MAX-PLANCK-GESELLSCHAFT

Annual Report 2000

Max-Planck-Institut für Gravitationsphysik
Albert-Einstein-Institut

Preface by the Managing Director

As in previous years, the Max Planck Institute for Gravitational Physics (Albert Einstein Institute) saw many important developments during the past year 2000. Most importantly, the scientific output of the institute continues to be vigorous and prolific with many noteworthy achievements in all areas of research covered by its three divisions. These achievements, some of which will be highlighted in this report, have consolidated the position of the AEI as one of the world's leading centers in gravitational physics.

Undoubtedly the most far-reaching development was the approval of Max Planck Society to enlarge the institute by two experimental divisions devoted to the physics of gravitational waves. One of these exists already as an “Außenstelle” to the Max Planck Institute for Quantum Optics at the University of Hannover. Under the leadership of Prof. K. Danzmann, the Hannover group has acquired an international reputation for its groundbreaking work on gravitational wave detectors, especially the GEO600 detector. The new “Teilinstitut” will remain located in Hannover, and will be jointly funded by the Max Planck Society and the Land of Niedersachsen. The combination of frontline experimental research with theoretical activities ranging from the numerical simulation of black hole collisions all the way to the abstract mathematics of superstring theory under the roof of one institute will offer a unique opportunity to galvanize and stimulate research in gravitational physics not only in Germany. We look forward to welcoming Prof. Danzmann and his team as new colleagues at the Albert Einstein Institute.

As a consequence of the proposed enlargement there will be a substantial need for extra office space. We are therefore grateful to Max Planck Society for having approved, in a second step, an extension to the institute building in Golm. Extra office space is not only needed for our future colleagues from Hannover, but also in view of the institute's numerous successful applications for outside funding, which have led to an increase in the number of postdocs and visitors beyond the one foreseen in the institute's Stellenplan. The institute is presently a participant in four EU networks, one of which it coordinates, as well as a DFG Sonderprogramm and various other programs. Last but not least, the institute's international standing is reflected in the growing number of scientists from all over the world who would like to spend extended periods of time at the institute with their own money, and for whom office space should be made available.

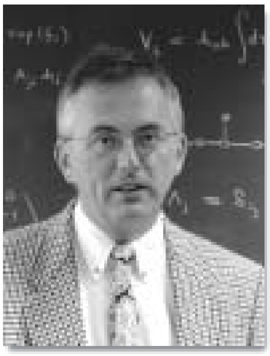
Important developments also took place in the computer division. A new supercomputer has been commissioned to replace the Origin 2000, and will be installed during the course of the year 2001. Although the Y2K bug did not bite, some difficulties had to be overcome. Due to the rapid growth in the software industry, our most qualified computer personnel continues to be attracted by more lucrative offers from private industry. Although the special working conditions at the institute can in part make up for lower salaries, we were not entirely successful in keeping all the specialists under contract. For this reason we had to outsource some tasks, thereby putting extra strain on the institute finances. The problem is shared by other Max Planck Institutes, especially in the East, and we do not expect that it will go away soon. We are therefore pleased that Max Planck Society has set up a task force to study the problem and to look for longer term solutions.

After the great success of STRINGS'99 in the previous year, the Albert Einstein Institute again hosted a big international conference in 2000:

the 3rd LISA symposium, which took place in Golm from 11-14 July attracted some 200 participants, including representatives from NASA, ESA, and Astrium. The meeting was not only a success from the scientific point of view, but also provided a first real test of the Golm facilities and infrastructure. Participants were generally impressed with what they saw, and we believe that the success of the meeting confirmed again that the institute is not only a center of active research, but also a place where major international conferences and workshops can be held. In addition to the LISA Symposium, several smaller meetings and workshops took place during the year. A special highlight was the meeting in honor of Jürgen Ehlers' 70th birthday at the beginning of the year, at which many leading relativists paid tribute to a founding father of our institute.

2000 had also been declared the year of physics by the Federal German Government. Following the call of Max Planck Society to contribute to the popular understanding of science, members of the institute played an active role in various public events, most notably the Berlin Centenary of Quantum Theory in December 2000. While it is important to advertize and popularize our research among interested laymen, an equally important aim is to foster research in general relativity and related areas at German universities. As in previous years, members of the institute fulfilled their teaching duties by giving lectures at universities and research schools, both at the undergraduate as well as the advanced level. We are happy that the interest and fascination for our research remain high among the younger generation, as can be seen from the numerous inquiries and applications that we receive from prospective diploma and PhD students, especially in the area of quantum gravity and string theory.

Finally I would like to take this opportunity to thank the staff of Albert Einstein Institute for their loyalty and dedication, and their excellent work over the past year.



Hermann Nicolai
(Managing Director)

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Max Planck Institute for Gravitational Physics (Albert Einstein Institute)

The Albert Einstein Institute (AEI) was founded in 1995 by the Max Planck Society for the purpose of pursuing research into the fundamental laws of gravitation. The Institute was established in Brandenburg as part of the expansion of the Max Planck Society after the reunification of Germany. Its establishment was an initiative of its founding Director, Jürgen Ehlers, who retired at the end of 1998. With a population of approximately 90 working scientists (including guest scientists) and a further 15-20 support staff, the AEI is the largest research institute in the world devoted to the study of gravitation.

Background: Relativity in Physics and Astronomy

The founding of the AEI came at a time of enormous expansion of interest in and importance of Einstein's theory of gravitation, general relativity. During the first 50 years after Einstein proposed his theory in 1915, mathematicians and physicists struggled to develop techniques that were capable of unravelling the mysteries of the equations and making sound physical predictions. No physical theory had been as challenging mathematically as general relativity. But work completed in the 1960's and 1970's had put the theory on a sound footing: theorists understood black holes, gravitational waves, gravitational lensing, and cosmology well enough to make confident predictions.

This was just in time, because the application of advanced technology to astronomical observing, and in particular the placing of observatories in space, led to the discovery of a wide range of new phenomena, for the understanding of which general relativity turned out to be essential. Black holes, gravitational lensing, the cosmological constant – it is a rare conference on astronomy today that does not deal in an almost routine way with some or all of these ideas, which two decades ago were regarded as exotic, if not impossible. On top of that, physicists studying fundamental physics had by the mid-1970's had considerable success in understanding, at least in outline, how all the forces of nature except gravitation fit together into a single theory. They were ready to try to include gravitation into the unified picture that was emerging. Virtual black holes, black hole entropy, the cosmological constant, inflation, wormholes, strings, eleven dimensions – fundamental physicists today work in the exciting border areas between classical gravitation and quantum field theory.

Structure of the Institute

The AEI captures both of these trends in the application of general relativity to the physical world and pursues them in an environment where scientists in these disciplines can talk to one another and with mathematical relativists, who continue to improve our methods for studying the theory.

The Institute has three divisions:

- The Astrophysical Relativity Division specializes in the applications of relativity in astronomy. It has two main groups, one concerned with the search for gravitational radiation and the other with the computer simulation of black holes and their dynamics. The gravitational radiation group will analyze data from the first generation of gravitational wave detectors, beginning with test data in 2001. The numerical relativity group is the largest in the world, and is a leader in the development of software that allows effective use of large parallel supercomputers for solving equations in physics.

- The Quantum Gravity Division studies methods for developing a theory of gravitation that replaces general relativity by making it compatible with quantum mechanics, and if possible unifying gravity with the other forces of nature at the same time. There are two main threads to research in this area around the world, called string theory and canonical quantization, and the AEI is one of the few places in the world where scientists study both.

- The Classical and Mathematical Relativity Division extends the techniques that have unlocked the basic meaning of the theory. In particular, extensive and successful investigations concerning the local and global properties of solutions to Einstein's equations have been carried out, deepening our understanding of the theory and developing new tools for solving problems in it. The presence on the AEI staff of experts in both mathematical and numerical relativity offers a unique opportunity for mutual stimulation and cooperation. The development of quantum gravity will surely require new and unexpected mathematics. Challenging as general relativity has been to mathematicians, it is fair to say that string theory today requires the invention of a still larger variety of mathematical structures.

No other institute brings together these three important branches of gravitational physics research. It was part of Professor Ehlers' original concept of the AEI that it should mix scientists in these disciplines together and benefit from the resulting cross-fertilization. In pursuit of this aim, for example, the AEI does not group offices of people working in the same division together: all subjects, plus visitors, are distributed throughout the Institute.

To support this work the AEI provides an extensive library and one of the best computing environments available to any research institute of its size. It maintains an extensive guest scientist program. The lists in this report of guest scientists and of seminars given at the AEI in 2000 show how rich the intellectual environment is. Even more than the physical facilities, the Institute sees the work of its support staff as a key part of its performance: caring for the needs of visitors, maintaining the computer systems and making them accessible to all, ensuring that the library responds to the needs of scientists – all of these must happen if the research environment is to be productive.

Role and Activities of the AEI

It is natural that an institute that is as large as the AEI in relation to others in its field will be seen as a focus for world-wide work in relativity. In fact, a good fraction of the world community of scientists working in relativity has already visited the AEI in its first 5 years. Since 1998, as a further service to this community, the AEI publishes a new kind of free electronic journal, called Living Reviews in Relativity. This is described later in this volume.

The AEI has organized a number of small informal workshops, choosing areas of its own research where it seemed that a critical problem could benefit from bringing together the experts from around the world. With its extensive guest scientist program, the institute can respond quickly to such needs. Furthermore, in 2000 the AEI hosted the Third International LISA Symposium, a meeting devoted to studying the science and technology of the LISA spacebased gravitational wave mission. LISA is a Cornerstone of the European Space Agency's program for the 21st century, and has been adopted as a joint mission with NASA.

The AEI occupies a key position in relativity in Germany as well. Despite the fact that general relativity was created in Germany, research in mathematical and astrophysical general relativity is unfortunately not strongly supported at most German universities. Apart from the contributions of a strong group at the Max Planck Institute for Physics and Astrophysics (which became the core of the AEI when it was established) and of a few individuals and small groups at German universities, the focus of the development of classical relativity in the 1960's through the 1990's was outside Germany. Today, increasing numbers of German students are going abroad to study the subject at an advanced level. Through its annual vacation courses in relativity, the AEI is providing students the opportunity to learn relativity here, and those who want to pursue the subject further now have the opportunity to do work at the AEI in one of the most active research environments in the subject anywhere. The Institute, through its partnerships with Potsdam University and the Humboldt University of Berlin, can supervise work towards advanced degrees of those universities. The AEI also trains young German postdoctoral scientists to the point where they can achieve their Habilitation. In time, and despite the current serious financial pressures on German universities, we hope that many of these talented young scientists will enter senior academic positions at universities, where they can continue their work on fundamental physics and enrich the intellectual experience of their students.

In a longer view of our research, there are goals and challenges that motivate AEI scientists. We work from day to day, writing papers, holding meetings and other discussions, thinking in quiet isolation, but all of this activity accumulates to move research in certain directions and to prepare for certain expected developments. Some of these are —

- The first direct detection of gravitational waves will place the AEI at the center of the interpretation of the observations in this new branch of astronomy. Already we are designing the instruments to build for the next generation of observations.

- Very soon, supercomputers will be large enough to do realistic calculations in general relativity, to perform long simulations of black holes and neutron stars merging, possibly to perform realistic calculations of the formation of neutron stars and black holes, and probably to explore mathematical questions, such as the development of singularities, that have not been solved analytically so far. This will raise new questions in mathematical relativity, and offer new opportunities for research there.

- The launch of new space-based astronomical observatories, not least the New Generation Space Telescope, will challenge us with unexpected discoveries about black holes, their relation to the formation of galaxies, the overall structure of the universe, and … what else?

- If the optimism of scientists working in string theory today is justified, then in only a few years we may see the emergence of a coherent but mathematically complex theory of all the forces of nature. Work to understand the theory and explore those of its predictions that will be testable by experiments and by astronomical observations will require new mathematics and creative young minds. For the first time it may be possible to ask sensible questions – and expect sensible answers – to questions like: what happens inside black holes, what happened “before” the Big Bang, what is space-time like on the very smallest scales, how many dimensions does space really have, and what is time?

The work of the AEI in 2000, as described in these pages, should be seen in the light of these challenges and opportunities. In almost every case, scientists at the AEI are addressing issues that lie at the heart of progress on these questions. A Max Planck Institute is a long-term investment in a research field, and for Gravitational Physics the prospects for the future are especially exciting.

Bernard F. Schutz

Einstein’s Lifelong Struggle with Quantum Phenomena

Unique and irreplaceable were indeed Einstein’s endeavours also in his papers about the quantum theory. Without his paper “On a Heuristic Point of View Concerning the Creation and Transformation of Light” of March 17, 1905, the development of physics in our century is unthinkable.
Res Jost, Princeton (1979)

The year 2000 was declared the year of physics, and the entry into the new millennium coincided with the birth of the quantum theory. Therefore it seems to be appropriate for the AEI to recall the unique role of Albert Einstein, first in the process of creation of the quantum theory (1905-1925) and later in the discussion of its conceptual basis.

Though it was Max Planck who, after six years of struggle, initiated a new era of physics with his famous “happily guessed” formula for the spectral distribution of the energy of thermal radiation (October 19, 1900) and his tentative, ground-breaking theoretical derivation of it (December 14, 1900), it was the patent clerk Albert Einstein who first clearly recognized and unambiguously stated, in the paper cited above, that
i. According to classical physics, thermal equilibrium between matter and radiation is impossible,
ii. Monochromatic radiation behaves as if its energy would consist of independent quanta of amount hn. He arrived at the second, startling conclusion, which contradicts Maxwell’s electromagnetic field theory of light, by an ingenious application of Boltzmann’s relation between entropy and probability to the energy fluctuations of thermal radiation. (In 1905 he used Wien’s approximate radiation law to obtain (ii) for short wavelengths only, in 1909 he employed Planck’s law and removed that restriction, see below.) Einstein immediately went on to point out how several known, but unexplained phenomena could be understood quite simply in terms of light quanta, and he predicted observable relations pertaining to the photoelectrical effect, ionisation of gases and photo-luminescence, which have been experimentally confirmed, sometimes ten years later.

Between 1905 and 1917 Einstein persistently extended his analysis of elementary interaction processes between material particles and radiation, undisturbed by the almost total resistance of his colleagues to his light quantum hypothesis. In 1907 and 1911 he applied energy quantization to the vibrations of solids. Thereby he explained the thermal behaviour of solids at low temperature and its relation to elastic properties; this work marked the beginning of the quantum theory of solids. Another step, mentioned above already, concerned refinements of his 1905 analysis of thermal equilibrium between matter and radiation. He now also considered the exchange of momentum and introduced the momentum hn/c of a light quantum (1909). Thus the photon as a particle carrying both energy and momentum entered physics – if only in Einstein’s mind. It was generally accepted only in 1923 when Arthur Compton established experimentally that scattering of X-rays by electrons could be described straight forwardly as a collision process between photons and electrons. In the same 1909 paper Einstein derived from Planck’s law a formula for the fluctuation of radiation energy in a small subvolume of the container enclosing the radiation. It gave, besides a contribution due to the “beats” between waves of different wavelengths, another part clearly indicating a discrete, particle-like energy distribution, which extended his 1905 result. The simultaneous presence of both terms shows that a satisfactory theory of radiation would have to account for wave-like as well as for particle-like properties of radiation; separately the two classical pictures would not do, as Einstein repeatedly emphasized.

Here I wish to insert a remark which is rarely mentioned, in spite of its importance: in the last part of the “three men paper” of Heisenberg, Born and Jordan (1926), Pascual Jordan, who was the sole author of this part, for the first time deduced Einstein's fluctuation formula by “quantizing” the electromagnetic field according to the rules developed in the preceding sections of that paper. I think this was the first result suggesting that fields should be treated according to the new quantum kinematics.

Bohr and Einstein in
Paul Ehrenfest´s home

In 1913 Niels Bohr introduced the concepts of stationary states of atoms and of transitions between such states accompagnied by emission or absorption of light. This raised the question whether one could derive Planck's law in accordance with Bohr's postulates for general atomic systems without recourse to classical mechanics and electrodynamics. Again, it was Einstein who solved the problem (1916, 1917) by introducing the notions of transition probabilities for spontaneous and induced emission and absorption processes. In these papers, in Wolfgang Pauli’s judgement the high point of Einstein’s contributions to the early phase of quantum theory, the exchange of momentum between the moving atoms and the radiation is also treated “generally and definitely”. Consistency requires that in each elementary emission or absorption process a photon carries a momentum hn/c in some direction while the atom loses or gains, respectively, the opposite momentum. It is a strange irony of history that the same person who showed that the interactions between matter and light can be accounted for convincingly and in accordance with experimental facts by assuming the elementary processes to be governed by probabilistic laws, never accepted such laws as basic; “God does not throw dice.” (See below, however.)

Bohr's quantum rules for periodic motions have been generalized by Arnold Sommerfeld (1915) and Paul Epstein (1916) to more complicated ones. In 1917, in a paper rarely mentioned, Einstein noticed that those rules had been formulated with reference to particular coordinates in the (configuration and momentum) phase spaces of those systems. The intrinsic meaning of the conditions, the restriction which the existence of such coordinates imposed on the systems were not clear. Therefore Einstein proposed and managed to give a satisfactory geometric formulation. I think at that time only Einstein was able to do that because it required the kind of intuition about higher-dimensional spaces and coordinate independence which he had acquired not long ago in his works on gravitation and cosmology (1907-1915). Einstein recognized the role of symplectic geometry for quantization; in effect he introduced what were later called Lagrangian submanifolds, and particularly invariant tori of phase spaces. (In his reasoning he also used the distinction between multiply-periodic and chaotic motions which attracted general attention much later.)

Even when he elaborated his theory of gravitation, the general theory of relativity, the quantum riddle was on Einstein's mind. In his second paper on gravitational waves (1918) we read: "It seems that the quantum theory will have to modify not only Maxwell's electrodynamics but also the new gravitational theory".

Einstein's last constructive contribution to quantum theory consists of three papers (1924, 1925) on the statistical thermodynamics of gases composed of bosons. Stimulated by a paper of Satyendra Nath Bose, he treated a gas of indistinguishable, massive particles which can be counted, but which cannot be identified as individuals. As in his light quantum paper of 1905, Einstein computed the energy fluctuation of such a gas and again found it to consist of two terms. While in the earlier case a particle-like term was surprising and suggested the existence of light quanta, now a wave-like term led him to associate a de Broglie-type wavefield with a gas of material particles. "Thus, Einstein was not only one of the three fathers of the quantum theory, but also the sole godfather of wave mechanics" (Pais, 1982. The other fathers are Planck and Bohr.)

The year 1927 separates, like a watershed, two sides of Einstein's efforts to cope with the quantum problem. Before that year he participated as a leader in the construction of a new building, later he acted as an interested, but sceptical, unsatisfied critic. While he acknowledged the great successes of the "new" quantum mechanics of Heisenberg, Born, Jordan, Dirac, Pauli, de Broglie and Schrödinger, he maintained that the new theory was incomplete. His many failed attempts to prove this by means of thought experiments have been told in detail by Bohr.

As Born pointed out in his Nobel lecture (1954), Einstein regarded quantum mechanics as unsatisfactory for two reasons. In quantum mechanics probabilistic laws are accepted as fundamental, whereas Einstein would have preferred deterministic laws. This has often been described; but in my understanding another aspect of quantum mechanics is the deeper reason for Einstein's dissatisfaction. Given an experimental setup, quantum theory allows to predict the probabilities of effects which may be registered by detectors, but it does not permit a description of what is "really going on" in spacetime. The theory does not include that some effects will, in fact, occur rather than just be possible, e.g. the motions of macroscopic bodies or, more generally, a "classical world". In other words, the process of actualisation of potentialities – whether governed by deterministic or by statistical laws – is not included in the theory's dynamics, instead it is "added on" (state reduction). In a letter to Born, Pauli tried to explain Einstein's realist position (1954). In Pauli's view the appearance of a definite result in an act of observation, though not influenceable by the observer and in that sense objective, cannot be deduced by laws of nature, but has to be regarded as an "act of creation outside of those laws". I think it was this incompleteness that deeply disturbed Einstein.

I should like to end these remarks by quoting from a letter of Einstein to his friend Michele Besso (1951) which highlights his never-ending concern. "Fifty years of pondering have not brought me nearer to the answer of the question: What are light quanta?"

Jürgen Ehlers

Classical and Mathematical Relativity Division

The force of gravity is a mutual attraction between all bodies in the universe. However, among all observations of nature, the ones whose explanation is most dependent on an understanding of gravitation are those belonging to the domain of the astronomer. It is clearly a task for an institute for gravitational physics to apply physical theories to provide this understanding. In so far as there are aspects of this question which cannot be treated by existing theories it is important to encourage new theoretical progress. An equally important goal is to reach an optimal understanding of the existing theories and the ways in which they are applied. This is the central theme of the Classical and Mathematical Relativity Division of the AEI. Apart from its considerable intrinsic interest, the research of the Division provides a solid foundation and technical resources for the other research directions mentioned above, which are pursued by the other two Divisions of the institute.

The two theories of gravitation which are extensively and successfully applied are those of Newton and Einstein. Einstein's theory, general relativity, is the most accurate. At the same time Newton's theory is good enough for many purposes. In general the difference between the predictions of the two theories only becomes practically important in the presence of extreme conditions, like very strong forces or high velocities, or when exceptionally high precision is required. As suggested by its name, the work of the Classical and Mathematical Relativity Division is mainly concerned with Einstein's theory. However Newton's theory is not neglected either since it is not only widely applicable, but also contributes to the conceptual understanding of Einstein's theory.

