Book presentation, 11 June 2010

You have listened, first, to the Allegro and, next, to the Adagio of the Sonata in d minor composed by Karl Friedrich Abel (1723-1787) for the viola da gamba, and played (one should rather say revived) by Ralph Rousseau Meulenbroeks. Music needs no words, but it is appropriate to recall that Ralph is not only an internationally renown soloist at the viola da gamba, but also a physicist by training, and a good one at that. He received his PhD in physics cum laude in 1996 and, shortly after that, he became the first group leader at Rijnhuizen of what was to become Magnum PSI (the big experiment occupying the main wing of this building and one of reasons Rijnhuizen will be transformed into a new national institute for energy research at Eindhoven): his career appeared to be all set. Yet, there is that higher love that needs no justification after what you have heard.

Let us thank Ralph for his willingness to descend once more, for just this afternoon, to the low lands of plasma science!

And now I have the very difficult task to say something that is worth listening to as well. I will try.

One of the privileges of being first author of this book is that I had to write the introduction. This is not something to be done last, but it is a continual process, going on from the beginning to the very end: first writing some key words and sentences, much later an entire paragraph, but then finally, at the moment of truth, the key question had to be addressed. Is there a particular *angle* on the field that makes our book different from all the other books that have appeared? Do we have a unique *view point*? As you expect, the answer to that question is affirmative, but let me guide you there.

I will do that by showing a few figures from the introductory chapters of our two books on magnetohydrodynamics. (I will frequently abbreviate that term by the common acronym MHD). The first figure is taken from "Principles of Magnetohydrodynamics" (the first book, written with Stefaan) and I will repeat some things I said on the presentation of that book in 2004, but the unfolding view point has become much more pronounced since then.

1. The standard view of nature: an incomplete view

The 20th century has been a great era for physics, with many great inventions, from the discovery of the quantum laws governing matter at the very small length scales, including the elementary particles, to the gravitational laws of space-time describing matter at the cosmological scales of the whole Universe. It has permanently changed our view of nature, as indicated in Fig. 1.8: *the Standard View of Nature*. It shows how the four fundamental forces of physics (strong and weak interactions, electromagnetism, and gravity) operate on increasingly larger length scales. At the scale of atomic nuclei (10^{-15} m), the nuclear forces give rise to positively charged nuclei and negatively charged electrons. In a certain sense, those forces are 'exhausted' beyond that scale, so that electric forces become the dominant interaction between the particles. The electric forces give rise to the next stage of the hierarchy, viz. that of 'ordinary' matter consisting of atoms and molecules with sizes of the order of 10^{-9} m. Since these particles are electrically neutral, all there appears to remain is the gravitational force, which requires the collective effect of huge amounts of matter over length scales beyond 10^9 m in order to become sizeable. This gives rise to the different astronomical systems of stars, galaxies, clusters of galaxies, etc. Since the gravitational force is a long range force which is solely attractive (there are no repulsive negative mass particles), this force is only 'exhausted' on the scale of the Universe itself. In a nutshell, this is what most physicists agree is a rather compelling view of nature.

Yet, something makes us feel uncomfortable with this view: There is a vast territory of 18 decades in the intermediate range, indicated by the dots, where nothing of fundamental interest appears to happen! There appears to be a big gap in our description of nature. I am not going to dwell on the evident, viz. the omission of the complexities of condensed and living matter, also in that range, but on something else that easily escapes attention: The tacit assumption that electrically neutral atoms and molecules are the building blocks of 'ordinary matter'. That assumption is false for most of the Universe: Astrophysicists agree that visible matter in the Universe consists for more than 90% of plasma, not of atoms and molecules.

Plasma is *the fourth state of matter*, solid, liquid and gas representing the first three. We are all familiar with the first three states: Heating of ice (solid, orderly arranged molecules) results in water (liquid), heating of water (e.g. in a magnetron) results in vapor (gas, completely disorderly arranged molecules). These phase transitions are rather minor changes compared to what happens next: When the vapor is heated to millions of degrees Celsius (which can still be done with a kind of magnetron, but a much more intricate one, experts here at Rijnhuizen can tell you all about it) the electrons are completed stripped from the atoms, which become bare nuclei, and a state is obtained called *plasma*. Like atoms and molecules, plasma is also electrically neutral, but the big difference is that the particles move about freely to constitute one big chunk of *collectively interacting matter* in which electrical currents and the associated magnetic fields are nearly automatically generated. In conclusion: *magnetized plasma is the ordinary state of matter,* occupying the intermediate levels of nature.

