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Nonlinear Evolution Problems

May 25th – May 31st, 2003

This conference was organized by K. Ecker (FU Berlin), J. Shatah (Courant Institute, New York) and M. Struwe (ETH Zürich).
The main aim of the meeting was to discuss progress on three classes of nonlinear evolution equations, namely geometric evolution equations (essentially parabolic type), nonlinear hyperbolic equations and dispersive equations and to show and establish connections between these.
Lectures were delivered mainly in the morning sessions with one talk in the late afternoon which left ample time for individual discussions. As at previous meetings, several exciting recent developments were presented:

Huisken and Sinestrari used mean curvature flow to establish a canonical topological decomposition for three dimensional hypersurfaces with positive scalar curvature in Euclidean space. This result bears relation to the work of Hamilton and Perelman which aims at proving Thurston's geometrization conjecture via Ricciflow, a geometric evolution equation.

Another most notable development were the results by Tataru and by Krieger on global well-posedness of the wave-map system for small data in the energy norm. This completes a long period of intensive research extending previous results of Struwe-Shatah and of Tao.

Rodnianski presented a new notion of weak null condition which is satisfied by the Einstein equations in the harmonic gauge. This fundamental contribution enables exciting applications to the problem of global nonlinear stability of Minkowski space.

Connections between the three areas of research become ever more apparent were the topic of many individual discussions and also of questions asked after the lectures. A common theme appears to the phenomenon of blow-up (singularity formation) for solutions and methods to describe the solution near these. Selfsimilar solutions and blow-up rates play an important role for all three types of equations. In geometric evolution equations, results in this direction are more advanced than for example for hyperbolic equations due to the availability of local energy quantities which behave monotonically in time.

Abstracts

Minimization problems and associated flows related to weighted p-energy and Total Variation

Yunmei Chen, University of Florida
(joint work with Murali Rao)

Motivated by the problem of edge preserving regularization in image restoration, in this paper we investigate the relations between weighted p energy based and total variation based minimization problems, and their associated flows. We prove that the weighted total variation based minimization and its associated flow in a weakened formulation can be approximated by the weighted p energy based minimization and its associated flows, respectively.
Moreover, we show that the flow of the weighted total variation based minimization converges weakly in BV and strongly in L^2 to the minimizer as $t \to \infty$.

On the continuity of the solution map to the wave map equation

Piero D'Ancona, University of Roma I
(joint work with V. Georgiev, Pisa)

We study the continuity properties of the solution map for the wave map equation in the critical spaces. We consider wave maps defined on the Minkowski space $R \times R^n$, with $n \geq 2$, with values in an arbitrary target manifold N; the only assumption concerning N is that it should not be a flat manifold, i.e., that there exists at least one geodesic which is not a straight line near one point. Then, assume the initial data are in the homogeneous space $X = \dot{H}^{n/2} \times \dot{H}^{n/2-1}$, which is critical both for scaling and for the local well posedness. Under these assumptions alone, it is not known if a solution exists in general (apart from the case of small data, as recently settled by Tataru following work of Tao). But assume a solution map, possibly not unique, is defined on some neighbourhood of 0 in the above spaces, and takes its values in the space $Y(T) = C([-T,T]; \dot{H}^{n/2})$ (or equivalently in $C^1([-T,T]; \dot{H}^{n/2-1})$) for some $T > 0$. Then such a map cannot be uniformly continuous from any neighbourhood of 0 in X to $Y(T)$.
Although this result does not exclude the local existence of solutions, it shows that a contraction mapping argument in the above spaces (or comparable topologies) must fail.

Some dynamical properties of volume preserving curvature driven flows

Joachim Escher, Universität Hannover

The intermediate surface diffusion flow (ISD) is a geometric evolution law for compact hypersurfaces which formally connects the surface diffusion flow (SD) with the volume preserving mean curvature flow (VMC). The first part of the talk provides a rigorous proof of one part of this conjecture: It is shown that the solutions to (ISD) converge in a suitable norm to the corresponding solution of (VMC).
In the second part of the talk it is shown that nonconvex solutions to (SD) in the plane form in finite time a singularity. Moreover, in this situation, an upper bound for the maximal time of existence is presented.