Both theories of gravitation, Newton's and Einstein's, have been around for a long time. The structure of the models themselves is well understood. What is much more difficult is to understand how the models lead to predictions in particular situations. In mathematical terms, the equations of the theory are well understood but it remains to understand their solutions in sufficient generality. It follows naturally from this that a central preoccupation of the research of the Classical and Mathematical Relativity Division is to understand the properties of solutions of the Einstein equations which are general enough. In particular, the aim is to do this for solutions which give physically realistic models of characteristic phenomena of general relativity such as black holes, gravitational waves and the big bang as well as more familiar types of object, such as stars and galaxies. In understanding solutions of Einstein's equations it is essential to make use of sophisticated mathematical techniques. Indeed it is often necessary to invent new mathematical tools, since known mathematics does not apply.

From the above it can be seen that there is a need for a strong interplay between abstract mathematics and applicable physics, particularly astrophysics, in the work of the Division. Since pencil and paper work cannot suffice to make precise quantitative predictions about real phenomena, computer calculations also naturally come in. For this reason, in addition to its mathematical investigations, the Classical and Mathematical Relativity Division pursues numerical work complementary to that done in the Astrophysical Relativity Division. Naturally, the former is more focused on conceptual and theoretical issues, in keeping with the general orientation of the research of the Classical and Mathematical Relativity Division.

The Einstein equations are a system of nonlinear partial differential equations which are essentially hyperbolic. The theory of nonlinear hyperbolic equations is not as far developed as we would like for applications to general relativity. In particular what is lacking is a good global theory which would allow statements about the behaviour of the gravitational field on large time-scales. This is what would seem necessary to model the propagation of gravitational waves all the way to the observer, or the approach to the big bang. One way of getting around this is to do a mathematical transformation which turns a global problem for solutions of one equation into a local problem for solutions of another. Ways of doing this have been developed by members of the Division and collaborators in the past. The “regular conformal field equations” accomplish this for the case of gravitational radiation while the theory of “Fuchsian equations” can be applied to study the spacetime singularity at the big bang.

The regular conformal field equations are the basis of a project within the Division to develop a numerical code for solving the Einstein equations suitable for treating isolated systems and gravitational radiation. Potential advantages of this approach are the avoidance of difficulties due to the artificial boundaries generally needed in other approaches and the relative ease of interpreting the output of the code physically. Data for this code representing weak gravitational waves were constructed for the first time in the year 2000. These data were then evolved and the decay of the waves could be followed reliably over a dynamic range of many orders of magnitude.

There have also been important technical advances in the application of Fuchsian equations during the year 2000. It was shown how to extend the range of Fuchsian techniques from the analytic to the smooth case. What this means in practice is an increase in flexibility. The restriction to analytic functions implies unphysical correlations between events at different spacetime points and so it was reasonable to believe that it should be possible to get rid of it. This has now been done in one of the key examples (Gowdy spacetimes) and the techniques used can probably be generalized to apply to many other situations.

In cases when Fuchsian techniques can be applied to determine the structure of spacetime singularities, the result is that when various quantities become unboundedly large near the singularity they do so in a rather uniform way. On the other hand, certain numerical calculations strongly suggest that spacetime singularities are not always like this and that it may be the case that the inhomogeneities in a given quantity grow faster than the quantity itself, resulting in highly irregular behaviour. During 2000 it was discovered how to produce spacetimes with this kind of property directly without the need for numerics and to give a rigorous mathematical analysis of their properties. The method used is to apply certain transformations to the spacetimes obtained by Fuchsian methods. These transformations do not preserve the uniformity of the singularity, but instead lead to inhomogeneous features which reproduce the behaviour previously observed numerically.

A crucial task for mathematical relativity is to examine the reliability of the approximation techniques which are used when applying general relativity to astrophysics. In particular, it is desirable to understand better the approximations used in the study of gravitational waves. In the end we would like to analyse the connection between the exact theory and the approximate models in a mathematically rigorous way. A more modest aim, where some success has been achieved in the Division recently, is to understand the approximate models themselves.

It was shown how to control the long-time behaviour of one such approximate model which incorporates the phenomenon of radiation damping. Other work in the Division, concerning perturbations of stellar models and gravitational lensing, is described elsewhere in this report.

Alan Rendall

Astrophysical Relativity Division

Research in the Astrophysical Relativity Division of the AEI has concentrated on two main themes. One is the numerical solution of Einstein's equations, and in particular computer simulations of the collisions of two black holes. The second theme is the detection and study of gravitational radiation. In both areas there have been exciting advances in the scientific results and important developments in computer software that supports the scientific work.

Numerical simulations

The numerical simulations group of the Astrophysical Relativity Division, led by Prof E Seidel, undertakes large-scale computer simulations of colliding black holes. Black holes are arguably the simplest phenomena in general relativity: their properties depend on only a few numbers, such as their mass and spin, and their gravitational fields are independent of the kind of material that originally formed them. Therefore, a simulation does not need to take into account fluid dynamics or other astrophysics: pure vacuum gravity is all one needs. The collision of two black holes is therefore one of the "cleanest" dynamical processes in all of Nature, but because of the complexity of Einstein's equations, it has been difficult to achieve a detailed understanding of it. That is all beginning to change through advances in our computer techniques and through a unique marriage of numerical and analytic approaches to solving the equations.

Head-on collisions of non-spinning black holes have been simulated accurately in the past by Seidel and collaborators, but it is still a great challenge to simulate the kinds of collisions we expect to occur in the real universe: black holes that are originally in a binary orbit, spiralling together and merging in a grazing-incidence collision. The new gravitational wave detectors now under construction (see the article on "Gravitational wave research at the AEI") may well see gravitational waves from such collisions early in their observing programs. We would like to have as much information about these collisions from numerical simulations, in order to recognize and interpret such signals. We have a good understanding of the so-called inspiral phase of the orbit, where the two holes move in roughly circular orbits that gradually shrink as the orbit emits gravitational waves. But at some point the orbit becomes unstable, and the two holes suddenly change course and plunge together, as if they had just fallen off a cliff. This crucial transition, and the subsequent merger, are the target of our numerical simulations.

Our computer simulations are challenging partly because they demand the largest and fastest computers, and partly because the software problems have not been fully solved. In general relativity, the whole of space is dynamical, and it is important to study the dynamics of space not only near the holes but also out to a considerable distance from them.

This strains the memory and speed of even the biggest supercomputers. In addition, black holes develop extremely strong gravitational fields, which create numerical problems that tend to bring simulations to a premature end.

Success of the Lazarus Project

During 2000 a group of AEI scientists calling themselves the “Lazarus Project” have managed to breathe new life into these prematurely dead numerical simulations (hence the name they chose for their project). It has turned out, a little unexpectedly, that if we start a simulation just as the holes are beginning to plunge together, then when the simulation is stopped by numerical difficulties, the holes seem to be close enough together that the gravitational radiation they subsequently emit closely resembles radiation emitted by a single, disturbed black hole. We would expect this to happen late in the collision, after the holes have merged. What is remarkable is that it happens much earlier, before the holes have begun to melt together.

The reason appears to be that spacetime becomes so strongly curved near the holes that it forms a kind of barrier around them, so that from the outside they appear to be closer together than they really are. Since single disturbed black holes can be described by relatively simple techniques that have been known for decades, the group can extend the time during which the emitted waves can be simulated by finding the right characteristics of the single black hole and its disturbance that match smoothly to the end of the numerical simulation. This matching is the key to the success of the project, and it took many months of effort to get it right.

The Lazarus Project has produced the first believable predictions of the gravitational radiation from the plunge and merger phases of black hole collisions. They reported their results to other AEI scientists in November 2000, and presented them publicly for the first time at a meeting in Texas a month later. This was a landmark stride forward. Their colleagues working on gravitational radiation detection are already beginning to build this information into their own data-processing computer programs, and not a moment too soon: the first data are expected in early 2002. Before then, the Lazarus group needs to study a representative sample of possible collisions: black holes of different masses, spinning black holes. The work of the Lazarus Project is described more fully in a separate article.

Full numerical simulations

Exciting as the Lazarus results are, we recognize that ultimately the numerical simulations must be improved so that they do not die a premature death. At the AEI there are two approaches to this. One is to improve the way the outer boundary of space is treated, far from the hole. This is described in the report on research in the Classical and Mathematical Relativity Division.

The other is to improve numerical methods so that they can cope with the ultrastrong gravitational field near and inside black holes. This is being pursued in Seidel’s group, and has recently also made important progress. One of the biggest limitations so far on the duration of simulations is the presence of strong and even singular gravitational fields inside the black holes. These have tended to suck the numerical grid into the hole, leaving the simulation with few numerical grid points outside the hole, leading to big inaccuracies. The group have attacked this problem in two ways, first by developing new coordinate conditions that sense the grid problem and correct for it, and second by actually cutting the interior of the black hole out of the numerical domain. This latter approach works because, even though it gets the wrong answer inside the black hole, no information can propagate to the outside, so the outside calculation can proceed accurately and without the disturbance of the strong singularity.

Both methods were proved to work in test problems in 2000. We expect that in 2001 we will be able to use them to perform fully numerical plunge-and-merger calculations that can be compared against the Lazarus results as a consistency check.

Big computers

The AEI group uses a variety of powerful computers: the AEI's own 64-processor Silicon Graphics Origin 2000 computer (doubled in size from 1999), supercomputers at the Garching Computer Center of the Max Planck Society and the Leibniz Computer Center in Munich, various supercomputers at the National Center for Supercomputing Applications (NCSA) in Illinois, and others. In 2000 we negotiated the purchase of a replacement for our own computer, using a grant from central Max Planck Society computing funds. During 2001 we expect to take delivery of the new computer, a 96-processor Origin3000i machine containing the latest Itanium processors from Intel. Preliminary tests indicate that we should get a ten-fold speedup over the computer we had in 1999. We have actually only purchased 64 of the processors; the other 32 are a grant to the AEI from SGI/Intel-IA64 Leadership Program for Key Applications. The grant is in recognition of the importance of the other major activity of the numerical relativity group, namely the creation of the application software called the Cactus Computational Toolkit.

The Cactus Computational Toolkit

Cactus was first publicly released in 1999, after undergoing considerable development within the collaboration starting in early 1997. Cactus is a framework that allows many users at many sites to collaborate on a single computer simulation code, and it provides them with a large variety of tools that they need to move their programs from single workstations to today's large parallel computers. The popularity of the program is growing rapidly, and it occupies a central place in the worldwide computer initiative called Grid Computing, which aims to make access to computers easier over great distances. Most of the numerical relativity groups in the world use and contribute to Cactus, and there are other users from fields as diverse as astrophysics and chemical engineering. Cactus played a central role in the numerical simulations of the Lazarus Project, and is the framework in which fully numerical mergers will be simulated.

Cactus is a good illustration of a phenomenon that occurs in many frontline fields of science. The scientists find that they do not have the technology they require to do the research, and so they invent it themselves. Once invented, the new technology acquires a life of its own as other users want to employ it. This fruitful interplay between pure science and technical spinoffs has a long history in the experimental sciences, but one sees it increasingly frequently in software, most strikingly of course with the World Wide Web. Cactus is free software supported by AEI staff, but as its user base grows we expect that it will be essential to form a private company or some other arrangement to continue supporting the program.

Cactus can be obtained from the website http://www.cactuscode.org

Gravitational waves

The other major activity in the Division during 2000 was research in support of the giant gravitational wave detectors that are being built in several locations around the world. Gravitational waves are the last great prediction of Einstein not yet verified directly by experiment or observation, and their direct detection by these instruments will be a landmark for physics. But in fact the indirect evidence for gravitational waves is strong, so it is not expected that they will be much different from the theoretical predictions. The main interest in detecting them is astrophysical: they open a completely new window on astronomy and the Universe. Gravitational waves can come to us from the dark, hidden parts of the Universe: black holes, the first fraction of a second of the Big Bang, the interiors of supernova explosions, and perhaps even some of the mysterious dark matter itself.

The AEI activities in this area are described in the article “Gravitational Wave Research at the AEI”. I shall only summarize these activities briefly here.

The AEI group specialises in the development of data analysis software for the gravitational wave projects. It is part of the GEO project, which is building a detector in Hannover. This is a cooperation between Germany (led by the Max Planck Society) and Britain (funded by the Particle Physics and Astronomy Research Council). The AEI role is to coordinate data acquisition and analysis for GEO. It also makes contributions of software to other gravitational wave projects.

The group also plays an important role in developing the scientific case for the planned LISA space-based gravitational wave mission. These activities, and the worldwide search for gravitational waves, are fully LISA figured strongly at the AEI in 2000. We hosted the 3rd International LISA Symposium. This is described more fully in a separate article by Curt Cutler.

During 2000 another exciting development began to take shape. The experimental group in Hannover that has built the GEO detector is presently a satellite group of the Max Planck Institute for Quantum Optics in Garching. During 2000 we began planning for the transfer of that group to the AEI and its enlargement into a full part of the AEI. According to present plans, the AEI will establish a new branch in Hannover dedicated to experimental gravitation in 2001. There will be two divisions, giving the group enough strength to maintain its contribution to both GEO and LISA. The AEI will then assume full responsibility for managing the GEO detector for the British-German collaboration. We are looking forward to the fruition of these ideas in 2001.

Bernard F. Schutz

Quantum Gravity and Unified Theories

Modern physics rests on two pillars. At very small distances - the world of atoms, nuclei and elementary particles - it is quantum mechanics and relativistic quantum field theory that reign supreme. The so-called standard model of elementary particle physics offers a most precise description of the phenomena at these scales. At large distances, on the other hand, physics is governed by Einstein's theory of general relativity. This theory, too, has passed numerous precision tests. With the unconfirmed discovery of the Higgs particle, and the evidence for a non-vanishing cosmological constant searches have only very recently yielded some tentative evidence for “non-standard physics”.

Inspite of this success in matching theory and experiment, however, there are some ominous fissures in the edifice of modern theoretical physics. Already the classical theory of general relativity carries in itself the seeds of its own destruction in the form of so-called singularity theorems. These predict the end of space and time, and hence all known laws of physics, in certain situations (which might be experienced, for instance, by an astronaut falling into a black hole). Worse yet, all attempts to reconcile quantum theory and general relativity have failed so far. These failures manifest themselves in the form of mathematically undefined expressions (infinities) when one applies the rules of quantum field theory to Einstein's theory. The difficulties are aggravated by the fact that quantum mechanics and general relativity are very different at the conceptual level: while quantum theory can only predict probabilities of certain events (such as the decay of an unstable particle), general relativity is a completely deterministic theory; it is furthermore characterized by a compellingly beautiful geometrical structure that has no counterpart in quantum theory so far.

Effects of quantum gravity should become visible at the so-called Planck scale characterized by the following three numbers (first computed by Max Planck in 1899!)

$l_{PL} = 10^{-33}$ cm
$t_{PL} = 10^{-43}$ sec
$m_{PL} = 10^{19}$ GeV

Obviously, these numbers are way beyond the range of present experimental techniques, and one might therefore argue that there is no real need for a theory of quantum gravity. Yet, we should not repeat the mistake of some physicists in the late 19th century who already saw the end of physics on the horizon, believing that they could understand all phenomena in terms of classical mechanics and Maxwell's equations. Of course, we now know better: the “internal” contradictions of the time (in particular the apparent paradoxes related to black body radiation) were the harbingers of the revolution which completely changed the course of physics in the early 20th century. It is therefore with good reason that many theorists now believe that the apparent incompatibility of quantum theory and general relativity is a hint of yet another revolution to come which will unify all of known physics into a single theory.

The search for a consistent theory of quantum gravity and its unification with the fundamental interactions of particle physics constitutes the biggest challenge for theoretical physics at the turn of the millenium. The conceptual and mathematical difficulties that must be overcome are enormous. There is at this time no theory that can pretend to be “the” theory of quantum gravity. Rather, there are promising ansätze, and it is hoped that these ideas - together with unmistakable signals of "new physics" in observational astrophysics and particle accelerator experiments - will eventually pave the way.

The approach to quantum gravity which is presently favored by the majority of researchers is based on superstring theory. This ansatz tries to cure the shortcomings of perturbatively quantized general relativity by a radical modification of Einstein's theory at very short distances (of the order of the Planck length). The fundamental "object" of the theory is a one-dimensional extended object, a relativistic string (or superstring, if fermions are included). The point-particles of conventional quantum field theory are identified with the quantized excitations of this string, and in the most optimistic scenarios the massless excitations should then correspond to the known matter described so well by the standard model of elementary particle physics. Remarkably, (closed) string theory predicts the existence of a massless spin-two particle, the graviton, whose self-interactions coincide with those of Einstein's theory at the lowest non-trivial order - in this way the existence of gravity itself becomes a (successful!) prediction of string theory. Superstring theory is at this time the only ansatz that succeeds in removing the inconsistences of perturbatively quantized Einstein's theory. The main task is now to find a non-perturbative formulation of the theory (sometimes dubbed "M-Theory").

Alternative approaches to quantum gravity, which are also represented at the Albert Einstein Institute, are based on canonical and path integral methods. Although the canonical quantization of Einstein's theory leads directly to a kind of Schrödinger equation for quantum gravity, the so-called Wheeler-DeWitt equation (actually a constraint equation), this approach had yielded little fruit until Ashtekar's discovery of new variables in 1986. The aim of this approach is to implement the guiding principles of Einstein's theory directly in a background independent theory of quantum general relativity; in particular, it has led to completely new ideas about the structure of space and time at very short distances.

Like canonical gravity, the path-integral approach has a long history. Only recently has it become possible to construct non-perturbative regularized path integrals for gravity which give a well-defined meaning to the notion of a "sum over all geometries". Of special interest in this context are models of quantum gravity with and without matter in two space-time dimensions.

Research Highlights in 2000

Current activities in the quantum gravity division at the Albert Einstein Institute reflect the diversity of the major approaches. While some of this work is reviewed in more detail in this volume, this brief summary reviews (in somewhat more technical terms) the scientific highlights in the quantum gravity division over the past year. Although it cannot do justice to all the work done it is hoped that readers will at least get a flavor of some of the frontline research being done in the division.

In canonical quantum gravity, a main focus was the construction of new background independent coherent states for gauge theories over compact gauge groups. These states are especially suitable for lattice Yang-Mills theory and non-perturbative quantum general relativity and are labelled by a point in classical phase space of these theories. Peakedness properties of these states in the configuration (connection), momentum (electric field) and phase space (Segal-Bargmann) representations were rigorously proved, and the corresponding Ehrenfest and minimal uncertainty theorems were established. These results represent first steps towards the goal of explaining the emergence of a classical (smooth) space-time from an underlying quantum spacetime. Some possible future applications of these states for semi-classical quantum general relativity are: (i) the rigorous proof that classical general relativity is a classical limit of quantum general relativity, (ii) the construction of photon and graviton states propagating on fluctuating metrics, (iii) contact with quantum field theory on curved backgrounds, and thereby with the low energy physics of the standard model), and (iv) computation of quantum gravity corrections to the standard model.

In the path integral approach, further evidence was found that a theory of quantum gravity can be constructed from Feynman path integrals for discrete Lorentzian geometries. The most exciting new result concerns the emergence of a ground state of well-behaved geometry in this completely non-perturbative construction in three space-time dimensions. This is remarkable in that one has at no stage built in any classical background geometry. It also points to a non-perturbative resolution of the "conformal sickness" of the path integral, a property supported further by an analytic calculation. This immediately suggests an application of Lorentzian dynamical triangulations to cosmological models and their Hartle-Hawking paraphernalia, a topic currently under study.

A most important challenge in the search for a unified formulation of superstring and M-Theory is the search for their fundamental degrees of freedom. The two currently most favored candidate theories come in guise of maximally supersymmetric Yang-Mills quantum mechanics (matrix theory) and the fundamental eleven dimensional supermembrane, with eleven dimensional supergravity as its effective "low energy limit". Here important progress was achieved over the past year. First, the one-loop effective action of SU(2) matrix theory could be deduced from a simple supersymmetry argument.
This result clarified the conjectured one-loop exactness of the leading effective interactions in the model and its agreement with eleven dimensional supergravity. In a second matrix theory project the asymptotic form of the SU(3) groundstate could be established. Investigations of the eleven dimensional supermembrane focused on its interactions in the massless sector. For this the concept of membrane vertex operators was introduced and their exact form could be established in the light-cone-gauge. These operators govern the emission of the massless d=11 supermultiplet from the membrane worldvolume and reduce to the massless superstring vertices under double dimensional reduction. A study of scattering amplitudes and the extension of the analysis to the massive sector is now under way.

In the same context dimensionally reduced supersymmetric gauge theories continue to be studied as tools to better understand non-perturbative aspects of supergravity, supermembranes and superstrings. In an ongoing project, which was already started some time ago, the group continued its investigation of maximally reduced gauge theories, the so-called Yang-Mills integrals. The most symmetric ten-dimensional version of these systems have been conjectured to furnish a non-perturbative formulation of IIB superstring theory (IKKT model). They are, however, also relevant for investigating the crucial issue of zero-energy bound states in matrix theory (related to the existence of gravitons in these models). Combining various numerical and analytic techniques, previous studies of unitary gauge groups were extended to more general gauge groups, and thereby to decide between two conflicting analytic, but non-rigorous methods for computing the above mentioned number of bound states for general groups.

