B5

3.1 Allgemeine Angaben zum Teilprojekt B5

3.1.1 Thema: Kollision und Verschmelzung Binärer Schwarzer Löcher und Neutronensterne

3.1.2 Fachgebiete u. Arbeitsrichtung: Numerische Relativitätstheorie

3.1.3 Leiter:

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Ist die Stelle des Leiters/der Leiterin des Projektes befristet?

☒ nein ☐ ja, befristet bis zum ___________

3.1.4 entfällt

3.1.5 In dem Teilprojekt sind vorgesehen:

• Untersuchungen am Menschen	☐ ja	☒ nein
• klinische Studien im Bereich der somatischen Gentherapie	☐ ja	☒ nein
• Tierversuche	☐ ja	☒ nein
• gentechnologische Untersuchungen	☐ ja	☒ nein

3.1.6 Bisherige und beantragte Förderung des Teilprojektes im Rahmen des Sonderforschungsbereichs/Transregio (Ergänzungsausstattung)

Haushaltsjahr	**Personalkosten**	**Sächl. Verw.-ausgaben**	**Investitionen**	**gesamt**
2003	**81,6**			**81,6**
2004	**81,6**			**81,6**
2005	**81,6**			**81,6**
2006	**81,6**			**81,6**
Summe 2003-2006	**326,4**			**326,4**

(Beträge in Tausend EUR)

3.2 Zusammenfassung

Gravitationswellen werden von verschiedenen astrophysikalischen Phänomenen erzeugt, die sich in der Häufigkeit ihres Auftretens, ihrer Dauer, Frequenz und Stärke des Signals stark unterscheiden.

Gerade für die erste Generation der interferometrischen Gravitionswellendetektoren erwartet man, dass Binärsysteme Schwarzer Löcher eine der wichtigsten Quellen darstellen werden.

Zwei Schwarze Löcher stellarer Größe, die in einem Binärsystem um einander kreisen, verlieren über viele Millionen Jahre Energie und Drehimpuls durch die Abstrahlung von Gravitationswellen. Dadurch kommen sich die Schwarzen Löcher langsam näher, laufen also nicht auf einer Kreisbahn oder Ellipse umeinander, sondern auf einer Spirale. Letztendlich werden die Schwarzen Löcher zusammenstoßen und zu einem einzigen Schwarzen Loch verschmelzen, wobei eine gewaltige Energiemenge in Form von Gravitationswellen freigesetzt wird.

Um die letzten Orbits der Schwarzen Löcher und ihren Zusammenstoß zu beschreiben, müssen Einsteins Gleichungen der Allgemeinen Relativitätstheorie gelöst werden. In diesem Bereich der extrem starken und nichtlinearen Gravitationsfelder kommen Methoden der Numerische Relativitätstheorie zur Anwendung. Man versucht, mit dem Computer die Evolution der Schwarzen Löcher zu simulieren und die erzeugten Gravitationswellen zu berechnen. Das ist ein schwieriges Problem, nicht zuletzt wegen der Raumzeitsingularität innerhalb der Schwarzen Löcher. Zur Zeit kann der allgemeine Fall nur für Teile eines einzigen Orbits berechnet werden, während die Verschmelzung mittlerweile einigermaßen in den Griff bekommen werden konnte.

Ziel dieses Teilprojektes ist es, die Numerische Relativitätstheorie in entscheidenden Teilbereichen voranzubringen, so dass astrophysikalisch relevante Information berechnet werden kann. Dazu gehören insbesondere die Berechnung von realistischen Anfangsdaten von Schwarzen Löchern und die Entwicklung von für die Numerik besser geeigneten Evolutionsgleichungen. Ein besonderes Problem in der Relativitätstheorie ist gerade bei Schwarzen Löchern auch die Koordinatenwahl. Die Physik ist von den Koordinaten unabhängig, aber der Computer benötigt eine explizite Wahl der Koordinaten, die typischerweise dynamisch während der Evolution getroffen wird. Computersimulationen von Schwarzen Löchern sind extrem aufwändig, aber die Gruppe am Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut, AEI) hat in Form des Computerprogramms ‚Cactus' wesentliche Teile der erforderlichen Infrastruktur zum Hochleistungsrechnen auf Parallelcomputern schon selbst entwickelt.