Transonic shocks and free boundary problems

Mikhail Feldman, University of Wisconsin-Madison
(joint work with G.-Q. Chen)

We consider transonic (elliptic-hyperbolic) shocks for steady solutions of compressible Euler equations in multiple dimensions in unbounded domains. We show existence and stability of such solutions near flat and spherical transonic shocks, and study asymptotics at infinity. The method is to reduce the problem to a free boundary problem for nonlinear elliptic equations.

Decay estimates for the wave equation with potential

Vladimir Georgiev, Universita di Pisa
(joint work with Nicola Visciglia, SNS Pisa)

We consider a potential type perturbation of the three dimensional wave equation and we establish a Strichartz type estimate for the associated propagator. For the potential $V(x)$ we assume that it is non - negative and has the following L^∞ bound

$$\left\| \left(|x|^{2+\varepsilon} + |x|^{2-\varepsilon}\right) V(x) \right\|_{L^\infty} \leq C < \infty,$$

where ε is arbitrary small positive number. The main results establish dispersive type estimates of the same type as the linear wave equation as well as Strichartz type estimate for the corresponding Cauchy problem with potential perturbation. The case of spherically symmetric potential of type $V(x) = a/|x|^2$ is considered in [PSS], [BP].

[BP] Burq, N.; Planchon, F.; Stalker, J.; Tahvildar-Zadeh, S. *Strichart estimates for the Wave and Schrödinger Equations with the Inverse-Square Potential.* Preprint, 2002.

[PSS] Planchon F.; Stalker J.; Tahvildar-Zadeh, S. *L^p estimates for the wave equation with the inverse-square potential*, will appear in Discrete and Cont. Dyn. Systems.

Motion of a surface by binormal Mean Curvature

Manoussos Grillakis, University of Maryland
(joint work with H. Gomez)

Let us examine the motion by binormal mean curvature of a surface embedded in a four dimensional space. Consider $\Sigma \subset R^4$ where Σ stands for the surface which can be described by some internal, but arbitrary, coordinates via $\Sigma := \{\mathbf{x} \in R^4 : x^j(u^\alpha)\}$ where $j = 1, 2, 3, 4$ and $\alpha = 1, 2$. Assume that R^4 is equipped with the flat Euclidean metric and let us adopt the summation over repeated indices convention. The tangent vectors to the surface are defined via $\mathbf{t}_\alpha = \partial_\alpha \mathbf{x}$. The metric on the surface and the Laplacian of the position vector are given by

$$g_{\alpha\beta} \stackrel{\text{def}}{=} \langle \mathbf{t}_\alpha, \mathbf{t}_\beta \rangle \quad ; \quad g \stackrel{\text{def}}{=} \sqrt{det\left(g_{\alpha\beta}\right)} \quad ; \quad \Delta_g \mathbf{x} \stackrel{\text{def}}{=} \frac{1}{g} \partial_\alpha \left(g \; g^{\alpha\beta} \partial_\beta \mathbf{x} \right) \; . \tag{1}$$

Using the totally antisymmetric form $\epsilon_{\alpha\beta}$ on the surface and the antisymmetric tensor ϵ_{jklm} on the ambient space R^4 we define the two forms

$$\sigma^{lm} \stackrel{\text{def}}{=} \epsilon^{\alpha\beta} t^l{}_\alpha t^m{}_\beta \qquad ; \qquad \omega_{jk} \stackrel{\text{def}}{=} \epsilon_{jklm} t^l{}_\alpha t^m{}_\beta \epsilon^{\alpha\beta} \; . \tag{2}$$

The equation of motion is $\partial_t x^j = \omega^j{}_k \Delta_g x^k$. In order to proceed further we have to examine the basic structural properties of the embedded surface. We introduce a complex mean curvature on the surface, say Ψ, and a gauge field A_α, the point of the construction being that the equations are gauge invariant. Finally we derive an evolution equation for Ψ which is quasilinear of Schrödinger type. There is presently no general theory for existence of this type of equations except some recent work by Kenig, Ponce and Vega.

