Old and new advances in black hole accretion disc theory

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A summary is given of the high-lights during the Reykjavik Midsummer Symposium on Non-Linear Phenomena in Accretion Discs around Black Holes. Such high-lights include the recent advances on understanding: 1) the accretion disc solution branch dominated by advection (i.e., advection dominated accretion flows, ADAFs), 2) the importance of magnetic fields in many different respects, most importantly being responsible for the self-sustained MHD-turbulence giving rise to the disc viscosity, and 3) the details of the radiation processes giving rise to the X/γ-ray continuum originating close to the black hole.

Some old advances are unfortunately also necessary to discuss here. It is pointed out to the accretion disc research community, that many of the research papers published on ADAFs 1994-1997 do not accurately present the history of ADAF research. Some of the results that were presented as new and original actually appeared in a paper by Ichimaru already in 1977. Also not quoted are the papers from the 1970’s and 1980’s calculating the temperature structure of and the spectra from quasi-spherical accretion flows onto black holes. As the ADAFs are close to being quasi-spherical, the resulting spectra of ADAFs and quasi-spherical flows are almost identical. Further of the recent ADAF results are therefore not new results as is sometimes claimed.

In spite of all the recent progress of various aspects of accretion flows around black holes, many of the research lines have still not been merged providing potential for further dramatic progress in coming years.

1. Why Iceland?

This is the very first conference in astrophysics that has ever taken place on Iceland, a country with only about 2-3 astronomers. It is natural to ask the question: Why was it organized on Iceland? This question fortunately has several reasonable answers:

First, the astronomy population on Iceland is not that small as it may seem at first sight. It is approximately similar to that in other Western countries, i.e., about 1 astronomer per 100 000 in population. Iceland’s 250 000 citizens imply a total of 2.5±√2.5 astronomers, in good agreement with the actual number.

Second, one of these 2.5 astronomers works on accretion discs which makes Iceland probably the country with the world’s largest fraction of astronomers working in this field.

Third, in the past, at least according to classic literature, there has been at least two historic studies of “black hole interiors” originating on Iceland. In Jules Verne’s Voyage au Centre de la Terre (1864), the research team led by Professor Otto Lidenbrock from Hamburg entered a hole (most likely being black) on the bottom of the crater of Snaefell in 1863. Here, they followed in the footsteps of the 16th century Icelandic scientist Arne Saknussemm who had explored this black hole before them as described in Jules Verne’s novel.

Fourth, and maybe the most important reason is that the research area of accretion discs has grown rapidly, not only worldwide, but also in most of the Nordic countries (Denmark, Finland, Iceland, Norway, Sweden) over the last 10 years. Because of this, all the support for this conference originated from these countries directly or indirectly.
with the requirement, of course, that the conference had to take place in one of these countries.

The summary talk summarized most of the talks at the Midsummer Symposium. However, as the chapters in this monograph were written up to a year after the symposium, their content are often different from that of the symposium talks occasionally being influenced by the summary talk. This summary chapter still summarizes the symposia talks, but also includes some comments on the material in the written reviews.

2. Accretion discs

One of the main topics of this Midsummer Symposium is the recent research bandwagon on advection dominated accretion flows (ADAFs) starting in 1994 with probably the order of 100 papers since then. Many of the results are covered in Abramowicz (this volume), Björnsson (this volume), Narayan, Mahadevan, & Quataert (this volume), and Lasota (this volume). The problem is that in all the papers written before the summary talk of this symposium, the history of research on ADAFs has not been accurately presented. In my summary talk, I wanted to take the opportunity to set the record straight. I therefore here quote a few paragraphs from the section on the history of theoretical accretion disc research in my chapter (Svensson 1997) in Relativistic Astrophysics: A Conference in Honour of Prof. I.D. Novikov's 60th birthday:

2.1. Theoretical history (from Svensson 1997)

The underlying framework for almost all efforts to understand active galactic nuclei (AGN) is the accretion disc picture described in the classical papers by Novikov & Thorne (1973) and Shakura & Sunyaev (1973). This original picture was partly inspired by the extreme optical AGN luminosities. Here, effectively optically thick, rather cold matter forms a geometrically thin, differentially rotating Keplerian disc around a supermassive black hole. The differential motion causes viscous dissipation of gravitational binding energy resulting in outward transportation of angular momentum and inward transport of matter. The dissipated energy diffuses vertically and emerges as black body radiation, mostly in the optical-UV spectral range for the case of AGN.