Es besteht die konkrete Möglichkeit, dass während der Laufzeit des Projekts erste Gravitationswellendaten von den Detektoren erhalten werden. Es ist daher eine dringliche Aufgabe, theoretische Ergebnisse zum Phänomen der Verschmelzung zweier Schwarzer Löcher zu erarbeiten.

3.3 Stand der Forschung

This project is an ambitious program to further develop the capability to carry out astrophysically relevant simulations of orbiting, coalescing black holes (BHs), and further, to carry out parameter studies over the lifetime of the project to understand the details of waveforms expected for gravitational wave astronomy for various classes of coalescence configurations. There is the very real possibility that waves from BH coalescence will be detected during this project, in which case detailed simulations will be needed to interpret these signals. Information from these simulations could also be crucial to enabling BH mergers to be detected [1, 2].

This Teilprojekt focuses closely on these problems.

However, numerical simulations of dynamic BHs are very difficult due to singularities inside, and due to various instabilities present in current treatments of the Einstein equations (EEs), limiting the length of time they can be accurately evolved at present. In 3D, the huge computational and memory requirements exacerbate these problems. A very large, $ 4.5 M project, aimed specifically at this problem, was funded for 5 years in the US by the National Science Foundation, involving 8 universities, from 1993-1998 (Seidel was a PI on that at the U of Illinois before moving to AEI.). This project was not able to solve this problem, although much was learned about the difficulties! In summary, work of this project and follow-on work at the AEI is as follows: The most advanced 3D (Cauchy) calculations, utilizing massively parallel computers, were able to accurately evolve dynamic BHs (spherical [3], colliding [4] or distorted BHs [5]) for less than half the time required to follow a full orbital merger. However, much physics has been learned and progress has been made, in both 2D and in 3D. In axisymmetry, calculations of distorted, rotating BHs (see, e.g., [6], and colliding BHs, including boosted and unequal mass BHs [7, 8], have all been successfully carried out, and the waveforms generated during the collision process were extensively compared to calculations performed using perturbation theory [9].

Crude binary BH coalescence simulations were attempted in 1997 by Brügmann [10], and later in [11], but aside from recent work of the AEI group, little other progress has been made in this area.

At the same time as these BH studies, a serious search by the community has been undertaken to find better formulations of the EEs for numerical treatment. By the early 1990’s, first order hyperbolic systems became favored as the most attractive way to formulate the EE for numerical studies, due to their clean mathematical structure. However, in most existing efforts, the numerical integration of these first order hyperbolic systems in full 3D has not yet led to a substantial improvement over those using the traditional ADM equations. In parallel with these developments, there have been various attempts to re-write the traditional ADM form of the evolution equations by separating out the conformal degrees of freedom [12]. A recent re-formulation of such an approach was introduced by Baumgarte and Shapiro in [13], where it was shown that this new formulation leads to highly stable numerical evolutions.

Similarly, over the last 10 years, the community has devoted significant effort to “singularity excision” techniques for evolving black holes [14, 15, 16]. Because the region of spacetime inside a BH horizon cannot causally affect the region outside the horizon, the interior domain containing the singularity can be safely excised, and there is in principle no reason why BH codes cannot be made to run indefinitely without crashing. However, this has been a very difficult problem in practice, and to date no stable algorithm has been demonstrated for the general case of 3D, orbiting, binary BH coalescence.

Finally, initial data for the binary BH problem have been developed over the years [17, 18], and recently progress has been made to understand how to create astrophysically motivated versions of such data [19, 20, 21, 22]. There is general agreement that such data sets are beginning to address the issues of creating astrophysically relevant initial data, but there are significant differences in the results and much remains to be done to refine them.