Progress in Mean Curvature Flow in $\mathbb{R}^3$

TOM ILMANEN, ETH ZÜRICH
(joint work with R. Schätzle, Universität Bonn)

Let M_t, $0 \le t < T$, be compact, smooth hypersurfaces surfaces moving by mean curvature in $\mathbb{R}^n$. Fix $x_0 \in \mathbb{R}^n$. It is known from Huisken's monotonicity formula that the centred rescalings about (x_0, T), namely the flows

$$M_t^\lambda := \lambda^{-1} \cdot (M_{T+\lambda^2 t} - x_0), \qquad -T/\lambda^2 \le t < 0,$$

converge subsequentially in a *weak* (varifold) sense to a self-similarly shrinking weak mean curvature flow

$$N_t = \sqrt{-t} \cdot N_{-1}, \qquad t < 0.$$

Theorem in Progress. *Suppose M_t is embedded and $n = 3$. Then N_t is smooth and $M_t^{\lambda_i}$ converges to N_t locally in C^∞.*

It was already known (1993) that N_t is smooth; the difficult point is to show that the convergence occurs smoothly. In principle there could be several layers of $M_t^{\lambda_i}$ over N_t connected by small necks that move around unpredictably and serve to drawn the layers together. The idea of the proof is to show (using the Gauss-Bonnet formula) that the necks have small parabolic 2-capacity in a certain sense. As a result the layers behave almost as if they were unconnected without any necks. Then because of embeddedness, the average distance between the layers is nearly nonincreasing. Since the spatial scale is shrinking like $\sqrt{T-t}$, this implies that there can actually be only one layer in the limit. Smoothness of the convergence then follows by Brakke's local regularity theorem.

Applications include: an effective dimension-reducing argument; sup estimates of curvature on self-shrinkers; self-shrinkers are smoothly asymptotic to cones and/or cylinders at infinity; if N_t has no cylinders, then M_T has an isolated singular point at x_0, M_T has smooth tangent cones, and M_t regains smoothness near x_0 for $t > T$.

This gives good prospects for a partial regularity theory for embedded mean curvature flows in $\mathbb{R}^3$. (Vide also considerable progress by B. White.) Open questions include:

1. If a self-shrinker N_t has an end asymptotic to a cylinder, must N_t be isometric to the standard cylinder?
2. If an asymptotic cylinder is present in N_t, show that the singular set of M_T is either an isolated point, or a closed curve (and M_t is a torus that shrinks to this curve and disappears). In the first case, show how to continue the evolution smoothly past the singular time.

Scattering for rough solutions of a Nonlinear Schrodinger Equation

Markus Keel, University of Minnesota
(joint work with J. Colliander, G. Staffilani, H. Takaoka, and T. Tao.)

We prove global existence and scattering for the defocussing, cubic nonlinear Schrödinger equation in $H^s(R^3)$ for $s > 4/5$. The main new estimate in the argument is a Morawetz-type inequality for the solution ϕ. This estimate bounds $||\phi||_{L^4_{x,t}(R^3 \times R)}$, whereas the well-known Morawetz-type estimate of Lin-Strauss controls $\int_0^\infty \int_{R^3} \frac{|\phi(x,t)|^4}{|x|} dxdt$.

Transport and dispersion for the Benjamin-Ono equation

Herbert Koch, Universität Dortmund
(joint work with Nikolay Tzvetkov)

The Benjamin-Ono equation is a close relative of Burgers equation and the Korteweg-de-Vries equation. Its solutions show the competing effects of transport and dispersion. We construct a two parameter family of solutions with interacting low and high frequency parts. As a consequence, the map from the initial data to the solution at fixed time cannot be uniformly continuous. On the other hand we show local wellposedness for initial data with $s > 5/4$ derivatives in L^2.