Observations have also been the driving force in the discovery of two other solution branches.

a) Hard X-rays from the galactic black hole candidate, Cyg X-1, as well as the discovery of strong X-ray emission from most AGN led to the need for a hot accretion disc solution. Shapiro, Lightman & Eardley (1976) (SLE) found a hot, effectively optically thin, rather geometrically thin solution branch, where the ions and the electrons are in energy balance, with the ions being heated by dissipation and cooled through Coulomb exchange, leading to ion temperatures of order $10^{11} - 10^{12}$ K. The efficient cooling of electrons through a variety of mechanisms above $10^9$ K, leads to electron temperatures being locked around $10^9 - 10^{10}$ K. The SLE-solution is thermally unstable.

b) Observations of Cyg X-1 and of radio galaxies led to two independent discoveries of the third solution branch. Ichimaru (1977) developed a model to explain the soft high and hard low state of Cyg X-1. The soft high state is due to the disc being in the optically thick cold state, and the hard low state occurs when the disc develops into a very hot, optically thin state. This solution branch is similar to the SLE-solution, except that now the ions are not in local energy balance. It was found that if the ions were sufficiently hot they would not cool on an inflow time scale, but rather the ions would heat up both by adiabatic compression and viscous dissipation and would carry most of that energy with them into the black hole. Only a small frac-
tion would be transferred to the electrons, so the efficiency of the accretion is much less than the normal ~ 10%. As the ion temperature was found to be close to virial, these discs are geometrically thick. Just as for the SLE-case above, the electrons decouple to be locked at $10^9 - 10^{10}$ K. The flows resemble the quasi-spherical dissipative flows studied by, e.g., Mészároz (1975) and Maraschi, Rosario & Treves (1982). Independently, Rees et al. (1982) and Phinney (1983) proposed that a similar inefficient accretion disc solution is responsible for the low nuclear luminosities in radio galaxies with large radio lobes and thus quite massive black holes. These geometrically thick discs were named ion tori. Rees et al. (1982) specified more clearly than Ichimaru (1977) the critical accretion rate above which the flow is dense enough for the ions to cool on an inflow time scale and the ion tori-branch would not exist. Further considerations of ion tori were made by Begelman, Sikora & Rees (1987). Ichimaru (1977) emphasized that his version of ion tori is thermally stable.

The ion-tori branch has been extensively studied and applied over the last two years (1995-1996) with more than 30 papers by Narayan and co-workers, Abramowicz and co-workers, as well as many others. These studies confirm and extend the original results, although some papers do not quote or recognize the original results. New terminology has been introduced based on an Eulerian viewpoint rather than a Lagrangian. Instead of the ions not cooling, it is said that the local volume is "advectively cooled" due to the ions carrying away their energy. The ion tori are therefore renamed as advection-dominated discs.

2.2. Why did history go wrong?

From the above, it is clear that just 4 years after the start of research on modern accretion disc theory in 1973, the pioneering work on three of the four major accretion disc branches had been done (see Narayan et al., this volume for a description of the four branches). As a graduate student with a side interest in accretion discs, I myself read the paper by Ichimaru back when it was published and a few times since then. When the ADAF research bandwagon got going in 1995, I noted that Ichimaru’s pioneering work was not quoted and that the importance of the work by Rees et al. (1982) and Phinney (1983) initially was downplayed. Instead, the ADAF-solution was presented as a new discovery. Even the issue of whether the ADAF-solution was new or not was discussed in some papers. Let me give a few quotations: “Recently, a new class of two-temperature advection-dominated solutions has been discovered”; “We have found new types of optically thin disc solutions where cooling is dominated by the radial advection of heat”; “Is our new solution really new? Certainly, to the extent that we have for the first time included advection and treated the dynamics of the flow consistently, the advection-dominated solution... is new. But even more fundamentally, it is our impression that the existence of two hot solutions was not appreciated until now”. In order to correct the history of ADAF research, I wrote the paragraphs above in June 1996 as part of a review on X-rays and gamma-rays from AGNs (Svensson 1997), submitted it to the pre-print archives, sent preprints to about 150 astronomical libraries, and spread 100s of copies at conferences. But even so, the information did not penetrate the research community. So, as a summarizer of this accretion disc symposium, I took the liberty to show that the most important results of recent ADAF-research were already obtained by Ichimaru in 1977. Although Ichimaru’s work was not mentioned in any of the talks at this symposium, it is gratifying to notice that he is quoted in three of the chapters. Furthermore, Ichimaru is now regularly quoted in ADAF-papers appearing since this symposium.