As shown below (“Eigene Vorarbeiten”), recent work on new formulations of the Einstein equations, and new techniques designed to extend BH simulations, have made dramatic improvement in the long term stability of BH simulations. With these improvements, and increasing improvements in the creation of the SFB we can expect to perform the first accurate 3D merger simulations for grazing collisions without a long orbital phase, and to extract accurate waveforms over the lifetime of the project.

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3.4 Eigene Vorarbeiten

The AEI group has been a traditional leader in this area, being among the first to evolve 2D rotating BHs [1, 2, 3], 2D colliding BHs [4, 5, 6], 3D single [7, 8] and colliding BHs [9, 4, 5]. We were also the first group to develop BH excision techniques [10, 11, 7], and new “puncture” BH initial data [12].

In recent years the AEI group has made significant progress in the development of binary BH initial data, gauge conditions needed for binary BH orbits, excision techniques, and further development of stable and accurate formulations of Einstein equations for numerical relativity. Based on these developments, we are in a position through this SFB to carry out fully nonlinear simulations of BH mergers from the various orbital configurations, through the final merger and ringdown, and to extract waveforms.

Our treatment of BH simulations is built on four independent components: new formulations of Einstein’s equations, new gauge conditions, singularity excision techniques, and a nonlinear-perturbative technique. This approach to 3D BH simulations has come together dramatically in the last years, improving by orders of magnitude the evolution times previously achievable, and reducing numerical errors by large factors. It provides an excellent starting point for work to be carried out in this SFB.

As described above, much effort has been spent in recent years in trying to develop and test different formulations of the Einstein equations (EE) that can provide us with more stable, accurate and robust numerical implementations. A detailed study of the BSSN approach using pure gravitational wave systems carried out by our group [13] confirmed that it has many advantages over the standard ADM formulation. We further studied and developed this conformal approach in [14, 15]. These improved formulations have allowed us to obtain far more stable evolutions than ever before, both with and without matter (see [16, 14, 17, 18, 19]).

The development of new classes of gauge conditions, including both the lapse function and the shift vector, and the implementation of older conditions in full 3D, such as maximal slicing and the minimal distortion family of shift conditions, turns out to be critical to successful 3D evolutions. For the lapse, we have worked with both elliptic and hyperbolic conditions. For the shift, we experimented with families of elliptic, parabolic and hyperbolic conditions that relate the shift choice with the evolution of the conformal connection functions that appear as independent variables in the BSSN [20]. These are extremely powerful developments, as outlined in [19].

With the new formulations of the EE discussed above, we were able to carry out such simulations far beyond what was possible in [21]. These formulations enabled us to carry out the most advanced 3D grazing BH collisions to date, computing for the first time the gravitational waves emitted (see our recent PRL [18]).

By using new gauge conditions and excision, we can now significantly improve on these results. We are currently running fully 3D simulations of head-on collisions of BHs. Even though the evolution of such systems and the waveforms emitted are well known from axisymmetric codes, long-term stable evolutions in 3D have not been possible before. With our improved gauge conditions we have recently been able to obtain evolutions of head-on collisions lasting for more than 1000M, with very accurate waveforms, even without excision. Such results are proof of the strength and robustness of our gauge conditions.

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3.5 Arbeitsprogramm (Ziele, Methoden, Zeitplan)

We describe the various activities, their goals, and the person-months expected from this project.

Methods:

In order to achieve our goals of studying binary BH coalescence from a variety of orbital configurations, we will have to solve or make significant progress on a series of research problems, categorized roughly as

3.5.1 **Initial Data** (12 months)

The initial data problem, although in principle is now soluble, is still a very tricky problem because of the issue of developing initial data sets that correspond to astrophysically relevant orbital characteristics. For this, it seems the best approach to date is that of the Meudon group [1, 2]. However, even if this basic method could be used without modification, to give realistic binary BH initial models, it would still need to be extended to the cases of unequal mass BHs, and different spin (co-rotating, irrotational), etc., in order to perform a survey of orbital configurations. But even more, there are various indications that this method of creating data sets may itself require revision. A promising way to augment this approach would be combine it with a Post-Newtonian approach, as already under investigation by members of the AEI group, in collaboration with Schäfer at Jena.