Global regularity of Wave Maps in 2 and 3 spatial dimensions

Joachim Krieger, Princeton University

We explain our proof of global regularity of Wave Maps from the 3+1 Minkowski space to arbitrary targets, provided the initial data are smooth and small in the critical Sobolev norm. Similarly, we prove that Wave Maps from the 2+1 Minkowski space to the hyperbolic plane satisfy the analogous property. Our method relies on an 'intrinsic formulation' and the use of a global Coulomb Gauge (as in earlier work by Klainerman-Rodnianski and Shatah-Struwe), as well as exploiting a sophisticated null-structure in the nonlinearity of this semilinear system. We also rely on the complex Banach spaces invented by D. Tataru and further developed by T. Tao.

Willmore Flow and Removability of Singularities

Ernst Kuwert, Universität Freiburg
(joint work with R. Schätzle, Universität Bonn)

We consider surfaces $\Sigma \subset \mathbb{R}^3$ moving by the gradient flow of the Willmore functional, i.e. the L^2 integral of the mean curvature. We show that if the initial surface is a sphere with Willmore energy at most 8π, then the flow converges smoothly to a round sphere (of energy 4π). An example by Mayer & Simonett shows that the bound 8π is sharp. To prove the theorem we first show that if the flow develops a singularity, then a rescaling yields a Willmore surface which is neither a plane nor a round sphere. If that blowup is compact or can be smoothly compactified by an inversion, then results of R. Bryant imply that it has energy at least 8π, which is impossible. The decisive tool is then a theorem on removability of isolated singularities of Willmore surfaces with curvature in L^2 and density less than two at the singularity.

On the large body limit for the Landau-Lifshitz equation in micromagnetics

Roger Moser, MPI Leipzig

For a bounded, open domain $\Omega \subset \mathbb{R}^3$ and a number $\epsilon > 0$, we consider the functional

$$E_\epsilon(m) = \frac{\epsilon}{2} \int_\Omega |\nabla m|^2 \, dx + \frac{1}{2} \int_{\mathbb{R}^3} |\nabla u_m|^2 \, dx, \quad m \in H^1(\Omega, \mathbb{S}^2),$$

where $u_m \in H^1(\mathbb{R}^3)$ is the unique distributional solution of the equation

$$\Delta u_m = \operatorname{div} m \quad \text{in } \mathbb{R}^3$$

for the trivial extension of m. This is a simplified version of the micromagnetic energy of a ferromagnetic body of shape Ω with magnetization m. For constants $\alpha > 0$ and $\beta \in \mathbb{R}$, we study the Landau-Lifshitz equation for the functional E_ϵ,

$$\frac{\partial m}{\partial t} = -\alpha \, m \times (m \times H_\epsilon) - \beta \, m \times H_\epsilon,$$

where H_ϵ is the negative L^2-gradient of E_ϵ, i. e. $H_\epsilon = \epsilon \Delta m - \nabla u_m$. In particular we are interested in the limiting behaviour of this problem for $\epsilon \searrow 0$.

The formal limiting equation is a pseudo-differential evolution equation of order 0 with respect to the spatial variables. We prove that for Hölder continuous initial data, the corresponding Cauchy problem has a unique global solution. For initial data in L^∞, we prove the same by approximation with Hölder continuous maps. Moreover, we have a look at the problem of proving convergence of solutions of the original equation to a solution of the limiting problem for $\epsilon \searrow 0$.

On global existence of wave and Schrödinger maps at critical regularity

Andrea Nahmod, University of Massachusetts, Amherst

There are three evolution equations that are derived from the same geometric considerations. The heat flow for harmonic maps which has largely been successfully studied; the Schrödinger map equation into a complete Kähler manifold which has been less studied and the wave map equation into a complete Riemannian manifold which has experienced considerable attention and progress lately. We first survey recent work joint with A. Stefanov and K. Uhlenbeck for critical wave maps from Minkowski space $\mathbb{R}^{n+1}$ into (compact) Riemaniann manifolds in spatial dimensions $n \geq 4$ and for subcritical Schrödinger maps into the sphere $\mathbb{S}^2$ or hyperbolic space $\mathbb{H}^2$ in $n = 2$ spatial dimensions. We focus on the results obtained and some of the methods from harmonic analysis and gauge theory used. We then present a new gauge and a unified set up under which the $2+1$ space-time dimensional Schrödinger map system with H^1-*critical* data and the $3+1$ space-time dimensional wave map equation (for complete Riemannian manifolds with bounded geometry) behave in tandem, in the sense they can be written so that their nonlinearities have specific structures obeying similar corresponding estimates. The scheme we outline thus provide a path to establish global existence, uniqueness and regularity with small critical data for both problems above. These ideas are being developed jointly with A. Stefanov and K. Uhlenbeck.

