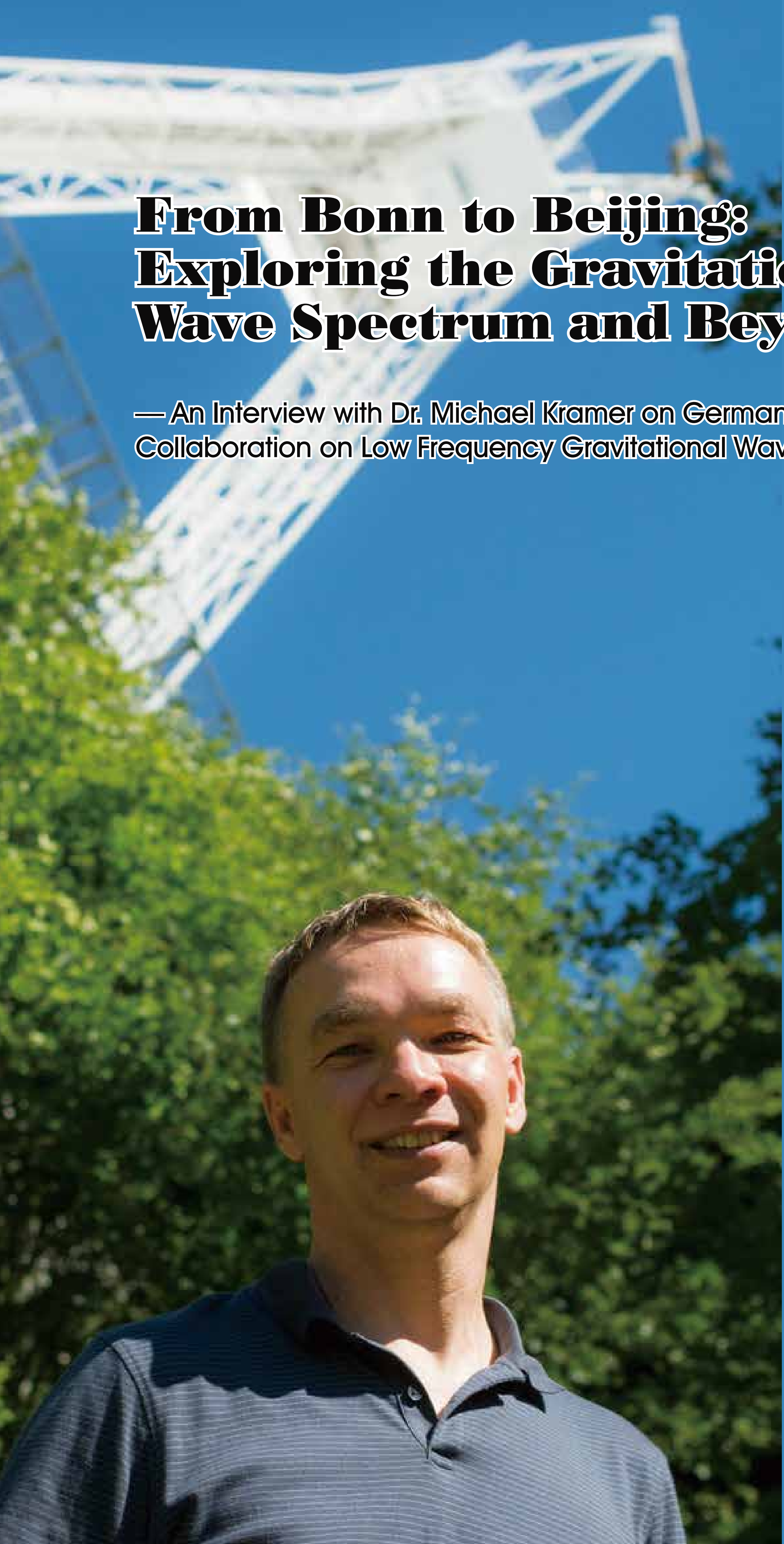
From Bonn to Beijing: Exploring the Gravitational Wave Spectrum and Beyond

— An Interview with Dr. Michael Kramer on German-Chinese Collaboration on Low Frequency Gravitational Wave Research



Dr. Michael Kramer in front of the focus cabin of the large fully-steerable 100m Effelsberg radio telescope. (Credit: MPIfR)

The successful detection of gravitational waves, or "ripples on the cosmic sea", not only confirmed Albert Einstein's theory of general relativity, but also opened a new window on the part of the universe we had never seen before. Since then, we have a novel, powerful tool to explore some of the most mysterious objects in the sky, such as black holes from far, far away. However, what has been detected by facilities like the Laser Interferometer Gravitational-Wave Observatory (LIGO) is only the tip of an iceberg: there is much more to discover about these waves, which carry key information about their sources. For instance, with waves generated by the merger of supermassive black holes at a lower frequency than what LIGO can catch, we may be able to answer: how massive are supermassive black holes? How do they behave? What does their existence tell us about the formation of galaxies?