Symmetry structure of eleven dimensional supergravity were also investigated. It could be shown that the bosonic degrees of freedom of that theory that become physical after dimensional reduction to three dimensions can be merged into an $E_{8(8)}$ group-valued matrix already in eleven dimensions, thereby showing that the "hidden symmetries" previously thought to arise only in the dimensional reduction have a role to play in eleven dimensions. The associated group action combines general coordinate and tensor gauge transformations, suggesting a partial unification of these symmetries. A related development was the construction of a nonlinear realization of $E_{8(8)}$ which is quasiconformal in the sense that it leaves invariant a suitably defined "light cone" in the 57 dimensional representation space. This is a first step towards the construction of irreducible unitary representations of $E_{8(8)}$, and the associated modular forms, about which very little is known, but a better understanding of which is expected to be crucial for the computation of higher order M-Theory corrections to Einstein's theory.

A breakthrough was the construction of maximal gauged supergravity in three space time dimensions (maximal gauged supergravities in dimensions D>3 had been known for almost twenty years), providing amongst other things the first example of a nonabelian duality between scalar and vector fields in three dimensions. In view of the very rich structure of superconformal field theories in two dimensions, these models are expected to be of particular importance in the context of the so-called AdS/CFT correspondence, relating supergravity in anti-deSitter spacetime to (super) conformal theories on its boundary.

Through the conjectured and much discussed AdS/CFT correspondence, weakly coupled string theory or its supergravity limit have been related to certain strongly coupled quantum gauge field theories. Members of the division have performed various non-trivial tests of this correspondence and have also explored its validity beyond the leading order in both the coupling constant and the number of colour degrees of freedom. The results about the corrections to the leading order expression for the Wilson loop were the first attempt to connect a string theory prediction at strong coupling to a known field theory results at weak coupling. Another central question is the identification of Kaluza-Klein fields in the supergravity theory and operators in the dual quantum field theory. Detailed calculations of correlation functions and operator product coefficients established new and entirely unexpected non-renormalization theorems. While most of the work on the AdS/CFT correpondence done to date relied on a specific dual pair, the group was able to perform a model independent analysis of the conformal anomaly of conformal field theories, with the sole assumption that a supergravity dual exists. Using only symmetry considerations, it was thus possible to derive the anomaly and also the non-local effective action.

A central role in all discussion of duality symmetries in string theory is played by the so-called D-branes. They are by now well-understood when embedded in flat space-time. Far more interesting and challenging are, however, branes in curved space. A main focus of the group were strings on group manifolds. Generalizing the known construction of non-commutative Yang-Mills theories from flat branes with background B-fields it was shown that the effective action of branes on group manifolds is a gauge theory on a "fuzzy" space. A number of interesting results on boundary renormalization group flows in two-dimensional field theories and on the K-theory of brane charges in background fluxed followed from this work. For instance, it is now possible to construct new families of boundary conformal field theories describing branes in string-size Calabi-Yau compactifications. Furthermore world-sheet techniques were developed to compute the superpotentials for a large class of such branes. Once the superpotential is known, one can discuss the issue of super-symmetry breaking in string theory. This is of utmost importance for the viablity of string theory as a physical theory.

The study of D-branes has also rekindled the interest in self-dual field theories without gravity. Members of the group first formulated and then used the requirement of self-duality in supersymmetric theories to construct the N=2 supersymmetric version of the Born-Infeld action. This is believed to be the world-volume action of D3-branes in six dimensions. The appearance of the Dirac-Born-Infeld action, i.e. the appearance of the scalars which are the Goldstone modes of the broken translational symmetries when an unstable brane decays into a brane of lower dimension by means of tachyon condensation could also be explained.

In the context of classical gauge theories, new results were obtained. A first order formulation of maximal supergravity was constructed for the first time, including the full supersymmetry transformation laws of the spin connection and of the four form field strengts. The first order formulations, which were given for any generic supergravity, are specially well adapted to superfield formulations. An additional motivation for studying first order theories is the computation of conserved charges in gauge invariant theories. A general covariant method which generalizes the Hamiltonian procedure of Regge and Teitelboim can then be implemented. For instance, in this way the so-called KBL superpotential generalizing the ADM mass could be reconstructed from first principles.

Finally, an alternative to Kaluza-Klein compactification was proposed recently in order to handle the higher spacelike dimensions intrinsic to M-Theory. This so-called brane-world scenario posits that we live on a brane-boundary of an higher dimensional spacetime such that only the gravitational forces interact with the bulk. The conserved charges associated with diffeomorphisms on this brane-boundary were computed.

Needless to say that much of this work was done in collaboration with scientists from other institutions, many of whom have spent extended periods of time as visitors at AEI during the past year.

Hermann Nicolai

Gravitational Lensing from a Spacetime Perspective

The deflection of light rays by the gravitational field of the Sun, as predicted by General Relativity, was verified for the first time during a total Sun eclipse in the year 1919. It was this observation that made Einstein famous even among non-physicists. Clearly, not only the Sun but every heavy mass acts as a "deflector" upon light rays, both in the optical and in the radio range, which leads to several interesting astrophysical phenomena. In essence, there are three different types of such phenomena which are summarized under the heading "gravitational lensing": (a) *multiple imaging* (e.g., an observer might see two or more images of a distant galaxy or quasar, owing to the gravitational light deflection produced by an intervening galaxy or cluster of galaxies); (b) *image distortion* (e.g., a distant galaxy or a radio lobe accompanying a distant galaxy might appear distorted, again owing to the gravitational light deflection produced by intervening masses); (c) *flux amplification* (e.g., a star might be seen brightening when passing behind a foreground star, owing to the focusing effect on light rays produced by that foreground star). The first candidate for multiple imaging was discovered in 1979, luminous arcs and radio rings (to be interpreted as highly distorted high-redshift galaxies and radio lobes, respectively) are known since 1987, and flux amplification is routinely observed since the early 1990s, primarily with the goal of detecting dark deflectors such as "brown dwarfs" in the galactic halo. Quite generally, it is to be emphasized that gravitational lensing is not only a method of verifying general relativity; much more importantly, it has grown into a major tool for astronomy and cosmology. To mention just two examples, gravitational lensing is instrumental in probing the density distribution of (dark) matter in the universe and in the determination of cosmological parameters.

For these reasons, gravitational lensing is a very active field not only for observational astronomers but also for theorists. The majority of theoretical studies in this field is done in a quasi-Newtonian approximation formalism which essentially relies on the assumptions that the deflectors are weak perturbations of a uniform background and that the bending angles are small. (However, the reader is cautioned that a precise derivation of this approximation formalism from general relativity requires some additional assumptions which are somewhat more subtle.) By contrast, my own work on gravitational lensing over the last years was concentrated on topics that use the 4-dimensional Lorentzian geometry framework of general relativity, without applying quasi-Newtonian approximations. This approach of investigating gravitational lensing from a spacetime perspective should be viewed as complementary to the quasi-Newtonian work. On the one hand, it allows to study qualitative features of gravitational lensing without unnecessary approximations. On the other hand, at least up to now it is restricted to kinematical considerations in the sense that Einstein's field equation is not used. In other words, one only considers the question of how light rays move in a gravitational field, without asking from which sources this gravitational field can be derived. In the following I am going to report on some recent results in that direction.

The first issue I want to address is the definition of a "lens map" in a Lorentzian geometry setting. Roughly speaking, the purpose of a lens map is to assign, for some fixed observer, to each image position the corresponding source position; thus, multiple imaging situations are characterized by non-invertibility of the lens map. The quasi-Newtonian formalism uses a lens map that is defined on a plane in 3-dimensional Euclidean space (the so-called deflector plane) and takes values in another plane (the so-called source plane). Building upon recent ideas of Ted Newman, Simonetta Frittelli and Jürgen Ehlers, an analogous lens map can be introduced in a Lorentzian geometry setting in the following way. In an arbitrary 4-dimensional Lorentzian manifold (spacetime) one fixes a point p (observation event) and a family of timelike worldlines (light sources) smoothly labeled by the elements of a 2-dimensional manifold N in such a way that they make up a timelike hypersurface with topology $N \, x \, \mathbb{R}$. To define the lens map we have to follow each lightlike geodesic from p into the past until it meets a worldline of the prescribed family. This gives the desired lens map as a map from the celestial sphere at p to the 2-manifold N, provided that the prescribed sources surround the observation event and that no lightlike geodesic from p is trapped or blocked before it could meet a worldline of one of those sources. Clearly, the latter condition excludes the possibility that there is a non-transparent deflector between observer and light sources.

If N is orientable, we may assign a mapping degree to the lens map. Quite generally, the mapping degree is a topological invariant, defined for maps $f\colon A \longrightarrow B$ where A and B are oriented manifolds of the same dimension and A is compact; roughly speaking, it tells how often $f(A)$ covers any generic point of the target manifold B, counting each layer positive or negative depending on orientation. The mapping degree of the lens map can be interpreted as the number of images with even parity minus the number of images with odd parity for a light source in generic position. (The non-generic light sources which have to be excluded are those whose worldlines meet the caustic of the past light cone of p. Thus, the question of whether the observer at p sees an even or odd number of images of a light source in generic position reduces to the question of whether the degree of the lens map is even or odd. This observation can be used to prove that, under certain additional assumptions, a transparent deflector produces an odd number of images. The additional assumptions are satisfied, for example, if the gravitational field of the transparent deflector can be mathematically modelled as an “asymptotically simple and empty spacetime” in the sense of Penrose; roughly speaking, this means that the deflector can be viewed as isolated from all other masses in the universe. In the quasi-Newtonian formalism, the result that a transparent deflector produces an odd number of images is well-known. Here, however, this result is generalized to cases where the deflectors need not be weak perturbations of a uniform background and the deflection angles need not be small.

To get an intuitive idea of why a transparent deflector is expected to produce an odd number of images, whereas this number might be even for a non-transparent deflector, the reader should take a look at the two pictures on the right. The first shows the past light cone of an observer at some event p in a spacetime with a non-transparent deflector whose “world-tube” is indicated by the fat vertical line D. The second picture shows an analogous situation with a transparent deflector. In the first case it is geometrically evident that there are inextendible worldlines (of hypothetical light sources) that meet the light cone exactly twice. In the second case, however, all those worldlines have a third intersection with the light cone, owing to the additional sheet of the light cone consisting of lightlike geodesics that had been blocked by the deflector in the first case.

The second issue I want to mention goes under the heading “Morse theory”. This is based on the fact that in an arbitrary Lorentzian manifold the lightlike geodesics joining a point p (observation event) to a timelike curve g (worldline of a light source) are characterized by the following version of Fermat's principle: Among all (past-oriented) lightlike *curves*

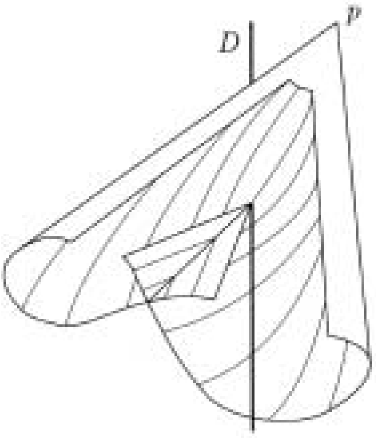


Figure 1: Light cone in a spacetime M with a non-transparent deflector. The light cone has a crossover line, but no caustic; D does not belong to M. Please note that the light cone is *not* a closed subset of M.

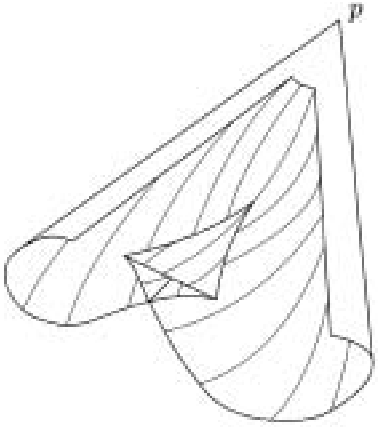


Figure 2: Light cone in a spacetime M with a transparent deflector. There is a crossover line and a caustic. The light cone is a closed subset of M.

from p to g the lightlike *geodesics* are of stationary arrival time. Here "arrival time" refers to an arbitrary parametrization of g and "stationary" means a minimum, a maximum or a saddle. Based on this variational principle, which was formulated by Israel Kovner in 1990, a Morse theory can be established. Quite generally, Morse theory relates the number of solutions of a variational problem to topological invariants (Betti numbers and Euler characteristic) of the space of trial maps. In the case at hand, the number of solutions to the variational problem corresponds to the number of images in a multiple imaging situation, and the space of trial maps is the space of lightlike curves from p to g.

The latter is a rather complicated infinite dimensional object, but at least for a certain class of globally hyperbolic spacetimes it can be shown that this space has the same Betti numbers and the same Euler characteristic as the loop space L(C) of a Cauchy surface C. (The loop space of a connected topological space is the space of continuous curves starting and ending at some fixed point. For homeomorphic to $\mathbb{R}^3$, S^3 , T^3, $S^1 \times S^2$ or similar standard examples the Betti numbers and the Euler characteristic of L(C) are well known.) For multiple imaging situations in a spacetime of this special class Morse theory allows to give lower bounds for the number of images in terms of the Betti numbers of L(C), and it says that this number is odd if and only if the Euler characteristic of L(C) is odd. This Morse theory for Fermat's principle has been established over the last years by Fabio Giannoni, Antonio Masiello, Paolo Piccione and myself. The future program is (a) to generalize the results to light rays in a medium, e.g. in a plasma, and (b) to work out special examples. On the latter point I am presently collaborating with Wolfgang Hasse.

Both issues mentioned so far refer to the phenomenon of multiple imaging. In the recent past I have also become increasingly interested in the phenomenon of image distortion. Quite generally, the focus of gravitational lensing theorists has shifted towards image distortion over the last years, triggered by rapid changes on the observational side with the recent advancement of CCD mosaic cameras. It is now possible to detect distortion effects by evaluating large samples of galaxies statistically. This method has become a major tool for probing (dark) matter in the universe. From a Lorentzian geometry point of view it is interesting to note that, in lowest order with respect to the distance between light source and observer, image distortion is completely determined by the Weyl tensor (conformal curvature tensor) at the observation event. In recent work with Thoralf Chrobok I have used this fact to classify image distortions in terms of the Petrov type of the Weyl tensor.

All three issues demonstrate that gravitational lensing, among other things, has the attractive feature of relating beautiful Lorentzian geometry to observable properties of the universe.

Volker Perlick

Oscillations and Stability of Black Holes and Rotating Relativistic Stars

Stars can be described by self-gravitating compressible fluids, or more roughly as “gas balls held together by gravity”. Perturbations lead to oscillations which, for instance, for the famous Cepheids result in periodical changes in brightness visible to the distant observer. In this way the oscillations provide important information about the internal stellar structure which is otherwise not easily accessible.

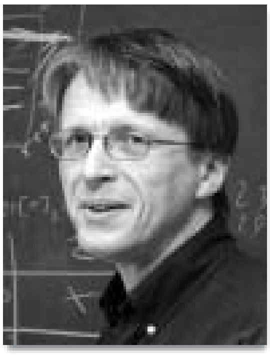
The study of these oscillations is an important and exciting field of classical and relativistic astrophysics. Through period-luminosity and period-radius relationships, variable stars provide important “yardsticks” for measuring distances in the universe. Recently, helioseismology and asteroseismology have provided otherwise unknown information about the internal structure of stars, while proposed gravitational wave asteroseismology promises to reveal the supranuclear equations of state for neutron stars. Finally, neutron star pulsations and instabilities may be a source of gravitational radiation detectable by the new generation of gravitational wave detectors, LIGO, VIRGO and GEO600 as well as by proposed detectors like EURO.

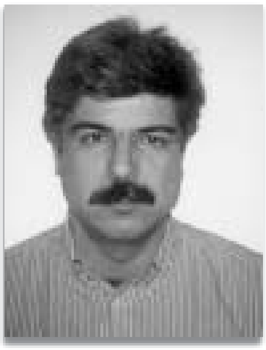
The adiabatic oscillations of spherical Newtonian stars can be expanded into a complete set of modes consisting of purely radial, spheroidal (or poloidal) and toroidal (or axial) modes. These last modes are connected to “trivial” rotations of the equilibrium model and contain no energy. In a relativistic treatment these oscillations are damped through gravitational radiation. In particular if the star is set into uniform rotation the Coriolis force acts as a restoring force for toroidal motions and the family of *r*-modes or Rossby waves appear. Recently it has been suggested by Andersson, Friedman & Morsink that these modes are generically unstable via the gravitational radiation induced CFS (Chandrashekhar-Friedman-Schutz) instability.

One of the basic predictions of General Relativity is the dragging of inertial frames around a relativistically rotating body. This dragging also influences the pulsation spectra of relativistic stars and seemingly in a more dramatic way for toroidal oscillations. Kojima suggested that if one calculates the *r*-mode frequencies using general relativity to lowest order in the angular velocity of the background star a continuous part occurs in the spectrum, in contrast to the calculations from Newtonian theory where the spectrum is “discrete”.
Spectra containing continuous parts have been found in many cases in the past in the study of differentially (= “non uniformly”) rotating fluids. The continuous part in these cases was again seen for the r-modes together with many interesting phenomena such as: the passage of low-order r-modes from the discrete into the continuous part as the differential rotation increases; and the presence of low order discrete *p*-modes in the middle of the continuous part for more rapidly rotating disks. The stars under consideration here have no differential rotation and the existence of a continuous part in the spectrum is attributed to the dragging of inertial frames due to general relativity.

The authors of this article jointly provided a rigorous proof of Kojima's suggestion. Note here that these values are in general not just eigenvalues as Kojima assumed, but mathematically analogous to spectral values associated with scattering states in quantum mechanics. Hence the associated “modes” cannot be assumed to satisfy usual boundary conditions. In the sequel, we dropped Kojima's slow motion assumption. The results here are still preliminary but very promising. They suggest that the continuous part is not an artefact of the slow motion approximation. But they also indicate a “discontinuous” dependence of the spectrum on the fact whether the underlying space is finite (accompanied by a boundary condition at a finite radius) or infinite. Of course nearly every numerical calculation necessarily has to assume a finite space. If this feature persists it will have important consequences on the methods to compute these values. Furthermore, recent numerical calculations indicate that the existence of a pure discrete *r*-mode is in question. Results by Ruoff and Kokkotas indicate that *r*-modes satisfying the usual boundary conditions exist only for neutron stars with a very stiff equation of state or for stars which are not relativistic.

Supported by many observations black holes are nowadays believed to exist in the center of nearly every galaxy and to be a significant part of the stellar population of each galaxy. All scenarios for the creation of black holes predict as the end product a Kerr black hole. Non-rotating (Schwarzschild) black holes are unlikely to occur, but it is only for these that linear stability under small perturbations has been proven. The important question whether the Kerr black hole is also stable is still largely open and a classical unresolved issue. Progress was made in this direction by applying an abstract mathematical framework based on semigroup methods which Beyer developed to describe oscillations of rotating stars. Within this framework the question of linear stability reduces to the purely mathematical question of whether the spectrum of a related operator polynomial is contained in the upper half plane of the complex frequency plane. Thus the problem is open to attack by purely mathematical methods. These methods usually avoid the use of “modes” because these are mathematically difficult to control and also difficult to define if they correspond to a value from a continuous part of a spectrum. Such a part is very likely to occur in the spectrum of the operator polynomial. Using this technique Beyer proved stability of the axial solutions of the Klein-Gordon equation on a Kerr background if the mass exceeds a given bound. Note that for smaller masses previous results suggest the existence of exponentially growing and hence unstable modes. Note also that for both the wave equation and the Teukolsky equations, there is a result showing the absence of exponentially growing mode solutions. Hence the results show a peculiar dependence on the mass of the perturbing field.





Finally, some mathematical remarks. All these questions, related to the spectra and stability of relativistic stars and black holes, lead to the problem of finding the spectrum of a linear operator, which is non self-adjoint in the case of a rotating star or if there is a dissipation mechanism like emission gravitational radiation. In contrast to the self-adjoint case for which there is a well developed spectral theory *a comparable theory does not exist for such operators*. The development of such a theory is still a major mathematical problem. As was the case for self-adjoint operators it may be necessary to a make a detailed study of many concrete special examples taken from applications from which such a theory can be abstracted. Unfortunately, this time such examples are not likely to be found in quantum theory, since there self-adjointness of the observables is a basic assumption. Fluid mechanics, astrophysics and especially stellar oscillation theory are playgrounds on which such problems can be found. Therefore the study of these operators deserves more mathematical attention. Such a study serves two purposes, first, better understanding of the physics of perturbed astrophysical bodies and second development of the spectral theory of non self-adjoint linear operators.

Horst Beyer & Kostas Kokkotas

Searching for Spinning Neutron Stars at the AEI

An international network of km-scale laser-interferometer gravitational wave detectors will be coming on-line in the next couple of years: GEO600 and LIGO will start engineering operation by the end of 2001, allowing observations with unprecedented sensitivity at frequencies ranging from a few tens of hertz to one kilohertz. We are optimistic that in the following years, they will achieve sufficient sensitivity to make the first direct detections of gravitational waves.

An important research effort in our group is the development of techniques for detecting continuous, nearly periodic gravitational wave signals. These sources form an interesting subclass of potentially detectable astrophysical objects, due to the possibility to improve the sensitivity of a weak periodic signal in noisy data by increasing the observation time. Spinning galactic neutron stars with a deformation misaligned from their rotation axis are good candidates for such sources. Several mechanisms may produce such deformation and hence lead to gravitational wave generation. Optimistic estimates suggest that both GEO600 and LIGO I could detect such objects with an observation time of the order of one year. Our group at the AEI has taken the lead role in the international effort to develop data analysis software for continuous, nearly periodic gravitational wave signals.

A neutron star with non-zero m=2 quadrupole moment produces gravitational waves at a frequency equal to twice its rotation frequency. If the star precesses, the gravitational waves will be produced at the inertial-frame precession frequency, which is very nearly the spin frequency. Neutron stars can be classified depending on their age [young (>40 yr) or old (>1000 yr)] and rotation frequency [slow (<200 Hz) or fast (<1000 Hz)], and different strategies can be pursued in order to search for them.

