Dynamics of Astrophysical Discs

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Scientific Background and Objectives

Configurations taking the form of a flattened disc commonly occur in astronomy. When highly flattened, the material in these objects typically orbits in circles such that centrifugal force to a first approximation balances a gravitational attracting force. The latter is often due to some external gravitational potential into which the matter has fallen, but can also, in part or in whole, be caused by the self-gravity of the material itself.

Discs form whenever the material within them can �cool� on a shorter timescale than the one on which it can transport away its angular momentum. The material itself can come in a variety of forms.

In disc galaxies, the material is in the form of stars, which obey the equations of collisionless stellar dynamics. In Saturn�s rings (and in other planetary ring systems), the material consists of particles with sizes which range from those of rocks and boulders down to those of marbles and dust. Planetary rings are marginally collisional in that typical mean free paths are comparable to the vertical thickness. Discs consisting of dust, and also probably larger sized particles whose infra-red emission cannot be detected, are being discovered around a number of young main sequence stars. These discs are thought to be the remnants of the process of planet formation.

Gaseous discs are observed around compact objects in interacting binary star systems, and around very young stars which are still in the process of forming. They are widely believed to occur around massive black holes in the active nuclei of galaxies. These discs consist of highly ionised plasma, so that in them magnetic as well as purely hydrodynamic processes have to be taken into account.

Scientific Programme

Although astrophysical discs come in a variety of forms and have a wide range of length scales ranging from planetary to galactic, there can be a lot of common ground between them because of similar underlying dynamical properties. For this reason research problems in the area were grouped together according to similarity of dynamical properties, rather than under astronomical field.

One of the main benefits accruing from this research programme was that researchers working in different areas of astronomy, but on essentially similar problems were brought together and were able to compare methodology and discuss the results of ongoing work.

The programme involved people working in the general areas of hydrodynamics, magnetohydrodynamics, stability of self-gravitating differentially rotating systems, and the theory of turbulent dissipative fluid systems as they relate to astrophysical discs. Both analytic approaches and numerical simulations were involved.

The programme was split into three distinct, but related, phases in which different aspects of the dynamics of astrophysical discs were addressed.

1) Angular momentum transport

The long-term evolution of astrophysical discs is controlled by the rate at which angular momentum is transported outwards so allowing the disc material to sink deeper in the gravitational potential well. Associated with this process is dissipation of energy, and it is this �accretion luminosity� which attracts the attention of astronomers in the x-ray emitting binary stars and in active galactic nuclei. We explicitly excluded detailed consideration of these thermal processes from the programme because emission processes are always found to be specific to particular astronomical objects, and give little opportunity, if any, for cross-field fertilisation. However, consideration was given to where the energy is dissipated as this can have feedback into the disc structure, and so affect the angular momentum transport process.

Various mechanisms which can provide/affect angular momentum transport were considered:

For discs with non-negligible self-gravity non-axisymmetric self-gravitational instabilities are able to set in and transport angular momentum. These are thought to give rise to the spiral arms seen in disc galaxies, accompanied with the complication that the small amount of gas in the galaxies acts as a tracer for the spiral instabilities present in the stellar component.

Recent work on non-axisymmetric waves in galactic disks has focused on the importance of co-rotation. Any orbiting density fluctuation induces a supporting spiral response from the surrounding disk that co-rotates with the fluctuation. A random distribution of density fluctuations therefore induces a "kaleidoscope�� of transient spiral patterns with no particular symmetry preferred. More organised patterns may result from Landau excitation of waves from steep gradients in the density distribution. Such gradients could be created by resonant scattering from a previous wave, suggesting the possibility of a recurrent and self-perpetuating cycle of instabilities.

The discs around protostellar objects are almost certainly self-gravitating during the early part of their lives, although at later times, the central star dominates the gravitational potential. The discs around planets such as Saturn�s rings are marginally self-gravitating. The outer regions, and therefore the most readily observed parts, of the discs around active galactic nuclei are also calculated to have non-negligible self-gravity.

With regard to purely hydrodynamic phenomena, little progress has been made. The discs have a strong shear flow, so that one might expect hydrodynamic turbulence to set in. However, discs rotating with Kepler�s law are strongly stably stratified in the radial direction (Rayleigh criterion), and no linear or non-linear hydrodynamic instabilities have yet been found when boundaries are not reflecting. Although there is still no formal proof of nonlinear stability, with existing analytic treatments leaving the question open, this problem was widely discussed and some of the participants have embarked on collaborations to expand the parameter space that can be shown to be stable using numerical simulations and to attempt new analytic approaches.