A couple of years ago, scientists from Germany and China started to think about working together on the subject. By taking advantages of each other's strengths, they aim to push back the frontier of the detection and understanding of gravitational waves beyond LIGO's frequencies. In November 2016, a high-level round table meeting was held between the Chinese Academy of Sciences (CAS) and the Max Planck Society (MPG) in Beijing, where the two institutions inked an agreement to foster partnership in the field. In March 2017, a Chinese delegation of gravitational wave experts visited Bonn and exchanged with their German colleagues on all possible collaboration areas. Their proposal was soon approved by MPG, winning about 30 million euro worth of grant to pair up with the 200 million yuan Chinese investment to support joint research by the two sides. Specifically, the Germans planned to use their 100m Effelsberg radio telescope and decades-long research experience and data reservoir to team up with the Chinese, who had just completed the world's biggest single dish radio telescope (500m aperture), to go for a historic breakthrough in using radio telescopes and pulsars to detect gravitational waves from the merger of supermassive black holes. Meanwhile, the Germans would also help China to build a space-based interferometer similar to the Laser Interferometer Space Antenna (LISA) developed by ESA and NASA.

On November 22, 2017, the kickoff workshop on the MPG-CAS joint project "Low Frequency Gravitational Wave Astronomy and Gravitational Physics in Space" was convened at the National Astronomical Observatories of CAS in Beijing. Led by Dr. Michael Kramer from the Max Planck Institute for Radio Astronomy and Dr. WU Xiangping from CAS, scientists reviewed the status quo of their collaboration and shared visions for the future. *BCAS* reporter XIN Ling had the privilege to talk to Dr. Kramer during the meeting and hear his insights on a range of issues, from the rationale of using pulsars to detect gravitational waves to China's challenges in catching up with the world.

Pulsar Timing and Gravitational Wave Detection

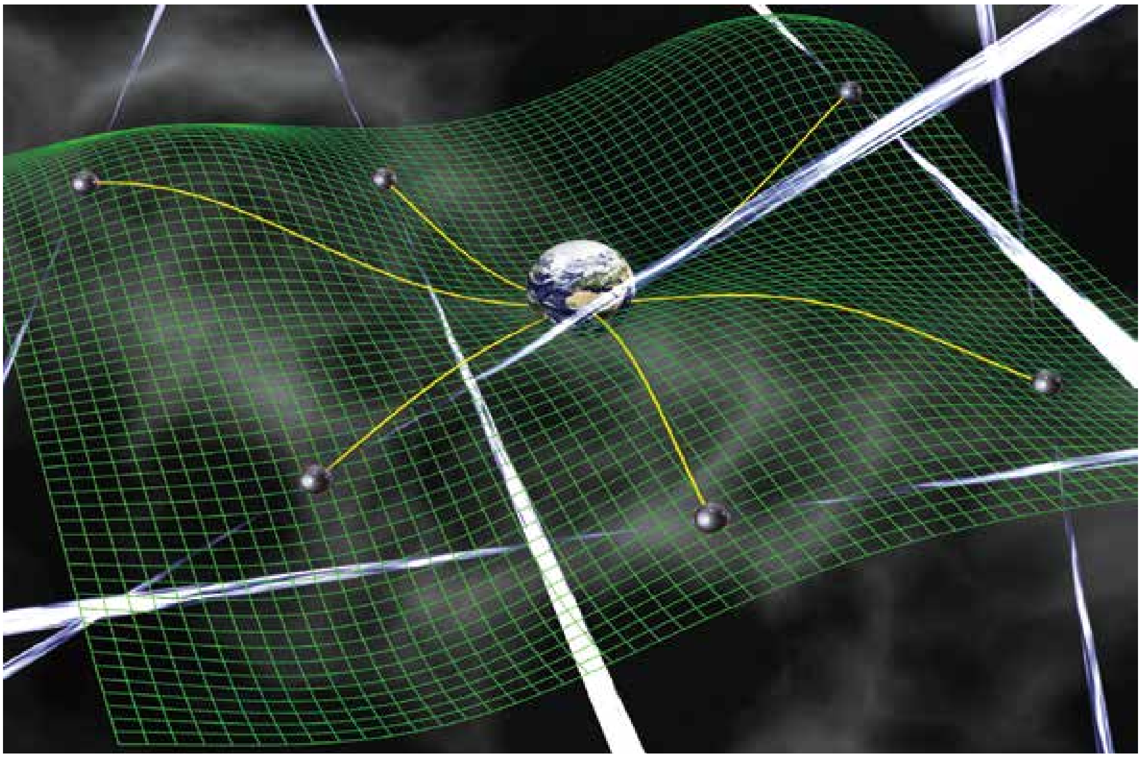
BCAS: Thank you Dr. Kramer. What brought you to Beijing this time?