3.5.2 **Evolution Systems** (24 months)

We will continue to work on improving the stability of our formulations, as described above. This will require collaborations with other members of the SFB, especially those at AEI, Jena, and Tübingen.

3.5.3 **Gauges** (24 months)

In spite of great progress made in recent years, it remains to be seen how much more development will be needed to carry out routine orbits of binary BH spacetimes. Present work indicates that although very powerful, our current family of gauge conditions requires significant fine tuning in order to achieve a significant fraction of an orbit. Furthermore, we have shown it is very important to bring the binary pair into a co-rotating frame, and we have developed gauge conditions to do this that work in some cases, but it is not yet clear how much these conditions need to be improved before orbits can be routinely carried out.

3.5.4 **BH Excision** (12 months)

Presently, BH excision techniques have been developed that do not allow the BHs to move across the computational grid. Although for orbiting BHs, this may seem to be a problem, to date we have found that by using a co-rotating frame, as described above, it is possible to use this restricted form of the excision technique. However, it may turn out to be important to develop an extension of this technique to allow the holes to move across the grid. Such techniques have been developed by other groups (e.g., Penn State), and so we know it is possible to do this if it becomes necessary.

3.5.5 **Outer Boundary Conditions** (12 months)

Boundary conditions have received perhaps the least amount of attention to date. At present, simulations have typically been carried out only through part of one orbit, and the boundaries are places far enough away that even with our fairly crude outer boundary conditions, the effects on the waveforms are not serious. However, once **we** begin to carry out multiple orbits, as we expect in this project, much more attention will need to be placed on developing techniques to handle better the outer boundary.

3.5.6 **Computational Problems** (12 months)

We use the Cactus framework for virtually all our 3D computations proposed. Our group develops Cactus not only for our own research, but for the entire community (actively used by roughly a dozen groups in relativity worldwide). As in the past, many routines developed as a result of this proposal will be available to the community. Our evolution algorithms are based on explicit, second order finite difference techniques on regular 3D cartesian grids (and where AMR is used, nested hierarchies of 3D regular cartesian grids). Second order convergence of our results is generally expected and achieved. For 3D spacetime evolutions, a 3-step iterative Crank-Nicholson time stepping procedure is used, and for hydrodynamics HRSC methods are employed. We also have an extensive set of test suites for most thorns in Cactus, so that any changes made to routines can be immediately and automatically checked against many different known results, on multiple architectures, and on multiple processors. All code is maintained in a central CVS repository, so all users around the world can check out, update, or if authorized, commit new and improved versions of code, or just as importantly, they can restore a newly corrupted routine to its previous (working) state. Routines in Cactus run on all major architectures, and very efficiently, scaling well to thousands of processors, using an explicit MPI layer for parallelism. We have benchmarks on all machines proposed, which are documented at http://www.cactuscode.org. We are also leaders in Grid computing, and can run our production codes across multiple supercomputers. Last year we developed new efficient, distributed computing techniques, for which we won the 2001 Gordon Bell Prize.

The developments listed above will continue in parallel, as needed, totally 96 months.

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3.6 Stellung innerhalb des Sonderforschungsbereichs/Transregio

This Teilprojekt links to others in various ways. In order to carry out realistic binary BH coalescence studies, it will be necessary to have astrophysically relevant initial data. Development of better initial data sets will be carried out in conjunction with B4 (Einspiralende binäre Schwarze Löcher und Neutronensterne). The Cactus Computational Toolkit may be used for work done in A2 (Numerische Berechnung von Gravitationswellen isolierter Systeme), in which case many numerical techniques and routines may be able to be compared and shared; new developments from A2 may be useful for B5 and vice versa. As the group will be continually refining its simulations for coalescing BHs, in hopes of making them as useful as possible for the gravitational wave detectors, it will work very closely with C2 (Interpretation von Gravitationswellensignalen) throughout the project.

