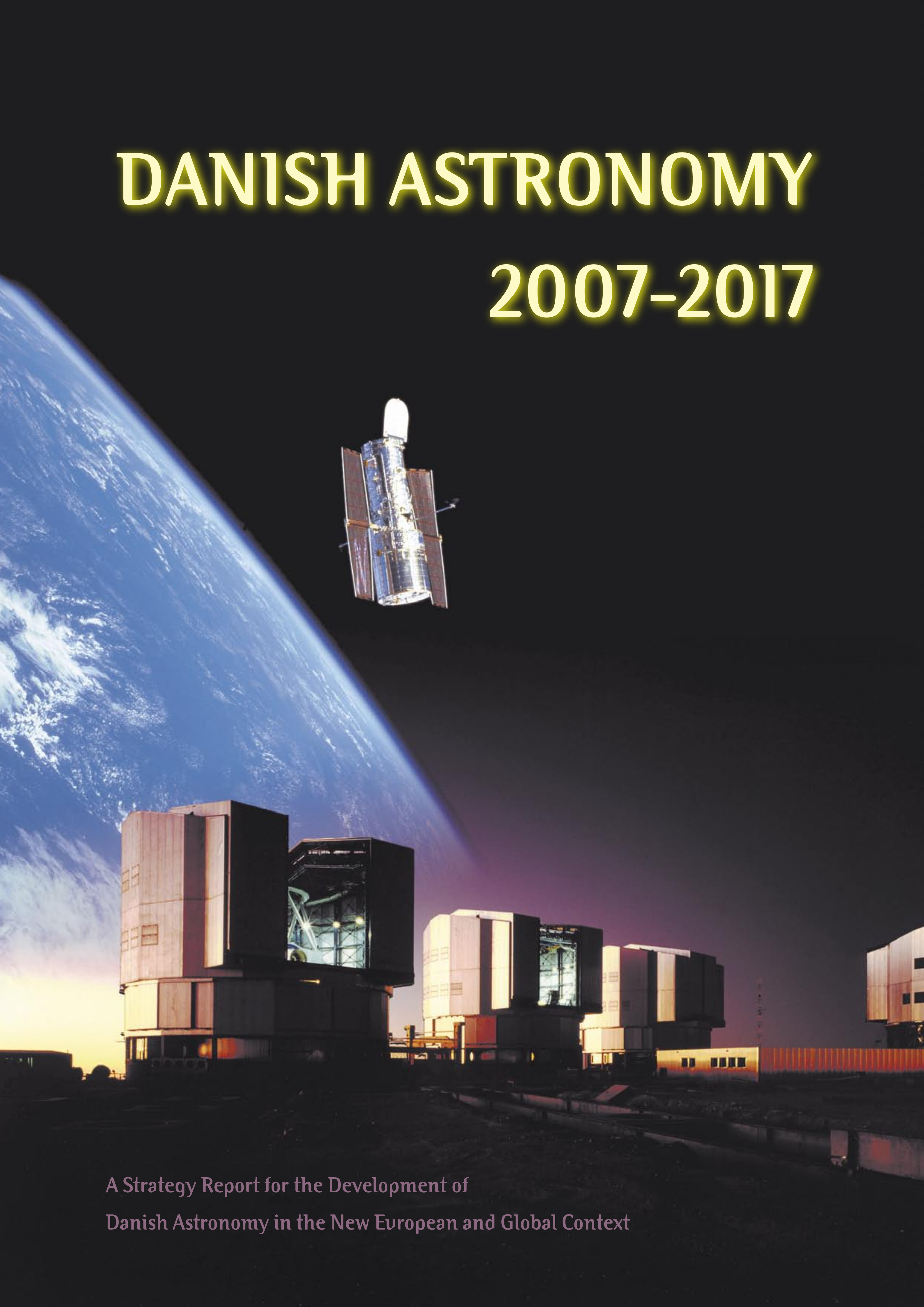
DANISH ASTRONOMY

2007–2017



A Strategy Report for the Development of

Danish Astronomy in the New European and Global Context

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June, 2007

Danish Astronomy Committee/Astronomisk Udvalg

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PREFACE

Danish astronomers are active or leading in several of today's most vigorous areas of research, and the future holds great promise for new discoveries. A new generation of powerful research tools is being built or planned in Europe and in the world, and Europe is working – for the first time ever – on a joint, comprehensive plan to exploit these new opportunities, based on an agreed, long-term Science Vision. The future looks bright indeed.