Frequency modulation due to the Doppler shift induced by the detector motions, and the intrinsic frequency variations due to the loss of angular momentum to gravitational waves, are two easily parameterizable examples of properties of a realistic signal that will dramatically increase the difficulty of the data analysis. In fact, for all but the simplest types of searches, the data analysis will be sub-optimal because of computational limitations. More complications are likely to arise if the source is located in a binary, due to the additional frequency modulation and possibly larger or random intrinsic frequency variations that are expected if the source is accreting.

These considerations have driven serious efforts among different groups to define data analysis schemes that would maximize the sensitivity of a search, given a maximal available computational power. The usual matched filtering analysis would be computationally prohibitive, and therefore non-practical, for all-sky searches over long time periods (longer than a few days), but nonlinear hierarchical strategies such as the stack-slide technique (developed at the University of Wisconsin, Milwaukee) or the hierarchical Hough transform algorithm, that is being developed and implemented at the AEI, are considered the best of all known techniques. The Hough transform is a well known technique in image processing for pattern-recognition. It was invented to assist particle physicists search for particle tracks in bubble-chamber photographs. It is called transform because it is indeed a transformation between the data and the space of parameters that describe the signal. The outcome of the Hough transform is a histogram in parameter space, and significant clustering in a pixel of parameter space indicates likelihood of the data containing a signal having the parameters of that pixel.

The hierarchical Hough transform search strategy that we are developing is an efficient and highly parallel computer algorithm. It consists of three basic steps:

- The initial data are segmented into shorter intervals, and their power spectra are constructed using a coherent method. For these shorter intervals, only a small number of points in parameter space have to be investigated.
- The Hough incoherent search over the total observation time to track the frequency evolution of peaks in the spectra, which is known in advance for some choice of the source parameters. This will be performed on a finer grid of the parameter space than the previous step.
- Finally, again a coherent search with a time-baseline that is a sizeable fraction of the total observation time, but limited only to those regions in parameter space “around” the candidates produced in the Hough transform stage.

This algorithm is of particular interest to the GEO600 project because it will be unique among the first interferometers in being able to operate in narrow-band mode which will give it better sensitivity to continuous, nearly periodic signals than the larger projects would have in the selected bands.

For the next annual report, we will be in a position to describe the first area surveys performed on preliminary and/or good quality data. Although there are lots of uncertainties, we are sure that this is going to be a very interesting year!

Alicia M. Sintes

The Lazarus Project: Gravitational Radiation from Black Hole Mergers

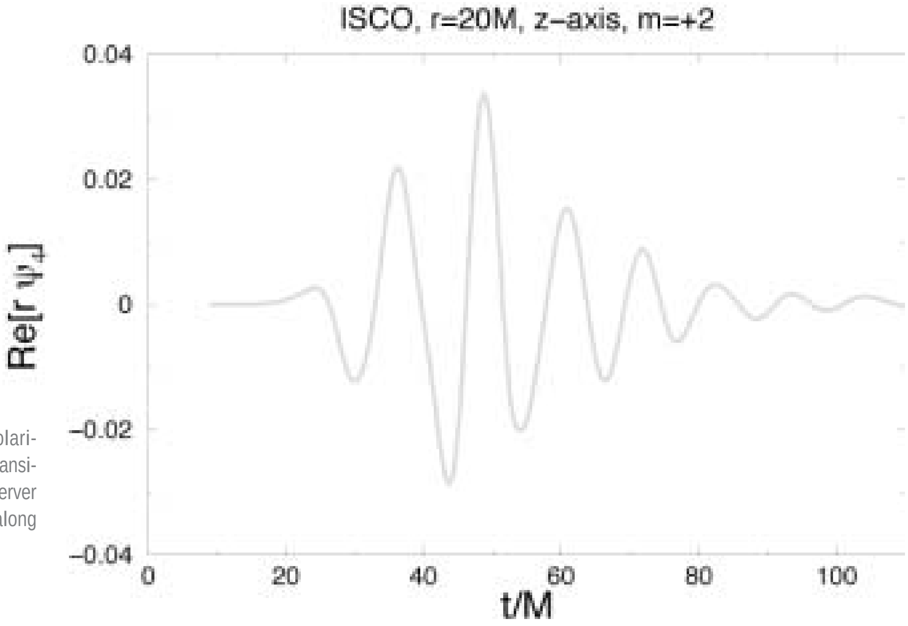
Black holes are the most interesting and peculiar objects predicted by Einstein's General Relativity. If black holes are common in nature then, because of their very strong gravitational field, they would capture each other to form binary systems. Black hole binaries can also result from the evolution of two stars that are born in a close binary and that eventually survive two supernovae. There is nowadays increasing astronomical evidence of black hole binaries in many galaxies, and some interesting simulations indicating that these systems may be commonly generated in globular clusters.

Binary black holes orbiting each other lose energy due to emission of gravitational radiation, spiral inwards, and eventually reach the innermost stable circular orbit (ISCO). This is a uniquely relativistic phenomenon, the point where gravity becomes so strong that circular orbits are no longer possible. The holes plunge together and merge violently into a final distorted black hole, releasing more energy than any other event in our universe. For this reason, black hole mergers are widely regarded as the most promising sources of gravitational radiation. New extremely sensitive gravitational wave interferometers (LIGO and GEO) are now nearing completion, and should begin taking scientific data in 2002. The extraordinary sensitivity of these devices should add soon gravitational waves to the very short list of media by which we can gain direct information about the cosmos, otherwise unobtainable from optical or radio astronomical observations. Listening to the universe via a new medium will enable the observation of otherwise invisible events, such as the merger of black hole–black hole binary systems. It is thus not surprising that on the theoretical side the study of binary black hole mergers became one of the most exciting and challenging topics in the whole astrophysically motivated relativity community.

Several theoretical approaches have been developed for treating these systems. The post-Newtonian approximation has provided a good understanding of the early slow adiabatic inspiral phase of these systems. When black holes are close enough to each other to sit inside a common gravitational well, one can apply the “close limit” approximation, developed by Price and Pullin in 1994, which effectively describes the whole system as a pertubation of a single (rotating) Kerr black hole which rapidly “rings-down” to stationarity. Before this last stage, though, when the black holes are still close to the ISCO, and the orbital dynamics is expected to change from inspiral to a rapid plunge and coalescence, no approximation method can be applied and one can only treat the system by a fully nonlinear simulation of Einstein's equations.

Intensive efforts have been underway in the past decade to write numerical codes able to solve Einstein's general relativity equations, by the use of powerful supercomputers (massively parallel computers). These equations are a very complicated set of 10, coupled, nonlinear partial differential equations which can be solved analytically only in very few cases where the spacetime symmetry helps considerably to simplify the problem. In the U.S., the efforts were primarily undertaken by a Grand Challenge collaboration and then continued in a number of groups, most notably in the Cactus code collaboration, led by Ed Seidel, at the Albert Einstein Institute (AEI). So far, the numerical treatment of black hole systems in full 3 spatial dimensions (3D) has proved to be very difficult and challenging because of the huge computer memory requirements, on one hand, and of very severe numerical instabilities, on the other, which make codes to fail before useful gravitational wave information can be extracted. In spite of such difficulties, important progress was made in 1999 at AEI, when a true 3D simulation based on the traditional 3 +1 decomposition of space and time has been successfully carried out for the so-called nonaxisymmetric "grazing" collisions of two black holes. However, these simulations must still begin too late in the plunge due to the limited evolution time achievable before the code become unstable. And in most of the cases, the close limit approximation theory represents a good alternative model for the late time dynamics of these systems.

Taking advantage of the above results, a group of people at AEI (John Baker, Bernd Brügmann, Manuela Campanelli, Carlos Lousto and Ryoji Takahashi) have pursued a new eclectic idea to the binary black hole merger problem, called the *Lazarus Project*. Motivated by the desire to provide gravitational wave observers with some estimate of the full merger waveforms and to guide future, more advanced numerical simulations, the Lazarus group has provided the first astrophysically plausible, theoretical predictions for the gravitational radiation waveforms and energy to be expected from non-axisymmetric binary black hole mergers starting from the ISCO.



ISCO waveform for one of the two polarizations of the gravitational field, for a transition time of T = 10 M, as seen by an observer located at radial coordinate r = 20 M along the orbital pole.

The underlying idea of the Lazarus project is very simple: apply the full numerical and close limit treatments in sequence, moving back the finite time interval of full nonlinear numerical evolutions to cover the earlier part of the plunge, where no perturbative approach is applicable. After this, compute the complete black hole ring-down and the propagation of radiation into the wave zone with a close limit perturbative treatment. The perturbative model not only allows an inexpensive and stable continuation of the evolution (which is then allowed to live again like the biblical Lazarus), but also supplies a clear interpretation of the dynamics not manifest in the generic numerical simulation. Clearly, the heart of the problem of the Lazarus approach has been the engineering of the transition interface between the full numerical simulations and the close limit approach. The details and difficulties of that task made what apparently seems an "obvious" step a real achievement.

In the Lazarus approach the numerical calculation start with black holes at the ISCO, which is at about three times larger separation than in the previous “grazing” collision cases. Once the gravitational field has evolved from the ISCO stage to the point at which an almost stationary Kerr horizon is formed, a transition (on a spacelike hypersurface) to the close limit perturbative evolution must be made. If the binary system has reached a regime where all further evolution can be described by the linearized Einstein equations (such as in the perturbative evolution), the final results should not depend on the choice of the transition time T. In practice, the transition must be neither too early nor too late. If the transition time is taken too early, the numerically evolved spacetime will not yet be a pertubation of Kerr. If the transition time is too late, the numerical code will become instable and the results are affected by numerical inaccuracies. To help deciding at what time one can start to make this transition, the Lazarus group also compute at a regular time interval of evolution a newly invented quantity, the speciality index S, a combination of curvature invariants, that is 1 for a single Kerr black hole spacetime, and provides a measure of the size of deviation from Kerr for any general numerical spacetime. This inherent feature of the Lazarus procedure is systematically used as a strong self-consistency test of the results. In the subsequent perturbative evolution, the dynamics can be described by a single complex scalar for the outgoing gravitational radiation field, the Teukolsky function, obeying a rather simple linear hyperbolic equation on a fixed Kerr background black hole.

During its development, the Lazarus method passed many tests. However, to better understand the new physics of the plunge the Lazarus group designed a set of sequences approaching the ISCO by varying one of its physical parameters. The resulting waveform for black holes mergers starting at the ISCO (Fig.1) presents a non negligible signal lasting for $t \sim 100\ \mathrm{G}M/\mathrm{c}^3$ for a system of total mass M. It is characterized by an early “ring-up” with increasing amplitude followed by the “ring-down” of the final Kerr black hole. This figure presents our first glimpse at what the radiation from a merging black hole binary might look like.

In the frequency decomposition of the waveform signals one can see a dominating component with a period close to the two most weakly damped quasi-normal oscillation frequencies of the final black hole. For a system with total mass 35 $M_\odot$, our two principal frequency components correspond to frequencies of roughly 600Hz and 900Hz, which are within the sensitive range of typical interferometric gravitational wave detectors.

The estimate for the total radiated energy after ISCO is 3 - 4% of the total black hole mass-energy, coming almost entirely along the polar direction to the orbital plane. This is larger than the 1.4% obtained by extrapolating post-Newtonian results and the 1 - 2% obtained by extrapolation of the close limit. Besides from the fact that the above numbers are very significant for the detectability of black hole mergers, this result also demonstrates that the full 3D numerical evolution was essential to describe the non-linear interaction of binary black holes. Concerning the angular momentum loss from the binary system, the Lazarus calculations give an estimate of around 1 - 2% for the total radiated angular momentum, confirming the expectation that not much angular momentum is lost during the plunge and ring-down, because higher frequency radiation carries angular momentum inefficiently.

In conclusion, with the Lazarus technology it has been possible for the very first time to study the fundamentally non-linear processes taking place during the final plunge phase of the collision of two well-separated black holes starting from the ISCO. Many follow-up projects are now possible like the study of different black hole initial data sets, such as black holes with spins and unequal masses, and the inclusion of a new interface between post-Newtonion inspiral calculations and full numerical simulations. The extrapolation of the Lazarus results so far support the idea that the transition from adiabatic inspiral to dynamical plunge at the ISCO is fairly gradual. To further explore such questions the Lazarus team has already planned to do a systematic study of several pre-ISCO configurations, with black holes at larger separations and/or larger transverse momentum than ISCO. For this reason, it will be very important to extend the useful duration of the numerical simulations with newer more stable numerical schemes. With Lazarus the expected improvements in AEI code stability that will be achieved in 2001 can quickly be turned into improvements in our understanding of the new black hole merger physics.

Manuela Campanelli

Gravitational wave research at the AEI

One of the activities in the Astrophysical Relativity Division is in supporting the development of gravitational wave detectors. This group, led by C. Cutler, concentrated in 2000 on the development of the computer-based search methods that will be used to analyse data from the detectors beginning in 2002.

Gravitational radiation is a prediction of Einstein's general relativity, that changes in the gravitational field should move through space at the speed of light. This radiation is not only interesting as a fundamental verification of the correctness of general relativity; it is a new window on the universe, a way to get information about astronomical objects that is radically different from normal astronomical observing. With gravitational waves we should for the first time “see” black holes directly; we may discover nearby objects, such as neutron stars, that are dark and invisible to optical telescopes; we should detect mergers of neutron stars in distant galaxies, and of giant black holes anywhere in the Universe; and we should eventually detect gravitational radiation from the first instant of time, a tiny fraction of a second after the Big Bang.

Gravitational waves have been indirectly detected by observing the slow spiralling together of two neutron stars, caused by their loss of orbital energy to gravitational waves. This observation, made with radio telescopes because one of the neutron stars is the pulsar PSR 1913+16, won the Nobel Prize in Physics in 1993 for the discoverers of the system, Russell Hulse and Joseph Taylor. The inspiral rate matches exactly the predictions of Einstein's theory, so we have confidence that the theory is correct.

Nevertheless, we have not yet detected the waves. They are weak and have been beyond the reach of technology. But today there are four detectors under construction around the world that could in principle achieve the sensitivity required for making regular detections. Two projects may, if all goes well, turn on their detectors early in 2002: GEO600 and LIGO. GEO600 is under construction near Hannover. The Director of the Astrophysical Relativity Division, B Schutz, is the Principal Investigator with responsibility for data acquisition and analysis. Work in these areas for GEO is shared between the AEI and Schutz's former group at Cardiff University, Wales, where Dr B Sathyaprakash now leads the research. GEO600 is an interferometer with 600-m long arms, which uses very advanced optical techniques to achieve sufficient

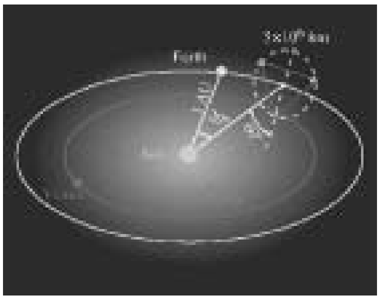
The aerial view clearly shows the general configuration of the Michelson-type interferometer. The vacuum tubes containing the 600-m interferometer arms are suspended inside a roofed trench by a wire pendulum from rollers running along a rail.

sensitivity. LIGO is an American project building two interferometers with 4-km arms and one with 2-km arms. With their greater size, these detectors can employ a more conservative optical design to achieve roughly the same expected initial sensitivity as GEO600. It is planned that a future upgrade to the LIGO design will be made in partnership with GEO; marrying the advanced GEO optics with the larger LIGO size should improve sensitivity by a factor of 10 or more over these first instruments. A further 3-km instrument is under construction in Italy; called VIRGO, it could begin operations about a year after LIGO and GEO. It will incorporate some GEO-designed components from the start.

The laser beam runs through an evacuated tube in order to avoid perturbations from air pressure fluctuations. The vacuum tubes of 60 cm diameter and 0.9 mm wall thickness are suspended in a trench.

In addition, AEI scientists are members of the LISA team, which is managing the European Space Agency (ESA) project to place a large gravitational wave detector in space, in orbit around the Sun, an interferometer with arms 5 million km long. During 2000 ESA confirmed the status of this project as one of its Cornerstone Missions, and agreed to develop it jointly with the American space agency NASA. The AEI hosted the Third International LISA Symposium in July 2000. This is described elsewhere in this report.

Once the various interferometers are built, detecting gravitational waves will still not be straightforward. Their sensitivity will depend on how effectively the data are analysed. The signals will be weak and buried in instrumental noise. Sophisticated pattern-recognition techniques must be used to recognize the signals. During 2000 the AEI group focussed on incorporating our current understanding of expected signals into its search program. This understanding came about from research at the AEI in earlier years, from the numerical simulations of the Lazarus Project described in a separate article, and from much work done elsewhere.



The current LISA mission plan calls for three satellites in individual solar orbits forming a stable equilateral triangle. They are connected by the 5 million km long laser beams forming the interferometer arms.

Using this information in computer-based searches is itself a challenging task. In addition, the data from detectors must be prepared for analysis: its quality must be verified and known instrumental artefacts removed. Preparations for these twin tasks occupied most of the energy of the group. Much of this work is undertaken in close cooperation with scientists in the LIGO Science Collaboration, and the main data-analysis system is being created cooperatively by the two projects. During 2000, the AEI was pleased to host a 6-month visit by Prof. Bruce Allen of the University of Wisconsin at Milwaukee, one of the leading US scientists in the LIGO data-analysis software development effort.

The AEI group tested and released to LIGO its Coherent Demodulation Code, a new kind of software for performing optimally-sensitive searches for long-duration signals. It approximates a method called the Fast Fourier Transform (FFT), on which much signal analysis is based. The new software is designed to work with data that is too large to fit on a single computer processor, but must be analysed on parallel computer systems. It achieves effectively the same result as the FFT, but much more rapidly on loosely-coupled computer systems called clusters. These are much cheaper than supercomputers like the AEI's Origin, and so the Coherent Demodulation Code will allow large signal-analysis applications to achieve their results much more cheaply. The group is now preparing the code for a general public release in 2001.

There is a website for the code at
http://www.aei.mpg.de/research/grawave/projects/cohtrans.html

Another software method devised by the group is called the Hough Transform. It allows long-duration searches to be extended beyond the limit where the Coherent Demodulation Code (or the FFT) would be beyond the resources of a given computer system. This will happen for gravitational wave searches looking for pulsars in stretches of data longer than a day. In fact, astronomical evidence suggests that we must accumulate data over periods of several months or even years in order to find these ultra-weak gravitational waves. The Hough Transform is an elegant pattern-searching technique on which a hierarchical search using the Coherent Demodulation Code can be built. The Hough Transform made considerable progress in 2000 through a collaboration with computer scientists from CASPUR at the University of Rome. It will be delivered to LIGO during 2001. This is more fully described in the article “Searching for spinning neutron stars at the AEI”.

One of the most difficult problems in data analysis is to prepare for the unexpected. How will we recognize and interpret signals from sources that we did not anticipate? Can we develop methods to enhance our sensitivity, based on an incomplete anticipation of the structure of the signals? In 2000, AEI scientists continued their work on new time-frequency methods that could do this. The group in addition continued developing its software to recognize and remove interference from “raw” gravitational wave data before it is processed through our detection software.

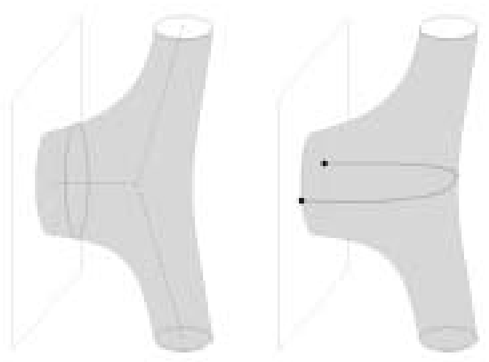
Planning continued for integrating the different components of the GEO data analysis and data archive systems: hardware, communications/networking, software. We acquired the first 10 computers of our eventual cluster computer system at the end of 2000. We will wait until the last minute to enlarge the system, to take advantage of regular increases in processor speeds. We advanced our plans to store the GEO data archive at the Konrad Zuse Center in Berlin.

LIGO and GEO are planning to take joint “engineering” data at reduced sensitivity midway through 2001, which should test our computer systems to the full, and which could in fact be the most sensitive search for gravitational waves undertaken so far. With that exercise just around the corner, and full-sensitivity data expected a few months later, we are looking forward to 2001 with considerable anticipation.

Bernard F. Schutz

Strings, Branes, and Non-commutative Geometry

The old proposal that space-time is modeled by general relativity seems to run into severe problems when we try to combine it with our usual descriptions of short distance physics. This has lead to the idea that general relativity should only be applied to large distance physics and that it has to be replaced by a more fundamental theory in order to capture the behavior of space-time at small scales. (Super-)string theory provides one possible candidate for such a fundamental theory. Its basic objects are closed strings. They have many different vibrational modes out of which one can be identified with the graviton. Investigations of (super-)gravity theories predict interesting objects which have a mass that is distributed along some higher dimensional surface in spacetime. These objects are called branes and they are somewhat similar to black holes, only that they may be stretched out in several directions so that they could look like walls in space-time. Once we decide to replace gravity by a more fundamental model, such as string theory, we are facing the obvious task to identify and study branes within the new theory. As we mentioned before, branes are massive objects and hence they interact with other (massive) objects through exchange of gravitons. In particle physics, such a process could be described by the dashed lines in the figure below. String theory suggests to replace all the lines by cylinders which keep track of closed string's motion in space-time. Hence, we now see a closed string coming in from far away, hitting another closed string that is emitted from the brane (possibly describing a graviton) and being deflected before it escapes back to infinity. We have depicted this scenario on the left hand side of the following figure.