The AEI numerical relativity group, which will be carrying out the work described above, is also active in areas covered by some of the other Teilprojekte. For example, the group is active in simulating coalescing neutron stars, and will share its codes and expertise with B6 (Verschmelzung von Neutronensternen). The codes it develops are also useful for studying properties and oscillation modes of single neutron stars and black holes, and hence will be very useful for B1 (Rotierende Neutronensterne und Schwarze Löcher).

The Teilprojekt B5 also will benefit from interactions with A1 (Analysis asymptotisch flacher Raumzeiten), A3 (Kollidierende ebene Gravitationswellen), and A4 (Analytische Näherungsverfahren).

3.7 Abgrenzung gegenüber anderen geförderten Projekten

The AEI numerical relativity group, responsible for B5, is also very active in other, independently funded projects that have some bearing on this work. They include:

- **EU Astrophysics Network**. (http://www.eu-network.org) This project, led by Seidel, is an EU-funded collaboration of 10 institutes across Europe (including Jena). It ends officially in September, 2003. The aims of this project include the development of codes and techniques for studies coalescing neutron stars and black holes, and training young scientists in this field, rather than on the research itself. Hence it augments work of this SFB by providing a good starting point for some of the work, both in terms of tools and techniques that may be used, and personnel who may be hired for the SFB. The aims of the SFB are more advanced than the EU project, targeted towards application of these tools to realistic simulations of signals to be detected by the gravitational wave detectors.

- **DFN-Verein GriKSL project.** (http://www.griksl.org) Another project led by Seidel, this aims to develop computational tools for remote visualization and computational steering on computational Grids. Although not related to the Physics of this project, the technologies it develops could be very useful for the computations to be carried out. This project ends in April, 2004.
- **EU GridLab Project.** (http://www.gridlab.org) This is a very large EU-funded project involving leading computational science groups around Europe, including the AEI. It is also aimed at developing tools for Grid computing, especially focusing on the needs of numerical relativity and gravitational wave astronomy community. Hence, although it does not overlap with the current project, it does nicely complement it, providing advanced computation tools that can be used by the various groups if they are involved in computation.

3.8 Ergänzungsausstattung für das Teilprojekt

PK: Personalbedarf und -kosten (Begründung vgl. 3.8.1)
SV: Sächliche Verwaltungsausgaben (Begründung vgl. 3.8.2)
I: Investitionen (Geräte über 10.000,- EUR brutto; Begründung vgl. 3.8.3)

	Bewilligung 2002 1)			**2003**			**2004**			**2005**			**2006**		
PK	**Verg.-Gr.**	**Anz.**	**Betrag EUR**	**Verg.-Gr.**	**Anz.**	**Betrag EUR**	**Verg.-Gr.**	**Anz.**	**Betrag EUR**	**Verg.-Gr.**	**Anz.**	**Betrag EUR**	**Verg. Gr.**	**Anz.**	**Betrag EUR**
				IIa	1	56.400	IIa	1	56.400	IIa	1	56.400	IIa	1	56.400
				IIa/2	1	25.200	IIa/2	1	25.200	IIa/2	1	25.200	IIa/2	1	25.200
	zus.:			**zus.:**	**2**	**81.600**	**zus.:**	**2**	**81.600**	**zus.:**	**2**	**81.600**	**zus.:**	**2**	**81.600**

SV	**Kosten-kategorie oder Kennziff.**	**Betrag EUR**	**Kosten-kategorie oder Kennziff.**	**Betrag EUR**	**Kosten-kategorie oder Kennziff.**	**Betrag EUR**	**Kosten-kategorie oder Kennziff.**	**Betrag EUR**

I	**Investitionsmittel insges.**	**Investitionsmittel insges.**	**Investitionsmittel insges.**	**Investitionsmittel insges.**