At the same time, the basis for Danish astronomy is in a state of transition on several fronts. A whole generation of senior researchers is retiring in favour of fresh young people, and the structure of research and research institutions in Denmark is being recast. The repercussions of these changes will be felt throughout the decade considered in this report. Opportunities abound; uncertainties and difficulties as well.

The challenge is to manage this transition to achieve maximum benefit for Danish science and science education. A balance must be struck between focusing the effort on areas of strength vs. seizing new scientific opportunities as they arise; between long-term community commitments to major European or global projects vs. pursuing individual research goals; and between investing scarce human resources in efforts to attract and train Danish students vs. exploiting the great scientific opportunities offered through international collaborations.

Accordingly, the time is ripe to review current developments and future challenges and assess what strategies may support a healthy development most effectively. This report attempts to do so, but cannot be a final answer; the *Danish Astronomy Committee* ("Astronomisk Udvalg") welcomes input from the community at any time (see *http://www.nbi.ku.dk/astronomiskudvalg*).

J. Andersen

Chair
Danish Astronomy Committee/
Astronomisk Udvalg

C O N T E N T S

Appendices:

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EXECUTIVE SUMMARY

Danish astronomy is growing in scientific vitality at a rate unprecedented for decades and increasingly integrated in the European and global research enterprise. Even greater and more diverse research opportunities appear on a daily basis. Managing the limited human and financial resources of Danish astronomy to achieve maximum scientific and societal returns is the challenge before us. The *Danish Astronomy Committee* (DAC; "Astronomisk Udvalg") is charged with providing strategic advice for this process; this report is our attempt to do so.

A small country cannot be competitive in all of astrophysics. We believe that the fields of *(i)* cosmology; *(ii)* the life cycle of matter in gas, stars, and planets; *(iii)* extreme astrophysics; and *(iv)* research at the interface to other sciences offer the most promise for competitive Danish contributions. We note that Danish astronomy has been restructured along similar lines, and that recruitment of tenured staff in these areas, combined with a number of new initiatives, has had a notably positive effect on productivity in both research and education since our earlier report from 2003.

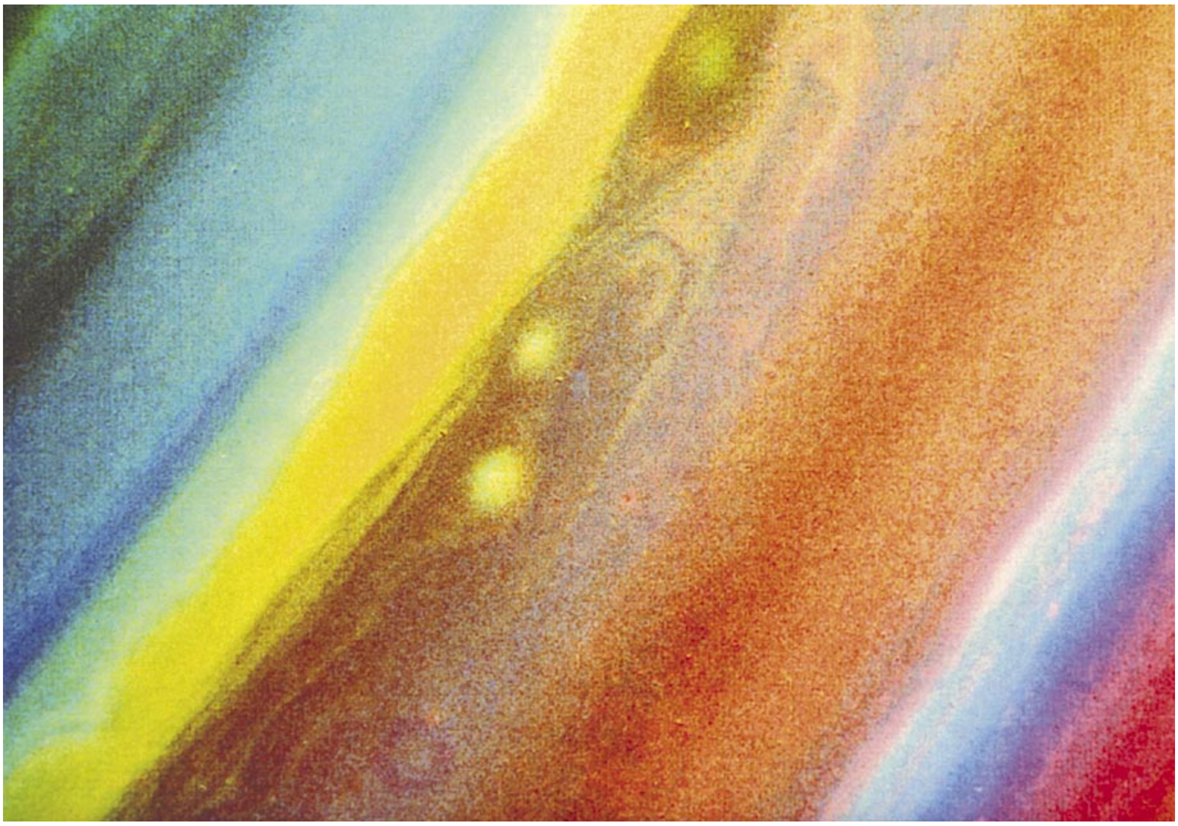
Accordingly, we recommend that this policy be maintained and strengthened in the future. Noting that another 13 senior scientists will retire during the decade covered by this report, we make specific proposals for staff renewals in the short term and recommend that a plan be prepared for the renewal of the rest of these key positions.

