development of black holes and the formation of stars in a galaxy. That really is a puzzle. For example, we know that in the core of each galaxy there is a black hole that has about 1000th of the mass of the entire galaxy. This ratio is incredibly constant. So somehow or other that enormous galaxy knows about the small black hole in its core. And this means that there must be a connection between the two.'

'Somehow that enormous galaxy knows about the small black hole in its core.'

‘Without SPICA/SAFARI, we would soon be half blind for the heating and cooling process that could shed new light on the connection between the evolution of black holes and the evolution of young stars.’

With the Herschel-ATLAS project, Van der Werf has already realized an important breakthrough: together with several colleagues he discovered the so-called gravitational lenses that make it possible to study extremely distant galaxies in detail. Van der Werf: ‘With Herschel we could study several unexpectedly bright infrared sources in detail. At the position of these sources we found visible galaxies located at a relatively small distance from earth. However, the infrared radiation that we observed with Herschel originated from far greater distances from earth. The visible galaxies were found to be acting as ‘gravitational lenses’. They are located between the earth and the far infrared galaxies and their gravity diffused and amplified the light from these far galaxies. Thanks to this effect, the distant galaxies in the infrared are far brighter than they would be without this gravitational lens effect.’

The James Clerk Maxwell Telescope (JCMT) with its 15 m diameter is the largest single submillimetre telescope in the world. The JCMT is located at an altitude of more than 4 km on top of Mauna Kea, the highest volcanic mountain of Hawaii. (N. Szymanek)

The American-Dutch-British infrared astronomical satellite (IRAS) was a highly successful satellite for the observation of infrared radiation. (Fokker Space/Dutch Space)
Cosmic clocks
To be honest, Van der Werf does not find the chemistry of the early universe particularly interesting, as in such galaxies you can only see the strongest spectral lines, carbon monoxide and water for example. Yet slowly but surely an unmistakable enthusiasm emerges in his argument. ‘Now that I think about it, isotopes are actually very interesting. Isotopes can give information about how a chemical element has been built up over the course of time and they therefore serve as cosmic clocks of the universe.’

‘With SPICA-SAFARI new breakthroughs are looming in all of these areas’ concludes Van der Werf. ‘SPICA-SAFARI is the next step after Herschel, just as the James Webb Telescope is the next step after Hubble. And SPICA-SAFARI fits exactly in the wavelength region between ALMA and the James Webb Telescope. James Webb mainly observes the stars, ALMA the cool gas, the material from which the stars have formed, and SPICA-SAFARI will soon look at the warm gas that actively participates in star formation and that closely surrounds it so to speak. Therefore without SPICA/SAFARI, we would soon be half blind for the heating and cooling processes that could shed new light on the connection between the evolution of black holes and the evolution of young stars.’

Paul van der Werf

Stravers

Most of our knowledge of the cosmos has been obtained through observations of all types of light. The light that we see with our own eyes is a very important source of information for these observations. However, over the past 100 years we have increasingly used light of other wavelengths to determine what happens in space. As we can only study our own surroundings, we are learning more about the life stage of clouds and the influence their surroundings exert on the clouds. SAFARI will add new chapters to this fascinating story when it is launched in 2018.

Panta rhei
Panta rhei (‘Everything flows’ or ‘Everything is in motion’), the famous aphorism of the Greek philosopher Heraclitus, is particularly applicable to the water vapor around young stars (there is no liquid water between the stars). During the formation of stars, strong jet streams of molecular gas develop that the young star blasts into space from its polar areas. These jet flows light up clearly in spectral lines of water. As HIFI is so good at unraveling infrared light into its frequency components, we can even study how the velocities in the gas are correlated with the temperature and density in that same gas. After all, frequency and velocity are related via the Doppler effect. Gas that moves away from us is red-shifted and gas that moves towards us is blue-shifted.

HIFI has already succeeded in giving us an improved picture of the interaction between young stars and their molecular jet streams.