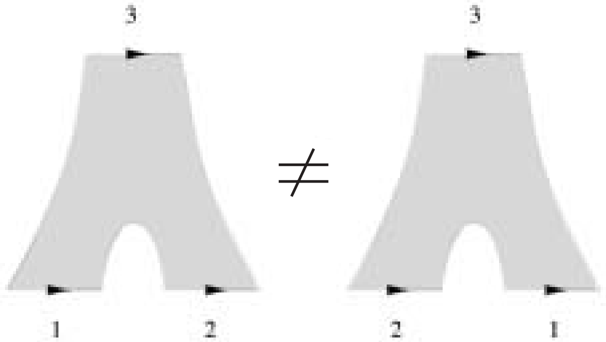


It is a crucial observation that the same picture admits for a very different interpretation illustrated on the right hand side. This starts once more from a closed string falling in on the brane. At some instant the closed string opens up into an open string which has both its ends attached to the brane. The configuration of a brane with an open string attached to it may be considered as an excitation of the brane which decays later by sending off a closed string. The second interpretation implies that branes in string theory are *objects on which open strings can end*.

In trying to incorporate branes into string theory, open strings have entered the stage. These open strings are free to move around except that their end-points are not allowed to lift off from the brane. If we look at such open strings from far away (or at low energies) they appear as particles moving along the brane and their behavior can be encoded in a field theory living on the surface on which the brane in localized. The field theories which arise in this way are gauge theories with matter, somewhat similar to the models we use in high energy physics. This opens an interesting possibility to consider many of the known particles (e.g. electrons, photons, etc.) as vibrational modes of an open string.

Actually, there can be several different branes in space-time and we can combine them into numerous configurations. Their open string excitations give rise to field theories whose properties (such as their particle content or the amount of super-symmetry) depend drastically on the brane configuration we choose to consider. Not all of these models are conventional field theories. It turns out that the resulting models may live on a “quantized” or “non-commutative” surface.

To explain these notions is beyond the scope of this text. But at least we want to convince ourselves that open string scattering amplitudes indeed have some property which seems somewhat difficult to accommodate in conventional particle physics. For this purpose we consider two oriented open strings, named “1” and “2”, that combine into a single open string “3”. Obviously, there are two diagrams which we can associate to this process. They differ by the order of “1” and “2” as shown in the following picture.



The two diagrams are not related by any deformation or symmetry except from being mirror images of each other. Consequently, in a world which is not symmetric under passing to its mirror, there is no reason for string theory to assign the same number to these two diagrams. Computations in string theory show that there are indeed many examples in which the scattering amplitudes change upon changing the order of the incoming open string states. This property of the amplitudes is obviously related to the fact that open strings are extended objects. We can only capture it in particle physics by allowing for so-called “non-commutative” field theories.

In collaboration with scientists in Uppsala (Sweden) and at Rutgers University (USA) we have developed techniques to compute the field theories describing open strings ending on branes and we have obtained various different types of ordinary and non-commutative field theories. Since open strings arise as excitations of branes, their behavior can provide important insights on the branes themselves. One may compare this to the spectrum of excitations in an atom being the key towards understanding atomic physics. Our investigations of open strings and their field theories revealed new aspects of brane physics. To give just one example, we identified processes in which brane worlds can dynamically grow new dimensions, provided they are placed in a curved region of space-time. It is the hope that such studies will ultimately show how to embed realistic particle models into string theory and, hence, how to unify all known interactions.

Volker Schomerus

Strings, Supergravity and Gauge Theories

Before the advent of non-abelian gauge theories, string theory had been developed as a theoretical framework that should bring order into the zoo of the numerous hadronic resonances which were found in experiments at the time, more than thirty years ago. Soon is was realised that string theory is a more suitable candidate for a theory of quantum gravity and it has mostly been developed with this goal in mind. The last major jump in our understanding of string theory occurred when it was discovered that various string theories that had hitherto been considered as completely separate are in fact related by so called duality symmetries. For this insight it was necessary to go beyond perturbation theory, which is the framework commonly used in all areas of theoretical physics when a problem cannot be solved exactly. Going beyond perturbation theory, which is e.g. necessary if one wants to consider strongly interacting theories, is difficult since the strongly coupled theory often has little resemblance with its weakly coupled and well understood counterpart. In the context of string theory one found that one has to consider, in addition to strings, also so called branes as dynamical objects (see the contribution of Volker Schomerus).

If one only wants to study the gauge theories whose particle excitations - as they arise from open strings - are confined to live on the brane, one has to decouple gravity which, via emission of closed strings, constitutes the interaction with the surroundings of the brane. One can study this decoupling limit in both appearances of the branes, as gravitating solutions of the supergravity equations of motion and as objects on which open strings can end.

Doing this carefully one makes the surprising observation that there is a duality between a string theory which, in this limit is well approximated by a supergravity theory, and a gauge field theory without gravity. Furthermore, while the gauge theory lives, in the simplest but also most interesting version, in a four-dimensional space-time, the string propagates in a ten-dimensional spacetime. The validity of the approximations made, which lead to the identification of this duality pair, demands that the string theory is weakly coupled and fixes the shape of the spacetime geometry through which the string moves and also requires it to have small curvature.

The most interesting observation is now that this range of parameters, weak string coupling and small curvature, translates in the dual gauge theory to strong gauge coupling and large number of colour degrees of freedom. Strongly coupled gauge theories are of great interest - after all QCD, the theory of the strong interaction is, at low energies, a strongly coupled gauge theory which we need to understand if we ever want to be able to compute the spectrum of mesons and baryons and to explain the phenomenon of confinement.

If one can make the duality between a strongly coupled gauge theory and a weakly coupled string theory precise, one is able to compute strong coupling effects in the gauge theory via the detour of a weakly coupled string theory, where perturbative methods are applicable.

An amusing aspect of this duality is that it realizes one of the original motivations for string theory, namely to explain the strong interactions between quarks, albeit in a surprisingly different way. In both pictures does the string bind the quark and anti-quark at its two ends to a meson. While the naive idea was that the string connects the two particles like a spring which tries to minimize its length (figure a), the duality between

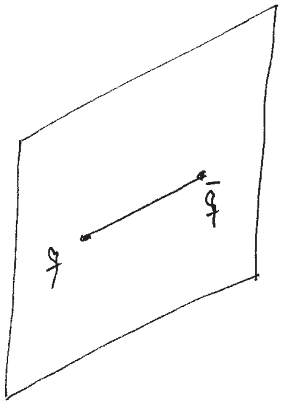


Figure a:
4-dimensional Minkowski space-time

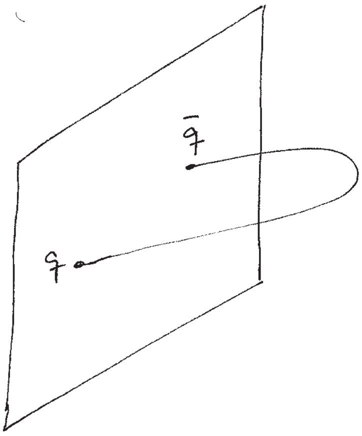


Figure b:
4-dimensional Minkowski space-time
String connects q with q̄ via "detour"
through higher dimensional space-time

a four-dimensional gauge theory with a higher dimensional supergravity theory leads to a different picture (figure b): the string which connects the two particles now extends into the additional dimensions. In fact, given the curved geometry which corresponds to the brane solution of the supergravity equations of motion, this is again the shortest distance; the picture, which is drawn on a plane piece of paper, cannot correctly convey this. Before one can use this unexpected duality to explore strongly coupled gauge theories one has, one the one hand, to identify which aspects of the string theory correspond to interesting physical quantities, such as e.g. the inter-quark potential or the baryon masses on the gauge theory side. On the other hand one has to find means to test the duality, explore its range of validity and, if possible, extend it. This is necessary, since in its original version it only applies to a maximally supersymmetric version of QCD, which is certainly not realised in nature. In addition, the number of colour degrees of freedom is three but the duality assumes it is large. Corrections have to be computed which will require the full string theory rather than its supergravity approximation. Once these steps are successfully done one can use the duality as a reliable tool to do computations in the strongly coupled gauge theories.

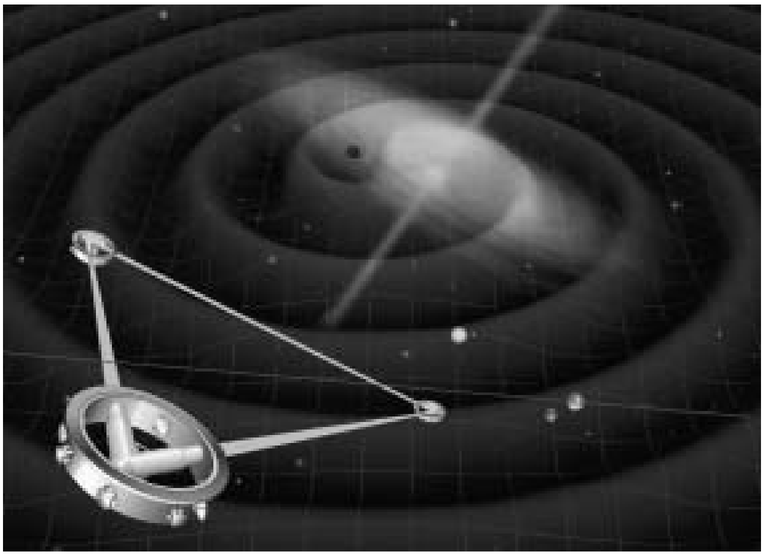
A major part of our work during the past years was concerned with these issues: testing and extending the duality, making predictions about the gauge theories and, if possible, find independent means to test them. While working on these issues we found interesting and unexpected features of supersymmetric gauge theories. Even though they could be partially verified within the gauge theory, they would have been very difficult to find there directly and, in fact, had first been found via the dual supergravity theory. In another project we made first steps to connect the predicted result of the inter-quark potential at strong coupling to the known result at weak coupling by computing the leading quantum corrections. We also found interesting manifestations of higher dimensional space-time symmetries in the dual lower dimensional field theories.

While many difficult questions are still waiting to be answered before we can use string theory to make experimentally verifiable predictions, the developments in the recent past, of which the duality between a gauge theory without gravity and a gravity theory is one of the most surprising ones, have opened up new alleys along which the solutions to some of the as yet unexplained secrets of nature might be found.

Stefan Theisen

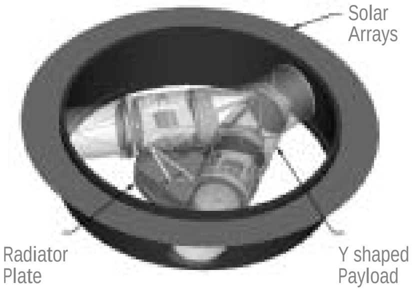
3rd International LISA Symposium

The 3rd International LISA Symposium was held here at the AEI on July 11-14, 2000. LISA is a proposed satellite mission to detect gravitational waves. It is essentially a space-based version of the kilometer-scale laser-interferometer gravitational wave detectors that are now coming online: LIGO, VIRGO, GEO600, and TAMA300. However LISA's sensitivity band differs substantially from the ground-based detectors; LISA will be sensitive to waves in the millihertz to 0.1 Hz range, while the ground-based detectors look for waves in the 10 to 1000 Hz range. Correspondingly, LISA will look at a different set of astronomical sources.



An impression of the current LISA configuration.

LISA would assuredly detect thousands of short-period binary star systems in our own galaxy. More excitingly, there is a good chance it would detect mergers, in cosmologically distant galaxies, of supermassive black holes (SMBH's) weighing millions of solar masses. (LISA could definitely "see" the mergers if they occur, but the merger rate in the observable universe might be as low as once per hundred years - or it could be as high as several hundred per year.) LISA could also detect compact stars spiraling into such SMBH's. And it would look for a cosmological background of gravitational waves produced in the Big Bang. (The gravitational wave background predicted by standard inflationary scenarios is too weak for LISA detection, by a few orders of magnitude, but some other scenarios yield detectable gravitational wave backgrounds.)



The current LISA mission plan calls for a constellation of three satellites to be placed in orbit around the Sun. The satellites are at vertices of an equilateral triangle, whose arm lengths are five million kilometers. The constellation follows the Earth around the Sun, trailing behind the Earth by twenty degrees to minimize the Earth's gravitational influence. Gravitational waves will cause the distance between satellites to oscillate by roughly one billionth of a centimeter. These tiny displacements are measured by laser beams bouncing back and forth between the satellites. The satellites will use drag-free technology to compensate for deflections by the solar wind, which would otherwise swamp the gravitational wave signal. The total cost of LISA is estimated at 500 million Euros. A detailed description of the LISA Mission, the recent LISA STS Report, is available online at *ftp://ftp.rzg.mpg.de/pub/grav/lisa/sts_1.02.pdf*.

If LISA flies, it will probably be as a joint European/American (ESA/NASA) mission, with launch around 2010. It was important that LISA did very well in the recent U.S. Taylor/McKee decadal review of

Astronomy, being the second-highest ranked "moderate" sized mission. But before LISA can get final approval, there probably needs to be a much smaller, technology demonstrator mission (launched, one hopes, around 2005-6) with the goal of demonstrating drag-free performance within one order of magnitude of the LISA requirement.

LISA Symposia are being held every two years, with venues alternating between Europe and the U.S. The first LISA Symposium was held at RAL, near Oxford, in July, 1996; the second was held in July, 1998 at Caltech. The main organizing bodies for the 3rd LISA Symposium were the MPI für Gravitationsphysik and the MPI für Quantenoptik. There were about 100 participants. The Symposium proceedings will be published as a special issue of Classical and Quantum Gravity in July, 2001. There were about 50 talks, plus an evening session of lectures for the general public. The public lectures, given by S. Phinney (California Institute of Technology) and G. Hasinger (Astrophyical Institute Potsdam), drew an audience of about 150 from Potsdam and Golm. I will mention here just a few of the highlights of the scientific talks.

S. Phinney of the California Institute of Technology reported his estimates for the merger rate for supermassive black hole binaries (SMBH's), based on a hierarchical clustering picture of structure formation, where small galaxies form first and merge to form bigger galaxies. This picture leads to estimates of event rates of 0.1 to 10 per year, for million solar mass BH's out to a cosmological redshift of z=2. (Astronomers use this yardstick over cosmological distances. An event taking place at a redshift of 2 happened when the Universe was roughly 10-20% of its present age. Its gravitational waves have been traveling to us ever since then.) But, importantly, LISA can see far beyond z=2; Phinney argued that the LISA event rate could be one per day out to z=20.

J. Armstrong and M. Tinto (of JPL) discussed their very important work (done with F. Estabrook), showing how one can (with some changes in hardware) linearly combine the LISA data streams, with time delays, to form three linearly independent combinations for which the laser phase noise exactly cancels. Two combinations contain information on the two gravitational wave polarizations, and the third describes a "breathing mode" that doesn't couple to gravitational waves. This third mode can be used to help calibrate and eliminate noise sources, and to discriminate between non-Gaussian noise bursts and real gravitational wave bursts.

S. Hughes (California Institute of Technology) discussed solar-mass compact objects spiraling into SMBH's. He showed that when the SMBH is nearly maximally rotating (as is expected in Nature), the inspiral is strongly affected by scattering of gravitational waves from the BH horizon. The result is to "hold up" the inspiraling body and significantly increase the inspiral time.

Large extra dimensions (perhaps as large as 0.3 mm) are now much-discussed in string theory, and C. Hogan (University of Washington) showed how these might lead to a gravitational wave background observable by LISA. He argued that the early universe should produce copious gravitational waves with wavelength comparable to the size of the large extra dimension, which would be redshifted into the LISA band today. Something new for a LISA Symposium: there were several talks describing laboratory prototypes for LISA systems. H. Ward (Glasgow University) discussed his work on developing an interferometric read-out system. He also reported on tests of how well hydrogen catalysis bonding of optical elements would survive the rigors of launch and space - and

Beaming LISA participants pose for posterity - from left to right:
Sterl Phinney, Rüdiger Reinhard,
Karsten Danzmann, Bernard Schutz, Bill Folkner,
Thomas Prince

Karsten Danzmann (middle) fixing up a GEO600 mirror for the exhibition accompanying the symposium, assisted by Axel Hammesfahr (left) of ASTRIUM and Peter Westermaier, a member of the campus staff.

found the bonding held quite well under shaking and thermal cycling. O. Jennrich (Hannover University) described his experiment showing the feasibility of the LISA phase measurement scheme, using the same amount of light as will be available for LISA. M. Rodrigues described a laboratory prototype for the inertial sensor, and S. Vitale (Padua University) described a torsion pendulum test bench he is building to testing the performance of the inertial sensor. Michael Petersheim (Hannover University) discussed a prototype for the highly stable laser required by LISA. As Jennrich said, "LISA is now more than just ink on paper."

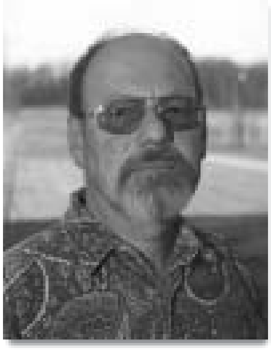
Curt Cutler

Symposium Honoring 70th Birthday of Jürgen Ehlers

On February 18 in 2000, a symposium in honor of Jürgen Ehlers took place to celebrate his 70th birthday. About hundred colleagues, friends, old and young collaborators and former Ph.D. students came to Golm. There was quite some excitement when they met in front of the lecture hall – some of the old friends had not seen each other for decades. The morning session was opened by Abhay Ashtekar of PennState University with a talk on “A Relativist's View of Quantum Gravity”. The second talk was “String Theory and Gravity” by Thibault Damour, Institut d'Hautes Etudes Scientifiques at Bure.

Scientists from all over the world travelled to Golm to honour the father of modern German relativity research

Before lunch break a monograph “Einstein's Field Equations and Their Physical Implications - Selected Essays in Honor of Jürgen Ehlers” - edited for the celebration by B.G. Schmidt, was presented to Jürgen Ehlers by Jirí Bičák from Charles University at Prague. With his well known sense of humour he gave a description of the book's contents, adding some personal remarks. The afternoon session started with “GHZ States and a simple Proof of the Kochen-Specker Theorem” by Norbert Straumann, ETH Zürich. He was followed by George Ellis, University of Cape Town, who spoke on “Relativistic Cosmology - Achievements, Problems and Prospects.” The last talk was “Gravitational Lensing as a Tool to see dark Matter” by Peter Schneider, Max Planck Institute for Astrophysics in Garching.



At the reception that followed more friends joined the company. Dinner was served in the nicely decorated cafeteria. After dinner Engelbert Schücking, New York University, gave a highly appreciated talk on his personal memories of Ehlers' scientific and semi-scientific life. Professor Hans Zacher, who was the President of the Max Planck Society when the AEI was founded, valued the role of Ehlers in the foundation process; he made it quite clear that without Ehlers accepting the responsibility the AEI would not exist today. For the next morning, Ehlers had invited to a seminar to discuss certain problems of Gravitational Physics. About 30 participants had come, and a very lively two-hour-discussion took place.

Bernd Schmidt

Jürgen Ehlers: Work and Style

In the 1950s the mathematical department of Hamburg University, with its stars Artin, Blaschke, Collatz, Kähler, Peterson, Sperner and Witt had a strong drawing power for Jürgen Ehlers, student of mathematics and physics. Since he had impressed his teachers he could well have embarked on a distinguished career in mathematics had it not been for Pascual Jordan and - I suspect – Hermann Weyl's "*Space-Time-Matter*". Jordan had just published his book "*Schwerkraft und Weltall*" which was a text on Einstein's theory of gravitation, developing his theory of a variable gravitational "constant". Only the rudiments of this theory had been formulated and Jordan, overburdened with countless extraneous commitments, was eager to find collaborators to develop his theory. This opportunity to break new ground in physics enticed Jürgen Ehlers and Wolfgang Kundt to help Jordan with his problems, and their work was acknowledged in the 1955 second edition of Jordan's book.

It didn't take Jürgen, who always was a systematic thinker, long to realize that not only Jordan's generalization but also Einstein's theory itself needed a lot more work. This impression was well described by Kurt Goedel in 1955 in a letter to Carl Seelig: "My own work in relativity theory refers to the pure gravitational theory of 1916 of which I believe that it was left by Einstein himself and the whole contemporary generation of physicists as a torso - and in every respect, physically, mathematically, and its applications to cosmology".

When asked by Seelig to elaborate, Goedel added: "Concerning the completion of gravitational theory of which I wrote in my last letter I do not mean a completion in the sense that the theory would cover a larger domain of phenomena (Tatsachenbereich), but a mathematical analysis of the equations that would make it possible to attempt their solution systematically and to find their general properties. Until now one does not even know the analogs of the fundamental integral theorems of Newtonian theory which, in my opinion, have to exist without fail. Since such integral theorems and other mathematical lemmas would have a physical meaning, the physical understanding of the theory would be enhanced. On the other hand, a closer analysis of the physical content of the theory could lead to such mathematical theorems".

Such a view of Einstein's theory was also reflected in the talks and discussions of the "Jordan Seminar". This was a weekly meeting of Jordan's coworkers in the Physics Department of Hamburg University to discuss Jordan's theory of a variable gravitational scalar. However, under Jürgen's leadership, the structure and interpretation of Einstein's original theory became the principal theme of nearly all talks. Jordan, who found little time to contribute actively to his theory, reluctantly went along with this change of topic. Through grants from the US Air Force and other sources he provided the logistic support for his research group. For publication of the lengthy research papers on Einstein's theory of gravitation by Ehlers, Kundt, Ozsvath, Sachs and Trümper, he made the proceedings of the Akademie der Wissenschaften und der Literatur in Mainz available. Jordan appeared often as coauthor, but I doubt whether he contributed much more than suggestions in style, like never to start a sentence with a formula. Some results were also written up as reports for the Air Force and became known as the Hamburg Bible.

