Mathematisches Forschungsinstitut Oberwolfach

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# Nonlinear Evolution Problems

May 20th – May 26th 2001

Die Tagung „Nonlinear Evolution Problems" diente dem Gedankenaustausch unter den 47 eingeladenen Wissenschaftlern. Diese kamen unter anderem aus Deutschland, Frankreich, Italien, Japan, der Schweiz, den USA. Die Tagungsleiter, Herr Klainerman (Princeton) und Herr Struwe (Zürich), konnten aus deren neueren Forschungsergebnissen ein interessantes Vortragsprogramm zusammenstellen. Schwerpunkte waren

- Wellenabbildungen (vor allem globale Existenz- und Regularitätsfragen)
- Geometrische Evolutionsprobleme
- Dispersionsgleichungen
- Evolutionsgleichungen in der Allgemeinen Relativitätstheorie

Die folgenden Seiten stellen diese Präsentationen als Kurzfassungen vor. Das Programm bot jedoch über diese Einzeldarstellungen hinaus ausgiebige Gelegenheiten, viele Probleme in kleineren und größeren Gruppen zu diskutieren, bestehende Projekte weiterzuverfolgen und neue Arbeitsgemeinschaften zu begründen.

# Abstracts

### Global CMC foliations

Lars Andersson

Constant mean curvature Cauchy surfaces of spatially compact vacuum spacetimes satisfy uniqueness properties which makes CMC time a natural time gauge for the Einstein equations. The Einstein equations are known to be hyperbolic in this gauge.
The standard conjecture for CMC foliations is that global existence holds in CMC time, i.e. that CMC time tr$K$ takes on all allowed values, depending on the Yamabe invariant of the Cauchy surface. This is known to hold in many cases with symmetry.
We consider some results for spacetimes with little or no symmetry. For flat spacetimes with hyperbolic spatial topology, global CMC foliations exist [L.A., 2000]. For spacetimes with $L^\infty$ curvature bounds, global CMC foliations and asymptotic geometrization are known [M. Anderson, 2000]. Small data global existence for CMC foliations is known for polarized $U(1)$ spacetimes, in the expanding direction [Choquet-Bruhat and Moncrief, 2001], as well as for 3+1 rigid spacetimes with hyperbolic spatial topology.

### Critical behaviour at the threshold for blowup

Piotr Bizoń

In order to gain insight into critical phenomena at the threshold for black hole formation in gravitational collaps, we study the threshold for blowup in toy models, such as wave maps in $3 + 1$ dimensions or Yang-Mills equations in $5 + 1$ dimensions. Using mixed numerical-analytical methods we show that the threshold for blowup is determined by the codimension-one stable manifolds of a self-similar solution. We also conjecture that the blowup in these models is generically asymptotically self-similar. We point out that the nature of blowup and transition between blowup and dispersion (global existence) is completely different in the critical dimensions ($2 + 1$ for wave maps and $4 + 1$ for Yang-Mills).

### Averages over spheres for kinetic transport equations

Nikolaos Bournaveas

We consider averages over spheres for kinetic transport equations in $d \geq 2$ space dimensions. In the case $d \geq 3$ we prove that averages over spheres satisfy the same estimates as averages over balls. In the case $d = 2$ however, 1/4 derivative is lost in the various forms of the Averaging Lemmas. We show that it is possible to recover the optimal regularity working in the hyperbolic Sobolev spaces $H^{s,\delta}$. Strichartz type inequalities follow with better exponents than those given by classical Sobolev imbeddings.

### Viscosity solutions for hyperbolic systems

Alberto Bressan

We consider a nonlinear strictly hyperbolic system of the form

$$\begin{aligned} u_t + A(u)u_x &= \varepsilon u_{xx} \\ u(0,x) &= \bar{u}(x) \end{aligned}$$

Assuming that the initial condition $\bar{u}$ has small total variation, we prove uniform BV bounds and Lipschitz continous dependence of the solution on the initial data, for all $t \geq 0$, $\varepsilon > 0$. Letting $\varepsilon \to 0$ we obtain in the limit a continous semigroup $S$, whose trajectories can be regarded as "viscosity solutions" to the hyperbolic $n \times n$ system $u_t + A(u)u_x = 0$. In the conservative case $A(u) = Df(u)$, the limit solutions coincide with the entropy weak solutions to the system of conservation laws $u_t + f(u)_x = 0$ obtained via the Glimm scheme. The proofs are obtained through a decomposition of the gradient $u_x$ as a sum of gradients of viscous travelling waves, via center manifold theory. Interactions among viscous waves are controlled by suitable new Lyapunov functionals.