There are additional possibilities for instability and angular momentum transport associated with wave propagation in a disc with at least one reflecting boundary. A disc with an inner edge has the possibility of supporting non-axisymmetric wave modes which propagate backwards azimuthally with respect to the fluid, but forwards in an inertial frame. Such modes can then grow by radiating angular momentum radially outwards. The presence of such processes in a disc depends on the disc being able to support locally trapped modes, and on the propagation properties through the disc. Some of the participants made progress on looking at this problem when the disc contains a global magnetic field allowing the propagation of Alfvén waves which provide the mode of angular momentum loss. Such considerations may be important for understanding MHD outflows but much more remains to be done.

There was interest in the possibility of setting up a self-sustaining hydromagnetic dynamo in which the required transport is provided through Maxwell stresses. This has been stimulated by the (re)discovery by astrophysicists of an mhd instability whose relevance had been overlooked by the mhd and dynamo community. Numerical computations had already begun to confirm that a self-sustaining dynamo can occur, and that it is this instability which enables the dynamo to exist, rather than the more familiar �alpha-omega� dynamo mechanism involving background turbulence. However, the applicability of some form of mean field theory was discussed which does seem to be able to fit some aspects of some of the simulations. This would be useful for a possible global description of the disc as simulations at present can only be carried out for a local piece of disc. Discussion of how to extend the simulation boundary conditions to be applicable to a force free corona took place. This is a fast moving area, and one of considerable importance for disc dynamics. It is probably related to the observational evidence that discs around protostars and in active galactic nuclei (AGN) appear to be capable of driving collimated and powerful jets along the disc axis, almost certainly powered by some mhd process. Tying the dynamo generation of fields in the disc, to the mhd driving of these jets is a big challenge in this area. A further consideration is that such mhd-driven outflows can also carry off angular momentum and so enhance the dynamical evolution of the disc.

Work was also begun to study disc oscillations in the presence of mhd turbulence by simulation methods. Such studies of the response produced in the turbulent steady state under varying conditions, such as angular velocity profile, may be useful for disc diagnostics. An example is to study conditions when the epicyclic frequency has a maximum (expected near a black hole) to see whether any characteristic oscillation signature may be obtained. In the Keplerian case epicyclic oscillations making up a linear vertical shear were found to have a surprisingly long life.

2) The shape of the discs

The simplest discs to consider are those whose elements follow circular orbits around a central potential in the same plane. However, due to interactions with external forces, discs are often neither coplanar nor circular. The dynamics of such discs was explored.

The dynamics of warped galaxy disks, in which the restoring force is self-gravity has been explored by analytic and by numerical means. A number of ideas to account for bends observed near the edges of galaxy discs have been explored, survivability is questionable since self-gravity which might hold things together, even in galaxies, seems too weak to overcome the differential precession rates. The difficulty is compounded by the existence of two effects that damp bending waves: Landau damping by stars in the disk whose natural vertical oscillation frequency is commensurate with the forcing frequency of the wave, and dynamical friction with halo material. Ideas that have been explored for warp excitation involve external processes, such as material infall.

A certain amount of work has also been carried out on eccentric and non-planar particle discs around planets. However, the situation with regard to fluid discs is much less clear. Some work has been done for example on marginally warped (linear or weakly nonlinear theory is assumed) fluid discs, that is those in which the tilt angle is much less than the opening angle of the disc. Here the warp can be regarded in some sense as an m=1 perturbation which can then propagate through the disc as a wave. In addition the tilt drives resonant vertical shear within the disc locally, upon which a small local viscosity can act, or which may itself be subject to shear instability. However, the real interest lies with strongly warped discs, which are of course those whose warps are detectable in some way by astronomical means. Here, the fluid dynamics is strongly non-linear and hard to calculate. Some progress has been made by some participants in treating such discs with smoothed particle hydrodynamics. The simulations indicate propagation of bending waves and show that diffusion of warps can occur much faster than by assuming the rate given by shear viscosity or the mass accretion rate.

Narrow planetary rings are often observed to be non- circular, exhibiting sometimes m=1 (eccentric ring) or m=2 distortions. This phenomenon can occur because the action of viscosity through the shear can destabilise non-axisymmetric density waves or modes (viscous overstability). Another possible cause is parametric instability induced by a tidal interaction with a companion satellite.