Astronomy is one of the most effective fields in attracting young people to the natural sciences. Danish astronomy is keenly committed to exploiting this strength through innovative initiatives and much-improved coordination of effort between the universities. Recent initiatives have already been so successful that it taxes the capacity of the teaching staff to the limit, and shortage of staff is beginning to curtail an otherwise healthy development. We strongly recommend that the decline in tenured teaching staff be reversed and the artificial barriers to nationwide collaboration and synergy between universities be removed.

Progress in astronomy relies increasingly on large research infrastructures at all wavelengths, on the ground, in space, and as computing resources for large-scale numerical simulations and data mining from archives. A new generation of very large infrastructures on a European or even global scale is on the horizon. Participation in the development in some of these is desirable when motivated by a strong scientific interest and backed by a corresponding investment in the scientific returns. However, individual university groups will be increasingly unable to maintain the critical mass needed for a visible participation in the very largest projects.

New forms of scientific-technical collaboration must be devised and investments made lest Denmark miss these opportunities for new technological know-how and spin-off. We propose that a working group with members from the scientific and technical university groups and from industry be formed to recommend a specific plan of action on this issue.

Danish astronomy relies strongly on international research organisations such as the European Southern Observatory (ESO) and the European Space Agency (ESA), and it is supported by a wide array of national and international funding sources. The *Instrument Center for Danish Astrophysics* (IDA) has played a very valuable role in optimising the returns of these investments, and we strongly recommend that IDA's activities be maintained and preferably strengthened in the future. However, neither IDA nor other current public funding sources can support Danish participation in medium-size projects (e.g. 5 MDKK/year), and we recommend that consideration be given to remedy this gap. Also, neither IDA nor DAC has any mandate to represent Danish astronomy in contacts with national and international organisations and other partners; a solution to this issue should be found as well.



Close up of Jupiter

1. Background and Rationale

Astronomy abounds with fundamental questions that excite astronomers and the public alike: A consensus view is emerging as to when and how the Universe formed and developed on the largest scales. Yet, this picture implies that 'normal' matter accounts for only 5% of the Universe: 95% consists of dark energy and dark matter of an utterly mysterious nature. Many planets have been found orbiting other stars; yet we do not know how Nature forms a galaxy like the Milky Way, a star like the Sun, or a planet like the Earth, how life began, and whether we are alone in the Universe.

That such simple, yet fundamental questions remain unanswered fascinates old and young alike, and universities throughout the world are adding astrophysics to their physics departments or strengthening their astronomy departments to capture this interest and recruit growing numbers of science students.

On the global scene, Danish astronomers are active or leading in several of today's most active research areas, and plans are under way for a next generation of ambitious research infrastructures in all wavelength domains, on the ground and in space. Our options for pursuing cutting-edge science in the future will depend on which of these will become reality, and how the existing complement of facilities will be adjusted to cope with the cost of building and operating the new projects.

How does nature form a galaxy like the Milky Way, a star like the Sun ...

Maintaining a scientific staff of adequate strength to secure the scientific and educational returns from these investments will be equally important. A related question is whether and how Denmark will be able to participate actively in the development of the new mega-facilities and reap the associated technical and educational benefits.

Finally, the way research is organised in Denmark and in Europe is also being transformed. A significant increase in funding for Danish science is on the horizon, to be distributed through increased competition and focused on improving our returns from the European research enterprise. The promise is great if we rise to the challenge and turn it into a vibrant future for Danish astronomy.

The *Danish Astronomy Committee* (DAC, "Astronomisk Udvalg") is charged by the Faculties of Science at Copenhagen and Aarhus Universities (CU and AU) and the Danish National Space Center (DNSC; Technical University of Denmark, DTU) to advise on strategies for the long-term development of Danish astronomy. Much has happened since our report, *"The Future of Danish Astronomy"* from 2003 (FDA in the following), and it is time to reassess the situation.