To avoid misunderstanding: Observational astronomy not only asserts that plasma is ten times more abundant than ordinary stuff like rock, dust and gas, but also that the gravitational book keeping requires the presence of hypothetical "dark matter" and "dark energy", which in turn should be ten times more abundant than plasma. However, we have no clue about what those states of matter might be, just that they are needed for honest book keeping. It might then be advisable to study in more detail those kinds of matter about which we can obtain solid knowledge, viz. of the plasma-astrophysical objects. In that respect, it is revealing that the standard picture of cosmology usually shows a pie chart with 90% dark stuff and the remaining sector labeled "gas" or "atoms", demonstrating an embarrassing lack of understanding of cosmologists of that part! Maybe, future book keeping will give rather different answers, with plasma playing the prominent role it deserves?

2. How do we know?: giants of the past opening two windows on nature

How do we know all this? It is appropriate at this point to pay tribute to two great scientific minds who contributed fundamentally new insights, dating 400 and 100 years ago (celebrated, or should have been celebrated, last year): Galileo Galilei and David Hilbert. The first represents modern astronomical observations, using the telescope, the second modern mathematical analysis, using mental concepts like Hilbert space. Here they are, looking at us, with a twinkle in their eyes: they see something!

When I first read about the history of the telescope, I was delighted to learn that it was invented in 1608 in my home town!, Middelburg, by Hans Lippershey or Sacharias Jansen (neighbors, quarreling about their right on the patent, hence both loosing). And then another anti-climax: sure the prince of Orange, Maurits, is interested in the "binocular": a great instrument to detect foes (recall this is during the negotiations of the 12 year armistice in the war of independence against Spain). And so, the instrument travels via Germany to Italy, and one can just imagine how, in the hands of Galilei, the thing transforms from a curiosity into something that will completely change our view of the Universe. A *change of angle* is involved, maybe obvious in hindsight but clearly not obvious at all at that time. His train of thought can easily be reconstructed though: "Of course, this instrument is not meant for bird watching, but I have to increase the angle from the horizontal plane upward to study the motion of the heavenly bodies!" And so, he directs it to the moon, observes craters there, and to Jupiter and he detects three nicely aligned little spots next to that planet: there are three moons revolving, not around the Earth, but around another center of gravitational attraction: Jupiter. And so, the Earth starts to move out of the center of our world view to an ever more accidental position in the Universe.

The detection of astronomical plasmas involves telescopes exploiting other parts of the electromagnetic spectrum (viz. X rays), but here, in 1609, the exciting evolution of observational astronomy begins to gain momentum: Vast space with all kinds of objects out there! Today, everybody can download pictures of galaxies of incredible resolution, produced by the Hubble Space Telescope. When I first saw those on a huge flat screen, with the camera moving in as it were, I was overwhelmed and gasped for air: so great!

How about that other view point, the mathematical one? If possible, this is even more amazing yet: How come, a mental picture like Hilbert space, a space *with infinitely many dimensions,* be so effective in describing nature? There is no Hilbert space out there, it just resides in our brains. The concept of such a space was introduced by Hilbert in 1909, sixteen years before the advent of quantum mechanics describing atoms and molecules (1925). Hilbert must have been amused to see, first, Heisenberg developing matrix mechanics (at the same university, Göttingen, in the physics department), and then, a year later, Schrödinger developing wave mechanics, and the two even quarreling about the superiority of their own view point, until they realize that these are just two equivalent representations of Hilbert space. And many more applications coming later, one of them being a major subject of our book, the waves and instabilities described by magnetohydrodynamics.

It would be wrong only to sketch these wonderful, exciting, revolutions in science. There is also the very dark side of history. We all know how the church, exercising a power without any justification, makes the life of Galilei miserable. In 1633 he is forced by the inquisition to revoke his correct scientific insights. Precisely 300 years later, another, more evil force yet, ruins Hilbert's mathematical department by kicking out all Jewish scientists, amongst them Emmy Noether, the most prominent woman-mathematician ever. (She is double handicapped: woman and Jewish.) Clearly, Hilbert's life also has been miserable to the end (1943): he did not live to see the end of the nightmare. The Jewish scientists that were "so lucky" as to be send in exile before the worst part started, must have been more than motivated to rebuild Hilbert's school elsewhere. And this they do: Richard Courant, Kurt Friedrichs and others create the Institute of Mathematical Sciences, later called the Courant Institute, in New York.

And I am so fortunate to become an associate research scientist there, shortly after my PhD. Here I am, on the same floor as Friedrichs, I see him passing by along my office, and he lectures on "Magnetohydrodynamics"! (He is actually the inventor of the basic structures of MHD, the characteristics.) And a younger great mathematician, Jürgen Moser (of the famous KAM theorem) teaches on "Linear operators in Hilbert space"! When I ask Harold Weitzner (presently still there, heading the magneto-fluid dynamics division): "What makes this institute different from all the other institutes?", his instant reply is "That we take our model seriously"! And thus, in 1972, I find my *angle*, serving me all these years up till now: *the model of ideal magnetohydrodynamics,* worth to be taken very seriously indeed.