Van der Werf studies this puzzling connection in galaxies that were formed during the first 2 to 4 billion years of the universe. But you can also do that in nearby galaxies that are very similar to their distant cousins, he says. ‘They are less spectacular, radiate less brightly in the infrared and are smaller but they have the advantage that you can use them as a local laboratory. A good example is the galaxy Arp 220, which emits very powerfully in the infrared and which was discovered about 25 years ago with the IRAS satellite. However, we still do not know whether the majority of this radiation comes from star formation or from the local black hole. And if we cannot establish that much with our cosmic neighbors then you can imagine that we certainly cannot answer that question for the early universe.’

‘Isotopes can give information about how a chemical element has been built up over the course of time and they therefore serve as cosmic clocks of the universe. With Herschel, ALMA and soon SPICA/SAFARI as well, Van der Werf hopes to use spectral lines from distant galaxies in the far universe, especially about the physical conditions in the dust and gas clouds in the early universe. ‘As SAFARI is far more sensitive than its predecessors, these spectral lines might be able to tell us more, for example, about the source of energy in a galaxy. We know that the gas in a galaxy cools down by emitting radiation. The gas should then become colder but, in reality, it does not. The gas is mainly reheated by either the formation of a black hole or the birth of a new star so that the galaxy remains in balance. The heating and cooling remain the same. By examining the cooling we can therefore learn something about the heating and it would be particularly interesting to find out if this happened in the early universe in the same way as it happens now.’

Molecules tell a new story about the gas between the stars

The flight model of HIFI is checked with black light in the classrooms of 2055. Any dust or dust particles on the instrument can be seen under this light and removed with a vacuum cleaner and a table hairbrush.
HIFI has already succeeded in giving us an improved picture of the interaction between young stars and their jet streams. With HIFI we have observed many star-forming areas during the past year and one of the biggest surprises was that the jet streams of light and heavy stars exhibit a striking number of similarities, which indicates that large and small stars really are born in the same manner.

At the same time, via their absorption lines, other molecules provide us with information about the ultraviolet radiation and X-rays that a young star also emits but which remain hidden behind the large quantity of dust in the enveloping clouds. One unexpected result from HIFI’s quest, for example, was the discovery of ionized water (OH+ and H2O+), which is a useful indicator for the invisible ultraviolet radiation in the dense dark clouds. The existence of ionized water is a direct indicator for ultraviolet radiation: ionized water does not occur naturally on Earth but it can be produced in the laboratory with a strong radiation source. The source of ultraviolet radiation in gas clouds within our Milky Way are young heavy stars, which destroy their surroundings with radiation thereby making them unsuitable for further star formation.

Invisible gas
Images made by the infrared cameras of the instruments PACS and SPIRE onboard Herschel reveal that the interstellar gas is a colorful collection of bubbles, condensations and shocks. We therefore have a global picture of a highly dynamic system in which gas can be compressed into condensations from which stars evolve and where supernova-blow bubbles. However a camera alone cannot reveal how all of these components in the system function: we can only find that out if we know the temperatures, densities and velocities of various components in the gas. After all, part of the gas remains ‘invisible’. Here HIFI provides us with new ‘informants’ in the shape of small molecules with hydrogen atoms – the hydrides of carbon, nitrogen, oxygen, fluorine and sulfur.

With these new observations, we discovered that there is a lot of variability in the atmospheres of the old stars and that these stars blow bubbles at a far greater velocity than had been expected.

Recycling of dust and gas
With HIFI, we are not only looking at the gas between the stars or gas involved in the formation of stars but also at the gas that is ejected by stars at the end of their lives. Stars similar to our sun eject large quantities of gas and dust at the end of their lives. This enriches the interstellar medium with heavier elements from the star and with new gas that can be recycled for the formation of new stars. Due to observations by telescopes on Earth as well as by the Hubble space telescope, for example, this process has given up part of its secrets already. However, HIFI can look far deeper into the gas bubbles. Right up to the star itself. With these new observations, we discovered that there is a lot of variability in the atmospheres of the old stars and that these stars blow bubbles at a far greater velocity than had been expected.