It was a principal concern in Jürgen's contributions to Einstein's theory to clarify the mathematics, separate proof from conjecture and insist on invariance as well as elegance. This clear and terse style, which always kept physical interpretation in mind, appeared already in his

Hamburg papers. His work in relativity resulted not only in books, published papers, supervised theses, critical remarks in discussions and suggestions for future work. By establishing the Albert Einstein Institute Jürgen designed a unique international center for research in relativity. As the founding director of this “Max Planck Institute for Gravitational Physics” in Brandenburg, he has led it to instant success. Through his leadership, research on Einstein's theory in Germany is flourishing again and his work and style has set a standard for a whole generation of researchers.

Engelbert Schücking, New York University

Conference at the Mathematical Research Institute, Oberwolfach

In July 2000, together with Gerhard Huisken (Tübingen) and Jim Isenberg (Oregon), Alan Rendall (AEI) organized a conference entitled “Mathematical Aspects of Gravitation” at the Mathematical Research Institute in Oberwolfach in the Black Forest. A number of other scientists from AEI made important contributions to the success of the meeting.

The institute in Oberwolfach is very well known to mathematicians but less known outside mathematics and so it seems appropriate to say a few words about it here. In Oberwolfach there is a conference on some mathematical topic in each of fifty weeks of the year (and often more than one). These conferences are international in nature and not confined to attracting only German or European participants. Despite the large number of conferences the competition for getting a slot in the programme is intense, with less than half the proposals being accepted. Thus we were happy that we succeeded in getting a meeting on the subject of mathematical relativity into the programme. Among the advantages of Oberwolfach as a venue is the fact that the participants can all live and eat together in the institute, an arrangement which tends to maximize scientific interactions. The institute has one of the best mathematical libraries in Germany. In addition the prestige of Oberwolfach and the excellent conditions there mean that mathematicians who are in demand to take part in many meetings are motivated to attend events there.

Library of the Mathematical Research Institute in Oberwolfach in the picturesque Black Forest

The purpose of the conference was to promote the exchange of information between relativists working on mathematical problems and mathematicians with interests in analysis and differential geometry which can be applied to general relativity. In view of this the number of talks was severely limited - less than half the participants gave a formal presentation - and the speakers were encouraged to give expository lectures. The conference was organized around four main topics. The first was the theory of asymptotically flat spacetimes which is the mathematics underlying the study of gravitational waves. The second was wave maps and critical collapse, a key area for the interaction between general relativity and the theory of hyperbolic partial differential equations. The third was spacetime singularities, a central theoretical topic in mathematical relativity theory. The last was connections between Riemannian geometry and general relativity.

My own impression, and the feedback I got from other participants, was that information flowed very effectively during the conference and that a lot of networking between scientists from the two disciplines involved took place. We hope to repeat the experiment in a few years time.

Alan Rendall

"A moment in the Pseudosphere" - Márton A. András

In his work, hungarian painter Márton A. András focuses on physics and mathematics, on the visible and the invisible universe. What better location for an exhibition of his paintings than an institute focusing on relativistic research? The LISA Symposium seemed an ideal venue for an attempt to paint a "larger picture" of science – to see physics through the eyes of an inspired artist. After being officially opened the evening before the conference, the exhibition in the central campus lobby was an instant success with groups of conference visitors and local scientists and staff clustering in front of the individual paintings and discussing their finer points.

Variation auf A.R. - Acrylic on canvas
Márton András, 2000

Traktrix - Acrylic on canvas
Márton András, 2000

Márton A. András is a master of the minimal: his paintings are of an austere elegance, their message is composed with almost aphoristic economy – reminiscent of a succinct mathematical theorem. Black or white lines cross the canvas and form contours reminding the beholder of atavistic cave paintings as well as exacting geometric constructions. Everyday phenomena such as light and shadow, space and forms of a simple architecture , letters, numbers or lines meet theoretical-physical metaphors. The universe of physical, real objects meets the dimension of abstract physics on a plane of execution blurring the division between method and medium i.e. paint and canvas. Content and structure, surface and depth merge – form becomes sign.

It is not a coincidence at all that Márton András feels committed to Paul Klee's paintings and philosophy – "exact science" and "pure poetry" meet in his works as well in an almost scrupulous unity.

Susanne Milde

Through the Eyes of a Visitor

I have been assistant of Hellmut Baumgärtel (Chair: Mathematical Physics I) at the Mathematics Department of the University of Potsdam until December 1999. Our group with interests in Operator Algebras and Quantum Field Theory has had regular scientific exchange with the AEI during these years. We have invited several of its members to our 'Oberseminar' and to the workshops we organized in 1998 and 1999.

Other groups in the Maths Department, with interests in Partial Differential Equations (Markus Klein/Elmar Schrohe/Bert-Wolfgang Schulze), have also been working with the AEI. I did participate as well in their joint seminar organized together with the mathematical relativity group (Helmut Friedrich/Bernd Schmidt). Thus my move as a postdoc to the mathematical group of the AEI in January 2000 was in many respects a local one. For example it implied the shift of my office within the same neighborhood from Sanssouci to Golm. Hence to get to my new job I just had to get off at the next train station. Moreover my main project at the AEI (together with Wolfgang Junker) was to use techniques from micro-*local* analysis to define and construct physically meaningful states for the electromagnetic vector potential quantum field on a gravitational background. (By the way, in this context the notion of *Einstein-locality* plays a distinguished role.)

But remaining within the same *local* neighborhood does not mean that there were no changes. On the contrary, in my situation I could appreciate much more the changes that are due to the Institute itself, since being a *local* visitor I was less distracted by the pleasant countryside, the unique Sanssouci park or the many cultural attractions of Berlin and Potsdam. Admittedly, one of those unexpected distractions were the amazing Golm-mosquitos that in summer started to look for dinner around 6pm. I remember the professional capability and friendliness of the staff of the administration as well as of the computer support during my first days at the AEI. One of my duties at the Maths Department has been to supervise the *local* library at the Chair Mathematical Physics I, so that, as an amateur librarian, I was very much impressed by the smooth efficiency of Frau Schlenk and Frau Lehmann. A typical day at the Institute started having a short chat with Frau Pappa (always in excellent mood) and ended in the evening with a 2000m run to get the train. In between there was a lot of science: I have benefited from many seminar talks and from uncountable conversations with members of the general relativity and quantum gravity groups.

In particular I still remember a few lunches with Jürgen Ehlers, from whom I learned many interesting facts about personalities like Michelson or Schwarzschild. Many conversations took also spontaneously place (in Spanish!) in the shared office 0.27, which had also the nickname *latin-connection-room*.

Most stimulating for me was the variety of scientific points of view at the Institute. This fact is also beautifully reflected in the program of one of the highlights of last year: the symposium on the occasion of the 70th anniversary of Jürgen Ehlers.

These eight months at the AEI have been one of the most productive periods for me until now. One important reason for this was that I could so easily keep the contact to my former Ph.D. advisor at the Maths Department. But also the atmosphere at the Institute and the constant presence of international researchers has been essentially stimulating. I'm looking forward to come back!

Fernando Lledó

Robert Helling and Germar Schröder win Schloeßmann Prizes

In 2000, one out of six Schloeßmann Prizes (5000 DM) was awarded to Robert Helling for his poster presentation on the M(atrix)-Model. Germar Schröder won a postdoctoral fellowship (2 years) at a Max Planck Institute of his own choice in recognition of the talk he gave at the Schloeßmann Seminar.

In order to promote interdisciplinary research in selected areas of the sciences a 3 day seminar is organized every year in memory of Dr. Ernst Rudolf Schloeßmann, a former Supporting Member of the Max Planck Society who died in 1993. Each Schloeßmann Seminar focuses on one question in highly specialised fields on the cutting edge of the natural sciences. In 2000 the seminar was given on "Mathematical Models in Biology, Chemistry and Physics". Funded by the Ernst Rudolf Schloeßmann Foundation up to six participants in such seminars can be awarded a prize each for outstanding contributions. Eight to ten junior scientists are awarded grants for carrying out promising research projects in Max Planck Institutes in their respective fields.

Vacation Course

The 2-weeks vacation course on “Gravitational Physics”, which the AEI started in 1999 together with the University of Potsdam, took place for the third time from March 6 to March 17. It is meant for students who have earned their "Vordiplom". The structure of the course was, as in the years before, two lectures in the morning; the afternoon to go through the material of the lectures. This time the course took place in the lecture hall of the Max Planck Campus in Golm.

As already in 1999, Jürgen Ehlers gave an “Introduction into General Relativity”. The second lecture series was given by Hermann Nicolai, whose topic was “Introduction into Supersymmetry und Supergravitation”.

About 25 students from the Berlin-Potsdam area and another 25 from all over Germany participated. Again the AEI could provide some financial support. The course was again greatly appreciated such that continuation is planned.

Science goes Public: Science Day on Telegraphenberg Potsdam

Potsdam is a region of cutting edge science and research. Biotechnology, astrophysics and last but not least, Einstein's general relativity are just some examples for the various research subjects that are covered by 22 institutes. On November 16th, 2000, this unique concentration of research institutes and the university presented itself to the Brandenburg pupils.

Schoolkids being introduced to Gravitational Physics research at the AEI.

Posters, computer animations, hands-on demonstrations, and popular talks attracted numerous young people to the Telegraphenberg in Potsdam. About 1500 pupils attended this event - a great success for science. Johanna Wanka, the Brandenburg Minister of Science, Research, and Culture was the patron of this important public relation event for natural sciences that is staged annually in different Brandenburg cities.

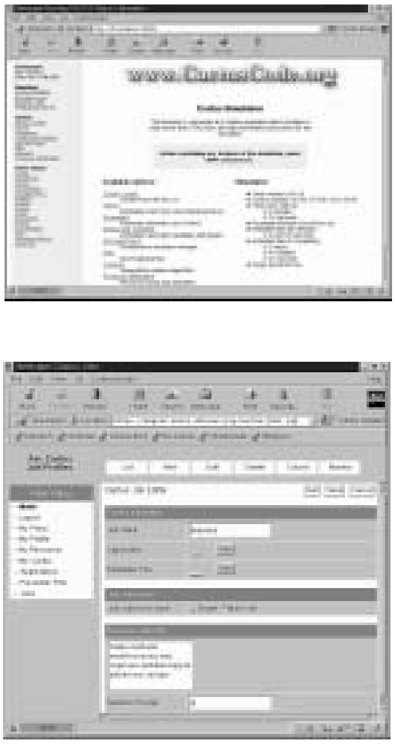
“Hey, do you want to know what black holes are?” Only few pupils were able to resist this enticing question and so the booth of the Albert Einstein Institute was always overcrowded with very interested young people. Markus Pössel, Michael Koppitz, and Oliver Henkel had to explain until they were hoarse. We had brought a laptop with a nice animation of colliding black holes. With this demonstration we offered an easy access to the sophisticated topic and many pupils wanted to know more details about neutron stars, black holes, and about what research means at an institute of theoretical physics.

Since less and less young people begin to study natural sciences we need good ideas how to get them interested in these subjects. A science event once a year may be a first step of a campaign focussing on science and research. Pupils especially should be encouraged by the motivation of scientists: scientific research is an ideal activity for creative and curious people and it provides a lot of fun.

Cactus Demonstrations at Intel Event & Supercomputing 2000

The Albert Einstein Institute is the home of the Cactus Code and it's main development team. Cactus is an open source general framework for High Performance Computing, motivated by the intensive computing requirements of the Numerical Relativity group, it is now used by a growing community of worldwide users for diverse applications.

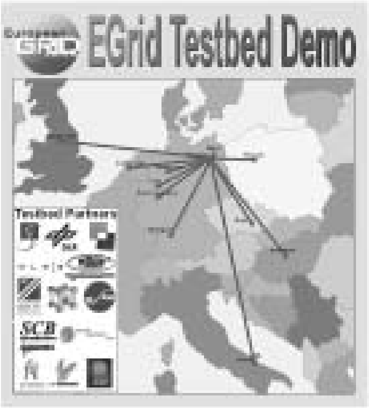
A number of computer science research projects are now using Cactus as the core infrastructure for their work, and the Cactus Team are directly involved in many of these projects. The successful TiKSL project (TeleImmersion: Collision of Black Holes), which was completed at the end of 2000, was a joint AEI/ZIB/RZG initiative funded by the Deutsches Forschungsnetz Verein (DFN), and provided remote and distributed computing and visualization tools, which are now being used by the Numerical Relativity group. A following project, GriKSL, to continue this line of development, will hopefully commence in 2001.


www.CactusCode.org

Cactus portal and server

An American NSF funded project to form an Astrophysics Simulation Collaboratory is developing collaborative tools, based around Cactus and the Globus Toolkit, which will provide the Numerical Relativity group with improved capabilities for massively parallel computation including adaptive mesh refinement, advanced interactive visualization, and a user portal enabling the use of their worldwide computer resources. The American NSF Next Generation Software project GrADS (Grid Application Development Software) is working towards simplifying distributed heterogeneous computing, and is collarating with the Cactus Team to develop dynamic Cactus applications which can exploit the worldwide Gridof computer resources. In the year 2000, talks and demonstrations about Cactus were given at many different exhibitions, conferences and tradeshows. General tutorials were given at HPDC-9, HiPer2000, SGI 2000, and Numerical Relativity tutorials at the Italian National Seminar Series on Theoretical Physics and the first meeting of the EU Network for Sources of Gravitational Wave Astronomy. The Cactus Team were invited to demonstrate at vendor booths at Linux World, the Intel Developers Forum and SC2000. Cactus meetings were hosted at NCSA in Champaign in July and LBL in August.

The most impressive demonstration of the year was given on the show-floor in Dallas in November, at Supercomputing 2000. In collaboration with the Applications and Testbed Working Group of the EGrid Consortium chaired by Ed Seidel, the Cactus Team developed a prototype for a new paradigm for Grid Computing. Called the Cactus Worm, this technology allows any Cactus application to dynamically exploit available resources. The Worm can query a central resource information server to locate the best possible resources it has access to, and then move itself to this new machine, either by transferring files between the different systems, or alternatively by streaming the necessary data without need for a physical file. The progress of the Worm is tracked by a central



application information server, from which the simulation can be remotely monitored, steered and visualized. During the demonstration the Worm moved around all the sites of the newly created EGrid Testbed, a collection of machines from ten sites in Europe who have joined together to create an environment for developing Grid infrastructure.

Cactus can be used on many different machine architectures. This year the code was ported to run on one of the Numerical Relativity groups new resources, the Hitachi SR8000-F1 machine at the Leibniz Computing Center. Cactus was also ported to the new generation IA64 processors, and as part of this process the Cactus Team has been working closely with the NCSA and Intel to optimize the Numerical Relativity applications for this architecture.

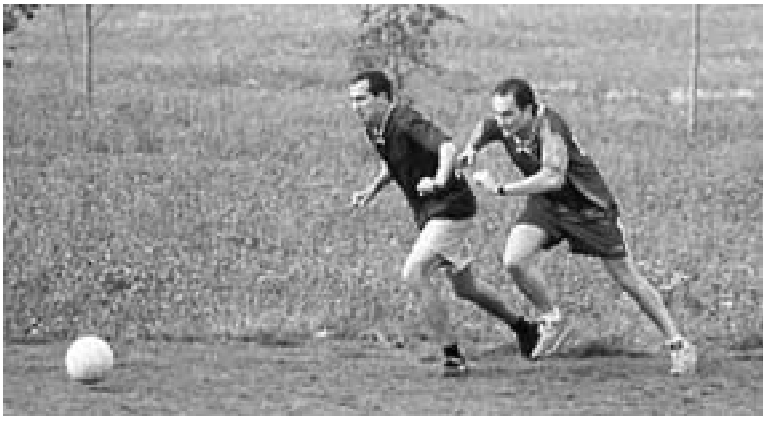
The Cactus Team at the Albert Einstein Institute consists of Ed Seidel, Gabrielle Allen, Werner Benger, Tom Goodale, Ian Kelley, Gerd Lanfermann and Thomas Radke. *More information about Cactus can be found at http://www.cactuscode.org.*

Computer Infrastructure News

The year 2000 was an important year in respect of the further development of the computer resources for the high performance parallel computing. The institute was granted 2 Mio DM by the BAR to be able to continue the leading work in numerical relativity. The decision has been made to buy the Origin3000i/SN-Itanium parallel computer from SGI with the coming Itanium processors of Intel. Due to a grant from the sgi/Intel-IA64 Leadership Program for Key Applications the institute was able to get 96 processors for the money available. This promises to be an excellent facility for further scientific work in numerical relativity. To bridge the time gap until the new parallel computer will be delivered the existing origin 2000 parallel computer has been upgraded to 64 processors mid of 2000. The number of workstation computers further increased due to the growing number of needed work places. To fulfill the requirements in respect of computer resources for scientific computing high performance workstations with the fasted available alpha processor from Compaq have been purchased. To support the mobility of the scientists the number of available laptops has been increased substantially. A new backup concept has been realized with the help of the Rechenzentrum Garching (RZG). The Backup data are now stored with ADSM at the RZG. This saved resources and increased the quality compared to the former inhouse solution.

And now for the Sports Results... Golm 2000 Football Festival

On 11th August 2000, the AEI Football team won the second place out of nine competing teams from six institutes of the Berlin/Brandenburg area.



AEI´s Jan Plefka (right) in a hard-fought fight for possession of the leather

The first place was taken by the team of the Fritz Haber Institute Berlin. Most notably the AEI team was the strongest of all the Golm Campus teams.

Cricket Goes Golm

A bunch of people, a ball being hurled on outstretched arm towards a strange wooden contraption protected by a lonely guardian holding a bat - can it be? Indeed, Cricket has arrived on Golm campus. Since the official foundation of the Golm Cricket Club (GCC) on November 30, 2000, enthusiasts from AEI as well as from the neighbouring Max Planck Institute for Colloids and Interfaces have met regularly on Thursday afternoons to bowl and bat, score runs, field balls and take wickets. And it is not only Australians and Indians that are drawn magically each week to the pair of wickets - triples of wooden stumps standing on the road behind the AEI. US-Americans in need of a fix of baseball, and willing to try anything similar, have thumped the ball to far corners of the field - and in addition, the Golm team has featured bowling Poles, catching Canadians, batting Britons and, of course, numerous members of the native German population, all trying their hand at the noble game. Newcomers and spectators are always welcome.

Batting and Bowling in the AEI backyard

Further information is available on the GCC homepage at http://galaxy.mpikg-golm.mpg.de/gf/english/caruso/cricket/

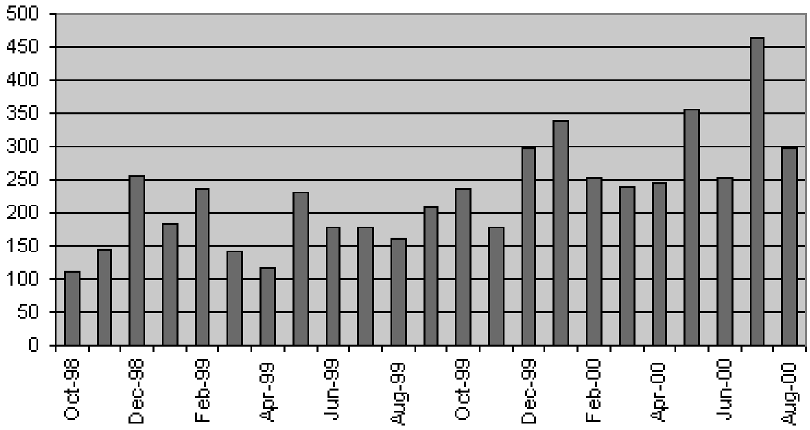
Living Reviews in Relativity
Three Years of Innovative Science Publishing

The Albert Einstein Institute publishes a pioneering, international physics journal, “Living Reviews in Relativity” at www.livingreviews.org. The journal is entirely web-based and offers refereed review articles on all areas of current research in relativity. As the journal's title indicates, its articles are “living”, i.e. authors revise their articles every six months to two years. Hence readers of the journal are guaranteed to find up-to-date information on the very latest research developments in gravitational physics.

The journal provides a service to physicists all over the world, from graduate student to professor, that complements and enhances the existing system of print and electronic resources. Living Reviews articles describe and evaluate areas of active research in gravitational physics, putting the most important works in the field into context. In this way, Living Reviews offers an entry point into the relevant literature, provides links to the most valuable web resources, and monitors progress made within the discipline.

The journal goes far beyond electronic dissemination of conventional print articles; it delivers carefully edited and peer-reviewed, up-to-date information, combined with an attractive and highly functional web interface. All articles are readable online in HTML, with colour figures and animations integrated into the text. Navigation support within the articles is offered through pop-up windows containing equations and footnotes, and buttons to track citations through the text. All references cited in Living Reviews articles are collated into a literature database, linked back to and put into context by the annotation within the respective review articles.

Since the journal went online three years ago, on 26 January 1998, it has received an enthusiastic reception within the scientific community. Its concept of providing “living” review articles has attracted some of the most distinguished researchers in the field, who have been approached by the journal's editorial board to write and maintain a Living Review. In September 2000 a first analysis of the traffic on the main website revealed that each individual article had been downloaded several hundred times for reading and printing. This indicates that the journal is gaining considerable access to its target community, particularly since these numbers do not include visits to any of the 35 web servers worldwide that mirror the journal (a service courtesy of the European Mathematical Society's Information Service).