Dr. Kramer: We're having an exciting, new project together with CAS colleagues to work on the detection of low frequency gravitational waves using a range of technologies. We've been working on this experiment for a number of years, but what we're missing is sensitivity. The new telescopes from our CAS colleagues and their expertise offer a very good opportunity to bring this experiment forward to make detection in that frequency range.

The collaboration will use radio technology as well as space technology with a long term look to explore that low-frequency part of the gravitation wave spectrum, which isn't open yet. It's a much lower frequency than what the ground-based detectors like LIGO can see. There are many more sources and many more physics to be studied at very low frequencies.

BCAS: Can you tell us a little bit about the scientific background of this collaboration? For instance, we talked about pulsars during the workshop. What are pulsars, and what's their role in gravitational wave detection?

Dr. Kramer: Pulsars are the remnant of stars that have died because they are running out of fuel. Currently, the Sun is burning hydrogen into helium. The fusion releases energy, and powers the Sun as we see it. There's the stability between that pressure coming from the radiation and temperature against gravity which tries to pull the Sun together. The balance is there right now, and will be so for many more billions of years, providing us with some energy on Earth. But eventually it will run out of hydrogen. In the case of the Sun, it will



An artistic impression of a "Pulsar Timing Array" (PTA). A PTA experiment aims to detect low-frequency gravitational waves emitted by merging super-massive black hole in the center of two merging galaxies in the early phases of the Universe. By precisely measuring the arrival time of pulsars with telescopes on Earth over a number of years, astronomers can detect the impact of gravitational waves disturbing the local spacetime. In this way, a PTA acts like a galaxy-sized gravitational wave detector. (Image: David Champion).

simply expose its core. But more massive stars will burn helium into carbon and so on, until iron is produced and fusion is no more possible. As gravity still wants to pull the star together, and there's no pressure from temperature and radiation anymore, the star collapses in a fraction of a second. When this happens, some protons and electrons in the hot star literally squeeze together to form particles called neutrons, and at the center of the star, there is an object being formed which is called a neutron star. When these neutron stars eventually rotate, they emit radio emission and act like cosmic lighthouses. Whenever you see this rotating neutron star as sort of a beacon in the sky, we call it "pulsar".

A pulsar may emit radio emission, but since the emission is beamed in a very narrow angle on the sky, it's very likely that the beam doesn't actually reach us on Earth at all. We only see probably a fifth or sixth of all active pulsars in the Galaxy. However, they are very useful because their rotation is quite stable, as comparable to the sort of the stability of an atomic clock! They therefore act like cosmic clocks and we can use them for a lot of experiments, from time keeping to the study of effects that may be changed where time plays a role. We can also use them to probe theories of gravity such as testing Einstein's Theory of General Relativity.

BCAS: And to detect gravitational waves.

Dr. Kramer: Yes. What we do here is to use the effect that the signal is supposed to arrive very regularly on Earth. If the Earth is slightly displaced by a gravitational wave that passes through the Solar System, the pulse's arrival time is changed in a systematic way. And if you can detect the systematic variation of the arrival time of the pulse, like how it deviates from the expected arrival time, then we can probably say that the displacement is caused by a gravitational wave.