The Cahn-Hilliard equation with dynamic boundary conditions

Reinhard Racke, Universität Konstanz

We consider the Cahn-Hilliard equation $\psi_t = \Delta\mu$ where $\mu = -\Delta\psi - \psi + \psi^3$, subject on the boundary to the classical boundary condition $\partial_\nu \mu = 0$, and the following dynamic boundary condition

$$\sigma_s \Delta_{||}\psi - \partial_\nu \psi + h_s - g_s \psi = \frac{1}{\Gamma_s}\psi_t.$$

This problem was recently proposed by physicists to describe spinodal decomposition of binary mixtures where the effective interaction between the wall (i.e. the boundary) and two mixture components are short-ranged. The global stability and the uniqueness of solutions to this initial-boundary value problem are described (joint work with S. Zheng). We also report on recent progress on the maximal regularity of solutions, as well as on the existence of attractors.(joint work with J. Prüß, S. Zheng)

Blow up dynamics for solutions to the L^2 critical nonlinear Schrödinger equation

Pierre Raphael, Université de Cergy-Pointoise

(joint work with Frank Merle, Institut Universitaire de France)

We consider finite time blow up solutions to the critical nonlinear Schrödinger equation $iu_t = -\Delta u - |u|^{\frac{4}{N}}u$ with initial condition in the energy space H^1. Existence of such solutions is known, but the complete blow up dynamic is not understood so far. Our work focuses on small in a certain sense blow up solutions. A first result is finite time blow up for strictly negative energy solutions, and an upper bound on the blow up speed corresponding to numerical observations is proved: $|\nabla u(t)|_{L^2} \leq C\sqrt{\frac{log|log(T-t)|}{T-t}}$. This result relies on viriel type estimates on the solution. Similar techniques were first exhibited by Martel-Merle for the study of the generalized KdV equation. More generally, we prove stability in H^1 of the log-log upper bound, whereas blow up solutions outside this stable regime are proved to satisfy $|\nabla u(t)|_{L^2} \geq \frac{C(u)}{T-t}$ which is the rate of the known explicit blow up solution.

On the Cauchy problem for the Einstein vacuum equations

Igor Rodnianski, Princeton University

The talk describes the results obtained in joint work with H. Lindblad. We discuss the notion of null condition for general systems of quasilinear wave equations and its failure for the Einstein vacuum equations in harmonic gauge. We then propose a notion of weak null condition based on the idea of Friedlander's radiation field and show that it is satisfied for Einstein vacuum equations in harmonic gauge. We also discuss applications to the problem of stability of Minkowski space.

Convergence of the Yamabe flow for large energies

Hartmut Schwetlick, MPI Leipzig
(joint work with Michael Struwe, ETH Zürich)

We consider the Yamabe or scalar curvature flow on general compact closed manifolds. By showing convergence of the scalar curvature to its average value in all L^p norms for $t \to \infty$, we deduce via a concentration-compactness argument that the metrics either converge to a smooth Yamabe metric, or else concentrate in finitely many bubbles. In the presence of at most one bubble we identify a Kazdan-Warner type transversality condition that rules out concentration and therefore implies convergence of the flow. The condition is very natural and easily verified when the manifold is conformal to the standard sphere. Using the positive mass Theorem we proof that the criterion also holds on general manifolds of dimensions $3 \leq n \leq 5$ and in the local conformally flat case.

Ricciflow of L^∞-metrics on 3-manifolds

Miles Simon, Universität Freiburg

We consider the Ricci flow

$$\frac{\partial}{\partial t} g_{ij} = -2Ricci(g)_{ij},$$

of Riemannian metrics whose initial value $g_0 = g(0)$ is not necessarily smooth but which is controlled by a smooth background metric, in the sense that

$$\frac{1}{c} h \leq g_0 \leq ch,$$

for some smooth metric h. In particular we prove the following theorems.