Such phenomena may also occur in larger-scale gaseous discs where viscosity may also excite eccentricity rather than cause it to decay, and a combination of tides and parametric instability has been postulated as causing eccentricity in dwarf novae discs. However, the conditions required for these instabilities, which must depend on the form of viscosity, are poorly understood. There was an opportunity for cross-fertilisation between the two areas of planetary ring dynamics and accretion discs so that, as a result of future collaborations, we might expect a better understanding of the conditions required for viscously-driven non-axisymmetric distortions to occur in discs.

3) Disc interaction with external forces

We remarked above that discs can become non-planar and/or eccentric due to interaction with external constraints. For example, in the protostar field it is known that most stars have binary companions and that star form in crowded regions. Thus a protostellar disc is likely to be subject to interaction with a companion or even a passing interloper. Furthermore it is possible that when two stars come together to form a binary star, there can also be an exterior protostellar disc surrounding the binary system as a whole. What is of interest dynamically in such cases, is not just the result of this interaction on the disc, but also the back reaction of the interaction on the orbits of the stars themselves. If the discs contain sufficient mass, then the orbits of the stars can be severely affected. In particular an exterior disc around a binary system is capable of either increasing or decreasing the eccentricity of the binary orbit, depending on the details of the interaction, and on which resonances come into play in the disc.

Phenomena of this kind occur in most disc situations. In AGN the discs are believed to be fed by a surrounding star cluster with stars spiralling inwards to interact tidally with the disc. In addition these systems have been postulated to contain binary black holes where the partners have comparable mass. In this situation the tidal effects would be similar to those expected in protostellar or stellar discs. There would be important consequences for the accretion phenomenon.

In planetary rings orbiting satellites are seen to cause gaps and shepherd rings. In addition density waves are excited by tidal interaction which are observed to propagate into the disc. These phenomena are also expected to occur in other discs where the excited waves may induce angular momentum transport. Furthermore in the planetary ring case there are many small satellites orbiting within the rings which may be too small to cause gaps. The dynamics in this situation is similar to what is expected when protoplanets form inside protostellar discs. There one is interested in the flow dynamics, possible disc formation about, and observational consequences of accretion onto, the protoplanet. There was an opportunity for cross- fertilisation between planetary ring and accretion disc dynamics. Some work on the problem of gap formation and limitation of accretion onto protoplanets was carried out by some of the participants who were able to compare their latest results.

Organisation

The overall organisation was undertaken by JCB Papaloizou, JE Pringle, J Goodman, and JA Sellwood. Day to day matters were dealt with by J Papaloizou.

The informal colloquia held regularly on Mondays were organised by J Sellwood. The more formal colloquia held on regularly on Thursdays were organised by J Pringle. All four organisers played a significant role in organising the April workshop and the EC summer school.

The organisation of the programme was greatly facilitated by the dedicated, helpful and cooperative work of all of the staff at the institute. Without this the programme could not have succeeded.

Participation

The programme attracted 39 long-to medium-term participants staying for periods ranging from 15 days to the entire programme. In addition there were 52 short term participants. During the April workshop, 55 researchers took part and during the EC summer school there were 87 participants, including 26 young researchers funded by the EC.

Practically all of the leading theorists and applied mathematicians interested in accretion discs took part in the programme. The programme had participants from the US, Canada, Europe, the former Soviet Union, South America and the Middle East. Support from the Leverhulme Trust in particular enabled us to invite researchers from Eastern Europe, the former Soviet Union and South America.

Younger researchers were enabled to attend through the junior membership scheme. This was directed towards PhD students in particular.

Special efforts were made to involve UK researchers throughout the country. Overall participation was at the 30 percent level. The April workshop specifically had UK review speakers wherever possible.

Meetings and Workshops

We had two long workshops. These were as follows:

Workshop on Discs in Astrophysics, April 6-8 1998

This workshop was directed towards advanced graduate students, postdoctoral fellows and researchers and was intended to bring together scientists interested in physical processes that occur in Astrophysical discs. Special efforts were made to involve UK participants, both as review speakers and participants with the object that they should be able to take advantage of the opportunity to meet and interact with the international programme participants. The topics focused on were: hydromagnetic processes, turbulence, and external forcing as they applied to discs in the contexts of active galactic nuclei, galaxies, protostars and close binary systems.

The Organising Committee consisted of J Goodman (Princeton), J Papaloizou (London), J Pringle (Cambridge), and J Sellwood (Rutgers). Review speakers included: J Binney (Oxford), A Brandenburg (Newcastle), C Gammie (Harvard), J-P Lasota (Paris), G Ogilvie (Cambridge), C Parnell (St. Andrews), S Sridhar (Pune), A Whitworth (Cardiff), G Wynn (Leicester).