### Strong cosmic censorship and the spherically symmetric Einstein-Maxwell-Scalar field equations

Mihalis Dafermos

We consider a trapped characteristic initial value problem for the spherically symmetric Einstein-Maxwell-Scalar field equations. For an open set of initial data whose closure contains Reissner-Nordström data, the future boundary of the maximal domain of development is found to be a lightlike surface along which the curvature blows up, and yet the metric can be continously extended beyond it. This result is related to the strong cosmic censorship conjecture of Roger Penrose.

### A local monotonicity formula for mean curvature flow

Klaus Ecker

For the standard heat equation, a local mean value formula due to Fulks and Watson states that the temperature at a particular point in space and time equals the average temperature taken over heat-balls centred ar this point. Heat-balls are the subsets of space-time where the backward heat kernel is larger then a given number, their boundaries are the level sets of the backward heat kernel (or its translates in space-time).
We present a local mean value formula for submanifolds moving by their mean curvature and show how this is related to a monotonicity formula for mean curvature flow proved by Huisken.

### Transonic shocks for steady potential flows and free boundary problems

Mikhail Feldman, Gui-Qiang Chen

We establish the existence and stability of multidimensional transonic shocks for steady potential flows, via solving a nonlinear free bondary problem. The equations for the transonic shocks are nonlinear second order elliptic-hyperbolic equations of mixed type, which can be derived from compressible Euler equations consisting of conservation law of mass and the Bernoulli law for velocity. The free boundary is the location of the shock, dividing two regions of the smooth flow; and the equation is hyperbolic in the upstream region where the flow is supersonic, and elliptic in the downstream region. We show that for any sufficiently small pertubation of the supersonic flow there exists a unique elliptic (subsonic) solution in the downstream region, and the free boundary is stable.

## New results on inverse mean curvature flow

Gerhard Huisken

Inverse mean curvature flow is described by the nonlinear parabolic system

$$\frac{\mathrm{d}}{\mathrm{dt}}F(p,t) \;=\; \frac{1}{H}\nu(p,t)$$

for a family of surfaces $F\colon M^n \times [0,T] \to (N^{n+1}, g)$ in a Riemannian manifold. In joint work with Tom Ilmanen (ETH) new regularity estimates are established concerning lower bounds for $H$ on starshaped surfaces and the longterm asymptotic behaviour in asymptotically flat manifolds. In the asymptotically flat case it is also shown that the inverse mean curvature flow solution converges to the same center of mass as given by the constant mean curvature foliation near infinity.

## Stability of Ricci flows converging to flat metrics

James Isenberg

Motivated by studies of the Ricci flow of warped products $(\Sigma^2 \times \mathbb{S}^1, {}^3g = {}^2g(x) + \mathrm{e}^{U(x)}\mathrm{d}\theta^2)$, we consider the following stability question: Let the Ricci flow $g(t)$ of a given metric $(M^n, g_0)$ converge to a flat metric $(M^n, \eta)$. Does it follow that the Ricci flow $\tilde{g}(t)$ of a nearby metric $(M^n, \tilde{g}_0)$ must also converge to a flat metric $(M^n, \tilde{\eta})$?
Christine Guenther, Dan Knopf and I prove that indeed Ricci flow is stable in this sense. Our proof relies on a dynamical system picture of the flow, and on the maximal regularity theory for parabolic flows with a center manifold. Our sense of "nearby" is based on a "little Hölder" $2+\varrho$ $(\varrho \in (0,1))$ neighborhood of $g_0$. The techniques we employ to prove this result should be useful for the study of Ricci flow stability for higher dimensional $(m \geq 4)$ Riemannian metrics which are Ricci flat with nonzero scalar curvature.