Theorem 1. *Let $(M^n, g(t))_{t\in[0,T)}$ be a smooth solution to the Ricci-flow, where $\frac{1}{c}h \leq g(\cdot,t) \leq ch$, for all $t \in [0,T)$. Then the solution may be extended to $(M, g(t)_{t\in[0,T+\epsilon)})$ for some small $\epsilon > 0$.*

As an application we obtain the following theorem.

Theorem 2. *Let $(M^3, {}^ig)$, $i \in \mathbb{N}$ be a family of smooth metrics which satisfy $\frac{1}{c}h \leq {}^ig \leq ch$, for some constant c independent of i, and $sec({}^ig) \geq -\epsilon(i)$ where $\epsilon(i) \to 0$ as $i \to \infty$. Then there exists a smooth metric g' on M^3 such that $sec(g') \geq 0$ and so M^3 may be differentially/topologically classified using the theorem of R.Hamilton [Ha].*

[Ha] Hamilton, R. *Four-manifolds with positive isotropic curvature*, Comm. Anal. Geom. 5 (1997), no. 1, pp. 1–92.

Mean curvature flow with surgeries

Carlo Sinestrari, Universita' di Roma "Tor Vergata"
(joint work with Gerhard Huisken, MPI Potsdam)

An important task in the theory of geometric flows is to define a continuation of the flow after the singular time in such a way that the topology of the evolving manifold can be controlled. This has been achieved by Hamilton (1997) for the Ricci flow of four-manifolds by means of a surgery procedure.

In this work we introduce a similar procedure for mean curvature flow, which allows us to define a flow beyond singular time of three-manifolds with positive scalar curvature. In each surgery we remove a cylindrical region with high curvature and replace it by two spherical caps. We can prove that after a finite number of surgeries the remaining pieces are diffeomorphic to spheres or to tori. As a result, we obtain the following.

Theorem: *Let M be a smooth closed three-dimensional surface immersed in $\mathbb{R}^4$ with positive scalar curvature. Then M is diffeomorphic either to a sphere or to a connected sum of tori $\mathbb{S}^2 \times \mathbb{S}^1$.*

Rough solutions for wave maps

Daniel Tataru, University of California at Berkeley

Wave maps solve the Euler-Lagrange equation for the usual wave Lagrangian, but applied to functions taking values in a Riemanian manifold.
The result I talked about asserts roughly that the wave maps in 2+1 dimensions is well-posed in the energy space for small energy data, globally in time. This applies to any target manifold with "bounded geometry", i.e. bounded curvature (and its derivatives) and positive injectivity radius.
The well-posedness is of a nonlinear kind, in that it only provides solutions which depend continuously on the initial data.

Regularity of harmonic map flows under extra hypotheses

Peter Topping, University of Warwick

We consider the question of the regularity of the harmonic map flow from a 2D domain, at the time $t = T$ at which a smooth solution blows up. The map $u(T)$ can, we have shown, fail to be continuous. Here we discuss additional hypotheses under which we can be sure that $u(T)$ is even Hölder continuous.

Well-posedness and ill-posedness of the Cauchy problem for the modified KdV equation

Yoshio Tsutsumi, Tohuku University
(joint work with H. Takaoka, Kobe University)

We consider the Cauchy problem for the modified KdV equation in the one dimensional torus, to which is referred to as (mKdV). It is known that (mKdV) is time locally well-posed in H^s for s $\geq 1/2$, which was proved by Bourgain. The trilinear estimate plays a crucial role in the proof of Bourgain, which automatically yields the uniformly continuous dependence of solutions on initial data. On the other hand, Kenig, Ponce and Vega showed that this trilinear estimate breaks down for $s < 1/2$. We prove that if $1/2 > s > 1/8$, (mKdV) is time locally well-posed in H^s. In that case, the point-wise continuous dependence on initial data holds, though the uniformly continuous dependence fails.

Edited by Felix Schulze

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