Frank Helmich/Floris van der Tak

The European Herschel satellite was launched in May 2009 in French Guyana. There are three instruments onboard: HIFI (built under the leadership of SRON), PACS and SPIRE. (ESA)

If no strong background source is available then we need to resort to other methods. The flexibility of HIFI is particularly useful in that respect. For example, HIFI is particularly suitable for observing ionized carbon, which is a highly accurate measuring instrument for very rarefied gas clouds and serves as an adequate thermometer for a star-forming region. Ionized carbon has a very strong emission line at the upper limit of the HIFI receivers. Therefore with HIFI, this spectral line can be seen in almost every direction in our Milky Way. Now by using HIFI to search for ionized carbon in a large number of directions in the Milky Way, astronomers have observed hundreds of interstellar clouds. Some of these are known clouds which have previously been observed with telescopes on the ground. But many others were new. The wealth of clouds containing ionized carbon as opposed to carbon monoxide, the ‘normal’ variant, explains why astronomers have previously found so many clouds without carbon monoxide.

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Chemistry between the stars

The chemical reactions in the space between and around stars are nothing less than exotic. The challenge for astrophysicists, instrument makers and observers is to render the underlying processes visible, unraveling the chemistry of the universe in a purely forensic activity. Spectral fingerprints measured in the laboratory make it possible to detect molecules in space, from the microwave up to the ultraviolet region of the electromagnetic spectrum. SPICA/SAFARI will open up new windows for detecting molecules in the far and near infrared.

So far, more than 150 different molecules have been discovered in interstellar and circumstellar space. These consist of simple diatomic molecules (hydrogen, carbon monoxide and sodium chloride), positively and negatively charged ions (HCO+ and C6H−), exotic radicals (HC11N) and more complex organic molecules such as dimethylether and ethylene glycol. We know that these substances exist in space because accurate astronomical observations agree with the molecular fingerprints measured in laboratories on earth. In special plasma expansions (see photo on this page) interstellar clouds are simulated on a small scale. Asetylene diluted in helium is discharged in the expansion and as a result of collisions unstable molecules, such as those expected in space, are produced. Sensitive detection methods are then used to determine their spectra.

Just like a forensic detective, a laboratory astrophysicist has a range of measurement methods available to reveal these molecular fingerprints. One example is a so-called double modulation technique. The photo on the top of the page shows mirrors on the left and right on which the reflections of a laser beam are visible. The laser light traverses the plasma several times before falling on a detector. What the photo does not show is that the frequency of the laser light and voltage at which the plasma ignites are modulated. The subsequent detection of the absorption signal in a phase-sensitive manner, strongly suppresses the noise in the experiment thus making it possible to detect the spectra of molecules that are difficult to produce in large abundances. Once the spectrum has been measured in the laboratory then a molecule can be searched for anywhere in space. And not only that. The intensity of an astronomical spectrum reflects the density of the molecular carrier, and the local temperature determines the degree to which individual energy states in a molecule are occupied.

Chemical networks

The hunt for molecules in space is aimed at making chemical networks visible. Different molecules observed at the same location in space might be chemically related to each other. And that is where the problems start. The interstellar medium is empty and cold and hard ultraviolet radiation provides a continuous stream of high-energy photons. Particles collide at most once every few weeks, and "real" chemical reactions (in which three particles collide at the same time) do not take place. How can you then explain the multiplicity of molecules that have been observed in space?

Nowadays, it is assumed that reactions of ions and molecules dominate in the gas phase. Such reactions often do not need a third particle and the charge increases the action radius of an interaction. However, this still cannot explain the formation of larger organic molecules and in recent years it has become clear that surface reactions in ice on interstellar and circumstellar dust particles make an important contribution to the chemical enrichment of the interstellar medium. These dust particles fly around in space as a sort of open-beam and, in so doing, they freeze gas particles to their surfaces. A molecular reservoir is created. The ice also has a catalytic effect due to its stabilizing effect as a third particle. Reactions in the ice are the subsequent consequence of chemical triggers such as ultraviolet light, the impact of hydrogen atoms, free electrons or energetic ions.