## Vortex filament dynamics for Gross-Pitaevsky type equations

Robert Jerrard

We study solutions of the Gross-Pitaevsky equation and similar equations in $m \geq 3$ space dimensions in a certain scaling limit, with initial data $u_0^\varepsilon$ for which the Jacobian $Ju_0^\varepsilon$ concentrates around an (oriented) rectifiable $(m-2)$-dimensional set, say $\Gamma_0$, of finite measure. It is widely conjectured that under these conditions, the Jacobian at later times $t > 0$ continues to concentrate around some codimension 2 submanifold, say $\Gamma_t$, and that the family $\{\Gamma_t\}$ of submanifolds evolves by binormal mean curvature flow. We prove this conjecture when $\Gamma_0$ is a round $(m-2)$-dimensional sphere with multiplicity 1. We also prove a number of partial results for more general inital data.
A preprint is posted at http://www.mis.mpg.de/preprints/2000, where the paper appears as preprint number 45/2000.

**Viscous Hamilton-Jacobi equations**

Herbert Koch

The viscous Hamilton-Jacobi equations

$$u_t - \Delta u + \frac{1}{p}|\nabla u|^p = 0 \quad (u \geq 0,\ 1 < p < \infty) \tag{1}$$

combine good properties of the heat equation and the Hamilton-Jacobi equation.

Thm 1 : $$t^{\frac{1}{p}} \left| \nabla u^{\frac{p-1}{p}} \right| \leq \left( \frac{p-1}{p} \right)^{\frac{p-1}{p}}$$

for all nonnegative solutions.
Thm 2: For all nonnegative functions $u_0 \in \mathcal{C}(\mathbb{R}^n)$ there exists a unique solution to (1) with initial data $u_0$.
This is joint work with S. Benachour and Ph. Laurençot.

**Gradient flow for the Willmore functional**

Ernst Kuwert, Reiner Schätzle

The Willmore energy of a closed, immersed surface $f\colon \Sigma \to \mathbb{R}^n$ is the $L^2$ integral of its curvature. We consider the corresponding $L^2$ gradient flow, which is a quasilinear, fourth-order geometric evolution equation with critical scaling. We prove that if a smooth flow develops a singularity in finite time $T$, then the energy must concentrate on balls of radius $\varrho(t) = o((T-t)^{1/4})$, with centers possibly depending on $t$. A suitable blowup is shown to converge to a static solution, which is a properly immersed, nonumbilic Willmore surface. If $\Sigma$ is topologically a sphere, then the flow converges smoothly to a round sphere if the initial energy is not too big. A numerical example by Mayer and Simonett shows that in general singularities may occur.

**The blowup locus for the heat flow of harmonic maps**

Jiayu Li

Let $M$ and $N$ be two compact Riemannian manifolds. Let $u_k(x,t)$ be a sequence of strong stationary weak heat flows from $M \times \mathbb{R}^+$ to $N$ with bounded energies. Assume that $u_k \to u$ weakly in $H^{1,2}(M \times \mathbb{R}^+, N)$ and that $\Sigma^t$ is the blowup set for a fixed $t > 0$. In this talk we first prove $\Sigma^t$ is a $H^{m-2}$-rectifiable set for almost all $t \in \mathbb{R}^+$. And then we prove two blowup formulas for the blowup set and the limiting map. From the formulas we can see that if the limiting map $u$ is also a strong stationary weak heat flow, $\Sigma^t$ is a distance solution of the $(m-2)$-dimensional mean curvature flow. If a smooth heat flow blows up at a finite time, we derive a tangent map or a weakly quasi harmonic sphere and a blow up set $\cup_{t<0}\Sigma^t \times \{t\}$. We prove the blowup map is stationary if and only if the blowup locus is a Brakke motion.

**The motion of the free surface of a liquid**

Hans Lindblad

We study the motion of an incompressible perfect liquid surrounded by vacuum, without surface tension. This can be thought of as a model for the motion of the ocean or a galaxy. The free surface moves with the velocity of the liquid. The pressure is zero on the free surface and the pressure determines the acceleration. This leads to a free boundary problem for Euler's equations, where the regularity of the boundary enters to highest order. Together with Christoudoulou I proved local a priori bounds for Sobolev norms assuming a "physical condition", related to the fact that the pressure of a fluid has to be positive. Recently I showed that the linearized problem is well-posed.