Basically, it's just like what we use to measure the effect of gravitational waves with ground based detectors like LIGO. The gravitational wave changes the distance of LIGO's mirrors to the central point and into orthogonal

Aerial view of the Effelsberg Observatory near Bonn, Germany. Visible is the 100m Effelsberg telescope, the largest fully steerable telescope in Europe. Also visible are the low- and high-frequency antenna of the MPIfR's LOFAR station. Combined the observatory covers a frequency range from 10 MHz to 100 GHz. (Credit: MPIfR)

directions. It's the same with pulsars. The gravitation wave changes slightly the distance between the pulsar and the Earth, so the arrival time changes to this change of distance, and that's what we're trying to measure.

BCAS: That sounds like some REALLY precise measurement. How precise could it be?

Dr. Kramer: For instance, if a pulsar would be a light year away, we will need to measure about a change in distance of few meters. So it's a really tiny effect! And we won't actually see the Earth jumping around by a few meters. What we will see is that when we average enough information from many pulsars on the sky, we improve on the amplitude of this effect in quantity. That's why we are not only using one pulsar. We want to observe many pulsars in different directions.

BCAS: How many pulsars do you need?

Dr. Kramer: We probably need about 20 to 50. Now we're trying it with about 20 "good ones", and it's not enough. That's why it's important to find new sources that we can include in the experiment.

And we cannot use just any pulsar. Among the 3,000 or so pulsars discovered so far, about 10% are rotating much faster than the rest because they have a companion and the companion transfers matter (onto them). But even among these 300 what we call millisecond pulsars, not all of them are equally good. Just like a watch that you buy: some watches are more accurate than others. So we need to look at these "clocks" for a while to figure out which one is useful and which one is not. We typically observe a pulsar for a couple of years, then we decide, okay this one is good to be continued with in the experiment, or it may be replaced by something else. So it's a long term experiment. We need data sets of ten or 20 years to make a firm confirmation. That's where our Chinese colleagues can sort of benefit from us, because we've been doing this experiment for a very long time.

BCAS: What can China contribute?

Dr. Kramer: If we want to achieve the detection, we have two ways to improve our sensitivity. One is finding more pulsars, and the other is having bigger telescopes to get better precision on arrival time measurement. In both cases, FAST will be very good, because it's so sensitive that we can find lots and lots of new pulsars – it already does! At the same time, the size (of FAST) is so big that we can measure the arrival time very precisely. So, through this collaboration, we can combine high sensitivity data (from the German side) with a new, powerful telescope (the Chinese side). That's why it's a win-win situation for both sides.

BCAS: I see. When people talk about gravitational waves today, everybody thinks of LIGO. But before the first detection, there was actually a competition between LIGO and the pulsar community. For a time, the pulsar experiment seemed more promising. What happened?

Dr. Kramer: Well, it's a combination of several things. First let me briefly explain the similarity and differences between LIGO detection and the pulsar experiment. The principle of the two detections is the same: both measure the direct impact of gravitational waves on some mass in the local space-time. But with a Pulsar Timing Array – this is the name of the experiment I was describing earlier – the signal we're looking for is not a signal from stellar mass black holes like what LIGO observed. We're looking at black holes that are ten billion times heavier, which you can usually find at the center of galaxies. We believe that galaxies we observe today have gone through some merger processes, and whenever this merger happens, you have two massive black holes in the center of the two merging galaxies, forming a binary system for a certain period of time.

Based on our understanding of how galaxies form, merge, and evolve, theoreticians had estimated what the amplitude of the signal we should be expecting to find. It turns out that they were wrong. If the theoreticians have been correct, we should've seen gravitational waves already. We didn't, and LIGO won that race. Apparently there are certain things we don't quite yet understand about galaxy formation, and each of the little understood processes changed the amplitude expectation.

It seems that the first calculations were simplistic or the best guess at that time. Now we know much more, and the theoreticians have corrected the expected amplitude – to be just below where we are right now in our sensitivity. I guess the game continues. If you don't find something in the next couple of years, they will correct it again. But at some point there must be signals. And we can turn this around. By finally finding the signal, we will know what the signal is and we can feed that back into understanding galaxy formation. At the moment it's sort of a feedback from non-detection to the astrophysical theory. But once we find something, we'll have a feedback from detection to the theory to help us understand galaxy mergers much better.