Why was Ichimaru’s 1977 paper forgotten by almost everybody? It may depend on
the way literature searches are done. One searches a few years back, and assumes that the major reviews cover the most important old papers. And once the ADAF history was written, it became adopted by the research community. But it does not explain why the Ichimaru-paper was ignored already in the late 1970s. It was quoted in the Cygnus X-1 review by Liang & Nolan (1984) but not for providing a new accretion disc solution, or for its explanation of the two spectral states of Cyg X-1.

2.3. ADAF principles

Much of the recent work on different accretion disc solutions and on ADAFs, in particular, is summarized in Abramowicz (this volume), Björnsson (this volume), and Narayan, Mahavedan, & Quataert (this volume). The recent work has among other things developed self-consistent solutions for the dynamics of ADAFs, has elucidated the connections between the different solutions branches, and has calculated detailed spectra from such flows.

One of the outstanding questions is which of the solution branches (see Figure 1 in Abramowicz or Björnsson, this volume) a disc chooses. Narayan & Yi (1995) discussed three possibilities. In the summary talk, I provided names for these three options (and thank Andy Fabian for proposing the “strong” and the “weak” names).

- The Strong ADAF Principle: The disc always chooses the ADAF branch if it exists.
- The Weak ADAF Principle: The disc chooses an ADAF branch when no other stable branch is available.
- The Initial Condition Principle: The initial conditions determine which branch is chosen.

One should note here that already Ichimaru (1977) employed the weak and the initial condition principles in his scenario for the two states of Cyg X-1. Depending on the initial conditions at large radii, the disc gas either goes to the ADAF branch (hard state) or cools down to the gas-pressure dominated standard Shakura-Sunyaev branch (soft state). At some smaller radius in the latter case, radiation pressure starts dominating, the standard branch becomes unstable, and the weak principle says that the disc then makes a transition to the ADAF-branch. Furthermore, Ichimaru (1977) also obtained the result that there is a maximum accretion rate above which the optically thin ADAF branch does not exist, a fact not recognized in recent ADAF-papers where this critical accretion rate was rediscovered (for this accretion rate the cooling time scale becomes equal to the inflow time scale and the disc cannot remain in an ADAF state, see §3.2.2 in Narayan et al., this volume).

How unique are the ADAF-models and scenarios that are proposed for various phenomena? Depending on which ADAF-principle one uses, one gets different models and scenarios, which gives some latitude for the model-builder. It is therefore important to develop a physical understanding of the transitions (with changing radius or accretion rate) between the branches and to determine which principle applies. Furthermore, the whole solution structure with its different branches (see Figure 1 in Abramowicz, this volume, or in Björnsson, this volume) depends strongly on the type of viscosity prescription that is used. The prescription mostly used is \( t_{r,\phi} = \alpha P_{\text{tot}} \). Other prescriptions such as \( t_{r,\phi} = \alpha P_{\text{gas}} \) or \( t_{r,\phi} = \alpha \sqrt{P_{\text{rad}}P_{\text{gas}}} \) are likely to give very different solution structure and scenarios. This is rarely discussed in the ADAF-literature. Note that the solution structure in the Figure quoted only includes bremsstrahlung as a soft photon source for Comptonization. The more realistic case of unsaturated thermal Comptonization (without specifying the soft photon source) was considered by Zdziarski (1998).
2.4. Similarities between quasi-spherical accretions and ADAFs