Interstellar ice

In the laboratory, we can see that interstellar ice is indeed a superb medium for the formation of larger and more complex molecules. If carbon monoxide ice is bombarded with hydrogen atoms then formaldehyde and methanol are formed. If methanol ice is then irradiated with ultraviolet light, with an energy distribution as typical for the interstellar medium, then many of the more complex and organic molecules that have been identified in space are formed. As these reactions are investigated in the laboratory as a function of ice composition, temperature, hydrogen atom flux et cetera, it is possible to characterize the physical and chemical properties of solid-state reactions and, just as in a spectroscopic study, to determine unique parameters, such as diffusion rates or reaction barriers with the aim to quantify astronomical processes (see image below).

This information is needed as input for the astrochemical models that make it possible to simulate the chemical processes across astronomical timescales to be simulated. This is exactly where SPICA/SAFARI will play a role. The infrared is a spectral range in which interstellar ice is clearly visible. After the past decennia, the Infrared Space Observatory and the Spitzer space telescope have clearly observed ice between and around stars. SPICA has the unique property that it will be able to observe water ice in a wide range of different environments. This space telescope will provide snapshots of the role of water ice in, for example, protoplanetary discs and during planet formation. At present, however, it is not entirely clear how water is formed in space.

Highly promising

Recent experiments in which water is formed in surface reactions between free hydrogen atoms and O2, O3 and OH are highly promising. Furthermore, water appears to play an important role as a medium that increases the reactivity of other substances in the ice. That applies not only to simple ice components but also, for example, to polycyclic aromatic hydrocarbons (PAHs) that are frozen into the ice. In the infrared, PAHs have characteristic emission lines, and it is interesting to determine if they can absorb radiation as solid state components.

With SPICA/SAFARI a new instrument will become available that offers the possibility of collecting further pieces of a cosmic puzzle. The hope is that this puzzle will eventually provide a picture of how large, complex and prebiotic molecules are formed in space as precursors of the building blocks for life.

Harold Linnartz

Laboratory for Astrophysics, Leiden Observatory


The European Infrared Space Observatory, SPICA, was launched in 2015. One of the components onboard is a short wavelength spectrometer (SWS), which was developed by a consortium led by SRON. (ESA)

The Laboratory for Astrophysics, Leiden Observatory (LCO) was founded in 1995. One of the components onboard is a short wavelength spectrometer (SWS), which was developed by a consortium led by SRON. (ESA)
After HIFI another giant step …

As Principal Investigator, Peter Roelfsema is in charge of the development and construction of SAFARI. Although SPICA/SAFARI has not yet been defined as an official project by the space organization JAXA and ESA, the preparations for the instrument are fully underway. And that is where the challenge starts. After all, how can you build an instrument under the influence of gravity that must soon be able to effortlessly supersede its predecessors under the extreme conditions of space? What is the giant step that we still need?

Peter Roelfsema already has experience of developing and building a complex space instrument. He started with the development of software to support the analysis of data from the IRAS satellite. Later he became involved in the conceptual and design phase of the Herschel Ground Segment, and soon after the delivery of the HIFI instrument to ESA, he was appointed as SRON’s project manager of HIFI. That proved to be anything but a simple job. The construction of HIFI was a major technological challenge which the absolute latest techniques were applied to guarantee a maximum sensitivity and flexibility. And in the autumn of 2009, a cosmic particle hit the instrument causing a malfunction in the electronics, which put HIFI out of operation for several months. Under his leadership, the HIFI team, together experts from ESA, managed to trace the cause of the malfunction and to resolve this. Since then HIFI has produced a continuous stream of excellent scientific data. Devoting considerable attention to the so-called data reduction pipeline - which on Earth uses the data packages from the Herschel satellite to reconstruct the spectra observed – early in the project has paid off. The data from HIFI can be used directly by science.