## Smooth geometric evolutions of hypersurfaces

Carlo Mantegazza

We consider the gradient flow associated to the following functionals

$$\mathcal{F}_m(\varphi) \;=\; \int_M 1 + |\nabla^m \nu|^2 \, \mathrm{d}\mu.$$

The functionals are defined on hypersurfaces immersed in $\mathbb{R}^{n+1}$ via a map $\varphi\colon M \to \mathbb{R}^{n+1}$, where $M$ is a smooth closed and connected $n$-dimensional manifold without boundary.
Here $\mu$ and $\nabla$ are respectively the canonical measure and the Levi-Civita connection on the Riemannian Manifold $(M, g)$, where the metric $g$ is obtained by pulling back on $M$ the usual metric of $\mathbb{R}^{n+1}$ with the map $\varphi$. The symbol $\nabla^m$ denotes the $m$-th iterated covariant derivative and $\nu$ is a unit normal vector field to the hypersurface.
Our main result is that if the order of derivation $m \in \mathbb{N}$ is strictly larger than the integer part of $n/2$ then singularities in finite time cannot occure during the evolution.
These geometric functionals are related to similar ones proposed by Ennio De Giorgi, who conjectured for them an analogous regularity result. In the final section we discuss the original conjecture of De Georgi and some related problems.

## Modified wave operators for the Hartree equation

Kenji Nakanishi

We construct modified wave operators for the Hartree equation with the Coulomb potential. Those maps are defined everywhere in a weighted $L^2$ space, and the main novelty is that we can avoid derivative losses so that we have the image, strong convergence and continuity in the same weighted space. The lower bound of the weight is optimal in view of the scaling.

## Asymptotic decoupling of solutions of the Einstein equations

Alan Rendall

According to an idea of Belinskii, Khalatnikov and Lifshitz (BKL) solutions of the Einstein equations should be approximated near their singularities by solutions of a system of ordinary differential equations. A major obstacle to proving this for the vacuum Einstein equations is the existence of the Mixmaster solution. Lars Andersson and I showed that this can be avoided by adding a scalar field. Our results, which prove the existence of a large class of solutions conforming to the BKL proposal, still have some undesirable limitations. Methods of removing these restrictions have been tested on simple model cases, such as the Gowdy spacetimes.

### Improved regularity for the vacuum Einstein equations

Igor Rodnianski, Sergiu Klainerman

The vacuum Einstein equations for a Lorentzian metric $g$ say that the Ricci curvature $R_{\alpha\beta}(g) = 0$. In wave coordinates this becomes a system of the quasilinear wave equations of the form

$$\Box_g g_{\alpha\beta} = Q_{\alpha\beta}(g, \partial g)$$

We consider the Cauchy problem for the above equation with initial data set prescribed on $\mathbb{R}^3$ and show that it is locally well posed in the Sobolev space $H^{2+\varepsilon}$ for any $\varepsilon > 0$. The proof relies on the combination of the PDE and geometric techniques, as well as elements of harmonic analysis.

### Higher order curvature flows on surfaces

Hartmut Schwetlick

We consider a sixth order conformal flow on Riemannian surfaces, which arises as the gradient flow for the Calabi energy with respect to a higher order norm. Motivated by a recent work of M. Struwe which unified the approach to the Hamilton-Ricci and Calabi flow we extend the method to this higher order flow. Our results contain global existence and exponentially fast convergence to a constant scalar curvature metric.
Uniform bounds on the conformal factor are obtained via the concentration-compactness result for conformal metrics. In the case of the sphere we use the idea of DeTurcks gauge flow to derive first bounds up to conformal transformations.
We prove exponential convergence by showing that the Calabi energy decreases exponentially fast. The problem of the non-trivial kernel in the evolution of Calabi energy on the sphere is resolved by using Kazdan-Warner's identity.

### On the critical regularity of wave maps in higher dimensions

Jalal Shatah, Michael Struwe

We show global existence, uniqueness and preservation of regularity for the Cauchy problem for wave maps of the (4+1)-dimensional Minkowski space into a Riemannian target manifold of bounded curvature for initial data which are small in the critical $(H^2 \times H^1)$-norm. The proof is very direct; all estimates are carried out in physical space rather than frequency space. An essential tool is the use of endpoint Strichartz estimates and their Lorentz space improvement, established in a recent paper of Keel-Tao.