One of the ADAF-results is that the accretion is almost spherical. As the proton temperature is close to virial, the vertical scale height is close to the radius, \( R \). All physical parameters then scale with radius approximately as for free fall spherical accretion (see eqs. 3.15 in Narayan et al., this volume). The coefficients may be different depending upon the viscosity parameter, \( \alpha \), but for \( \alpha \) of order unity, even the coefficients are approximately the same. This means that the scenarios of dissipative quasi-spherical accretion of the late 1970s (e.g., Mészároz (1975) and Maraschi, Rosario & Treves (1982)) and ADAFs are essentially identical, the difference being that the workers of the late 1970s did not consider the dynamics in detail but rather used intuition to conclude that the flow scaled as free fall flows. Many of the resulting conclusions are the same. It was, e.g., noted in some early (quasi-)spherical accretion papers that the solutions depend on the black hole mass mainly through the combination \( \hat{m} \equiv M/M_{\text{Edd}} \propto \dot{M}/M \), and that therefore the solutions are similar for both galactic black holes and for super massive AGN black holes. Other results were that a two-temperature structure develops in the inner, say, 100 Schwarzschild radii; that the proton temperature remains close to virial, while the electron temperature saturates at about a few times \( 10^9 \) K; and that the luminosity scales as \( \dot{M}^2 \). Some of the radiation processes that were included were: self-absorbed cyclo-synchrotron emission, Compton scattering, and sometimes pion production in proton-proton collisions. The accretion rates, \( \dot{m} \), considered were of order unity as the purpose was to explain the luminous AGNs.

These results again appear in the ADAF literature (see, e.g., Figures 4, 6, and 7 in Narayan et al., this volume). One important difference now is that also small \( \dot{m} \) are considered giving rise to very different spectra (see Figure 6 in the chapter of Narayan et al., this volume).

2.5. Applications of ADAFs

The ADAFs have been included in scenarios and models for several astrophysical phenomena as described by Narayan et al. (this volume) and by Lasota (this volume). Such phenomena include explaining the quiescent state of three black hole X-ray transients, the different spectral states and spectral transitions of soft X-ray transients, low-luminosity galactic nuclei such as Sgr A* in the Galactic Center, the LINER NGC 4258, and possible “dead quasars” such as M87 and M60. Lasota (this volume) discusses in greater detail how the spectral properties of the outbursts of the soft X-ray transient GRO J1655-40 can be explained within a scenario with an inner ADAF + an outer cold disc.

As mentioned above, applying different ADAF principles give rise to different scenarios. One such case is the efforts to explain the different spectral states of soft X-ray transients. Chen & Taam (1996) apply the weak principle and finds the transition radius between the outer cold disc and the ADAF to increase with accretion rate. Esin, McClintock, & Narayan (1997), on the other hand, in their detailed work apply the strong ADAF principle and finds the transition radius to decrease with increasing accretion rate (see Figure 11 in Narayan et al., this volume).

Another case is the LINER NGC 4258 (Narayan et al., this volume), where the strong ADAF principle gives rise to an ADAF inside the masering molecular disc, while the weak ADAF principle gives rise to a standard thin disc (Neufeld & Maloney 1993). Narayan et al. (this volume) argue that the latter scenario has a too low accretion rate to explain the observed emission.
3. Evidence for the existence of black holes and surrounding accretion discs

These topics were covered by Andy Fabian in his talk. In this volume, most of the evidence is, however, discussed in the two observational chapters by Charles (Galactic black holes) and by Madejski (supermassive black holes), while the review chapter by Fabian is limited to the broad Fe emission lines generated by the inner parts of a cold thin accretion disc.

The evidence for supermassive black holes in galactic nuclei has in the past been indirect. X-ray variability has set an upper limit to the size of the emitting region and thus to the mass. The luminosity has provided an estimate of the mass assuming the object to be radiating at the Eddington luminosity. Measuring the velocity fields close to the nuclei of nearby galaxies has also provided an estimate of the mass enclosed within that region. Recently, there has, however, been dramatic progress as described by Madejski (this volume). The VLBA mega-masers in the LINER NGC 4258 showed a Keplerian velocity profile indicating a “point” mass of $3.6 \times 10^7 M_\odot$. And ASCA observations showed Fe-line profiles broadened and distorted in precisely the way expected for emission from a rotating disc just outside a black hole (see Figure 4 in Madejski, this volume, or Figures 5 and 6 in Fabian, this volume). Some observations even sets constraints on the rotation of the black hole. Future space missions with observing capability of the Fe-line will provide ample opportunities to explore the strong gravitational field close to the event horizon of black holes. The Fe-line at the same time provides evidence for the existence and the properties of a cold reflecting disc close to the black hole.