This report attempts to do so. After sketching the international context of Danish astronomy, we outline our recommended research priorities for the next few years. We then discuss staffing and recruitment policies for the institutes; education and outreach; the role of research infrastructures, instruments, and technology; and organisation, and recommend a number of initiatives in each (Sect. 7). An advanced draft of the report was discussed with a large audience at the annual astronomy meeting at Nyborg in 2006, but has been extensively revised to reflect the many significant changes that have occurred since then. The final version is the sole responsibility of the committee.

2. The International Context

Danish astronomy today is totally global: An astronomy paper with purely Danish authorship is rare nowadays. This is inherent in the nature of astronomy itself, but also happens because modern research facilities are built in international cooperation and located at a few remote sites, encouraging international experience, exchange, and cooperation among astronomers. Meaningful planning for the future must be prepared on this background.

International cooperation brings many benefits. First, it brings valuable new ideas – indeed, entire scientific networks – into the community. Cooperation also gives access to facilities, instruments, or software that might not be available otherwise. Finally, international exchanges and foreign staff members make the institutes livelier and more attractive places for students and nourish a global perspective early in their career. Foreign study visits and lifelong collaborations often result from such exchanges. International conferences serve similar purposes, and Denmark should host more such conferences (one is already scheduled for 2008).

The impact of the *European Southern Observatory* (ESO) on Danish astronomy is a striking example. Through ESO, we have access to first-class observing facilities at prime observing sites; without ESO and its Very Large Telescope (VLT), now the world's premier optical observatory, Danish astronomy would have remained a backwater today. But ESO has also fostered a new generation of European astronomers with personal contacts and networks formed through periods at ESO as observers, fellows, or staff members, a perspective they bring to the leadership positions they now assume. In parallel, the *European Space Agency* (ESA) has given Europe a front-row seat also in space astronomy.

Through the VLT, the new submm radio observatory ALMA, and the planned Extremely Large Telescope (ELT), ESO policies will have a decisive influence on the development of Danish astronomy. In particular, ALMA will very soon open an entirely new dimension of discovery in topics ranging from cosmology and the birth of stars, planets, and galaxies to the solar system. Similarly, the Danish membership of ESA provides rich opportunities to participate in space astrophysics, both in the science and voluntary programmes. Securing the best scientific and educational returns from these memberships must therefore be given high priority. The *Instrument Center for Danish Astrophysics* (IDA), funded by FNU, pursues this goal through a targeted, yet flexible portfolio of initiatives and support, with outstanding success.

Danish astronomy today is totally global

The task requires action on several fronts in parallel, both in the planning committees of ESO and ESA, and in training astronomers capable of making best use of their existing and future facilities. Participation in developing instruments for ground-based telescopes and spacecraft is another important activity, which offers not only privileged access to the resulting data, but also opportunities to profit from the technological know-how and spin-off associated with front-line technical development.

Finally, the major European funding agencies for astronomy, including ESO and ESA, have launched ASTRONET, an effort to establish the first-ever, coordinated long-term plan for the development of *all* of European astronomy – optical and radio, ground and space, and human as well as material resources (see Sect. 5). If successful, this initiative will take European astronomy to the next higher level of cooperation and achievement.