3. The ideal MHD model: describing global plasma dynamics

And so, here it is: the model of ideal MHD, with the two angles, of Galilei and of Hilbert: experimental (or observational) facts and mathematical analysis, intertwined in a most amazing manner. Experimental fact is that "*Plasma is a completely ionized gas, consisting of freely moving positively charged nuclei and negatively charged electrons*" (definition on the first page of our first book on MHD). The mathematical model involves "*differential equations describing the dynamics of such a plasma in a magnetic field*". I was tempted to show you those equations, because I love them so much. But it would serve no purpose. Of our love for those equations you can easily convince yourself by glancing in the book.

And so, here is what physicists do if they want to stress the importance of their equations: they put them in a box. The box represents all the implications of the equation shown. The equation itself is just very handy short-hand notation for all that it implies: hundreds and hundreds of scientific papers unfolding their consequences.

I have decorated the box with two long arrows sticking out of it: they represent the magnetic field, indicated by the bold symbol **B**. The box can also be interpreted as a small volume of plasma, just like one can imagine a small box of ice, or water, or vapor. It is very customary to consider such small volumes in physics: a kind of a sample of the material to be investigated. One can put such a sample under the microscope, or insert it into a spectroscope, to find out about its microscopic properties. *Not so with plasma!* It is impossible to extract a small volume of plasma without destroying its global structure, the confining magnetic field: plasma and magnetic field are inseparable! The consequence of one of Maxwell's equations is that the magnetic field lines have beginning nor end: they spiral endlessly on toroidal surfaces (like in a tokamak) or enclose huge volumes (like the magnetospheres around the planets). Hence, plasma is basically *a global dynamic magnetic structure*: very different indeed from ordinary solids, liquids, or gases.

One of the "kicks" of magnetohydrodynamics is that it precisely catches this *angle*. I could nor resist illustrating this with some symbols. The differential equations of ideal MHD are *scale-independent:* You can transform them to eliminate length scale (l_0), characteristic density (ρ_0), and magnitude of the magnetic field (B_0), and nothing changes! The MHD equations are *invariant* under that transformation. Consequently, these equations describe not only the dynamics of plasma in one possible future source of energy, but also the dominant contribution of visible matter in the Universe!

4. The grand vision: MHD applied to laboratory and astrophysical plasmas

Returning now to the question I posed at the beginning, do we have a unique angle? Here it is: It makes no difference whether you study the dynamics of a plasma in a nuclear fusion experiment, like ITER (size ~ 10 m), or in a galaxy, like the pinwheel galaxy (size ~ 10^{21} m = 100 000 light years): *the length scale is irrelevant for magnetohydrodynamics!* Of course, I am not suggesting that there are no differences between these enormously dissimilar structures, just that the differential equations describing them are the same. Hence, the essential difference between them can only reside in the boundary conditions, representing the forces exerted by the environment. In ITER those come from the coils where the magnetic field is generated: pressures of a hundred atmospheres exerted there, to be balanced by the "nuts and bolts" fixing the configuration to the building. In the galaxy it is the balance between the inward gravitational force and the outward centrifugal acceleration.

Here is where the story of our second book begins and ends. Actually, it does not end at all. As you can see from the two boxes on the last line: The essential character of astrophysical plasmas is that they are never static, always moving (usually at transonic and relativistic speeds) and rotating. This aspect has been largely ignored in fusion research because of the success of the basic "paradigm" of a static plasma, confined by the magnetic field, and quietly awaiting fusion. This paradigm has recently begin to fade (the plasma in modern tokamaks is rotating in both directions), and hence the first task of our second book was to do justice to this aspect. Quite nice new theory has been developed for that purpose (just read the book) and many applications are awaiting analysis. (I just returned from a three month visit to MIT, where I investigated the consequences of that theory for the resistive wall mode, a poorly controlled instability that will severely limit the performance of future fusion reactors.) The story continues!

Acknowledgements

-- I am very obliged about the privilege granted to me to keep an office at Rijnhuizen after official retirement so that I could devote my time entirely to writing. It is appropriate that I do that by thanking the management of Rijnhuizen of five years ago: Aart Klein, Niek Lopes Cardozo, Noud Oomens, and Jan Kranenbarg, who initiated an entirely new way of human resource management, which I admire and which has given me so much freedom. I hope to have lived up to their expectations. Thank you very much! I like to express this now by presenting Aart the first copy of Advanced Magnetohydrodynamics.