There has been similar progress regarding determining the dynamical mass of the compact object in several galactic soft X-ray transients (see Table 3 in Charles, this volume). Again, the progress is mainly observational depending on the X-ray satellites providing the discovery of the transients, and the very large ground-based telescopes providing the dynamical mass-determinations. Present and future X-ray missions with all-sky monitors will discover new transients increasing the statistics and possibly broadening the range of properties of galactic black holes.

In this context, one should note the exotic but qualitative contribution by Novikov (this volume) on the physics just outside and inside the event horizon. Of particular interest is the qualitative discussion of the tremendous growth of the internal mass (mass inflation) of the black hole interior during the formation process.

4. Radiation processes

While the classical rates for bremsstrahlung, cyclo/synchrotron radiation, and Compton scattering in the nonrelativistic and relativistic limits were sufficient in the early disc models, the electron temperatures of $10^9$ - $10^{10}$ K indicated by both observations and theory required the calculation of transrelativistic rates of the above processes as well as for pair processes that becomes important at these temperatures. Rate calculations as well as exploring the properties of pair and energy balance in hot plasma clouds were done in the 1980s by Lightman, Svensson, Zdziarski and others. The Compton scattering kernel probably received its definite treatment in Nagirner & Poutanen (1994). Recent improvements in some rates were obtained by Mahadevan, Quataert, and others. Much of this microphysics have been included both into the SLE-solutions and into the ADAF-models. One problem has been to determine the importance of electron-positron pairs in hot accretion flows. The most detailed considerations so far show that pairs have at
most a moderate influence in a very limited region of parameter space (see Björnsson, this volume).

To obtain approximate spectra, the Kompaneets equation with relativistic corrections and with a simple escape probability replacing the radiative transfer is sufficient (Lightman & Zdziarski 1987). However, if one want to obtain constraints on the geometry from detailed observed spectra, then methods to obtain exact radiative transfer/Comptonization solutions in different accretion geometries must be developed. Such methods were developed by Haardt (1993) (approximate treatment of the Compton scattering) and Poutanen & Svensson (1996) (exact treatment) who solved the radiative transfer for each scattering order separately (the iterative scattering method). These codes are fast enough to be implemented in XSPEC, the standard X-ray spectral fitting package, and exactly computed model spectra can now be used when interpreting the observations. The codes, furthermore, includes the reprocessing (both absorption, reflection, and transmission) of X-rays by the cold matter. These methods have mostly been used to study radiative transfer in two-phase media consisting of cold and hot gas with simple geometries, but they have also recently been integrated into the ADAF models by Narayan and co-workers.

Poutanen (this volume) concludes that the galactic sources with their smaller reflection are best fit with a hot inner disc surrounded by a cold outer disc, while the Seyfert galaxies with their larger reflection are best fit with a geometry where the X-ray emission originates from active regions (magnetic flares?) atop of a cold disc (extending all the way in to the black hole as the broad, distorted Fe-lines indicates). The spectral predictions of ADAF models have not been tested against the detailed spectral observations using $\chi^2$ fittings. One should therefore at the present moment have greater confidence in the conclusions of the work doing detailed radiative transfer and spectral modeling and fittings in simple geometries.

Poutanen also describes how the detailed spectra of the spectral transition between the hard and the soft states of Cyg X-1 can be described by a simple hybrid pair model (see Figure 9 of Poutanen, this volume) in a geometry with a hot inner disc surrounded by an outer cold disc and where the transition radius changes during the transition. The geometry is similar to the ADAF scenario suggested by Esin et al. (see Figure 14 in Narayan et al. this volume).

It is clear that the natural evolution is to merge the detailed spectral models with various accretion disc scenarios. One weakness of the ADAF-literature is that the spectral predictions of the (broad band) ADAF model is normally only compared with the standard (narrow band) disc model of Shakura & Sunyayev (1973). Other alternative scenarios, such as the two phase scenario where cold clouds are submerged in a hot medium (e.g., Krolik 1998 for a recent work on this scenario), are normally not discussed.

Another problem is the determination of the detailed spectral predictions from the cold disc, where the expected spectrum certainly is not that of a black body (Krolik, this volume).