Many young researchers attended and presented posters at the meeting.

EC Summer School, 22-27 June 1998: Astrophysical Discs

This school was held at the end of the programme with the object that the lecturers, most of whom were participants, should combine material they had been working on during the programme with a general review of the topic they were lecturing on. Overall a summary of the work undertaken during the programme would then appear in the context of the background of the field.

The Lecturers were: T Marsh (Southampton), F Verbunt (Utrecht), J Hawley (Virginia), J Sellwood (Rutgers), A Toomre (MIT), A Fridman (Moscow), C Chandler (Cambridge), P Armitage (Toronto), M Livio (Baltimore), C Gammie (Harvard), J Pringle (Cambridge), G Ogilvie (Cambridge), J Papaloizou (London), C Terquem (Santa Cruz), J Leahy (NRAL), L Tacconi (MPI), R Blandford (Caltech), I Yi (IAS), P Natarajan (Toronto), R Pudritz (Mcmaster), E Ostriker (Maryland), D Lin (Santa Cruz), A Toomre (MIT), P Nicholson (Cornell), S Sridhar (Pune), L Sparke (Wisconsin-Madison), R Nelson (QMW), G Laughlin (Berkeley), L Athanassoula (Marseille).

The school attracted around 40 young researchers, many of whom presented posters on their most recent work.

Throughout the programme an informal seminar series was held on Monday mornings. This was used as a mechanism for recently-arrived participants to present their most recent work and obtain feedback from the other participants.

In addition to these a more formal series was organised on Thursdays. The object here was to invite a speaker with an observational bias to give a talk and then to stay over for a few days to interact with the more theoretical participants, so providing a direction for their researches. Speakers included K Horne (St Andrews), A Kinney (Baltimore), A Fabian (Cambridge), M Stills (St Andrews), J Bouvier (Grenoble).

Outcome and Achievements

The main achievement of the programme was that it brought together researchers from widely different backgrounds in astrophysics and enabled them to interact in a good atmosphere for a long period in a situation they would be unlikely to find themselves in otherwise. The programme concentrated on younger researchers at their most productive stage and was instrumental in producing an environment in which new and potentially important collaborations were begun. It is difficult at this stage to predict the final outcome but it is likely that there will be important progress in the three areas that the programme focused on. An outline of the activities of some of the participants carried out at the institute is given below.

J Goodman made progress in constructing more accurate self-similar solutions for non axisymmetric waves in self-gravitating discs and also on the theory of the stability of such discs together with N Evans.

J Goodman, C Gammie and G Ogilvie studied parametric instabilities of vertical shearing motions in discs. These might lead to turbulence and anomalous viscosity which might damp warps. R Nelson, J Papaloizou and C Terquem studied bending waves and warps in discs using smooth particle hydrodynamics simulations. These enable calculation of the Bardeen-Petterson radius in the low viscosity regime. C Terquem, R Nelson, J Goodman and J Papaloizou compared results of tidal circularisation timescale calculations for a solar mass star. P Maloney, C Terquem, and J Papaloizou began a project to study the effect of density waves controlled by self-gravity on the possible radiation driven warping of discs. S Balbus and C Terquem begun a collaboration related to applying the new results of mhd simulations to observed protostellar discs. S Balbus and J Papaloizou began a collaboration on the stability of magnetised disks. J Sellwood and S Balbus collaborated on the application of mhd instabilities to galactic discs.

A Brandenburg began projects with H Spruit, J Goodman and E Agol on the decay of vortical structures and passive vector fields in a turbulent disc. C Campbell and J Papaloizou began a study of the application of mean field dynamo theory to the problem of magnetic field dragging through discs.

A Kinney, H Schmitt, and J Pringle worked on a statistical study of the jet orientation in Seyferts relative to the host galaxy. This study holds the promise of interesting future results which may relate to the underlying disc dynamics. R Stehle, J Larwood and M Tagger began a collaboration aimed at studying the properties of eccentric discs in binary systems. An important and up-to-now neglected aspect is to compare the performance of Lagrangian particle based schemes and finite difference grid based schemes.

D Syer, J Touma, and S Sridhar collaborated on making self-consistent models of eccentric discs comprising stars in near Keplerian potentials. Such a disc may exist in the centre of the galaxy M31 but a self-consistent model has yet to be made and progress towards one has been made at the institute.

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