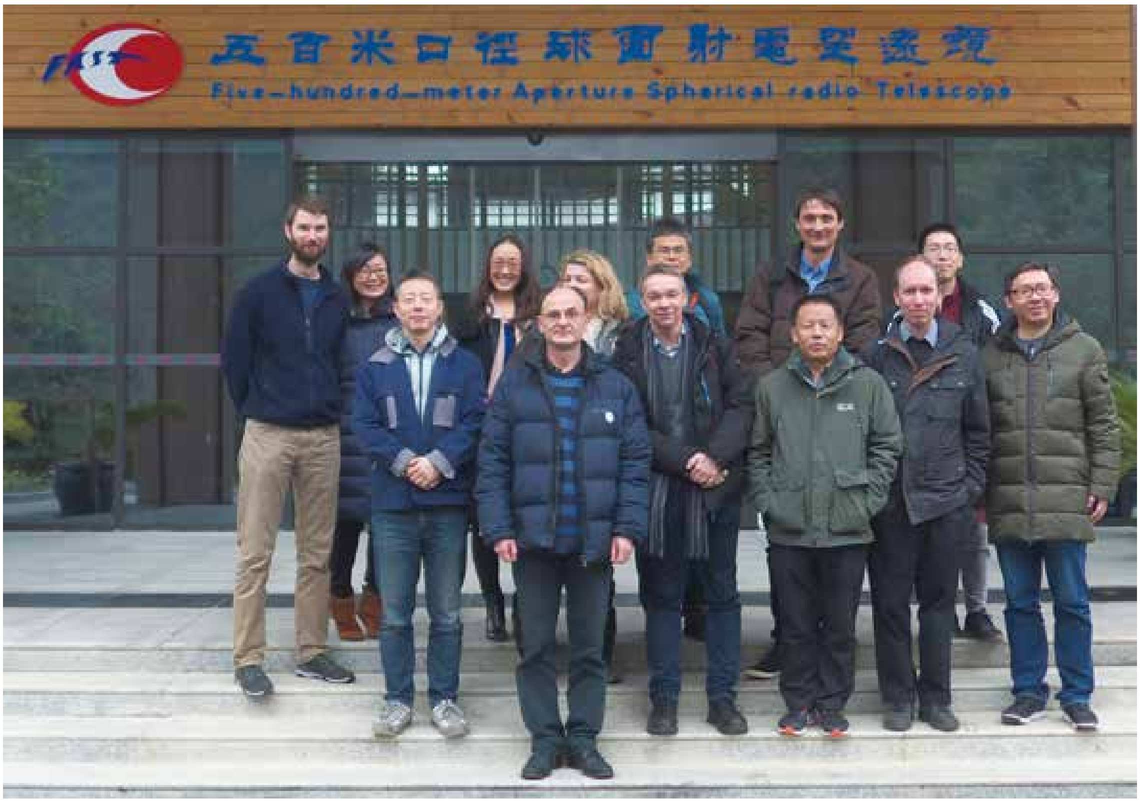
BCAS: So technically, we are still not fully ready for detection with pulsars?

Dr. Kramer: There are still two problems. First, we underestimated the sensitivity we need. With telescopes like FAST and SKA we can fix this problem. Then we also realized that when the signals from the pulsars propagate to the Earth, the arrival time is not only modified by the gravitation waves, but also by the medium between us and the pulsars. Interstellar weather – there are clouds of plasma that move and pass our direct line to the pulsars, and when that happens there's a small effect on the signal. In the past, we underestimated that effect. But again, we have a way of fixing this because the interstellar clouds interact in a different way (with the signal) depending on the observing frequencies. Once we have two or three measurements at different frequencies, we can determine what the medium is between us and the pulsar, and we can correct for this. We haven't done that in the past since we underestimated the effects. Nowadays we take measurements of different frequencies, and once we have accumulated enough data in that mode we should be able to detect something.

Space-based Detection and the Importance of Collaboration

BCAS: What about space-based detection? It's also part of the collaboration.