### The null condition and global existence for nonlinear elastic waves

Thomas Sideris

The nonlinear hyperbolic system of partial differential equations governing the evolution of the deformation of homogeneous, isotropic, hyperelastic materials filling space are studied. Under an additional nonresonance or null condition, the system has global smooth solutions close to a one-parameter family of dilations. The proof combines energy estimates with vector fields and a new decay estimate for the linear problem.

## A new approach to study the Vlasov-Maxwell system

Gigliola Staffileni

We give a new proof based on Fourier transform of the classical Glassey-Strauss global existence result for the 3D relativistic Vlasov-Maxwell system, under the assumption of compactly supported particle densities. Though our proof is not substantially shorter then that of Glassey-Strauss, we believe it to be more flexible for future progress on the outstanding problem of global existence, without the additional support assumption.

## Global regularity of wave maps

Terence Tao

Wave maps $\varphi\colon \mathbb{R}^{n+1} \to (M,g)$ are critical points of the Lagrangian

$$\int\int < \partial_\alpha \varphi \cdot \partial^\alpha \varphi > .$$

We are interested in the global regularity problem: Do smooth solutions to the Cauchy problem stay smooth for all time?
We establish regularity when the $\dot{H}^{\frac{1}{2}} \times \dot{H}^{\frac{1}{2},1}$ norm of the initial data is small, for $n \geq 2$, when the target manifold is a sphere.
The principal difficulties are (a) the failure of $\dot{H}^{\frac{1}{2}}$ to control $L^\infty$, and (b) technical problems in differentiating the equation in low dimensions.
(b) is resolved by using Littlewood-Paley projections instead of differentiation, and (a) is resolved by a gauge transformation of the wave map equation in frequency-localized connection form.

## Local well-posedness for the nonlinear wave equation with rough data

Daniel Tataru

We consider the local well-posedness question for a general quasilinear second order hyperbolic equation $\Box_g(u) = G(u)(\nabla u)^2$ in $\mathbb{R}^n \times \mathbb{R}$. The initial data $(u(0), u_t(0)) = (u_0, u_1)$ is taken in Sobolev spaces $H^s(\mathbb{R}^n) \times H^{s-1}(\mathbb{R}^n)$. Our result is that local well-posedness holds for $s > 7/4$ in dimension 2, and for $s > (n-1)/2$ in dimension three and higher. It is sharp in dimensions 2 and 3. This is joint work with Hart Smith.

## Blowup of complex valued solutions of the Korteweg–de Vries and other dispersive equations

Fred Weissler

Theorem (J. Bona and F.W.)
Let $u(t,x)$ be a regular, say $u\colon [0,T) \to \mathcal{C}(\mathbb{S}^1)$, solution of KdV:

$$u_t + u_{xxx} + (u^2)_x \;=\; 0$$

of the form

$$u(t,x) \;=\; \sum_{k=1}^{\infty} a_k(t) \mathrm{e}^{\mathrm{i}kx}$$

with initial value

$$u(0,x) \;=\; \sum_{k=1}^{\infty} a_k(0)\mathrm{e}^{\mathrm{i}kx}.$$

If $|a_1(0)|$ is sufficiently large, then $u(t)$ “blows up” in finite time.
More precisely there is a $\varrho$, $\varrho > 0$, such that if $u\colon [0,\infty) \to \mathcal{C}(\mathbb{S}^1)$ is a global solution of the above form, then $|a_1(0)| \leq \varrho$.
This theorem also holds for the generalized KdV equation, $u_t + u_{xxx} + (u^{p+1})_x = 0$, $p \geq 1$ integer, as well as for a wider class of equations of the form

$$\mathrm{i}u_t + R\left(\frac{1}{\mathrm{i}}\frac{\partial}{\partial x}\right)u - Q\left(\frac{1}{\mathrm{i}}\frac{\partial}{\partial x}\right)\left(u^{p+1}\right) \;=\; 0,$$

where $R$ and $Q$ are polynomials satisfying various conditions.

*Edited by Thomas Jurke*

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