Evolution of article download numbers. To date, a total 5235 times articles were downloaded in a suitable format for printing and off-line reading.

The journal has been developed and designed by physicists for physicists as a powerful tool for their community; linking, integrating, and communicating its current research activities. The Max Planck Institute for Gravitational Physics offers the journal as a free service to the community to maximize its impact as a central resource for current research and education in relativity. With a steadily growing coverage of topics "Living Reviews in Relativity" is becoming a primary entry point into the literature of gravitational physics and a forum for discussion and evaluation of current research. Further development of interactive features offered by the medium is planned in order to increase benefits to its users and to strengthen its role as a communicational forum.

Members of the Editorial Board of Living Reviews at their annual meeting in September 2000 - from left to right: Bernard Schutz, Ed Seidel, Bala Iyer, Bernd Brügmann, Bernd Schmidt and Jürgen Renn.

The "Living Reviews" concept potentially yields benefits well beyond the area of gravitational physics. "Living Reviews in Relativity" invites other research communities, in physics and beyond, to evaluate the concept, its benefits, and its applicability to their field. The Max Planck Institute for Gravitational Physics is happy to share its experience in setting up a Living Reviews journal and its software tools with sister projects.

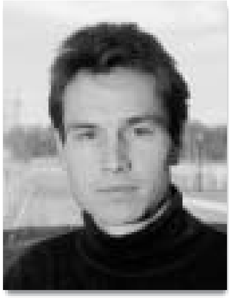
Further background information on the journal can be found at http://www.livingreviews.org/Project/. You are also welcome to contact the journal's Managing Editor, Theresa Velden (velden@aei.mpg.de, tel.++49/(0)331-567-7484.)

Theresa Velden

Academic Achievements 2000

Habilitation

Alan Rendall completed his Habilitation thesis on "Globale Eigenschaften von Lösungen der Einsteingleichungen mit Materie" and was habilitated by the Technische Universität Berlin in 2000.



Habilitation

Thomas Thiemann finished his Habilitation thesis on "Mathematische Formulierungen der Quanten-Einstein-Gleichungen" and was habilitated in theoretical physics by the Universität Potsdam.

Doctoral Thesis

Robert Helling completed his PhD thesis on "Scattering in Supersymmetric M(atrix)-Models" supervised by Prof. Hermann Nicolai. In July 2000 he was awarded his PhD from the Humboldt Universität Berlin.

Doctoral Thesis

Germar Schröder was awarded his PhD from the Universität Hamburg in July 2000. He wrote his doctoral thesis on "Discrete Duality Symmetries in String- and M Theory" supervised by Prof. Hermann Nicolai.

Diploma Thesis

Lars Nerger has completed his diploma in physics at the Universität in Bremen. It was written at the AEI under the supervision of Dr. habil. Bernd Brügmann on "Investigations of 3D binary Black Hole Systems".

Diploma Thesis

Hendrik Ulbricht graduated in physics from the Technische Universität Berlin. He wrote his diploma thesis at the AEI under the supervision of Dr. habil. Renate Loll on "Gravitational Aspects of the Holographic Principle".

The Fachbeirat of the AEI

The Fachbeirat is the Institute's scientific advisory and assessment Board, made up of internationally renowned physicists. The Fachbeirat advises the President of the Max Planck Society (MPG) on how effectively the Directors are managing the work of the Institute. Their advice helps the Directors to establish priorities and improve their management. The Fachbeirat is the main tool used by the MPG to evaluate its research institutes to ensure appropriate and effective development of funds. Every two years the members of the Fachbeirat meet for several days to evaluate the Institute and to prepare a report to the President of the MPG.

Members of the Fachbeirat in 2000:

Prof. Dr. Robert Beig
Institut für Theoretische Physik
Wien

Prof. Dr. Hubert Goenner
Institut für Theoretische Physik
Göttingen

Prof. Dr. James Hartle
Physics Department
University of California at Santa Barbara

Prof. Dr. Wolfgang Hillebrandt
Max-Planck-Institut für Astrophysik
Garching

Prof. Dr. Richard Matzner
Center for Relativity Theory
University of Texas at Austin

Prof. Dr. Roger Penrose
Mathematical Institute
University of Oxford/UK

Prof. Dr. Norbert Straumann
Institut für Theoretische Physik
Universität Zürich

Prof. Dr. Gerard ‘t Hooft
Institute for Theoretical Physics
Universiteit Utrecht

Prof. Dr. Kip Thorne
LIGO 130-33
California Institute of Technology, Pasadena

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Prof. Dr. Bernard F. Schutz	Astrophysical Relativity

Director Emeritus

Prof. Dr. Jürgen Ehlers	Classical and Mathematical Relativity

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Dr. Gabrielle Allen
Dr. Horst Beyer
Dr. Friedemann Brandt
Dr. Bernd Brügmann
Dr. Curt Cutler
Dr. Georg Dautcourt
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Dr. Alan Rendall
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Prof. Stefan Theisen
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Doctoral Students

Carsten Aulbert
Werner Benger
Simone Calogero
Massimo Centazzo
Stefan Fredenhagen
Tom Goodale
Andreas Hartl
Robert Helling
Oliver Henkel
Thomas Jurke
Ralf Kähler
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Hanno Sahlmann
Emanuel Scheidegger
Germar Schröder
Ryoji Takahasi
Oliver Winkler

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Dr. Adrian Butscher
Dr. Eric Chassande-Mottin
Dr. Sergio Dain
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Dr. Denis Pollney
Dr. Andreas Recknagel
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Dr. Alicia Sintes Olives
Dr. Fredrik Stahl
Dr. Bogdan Stefanski
Dr. Juan A. Valiente Kroon
Dr. Marsha Weaver
Dr. Peter Williams
Dr. Itoh Yousuke

Post-Docs (externally funded)

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DFG Fellowship
Dr. Manuela Campanelli
European Union
Dr. Peter Diener
European Union
Dr. Fotini Markopoulou
European Union
Dr. Gabriel Nagy
DAAD Fellowship
Dr. Sebastian Silva
European Union

Diploma Students

Mihai Bondarescu
Christoph Dehne
Lars Nerger
Hendrick Ulbricht

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Andreas Donath	Computer Systems Support
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Andre Werthmann	Computer Systems Support
Anne Wetzel	PR Assistant
Christina Weyher	Editorial Assistant Living Reviews
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Ramona Wittwer	Accounting
Helga Zander	Personnel Office

Guest Scientists

Alekseev, Anton Y.	Uppsala	17/04/00-20/04/00
Allen, Bruce	Milwaukee, WI	01/01/00-01/07/00
Ambjørn, Jan	Kopenhagen	26/06/00-14/07/00
Apostolatus, Harris	Thessaloniki	17/07/00-28/07/00
Ashtekar, Abhay	University Park, PA	16/02/00-19/02/00 04/07/00-02/08/00
Bahns, Dorothea	Freiburg	03/05/00-05/05/00
Balasubramanian, Ramanchandran	Cardiff	20/04/00-28/04/00
Bale, Derek	Seattle, WA	22/02/00-25/02/00
Bardeen, James	Seattle, WA	01/09/00-22/09/00
Beck, William	Boulder, CO	23/03/00-28/03/00
Becker, Katrin	Pasadena, CA	25/01/00-28/01/00
Becker, Melanie	Pasadena, CA	25/01/00-28/01/00
Berger, Beverly	Rochester, MI	19/06/00-14/07/00
Bicák, Jirí	Prag	15/02/00-15/03/00 01/08/00-15/10/00
Bishop, Nigel	Pretoria	07/11/00-24/11/00
Bizon, Pjotr	Krakau	26/03/00-31/03/00
Bojowald, Martin	University Park, PA	12/12/00-19/12/00
Bokhari, Ashfaque H.	Islamabad	01/07/00-29/08/00
Bombelli, Luca	Oxford, MS	19/07/00-21/07/00
Bordemann, Martin	Freiburg	05/01/00-12/01/00
Brandt, Friedemann	Hannover	01/10/00-31/03/01
Bray, Hubert	Cambridge, MA	21/02/00-12/03/00 22/06/00-16/07/00
Brill, Dieter	College Park, MD	18/02/00-19/02/00
Bruni, Marco	Portsmouth, UK	07/12/00-09/12/00
Buchman, Luisa	Saettle, WA	11/09/00-14/10/00
Buchmüller, Wilfried	Hamburg	15/05/00-16/05/00
Buric, Maja	Belgrade	01/02/00-29/02/00
Burinskii, Alexander	Moscow	20/03/00-01/04/00
Cafaro, Massimo	Lecce	27/09/00-30/09/00
Carrera, Matteo	Zürich	09/10/00-11/10/00
Centazzo, Massimo	Padua	01/02/00-01/04/00 01/04/00-07/04/00
Chamseddine, Ali	Beirut	18/09/00-23/09/00
Chu, Chong-Sun	Neuchatel	10/10/00-18/10/00
d'Inverno, Raymon	Southampton, UK	05/07/00-12/07/00
Dadhich, Naresh K.	Poona	23/04/00-05/05/00
Davies, Rob	Cardiff	30/11/00-01/12/00
de Wit, Bernard	Utrecht	18/04/00-20/04/00 30/09/00-04/10/00
Dick, Rainer	München	17/07/00-19/07/00
Ellis, George F.R.	Kapstadt	16/02/00-19/02/00
Englert, François	Brussels	02/04/00-07/04/00
Febo, Luca	Rom	01/03/00-13/04/00
Filk, Thomas	Freiburg	09/04/00-26/05/00
Finster, Felix	Leipzig	08/03/00-10/03/00
Fischer, Arthur	St. Cruz	05/09/00-12/09/00
Frauendiener, Jörg	Tübingen	20/11/00-21/11/00
Futamase, Toshifumi	Sendai	01/11/00-30/11/00
Gambini, Rodolfo	Montevideo	15/07/00-23/07/00
Garfinkle, David	Rochester, MI	22/07/00-05/08/00
Gomberoff, Andres	Syracuse	21/06/00-02/07/00
Gopakumar, Achamveedu	St.Louis, MO	02/06/00-30/06/00
Günaydin, Murat	University Park, PA	09/07/00-16/07/00
Gundlach, Carsten	Southampton, UK	07/11/00-12/11/00
Hajicek, Petr	Bern	28/08/00-08/09/00
Handrich, Garrit	Freiburg	03/05/00-05/05/00
Henneaux, Marc	Brüssel	03/02/00-04/02/00 05/07/00-07/07/00 09/08/00-14/08/00
Huisken, Gerhard	Tübingen	30/05/00-31/05/00 30/08/00-10/09/00
Husa, Sascha	Pittsburgh, PA	06/01/00-30/03/00 20/05/00-05/06/00
Isenberg, Jim	Brownsville, OR	26/07/00-17/08/00
Itoh, Yousuke	Sendai	01/11/00-31/01/01
Iyer, Bala	Bangalore	24/09/00-04/10/00
Julia, Bernard	Paris	12/02/00-18/02/00
Kannar, Janos	Budapest	26/06/00-02/07/00
Kaplunovsky, Vadim	Austin, TX	09/08/00-26/08/00
Kennefick, Dan	Cardiff	17/04/00-20/04/00
Ketov, Sergej	Hannover	09/04/00-06/05/00

Guest Scientists

Khanna, Gaurav	University Park, PA	28/03/00-05/04/00
King, Andreas	Tübingen	20/11/00-21/11/00
Kokkotas, Kostas	Thessaloniki	15/03/00-23/03/00
		06/12/00-11/12/00
Kopeikin, Sergei	Columbia, MO	10/09/00-12/09/00
Korotkin, Dimitrii	Montreal	06/06/00-16/06/00
Kristjansen, Charlotte	Kopenhagen	10/07/00-21/07/00
Krtous, Pavel	Prag	01/10/00-10/10/00
Kunze, Markus	München	12/03/00-17/03/00
Lehner, Luis	Vancouver, BC	15/12/99-02/01/00
Lewandowski, Jerzy	Warschau	16/02/00-20/02/00
		09/07/00-30/07/00
		15/08/00-15/09/00
		07/11/00-15/12/00
Lindblad, Hans	San Diego, CA	31/07/00-01/10/00
Lledó, Fernando	Potsdam	01/01/00-29/02/00
		01/05/00-31/10/00
Louis, Jan	Halle	14/08/00-23/08/00
Lusanna, Luca	Florenz	15/11/00-02/12/00
Maeda, Kei-Ichi	Tokyo	14/02/00-13/04/00
Maison, Dieter	München	25/07/00-28/07/00
Majumdar, Parthasarathi	Chennai	03/06/00-28/06/00
Malmendier, Andreas	Bonn	19/11/00-24/11/00
Mandal, Gautam	Genf	01/05/00-08/05/00
Mars, Marc	Wien	02/07/00-30/06/01
Martin-Garcia, Jose M.	Southampton, UK	03/12/00-10/12/00
Massaioli, Federico	Rom	16/07/00-27/07/00
		19/11/00-30/11/00
Matsubara, Keizo	Uppsala	15/11/00-15/12/00
Miksa, Brad	Urbana-Champaign, IL	22/05/00-29/05/00
Minasian, Ruben	Palaiseau	20/11/00-27/11/00
Mino, Yasushi	Tokyo	25/06/00-01/07/00
Misner, Charles	College Park, MD	06/11/00-30/04/01
Mohaupt, Thomas	Halle	22/02/00-03/03/00
Moncrief, Vincent	New Haven, CT	02/03/00-26/03/00
		01/08/00-10/09/00
Newman, Ezra T.	Pittsburg, KS	04/04/00-12/04/00
		21/06/00-02/07/00
Nunez, Dano	Mexico	07/01/00-14/01/00
Onofri, Enrico	Parma	09/10/00-10/10/00
Palomba, Cristiano	Rom	16/07/00-27/07/00
		19/11/00-30/11/00
Papadopoulos, Philippos	Portsmouth, UK	03/12/00-10/12/00
Peeters, Kasper	Cambridge, UK	02/07/00-07/07/00
Perelomov, Askold	Moskau	02/05/00-30/06/00
Perez, Alexandro	Marseille	04/12/00-08/12/00
Perlick, Volker	Berlin	01/04/00-31/12/00
Pfister, Herbert	Tübingen	17/02/00-19/02/00
Pioline, Boris	Cambridge, UK	28/08/00-07/09/00
Pullin, Jorge	University Park, PA	08/07/00-28/07/00
Pushkareva, Galina V.	Urbana-Champaign, IL	22/05/00-29/05/00
Rainer, Martin	Potsdam	01/01/00-31/01/00
Reshetikhin, Nicolai	Berkeley, CA	03/02/00-03/02/00
Roggenkamp, Daniel	Bonn	11/03/00-16/03/00
Römelsberger, Christian	Piscataway, NJ	04/07/00-16/07/00
Rossi, Matteo	Parma	08/10/00-16/10/00
Russell, Michael	Chicago, IL	22/09/00-05/10/00
Sá, Paulo	Faro	01/10/99-31/07/00
Samtleben, Henning	Paris	26/03/00-02/04/00
		02/07/00-07/07/00
		17/07/00-21/07/00
Sarkar, Tapobrata	Mumbai	20/11/00-26/11/00
Sathyaprakash, Bangalore S.	Cardiff	07/04/00-27/04/00
		29/11/00-02/12/00
Scardigli, Fabio	Bern	21/02/00-02/03/00
Schnetter, Erik	Tübingen	05/01/00-12/01/00
		17/07/00-22/07/00
Schröder, Yörk	Helsinki	21/12/00-22/12/00
Schroers, Bernd	Edinburgh	16/04/00-18/04/00
Shiromizu, Tetsuya	Tokyo	09/03/00-25/08/00
Simon, Walter	Wien	02/07/00-02/09/00
Smedback, Mikael	Uppsala	15/11/00-15/12/00
Smilga, Andrei	Nantes	25/01/00-31/01/00
		09/07/00-09/08/00
Smolin, Lee	London	21/02/00-25/02/00
		10/10/00-10/10/01

Guest Scientists

Stanciu, Sonia	Utrecht	02/04/00-09/04/00
Strobl, Thomas	Jena	10/08/00-14/08/00
Taylor, Ian	Cardiff	14/01/00-18/01/00
		12/10/00-14/10/00
Thornburg, Jonathan	Wien	14/05/00-27/05/00
		10/07/00-21/07/00
		20/08/00-10/09/00
Tiglio, Manuel	Cordoba	22/03/00-30/04/00
Tod, Paul	Oxford, UK	10/09/00-02/10/00
Tolksdorf, Jürgen	Mannheim	06/07/00-09/07/00
Ungarelli, Carlo	Portsmouth, UK	05/03/00-20/03/00
		02/07/00-10/07/00
Urban, Nathan	University Park, PA	14/05/00-07/07/00
Vanhove, Pierre	Cambridge, UK	25/06/00-08/07/00
Vardarajan, Suneeta	Chennai	20/10/00-05/11/00
Vasiliev, Misha	Göteborg	21/02/00-20/04/00
Vulcanov, Dumitru N.	Timisoara	01/09/00-31/10/00
Waldron, Andrew	Amsterdam	15/07/00-31/08/00
Wess, Julius	München	04/04/00-07/04/00
Whelan, John T.	Bern	19/02/00-24/02/00
		17/08/00-18/08/00
White, Simon	Garching	09/05/00-09/05/00
Whiting, Bernard F.	Gainsville, FL	09/07/00-16/07/00
Winicour, Jeffrey	Pittsburgh, PA	01/10/99-31/01/00
		01/02/00-15/03/00
		01/10/00-31/03/01
Woan, Graham	Glasgow	30/11/00-03/12/00
Wynter, Tom S.	Gif-sur-Yvette	31/07/00-03/10/00
Yoshida, Shijun	Sendai	01/11/00-31/01/01
		15/04/00-29/04/00
		03/01/00-30/01/00

Publications by the Institute

Max-Planck-Institut für Gravitationsphysik (Ed.)	Living Reviews in Relativity (03/2000) http://www.livingreviews.org

Publications by AEI Members and Guest Scientists

Abou-Zeid, M. and H. Nicolai	On space-time supersymmetry and string duality in nine dimensions, Nuclear Physics B (Proc. Suppl.) 88, 168-174 (2000).
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Invited Conference Talks Given by AEI Members

Alcubierre, M.	Simple Black Hole Excision / 11 January 2000 / ITP Mini Program on Colliding Black Holes, Santa Barbara, CA (USA)
Alcubierre, M.	Coordinate Conditions / 13 January 2000 / ITP Mini Program on Colliding Black Holes, Santa Barbara, CA (USA)
Allen, G.	The Cactus Code / February 2000 / GrADs Meeting, San Diego, CA (USA)
Beyer, H.R.	On the stability of the Kerr metric / 1 September 2000 / Applied Differential Geometry, Lie Algebras and General Relativity, Aristoteleion University of Thessaloniki (Greece)
Brügmann, B.	Black Hole Excision / 14 January 2000 / Colliding Black Holes: Mathematical Issues in Numerical Relativity, ITP Miniprogram on Colliding Black Holes, St. Barbara, CA (USA)
Brügmann, B.	Black Holes / 8 June 2000 / Sixth Annual German-American Frontiers of Science Symposium, Irvine, CA (USA)
Brügmann, B.	Kollision und Verschmelzung Binärer Schwarzer Löcher und Neutronensterne / 13 November 2000 / SFB Treffen, Universität Jena (Germany)
Brügmann, B.	Numerical Relativity with Cactus / 9 December 2000 / Cactus Workshop, EU Network Meeting, AEI, Golm (Germany)
Brügmann, B.	Binary black hole mergers in 3d numerical relativity / 11 January 2000 Colliding Black Holes: Mathematical Issues in Numerical Relativity, ITP Miniprogram, St. Barbara, CA (USA)
Campanelli, M.	The eclectic approach to binary black hole collisions / 8 June 2000 3rd CAPRA meeting on Radiation Reaction, Caltech, Pasadena, CA (USA)
Ehlers, J.	Einstein's Theory of Spacetime an Gravity / 19 January 2000 International Conference on Mathematics at the Tower of the Millenium, Cairo (Egypt)
Ehlers, J.	Foundations of Gravitational Lensing / 29 March 2000 Gravity Conference, University of Stockholm, Stockholm (Sweden)
Ehlers, J.	Light Cones and Gravitational Lensing / 9 December / Symposium in Honor of Ivor Robinson, University of Texas at Dallas, Texas (USA)
Friedrich, H.	Outer Boundaries: Problems and Solutions / 12 January 2000 ITP Mini Program on Colliding Black Holes, Santa Barbara, CA (USA)
Friedrich, H.	Das Cauchy Problem für die Einstein Gleichungen / 20 March 2000 DPG Frühjahrstagung Dresden (Germany)
Friedrich, H.	Conformal structure of gravitational fields / 17 July 2000 / Workshop on Mathematical Aspects of Gravitation, Mathematisches Forschungsinstitut Oberwolfach (Germany)
Friedrich, H.	Asymptotics: Analytical Results and Practical Applications 7 June 2000 / 9th Marcel Grossmann meeting, Rome (Italy)
Hübner, P.	3D Numerical Relativity Without Artificial Boundaries -The Conformal Approach / 13 January 2000 / ITP Mini-program on Colliding Black Holes, St. Barbara, CA (USA)
Hübner, P.	Numerische Relativitätstheorie mit konformen Techniken 20 March 2000 / Dresden (Germany)
Junker, W.	Microlocal analysis with finite Sobolev regularity and adiabatic vacuum states / 23 October 2000 / Workshop "Quantum Field Theory and Microlocal Analysis", Oberwolfach (Germany)
Loll, R.	Discrete Lorentzian quantum gravity / 20 August 2000 / XVIII International symposium on Lattice Field Theory, Bangalore (India)
Loll, R.	Quantum theory of space and time / 19 July 2000 / XIII International Congress on Mathematical Physics, London (UK)