1) nur bei Fortsetzungsanträgen

*) Werkstattarbeiten

3.8.1 Begründung des Personalbedarfs

	Name, akad. Grad, Dienststellung	engeres Fach des Mitarbeiters	Institut der Hochschule oder der außeruniv. Einrichtung	Mitarbeit im Teilprojekt in Std. /Woche (beratend: B)	auf dieser Stelle im SFB/TR tätig seit	beantragte Einstufung in BAT
Grundausstattung						
3.8.1.1 wissenschaftl. Mitarbeiter 1) (einschl. Hilfskräfte)	1) Prof. Edward Seidel 2) Dr. Denis Pollney 3) Dr. Gabrielle Allen 4) Dr. Bernd Brügmann	Num. Relativitätstheorie Num. Relativitätstheorie Num. Relativitätstheorie Num. Relativitätstheorie	MPI für Gravitationsphysik MPI für Gravitationsphysik MPI für Gravitationsphysik Penn State University	4 5 5 B		
3.8.1.2 nichtwissenschaftl. Mitarbeiter 1)						
Ergänzungsausstattung						
3.8.1.3 wissenschaftl. Mitarbeiter 1) 2) (einschl. Hilfskräfte)	5) NN (Doktorand) 6) NN (Postdoc)	Num. Relativitätstheorie Num. Relativitätstheorie	MPI für Gravitationsphysik MPI für Gravitationsphysik	20 40		BAT IIa/2 BAT IIa
3.8.1.4 nichtwissenschaftl. Mitarbeiter 1)						

(Stellen, für die Mittel <u>neu</u> beantragt werden, sind mit **X** gekennzeichnet)

1) Bitte durchnumerieren und Aufgabenbeschreibung nachfolgend erläutern

2) Bitte Verfahrensgrundsätze der DFG zur Bezahlung wissenschaftl. Mitarbeiter beachten

Aufgabenbeschreibung von Mitarbeitern der Grundausstattung

1) Prof. E. Seidel:	Coordination of the numerical relativity work
2) Dr. Denis Pollney:	Coordination of the numerical relativity work
3) Dr. Gabrielle Allen:	Coordination of the computational work
4) Dr. Bernd Brügmann:	Advice

Aufgabenbeschreibung von Mitarbeitern der Ergänzungsausstattung

We request a BAT IIa position and graduate student (1/2 BAT IIa) for this work, which will significantly augment the effort in the AEI numerical relativity group in this area. At present, we have several candidates in mind but no commitments to offer the positions to particular researchers. We expect the positions to be easy to fill. These researchers will carry out the tasks described in section 3.5 above, in collaboration with senior researchers listed above, and other members of the group.

5) Graduate Student (NN)

We can expect the student to focus on development of the improved initial data, evolution methods and simulations, and computational effort.

6) Postdoc (NN)

The full BAT IIa position, in addition to helping to supervise the work of the doctoral student, would be involved directly in development of gauges, excision techniques, and improved boundary conditions.

3.8.2 Aufgliederung und Begründung der Sächlichen Verwaltungsausgaben (nach Haushaltsjahren)

	2003	2004	2005	2006
Für Sächliche Verwaltungsausgaben stehen als **Grundausstattung** voraussichtlich zur Verfügung:	10.000	10.000	10.000	10.000

Für Sächliche Verwaltungsausgaben werden als **Ergänzungsausstattung** beantragt (entspricht den Gesamtsummen "Sächliche Verwaltungsausgaben" in Übersicht 3.8): Begründung zur Ergänzungsausstattung				

(Alle Angaben in EUR)

3.8.3 Investitionen (Geräte über 10.000,- EUR brutto und Fahrzeuge)

	Beantragt für das Haushaltsjahr			
	2003	**2004**	**2005**	**2006**
Summe:				

(Alle Preisangaben in Tausend EUR einschl. MwSt., Transportkosten etc.)