Dr. Kramer: Space technology is an important part of our collaboration. The pulsar experiment for the detection of gravitational waves is around nanohertz – 10^{-9} hertz, quite small frequencies. LIGO is at much higher frequencies around kilohertz. So there's a gap in between. If you want to study the sources in that gap, they will be black holes that are heavy but not quite as heavy as you will find with pulsars, and you need something that is space-based. So basically you take LIGO and fly it into space! The way they want to do is a project called LISA, the Laser Interferometer Space Antenna. The idea is that you have free floating satellites which shoot laser to each other, and by



Visit of the MPG delegation to the Five-hundred-meter Aperture Spherical radio Telescope (FAST) on November 24, 2017. (Credit: Gehard Heinzel)

measuring how long the light takes to reach one of the satellites, you can see the impact of a gravitation wave that deforms the consolation of the three satellites floating in space. It sounds like a crazy idea, but they have flown a mission called LISA Pathfinder where they essentially demonstrated that they could do it on a very small scale. The precision they have achieved is so good that there’s little doubt they can do this on a bigger scale. The European Space Agency is trying to launch LISA around 2034, and meanwhile it would be nice to have some contributions from China to speed up that time scale.

The technology is also quite useful to study the Earth and to have some information about where the water is, how these seasonal changes of the Earth go on, etc., by having basically a similar satellite system. Rather than flying far away from the Earth to measure the gravitational waves, they will fly very close to Earth to measure the gravitational potential, the gravity of the earth and so on.

BCAS: Is it what they call the “Chinese GRACE mission”?

Dr. Kramer: The so-called GRACE satellite is a joint mission between Germany and NASA. It was so successful that apparently China wants to have a similar system, and they said today that they are trying to launch it around 2020. On the other hand, the Germans might consider launching another system as a repetition of the previous experiment. So we actually may have two pairs of satellites flying around the Earth, and by combining information we should to be able to learn more. At the same time, on that second mission from Germany and the US (GRACE Follow-on), they’ll try to test some of the technology that will be useful for LISA as well.

BCAS: How do you see the competition within the domestic community?

Dr. Kramer: It’s not surprising, to be honest, because it’s a big country, and CAS is a big organization. You clearly have people with similar interests, and they compete for the same resources or the same science. However, it is almost always beneficial if all people work actually together. In the West, the community has learned to work with each other. For instance, even though LIGO and VIRGO were competing, they joined together to form the LIGO Consortium. Since they were the only one or two big experiments being undertaken, they had no choice in joining each other. I’m sure this wasn’t easy; it probably took much iteration to come to collaboration. Competition is good in some respect, but if competition draws too many resources, then you may be better off putting your resources together to achieve the goal faster. The European Pulsar Timing Array is a collaboration which has been there since 1994 or 1995, and we had 20 years to learn to trust and work with each other. It’s a big team effort and there is no competition between us, even though we have our own telescopes and clearly want to be the best on our own soil. But we do understand how good it is to work with each other, and it’s a lot of fun!

BCAS: How is the new collaboration going to work, specifically?

Dr. Kramer: We’ll use these few days in China to establish a kind of initial mode of operation. We’re not starting from scratch. We already have a number of key people who’ve been working in Germany before and now here at CAS. We know each other, and we’re already exchanging information. For example, FAST has already been sending us data about some newly discovered pulsars that they would like to confirm. We sure can help with that, and just need to make the collaboration more organized. By the way, FAST is so good at finding things that it would be almost a waste of time to try to confirm the pulsars. We thought we had time. We thought it would take longer for FAST to find a new pulsar, but it has been so successful and it almost came a bit too “fast” for us! So one of the things we will sit together later today to figure out is some kind of mode of operation. The idea is we stay in steady and firm collaboration for the years to come: we’ll have regular exchanges of staff, have common meetings, write common papers, and provide access to databases and so on.

BCAS: Thanks. One last question: how long would it take to make the detection (with pulsars)?

Dr. Kramer: It’s not the first time we get this question (laugh). I hope it's not like fusion reactors which always need 50 years before they actually produce energy! If you had asked me this question five or seven years ago, I would have said it’ll be now. But we didn’t (make the detection). I think we are not far away from seeing the signal. All of the experiments have seen some strange features thought to be a signal, but we all agree now they were probably just some features or data we need to correct for. But I think we’re not that far away. Maybe a couple more years when we have the best sensitivity data added to the dataset we have now. I think three to five years is totally realistic. With new telescopes coming up, and if they are really, really good, we may have a jump and shorten this time. You could be surprised to find sources that are much brighter than you expected, like LIGO did. You never know. The most exciting thing a telescope will find is not the one that it was built for. It’s something unexpected. So back to your question: yes, we still need a couple of years to take some data, in particular with FAST and SKA and so on, but I think we should see signals soon!