Invited Conference Talks Given by AEI Members

Nicolai, H.	Hidden Symmetries / 30 May 2000 / Conference Anniversaire du LPT-ENS, Paris (France)
Nicolai, H.	Zeit als relative Größe / 12 May 2000 / Symposium "Das Jahr 2000 findet nicht statt", Neanderthal Museum, Mettmann (Germany)
Nicolai, H.	Yangian (E8) symmetries in N=16 Supergravity / 6 January 2000 TMR Conference, Tel Aviv (Israel)
Nicolai, H.	Conformal and Quasiconformal Realizations of Exceptional Lie groups 9 September 2000 / 4. Annual European TMR Conference on Integrability, Non-perturbative Quantum Effects and Symmetry in Quantum Field Theory, Paris (France)
Nicolai, H.	Formation of the Universe: from Classical to Quantum Cosmology 13 December 2000 / Conference 100 Jahre Quantentheorie, Berlin (Germany)
Nicolai, H.	Conformal and Quasiconformal Realizations of Exceptional Lie Groups 14 September 2000 / Euresco Conference on Quantum Fields and Strings, Kolymbari, Crete (Greece)
Nicolai, H.	Hidden Symmetries in D=11 Supergravity / 20 June 2000 2nd Guersey Memorial Conference on M Theory and Dualities, Istanbul
Owen, B.J.	Crust formation and the r-mode instability 7 July 2000 9th Marcel Grossmann meeting, Rome (Italy)
Owen, B.J.	Latest news on continuous-wave sources / 16 March 2000 / LIGO Science Collaboration meeting, Livingston, Louisiana, USA
Owen, B.J.	Gravitational waves from disturbed neutron stars 2 June 2000 / KipFest, Caltech, Pasadena, CA (USA)
Owen, B.J.	How can the r-modes prevent crust formation? 8 May 2000 / R-Mode Mini-Workshop, Institute for Theoretical Physics, Santa Barbara, CA (USA)
Papa, M.A.	Searching for continuos gravitational wave signals: the hierarchical Hough transform algorithm / 6 June 2000 / Gravitational waves: a challenge to theoretical astrophysics, Trieste (Italy)
Papa, M.A.	Hough Hierarchical Pulsar Search: ASIS / 16 August 2000 LIGO Scientific Collaboration Meeting, Hanford, WA (USA)
Plefka, J.	Vertex Operators for the Supermembrane / 5 June 2000 E. Fradkin Memorial Conference, Moscow
Plefka, J.	Vertex Operators for the Supermembrane / 10 July 2000 / STRINGS 2000, Ann Arbor, Michigan (USA)
Plefka, J.	The Matrix Model of M-Theory / 23 May 2000 64. Physikertagung Dresden (Germany)
Rendall, A.D.	Blow-up for solutions of hyperbolic PDE and spacetime singularities 6 June 2000 / Journees EDP Atlantique, Nantes (France)
Rendall, A.D.	The Einstein equations and hyperbolicity / 2 March 2000 Eighth International Conference on Hyperbolic Problems, Magdeburg (Germany)
Schmidt, B.G.	Recent developments in classical relativity / 15 December 20th Texas Symposium, Austin (USA)
Schomerus, V.	Brane Dynamics and Fuzzy Geometry / 31 May 2000 / Workshop on String Theory and Non-commutative Geometry, Beirut (Lebanon)
Schomerus, V.	2D critical systems and non-commutative Geometry 15 June 2000 / AMS Scand 2000, Odense (Denmark)
Schomerus, V.	Fuzzy Geometry, Gluon Condensates, and Twisted K-theory 5 October 2000 / Workshop on Non-commutative Geometry and String Theory, Torino (Italy)

Schomerus,V.	Open Strings, Branes, and Non-commutative Geometry / 25 October 2000 / Workshop on Vertex Operator Algebras, Fields Institute, Toronto (Canada)
Schutz, B.F.	Sources of Gravitational Waves / 19 April 2000 / Lorentz Center, Leiden (Netherlands)
Schutz, B.F.	Testing Relativity with LISA / 11 July 2000 / 3rd LISA Symposium, Albert Einstein Institute, Golm (Germany)
Schutz, B.F.	Sources of Gravitational Radiation for LISA / 23 May 2000 PPARC Town Meeting on ESA Cornerstone Missions, London (UK)
Schutz, B.F.	Sources of Gravitational Waves / 4 April 2000 / CERN (Switzerland)
Schutz, B.F.	Gravitational Wave Sources - Changing Perspectives / 2 June 2000 Kipfest, Caltech, Pasadena, CA (USA)
Seidel, E.	Using Supercomputers to Collapse Gravitational Waves, Collide Black Holes (and study other Cataclysms) / 18 May 2000 California Institute of Technology (USA)
Seidel, E.	Numerical Relativity and Hyperbolic Systems / 2 March 2000 HYP2000, Magdeburg (Germany)
Seidel, E	Numerical Relativity / 20 March 2000 / DPG-Frühjahrstagung, Dresden (Germany)
Seidel, E.	The Cactus Computational Toolkit / 8 November 2000 Supercomputing 2000, Dallas, TX (USA)
Seidel, E.	Numerical Relativity / 12 October 2000 SGI 2000, Krakow (Poland)
Seidel, E.	The Grid / 21 September 2000 / Workshop at Maxwell Institute, Edinburgh (Scotland)
Seidel, E.	The use of the Cactus Computational Toolkit 8 February 2000 / GrADs Meeting, San Diego, CA (USA)
Seidel, E.	The Cactus Toolkit and Grid-based computing 12 April 2000 / Egrid Meeting, Poznan (Poland)
Seidel, E.	Numerical Relativity / 23 April 2000 / Maui High Performance Computing Center, Maui, Hawaii (USA)
Seidel, E.	The Cactus Computational Toolkit / 8 July 2000 Boeing Aerospace, Seattle, Washington (USA)
Seidel, E.	Grid Portals / 14 July 2000 / GrADs Meeting, Argonne, IL (USA)
Seidel, E.	The Cactus Computational Toolkit / 22 July 2000 / Cactus Portal Meeting, National Center for Supercomputing Applications, IL (USA)
Seidel, E.	The Cactus Computational Toolkit / 30 August 2000 Lawrence Livermore National Lab, Livermore, CA (USA)
Seidel, E.	The Cactus Computational Toolkit / 16 October 2000 Grid Forum Meeting, Boston (USA)
Seidel, E.	Grid Computing / 21 October 2000 / Grid Forum Meeting, Boston (USA)
Seidel, E.	Using Supercomputers to collide black holes / 23 May 2000 San Diego Super-computing Center, San Diego, CA (USA)
Seidel, E.	Colliding Black Holes, Collapsing Gravitational waves, Colliding Neutron Stars: Solving Einstein's Equations on Supercomputers / 13 May 2000 Astronomy Colloquium, University of Washington, Seattle (USA)
Seidel, E.	Recent Results in Numerical Relativity 6 June 2000 / Gravitational Wave Meeting, Trieste (Italy)
Seidel, E.	Dynamic Grid Computing / 24 August 2000 / First LASCI Symposium, Santa Fe, New Mexico (USA)

Invited Conference Talks Given by AEI Members

Seidel, E.	Numerical Relativity / 18 October 2000 / Special Invited Colloquium, University of Maryland (USA)
Seidel, E.	Colliding Black Holes / 7 November 2000 / Astronomy Colloquium, University of Chicago (USA)
Seidel, E.	The Cactus Computational Toolkit / 15 May 2000 Department of Applied Mathematics, Stanford University (USA)
Seidel, E.	Grid Computing: A User's Perspective/ 6 August 2000 / HPDC-9, Pittsburgh, PA (USA)
Seidel, E.	The Cactus Computational Toolkit / 15 August 2000 / Lawrence Berkeley Lab, Berkeley, CA (USA)
Seidel, E.	Computational Science Meets Einstein's Equations 24 October 2000 / CSIT Seminar, Florida State University (USA)
Seidel, E.	Colliding Black Holes / 13 September 2000 / 20th Texas Symposium on Relativistic Astrophysics, Austin, TX (USA)
Seidel, E.	Overview of the EU Network Project, Overview of the AEI Group Effort 8 December 2000 / EU Network Meeting, AEI, Golm (Germany)
Sintes, A.M.	Detector Characterization / 22 June 2000 / GEO Data Analysis meeting, Cardiff, Wales (UK)
Sintes, A.M.	Hough Hierarchical Pulsar Search / 16 August 2000 LIGO Scientific Collaboration Council (LSC) meeting 7. Hanford Observatory, Washington (USA)
Sintes, A.M.	Coherent Line Removal in the DMT Search 15 / 17 August 2000 / LIGO Scientific Collaboration Council (LSC) meeting 7. Hanford Observatory, Washington (USA)
Theisen, S.	Non-Linear Self-Duality and Supersymmetry 7 September 2000 / TMR-Conference, Paris (France)
Theisen, S.	Holographic Anomalies / 6 October 2000 / RTN network meeting, Humboldt Universität Berlin (Germany)
Thiemann, T.	Semiclassical Aspects of Non-Perturbative Quantum General Relativity 14 March 2000 / MPG-Tagung Dresden (Germany)
Thiemann, T.	A Coherent State Map for Loop Quantum Gravity Relativity 4 July 2000 / Ligo Scientific Collaboration Meeting, Hanford, WA (USA)
Thiemann, T.	The Infinite Tensor Product Extension for Quantum General Relativity 5 July 2000 / 9th Marcel Grossmann meeting, Rome (Italy)
Weaver, M.	Oscillatory approach to the singularity in vacuum T^2 symmetric spacetimes / 7 July 2000 / 9th Marcel Grossman Meeting, Rome (Italy)
Weaver, M.	Gowdy spacetimes with spikes / 19 July 2000 / Workshop on Mathematical Aspects of Gravitation, Oberwolfach (Germany)

Lectures and Lecture Series Given by AEI Members

Allen, G.	The Cactus Code: A Problem Solving Environment for the Grid 1 – 4 August / 2000 Ninth IEEE International Symposium on High Performance Distributed Computing 9, HPDC-9, Pittsburgh (USA)
Allen, G.	Cactus framework and its use for numerical relativity / 4 – 15 September 2000 / Ninth National Seminar Series on Theoretical Physics, Parma (Italy)
Allen, G.	Cactus framework / 11 – 14 October 2000 / SGI Users Conference, Krakow (Poland)
Allen, G.	Cactus framework for numerical relativity applications / 7 – 9 December 2000 / EU Network Meeting, AEI, Golm (Germany)
Cutler, C.	Gravitational Wave Damping of Neutron Star Wobble / December 2000 Institute for Theoretical Physics, UC Santa Barbara (USA)
Ehlers, J.	Einführung in die Allgemeine Relativitätstheorie / 6 – 17 March 2000 Ferienkurs AEI, Potsdam (Germany)
Ehlers, J.	Gravitationswellen / 5 June / Universität Erlangen (Germany)
Ehlers, J.	Das Standardmodell des Universums / 21 June / Universität Tübingen (Germany)
Ehlers, J.	Gravitationslinsen / 7 July / Universität Basel (Switzerland)
Ehlers, J.	Gravitationslinsen / 4 – 8 September / Advanced Courses on Physics, University of Jena, Saalfeld (Germany)
Ehlers, J.	Gravitational Lensing / 26 – 27 September and 3 – 4 October 2000 Inter-University Centre of Astronomy and Astrophysics IUCAA, Pune (India)
Ehlers, J.	General Relativity and its Empirical Foundation / 3 October 2000 InterUniversity Centre of Astronomy and Astrophysics IUCAA, Pune (India)
Ehlers, J.	Field Theory Aspects of Gravity / 10 October / Inter-University Centre of Astronomy and Astrophysics IUCAA, Pune (India)
Friedrich, H.	Ausgewählte Themen der Relativitätstheorie I / 17 October 2000 Universität Potsdam (Germany)
Hübner, P.	3D Numerical Relativity Without Artificial Boundaries - The Conformal Approach / 31 January 2000 / State College, PA (USA)
Junker, W.	Quantenfeldtheorie II / 13 April 2000 / Universität Potsdam, Potsdam (Germany)
Junker, W.	Microlocal Analysis of Singularities / 14 February 2000 / Frühlingsschule am Institut für Mathematik der Universität Potsdam, Potsdam (Germany)
Loll, R.	Nichtperturbative Theorien der Quantengravitation 10 September 2000 / 6. WE Heräus-Doktorandenschule "Grundlagen und neue Methoden der theoretischen Physik'", Saalburg (Germany)
Loll, R.	Quantentheorie II / 18 April 2000 / Fachbereich Physik, Universität Potsdam, Potsdam (Germany)
Nicolai, H.	Einführung in die Supersymmetrie und Supergravitation / 14 April 2000 Humboldt-Universität, Berlin (Germany)
Nicolai, H.	Introduction to Supersymmetry and Supergravity / 6 March 2000 Albert Einstein Institute (in the Auditorium), Golm (Germany)
Nicolai, H.	Recent Developments in Supermembrane Theory / 3 December 2000 4th Mexican School on Gravitation and Mathematical Physics, Huatulco (Mexico)
Plefka, J.	Einführung in die Stringtheorie / 15 October 2000 / Humboldt Universität zu Berlin (Germany)
Plefka, J.	Übungen zur Quantentheorie II / 15 October 2000 / Humboldt Universität zu Berlin (Germany)

Lectures and Lecture Series Given by AEI Members

Rendall, A.D.	New developments in the study of spacetime singularities / 24 August 2000 / Asia Pacific Centre for Theoretical Physics, Seoul (Korea)
Rendall, A.D.	Analysis für Informatiker / 16 October 2000 / Technische Universität Berlin (Germany)
Schomerus, V.	Nichtkommutative Geometrie und Stringtheorie / 13 May 2000 Universität Halle (Germany)
Schomerus, V.	Nichtkommutative Geometrie und Stringtheorie / 24 June / Universität Jena (Germany)
Schomerus, V.	Nichtkommutative Geometrie und Stringtheorie / 8 July / Universität Leipzig (Germany)
Theisen, S.	AdS/CFT Korrespondenz / 25 September 2000 / Herbstschule des Graduiertenkollegs, Universität Heidelberg (Germany)
Thiemann, T.	Semiklassische Methoden der Quantenmechanik / 1 July 2000 AEI, Golm (Germany)
Thiemann, T.	Semiclassical Methods of Quantum Mechanics / 1 September 2000 The Pennsylvania State University (USA)

Popular Talks Given by AEI Members

Brügmann, B.	Schwarze Löcher im Computer / 23 May 2000 / Astronomielehrer Berlin (Germany)
Ehlers, J.	Das Standardmodell der Welt / 2 March 2000 / Katholische Akademie, Berlin (Germany)
Ehlers, J.	Hatte Einstein Recht? / 14 April 2000 / Urania Berlin (Germany)
Ehlers, J	Die Zeit in Physik und Astronomie / 10 May / Vortragskreis Starnberg (Germany)
Ehlers, J.	Hatte Einstein Recht? / 1 July / Universität Würzburg Open House, Würzburg (Germany)
Ehlers, J.	Albert Einstein und der Zeitbegriff / 15 July / Initiativkreis Albert-Einstein-Haus Caputh (Germany)
Ehlers, J.	Vergangenheit und Zukunft des Kosmos / 17 August / Europäisches Forum Alpbach (Austria)
Ehlers, J.	Einstein, die Schwerkraft und das Weltall / 11 November / Urania-Verein Potsdam, Lecture at Geoforschungszentrum Potsdam (Germany)
Henkel, O.	Schwarze Löcher, weisse Löcher - Eine phantastische Reise in Paralleluniversen / 6 June 2000 / Max-Born-Gymnasium, Erasmus-Grasser-Gymnasium, Lion-Feuchtwanger-Gymnasium, München (Germany)
Henkel, O.	Einstein für Einsteiger / 20 May 2000 / Volkshochschule Bremen, Bremen (Germany)
Koepsell, K.	String-Theorie – Eine Einführung / 8 June 2000 / Max-Born-Gymnasium, München (Germany)
Nicolai, H.	Alles Fäden oder was? Hoffnungsträger Stringtheorie / 4 April 2000 URANIA, Berlin (Germany)
Pössel, M.	Zeitreisen und überlichtschneller Raumflug aus Sicht der modernen Physik / 30 October 2000 / Lecture Series on Star Trek, Universität Regensburg (Germany)

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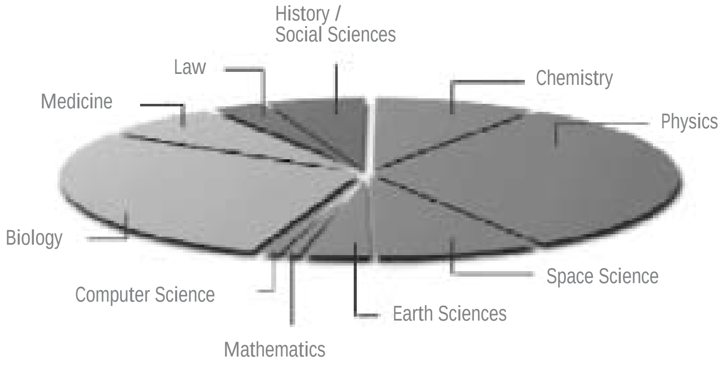

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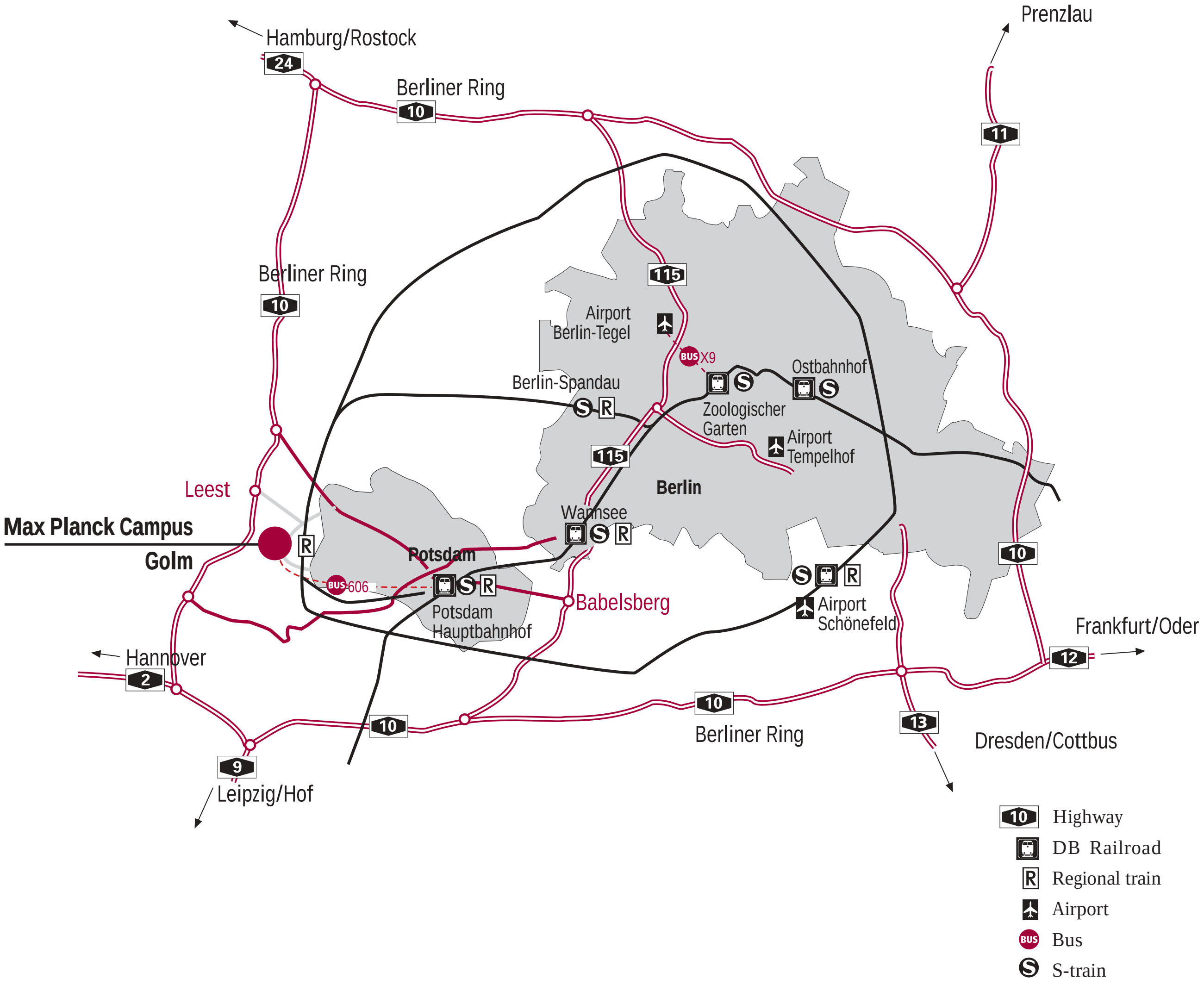

From the airports:

Tegel: Bus X9 to train station “Zoologischer Garten”
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Tempelhof: Underground U6 (direction Alt-Tegel) to “Friedrichstraße”

then take S-Bahn or Regionalbahn to train station “Potsdam Hauptbahnhof” and transfer to Regionalbahn RB 21 (direction Berlin-Spandau) leaving once every hour to Golm (+10 minutes walk) or take Bus 606 straight to the Max Planck Campus

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