Blinded by the mirror

How on Earth do you start with the construction of an instrument that must outstrip its predecessor in every single aspect? ‘You start with a number of questions,’ says Roelfsema. ‘What do I want to be able to observe? What would I like to do with the results? What is the next step? Which leap forwards can we manage? What technological breakthrough do we need for this? In this case, you start with the limitations of Herschel, despite the fantastic specifics of the space telescope. We cannot make the next step in sensitivity using the Herschel technology because at 100 degrees above absolute zero the telescope is, in fact, too warm. The new generation of more sensitive detectors would be blinded by the heat radiation from the mirror itself. That will mean that the instruments can detect even weaker infrared sources than Herschel can. This means that we’ll soon be able to observe background signals at the level of the cosmic background radiation, in a wavelength range of 30-210 micrometers.’

Roelfsema and his international team therefore need extremely sensitive detectors that are sensitive enough to obtain the maximum benefit from the cold mirror of SPICA. One major difference compared to HIFI, also developed under the leadership of SRON, is that SRON is doing far more of the R&D for the SAFARI detectors. After an intensive selection round, the SAFARI consortium chose the Transition Edge Sensors (TES) of SRON. ‘That ups the stakes, as more is expected from SRON now.’

Space simulator

The new detector technology also places the highest requirements on the calibration of the instruments and therefore the test facilities on the ground must be extremely light proof. ‘That is a considerable challenge,’ says Roelfsema. ‘But fortunately we have an advanced cryostat that can provide different temperature levels to test the various components of SAFARI, down to half a degree above absolute zero. The cryostat also has space for lamps that simulate the light of moving and distant stars, planets and gas clouds. In terms of strength, such a light source is comparable to a light bulb on the moon. We must therefore make extremely weak lamps and transmitters which are also movable mirrors to SAFARI. And that is anything but easy at a temperature just above absolute zero.’

The SAFARI instrument onboard the SPICA satellite will search for frozen water in the universe using 850 detectors at a temperature of 10 mK. The detectors are so sensitive that thermal radiation from an object at just 20 K will blind them.

‘There is now a strong internal drive and that is priceless.’

No technological barrier

Roelfsema is now very busy forming teams of specialists from the best research institutes in the world. Researchers from France will build the cooling equipment, researchers from Italy the central computer, researchers from Spain the casing for the measuring instrument, etc. However, not all of the positions have been filled yet. ‘And that is where the challenge starts. After all, how can you build a mechanism for the cooling equipment that works without gravity? We have been struggling with this question for a long time, but the solution is probably a magnetic levitation rail system that remains exactly in balance in space. Another challenge is to simulate the conditions in space quite well here on Earth thanks to the new space simulator we are currently developing. This is an advanced levitation rail system that remains exactly in balance in space. We have been struggling with this for a long time, but I hope that we are on the right track with it.’

Last of all, Roelfsema underlines the importance of a strong motivation. ‘There is now a strong internal drive and that is priceless. Ultimately, such a strong motivation is what makes the difference between an excellent instrument and one that is just good enough. Of course we’re going for gold. However, that means continuing to emphasize the goals we need to achieve and acknowledging all the efforts which make that possible. Even the inspired individuals who jointly work on SAFARI need that.’
Colofon

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SRON Netherlands Institute for Space Research is the Dutch expertise center for space research. The institute develops and uses innovative technology for groundbreaking scientific research in space, focusing on astrophysical research, Earth science and planetary research. In addition to this, SRON has a line of research into new sensitive sensors for X-rays and infrared radiation which now rank among the most sensitive in the world. SRON is part of the Netherlands Organisation for Scientific Research (NWO).

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Picture cover: The Japanese space telescope SPICA - which is due to carry SAFARI into space in 2018 - will have an ultra-cooled mirror. This means that astronomers’ observations will soon no longer be affected by the heat radiation emitted by the space telescope itself. SAFARI will therefore be able to detect extremely weak infrared sources that could not previously be seen as well as taking ‘pictures’ of the cosmos in three adjacent wavelength ranges.