-- My co-authors, Rony and Stefaan: You have done a marvelous job, not only in the collective effort of writing, in particular of the chapters on numerical and relativistic MHD, but also in the extended time of interacting with me: the perfectionist, criticizing everything that was written and always moving deadlines ahead. Thank you for your forbearance and friendship! I think it has produced a beautiful product.

-- Everyone will agree: life on this planet without women would be unbearable. But having a spouse as a companion in life goes far beyond that. All three of us agree that the support of our wives, Antonia, Rong Lu, and Micheline, was instrumental in the eventual success of writing this book. It is not only that they provided the push in our back, necessary at low speed, but frequently also a stiff breeze apparently coming from the opposite direction. It is only after you look around when maneuvering the sail boat: tacking on the wind is much more fun and the boat moves much faster! Thanks a lot!

-- Two people also provided essential support for the scientific effort: my parents. Very unlikely supporters, one would say: both born on a farm (my mother in 1909!) and, hence, six years of primary education were considered more than enough. My father was not fit for work at a farm though, so he got one more year of primary education to become a clerk at the local town hall: There you go, you are all set. Yet, they were extremely stimulating in the education of their children. It never even appeared to cross their minds how privileged we were and how poorly equipped they were send into life. When I got stuck with a wrong choice of study: "You do not like to become an engineer and you want to spend more time studying by switching to physics? Don't worry, we support you, just follow your interest!" I know no better way to honor them than by following their example and transferring what I received to a future generation of students. This I do by just reading the last paragraph of the Preface:

Finally, a frequently asked question is: "Will there be a third volume?" Yes, there will be, and you, the serious students of these two volumes who realized that these are just introductions to an enormous field of largely unexplored territory, are going to write it. Remember, with plasmas making up 90 % of all visible matter of the Universe, and plasma physics under-represented in the physics curriculum of the universities, there is no doubt that there will be completely unexpected discoveries for you in store. Nature is on your side!

The Standard View of Nature

Nuclear forces

⇓

quarks / leptons

nuclei (+) / electrons (−) 10^{-15} m

Electrostatic forces

⇓

atoms / molecules 10^{-9} m

(ordinary matter: electrically neutral)

⋮

Gravity

⇓

stars / solar system $10^{9}/10^{13}$ m

galaxies / clusters $10^{20}/10^{23}$ m

Universe 10^{26} m

From 10^{-9} to 10^{9} m:
nothing of fundamental interest appears to happen!

⇓

Something is missing:

the Universe is not made up of ordinary matter, but

90% of visible matter is plasma

⇓

Large-scale collective magnetized state

Galileo Galilei (1564–1642) – David Hilbert (1862–1943)

1609: Vast space out there ⇑

1909: Vast space in here ⇓

Two-fold angle

- **Experiments (laboratory) / Observations (astrophysics)**

  ⇒ **Plasma is a completely ionized gas, consisting of freely moving positively charged nuclei and negatively charged electrons** (Vol. 1, p. 3)

- **Mathematical model (scale-independent)**

  ⇒ **Differential equations describe the dynamics of plasma in a magnetic field**

⇒ **They are independent of length scale** (l_0), **density** (ρ_0), **magnetic field** (B_0)

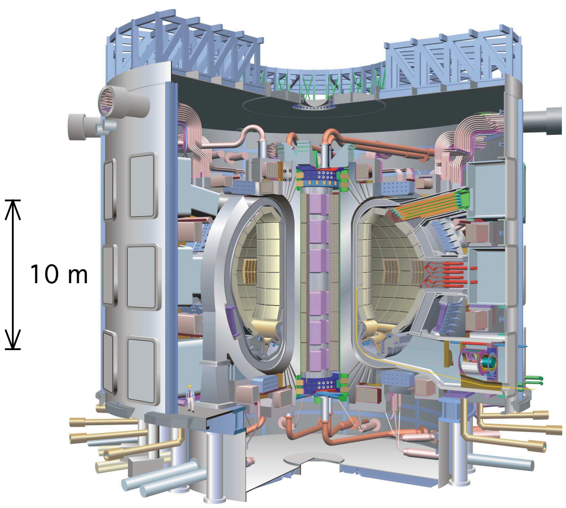
⇓

They describe global dynamics of both laboratory and astrophysical plasmas!

Magnetized plasma

is omni-present and described by magnetohydrodynamics

- Tokamak (Iter)



⇒ **Nuts and bolts** fix static plasma

- Pinwheel Galaxy M101 (HST)

⇒ **Gravity and rotation** fix moving plasma