5. The effects of magnetic fields

Magnetic fields are important in several respects in accretion discs around black holes. Several of these were discussed during the symposium and here some of them are listed:

- The most important influence of magnetic fields in an accretion disc is probably as being the agent generating self-sustained MHD-turbulence in a differentially rotating disc and thereby providing the necessary anomalous viscosity needed in black hole accretion discs. Brandenburg (this volume) describes the results of 3-D numerical simulations
schematically in Figure 2. The Keplerian shear gives rise to large scale magnetic fields that in its turn generates turbulence through the Balbus-Hawley and Parker instabilities. Finally, the turbulence regenerates the magnetic field through the dynamo effect. The energy flow is shown in Figure 5 (Brandenburg, this volume). Approximately the same power is released in Joule heating (of electrons and ions) as in viscous heating (of ions mainly). One of the most important results is the magnitude of the Shakura-Sunyaev viscosity parameter, $\alpha$, and the realization that $\alpha$ is not a constant.

- The magnetic field generates vertical stratification. There will be two different scale heights for the magnetic and the gaseous pressures. The magnetic field is more uniformly distributed vertically than the matter.

- The magnetic field plays a crucial role in the generation of a corona around the disc. The hope is to use a short time sequence from a simulation run of MHD-turbulence in the disc itself. This time sequence will form the driving background for a corona simulation. Nordlund speculated that spontaneous magnetic dissipation may generate self-organized criticality in the corona, similar to what has been found in simulations for the solar corona. Here, one should also note the partly unsuccessful efforts described by Wiita (this volume) in obtaining a self-organized critical state of the accretion disc itself.

- The magnetic field may act as a confining agent for cold gas (in the scenario where cold gas clouds coexist with a hot tenuous medium) as discussed by Celotti & Rees (this volume). The field may also be responsible for confining the matter or pairs in the active regions discussed by Poutanen (this volume).

- The magnetic field plays an important role as electrons (and positrons) in its presence generates cyclo-synchrotron photons in the radio to IR-range. These photons serve as seed photons in the Comptonization process, and is a crucial component in the ADAF models (Narayan et al., this volume).

- Under certain conditions, synchrotron self-absorption dominates over Coulomb scattering as a thermalizing mechanism. The electrons emit and absorb cyclo-synchrotron photons resulting in a Rayleigh-Jeans self-absorbed photon spectrum and a Maxwellian distribution for the electrons (Ghisellini, Guilbert, & Svensson 1988; Ghisellini & Svensson 1989; Ghisellini, Haardt, & Svensson 1998). The thermalization time scale is just a few synchrotron cooling times.

6. Larger scale phenomena

Some phenomena on larger scales were discussed during the symposium. In an interesting talk, Pringle showed how the radiation from the central source may cause radiation-driven warping of the disc on larger scales. In certain cases, the inner disc may even turn upside down relative the outer disc resulting in self-shadowing of the radiation from the central source. The resulting ionization cone may not necessarily be aligned with the central source.

Merging of galaxies containing supermassive black holes may lead to a supermassive binary black hole in the resulting galaxy. The question is: How does the binary black hole evolve? Artymowicz (this volume) discusses the history of the efforts trying to solve this problem. After some 20 years of research it now seems that dynamical friction does not cause the eccentricity of the black hole orbits to grow. The interaction of a binary black hole with a common disc may resolve the difficulty of getting black hole-black hole merging to occur in less than a Hubble time. In the process, the black holes are fed, and a periodic light curve may be observed. One such example is OJ 287 with a period of about 13 years. A black hole circling a primary black hole with an accretion disc
may cause warping of the disc as shown by Papaloizou et al. (this volume). The obvious application is the observed warping of the masering disc in the LINER NGC 4258.

Another issue discussed was the survival of vortices in accretion discs. The common notion is that Keplerian shear would kill such vortices on a few rotation time scales. In Spiegel’s talk (and in Bracco et al., this volume) it was shown that coherent structures indeed form. On the other hand, in the local simulations by Brandenburg (this volume) including magnetic fields, vortices do not form. The issue of vortices, their survival and influence is not yet settled.

7. Conclusion

This was a most rewarding symposium where leading scientists presented the most recent dramatic developments regarding several of the physics areas needed for realistic modelling of black hole accretion flows. These areas include radiative processes in hot plasmas, radiation transfer in hot and cold plasmas, MHD in differentially rotating gas, the origin of disc viscosity, magnetic flares, gas or MHD-simulations of flows, and so on. Some of these research lines have already merged. As each subproblem is understood, further merging provides the potential for dramatic progress in coming years.

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