The VLT Observatory at Paranal, Chile © ESO

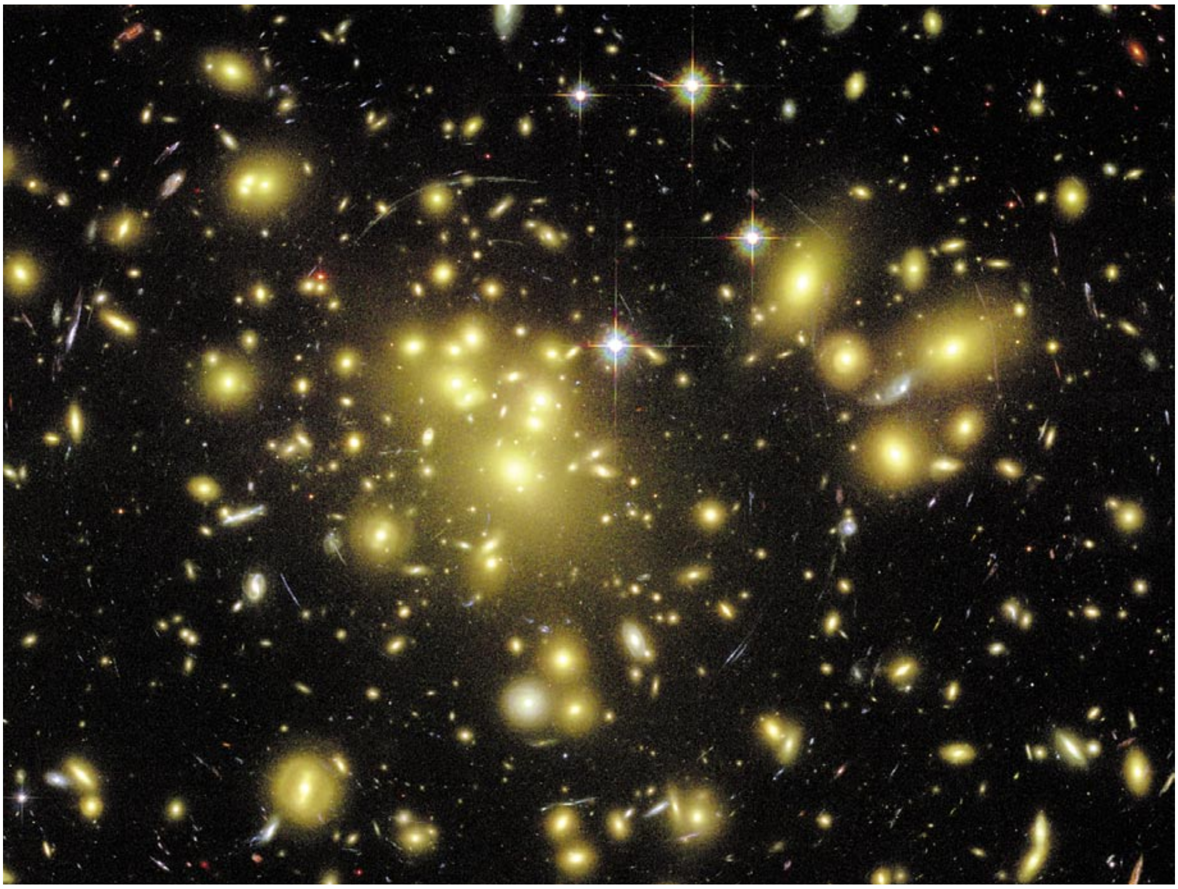
3. Scientific Priorities for Danish astronomy

In a community that cannot cover all of modern astrophysics, directions and priorities must be defined. In FDA we identified a few broad fields on the cutting edge of astrophysics, where Denmark has the potential to play an important role on the international scene and where the effort should be concentrated. All have close interaction between observation and theoretical/numerical studies and intensive international collaborations; together, they form a coherent research and teaching environment of proven merit. We believe that this overall strategy has proved correct and provide updated descriptions here to reflect developments since 2003.

3.1 Cosmology

Cosmology is the study of the early Universe and its evolution, including the formation of the first stars and of galaxies and clusters of galaxies. Cosmology is a central and expanding theme of astrophysics, in Denmark and internationally. A suite of advanced experiments and observational facilities is at our disposal or arriving soon. Theoretical ideas and computational progress are combined to address these questions, and there is a healthy interaction with fundamental physics.

The turn of the millennium marked the beginning of the era of precision cosmology,



The cluster of galaxies Abell 1689 © NASA largely enabled by technological developments and new observational facilities. For the first time, cosmological observations are beginning to provide clues to the initial conditions of the Big Bang. Observations of the cosmic microwave background lend strong support to the concept of inflation in which the flatness, homogeneity, and initial density fluctuations of the Universe are direct results of very early quantum effects. Cosmology will provide the only window on this hidden quantum world over the next decade or more.

Yet, while great advances have been made, e.g., in the determination of cosmological parameters, even the now standard 'concordance cosmology' leaves major issues open: Having totally unknown forms of dark matter and dark energy constitute more than 95% of the Universe is disconcerting indeed! New insight into the formation of galaxies may help to solve these puzzles: Galaxies are expected to form from over-densities in the primordial matter distribution, which subsequently grow in a way that is intimately connected to the nature of dark matter itself.

Thus, many key questions need answers: Can we detect dark matter directly? Does the need for dark matter point to revisions of the laws of gravity? What is dark energy: Vacuum fluctuations or large extra dimensions? Is our world model fundamentally flawed, observationally and/or theoretically? Progress in observations will be driven by new facilities and instruments, at all wavelengths, that will become available shortly on the ground or in space. Coupled to interaction with theory, they will ensure that cosmology remains a forefront topic of research in the foreseeable future.

The field has received a powerful boost by the creation of the *Dark Cosmology Centre* (DARK) at CU, funded 2005-10 by the Danish National Research Foundation. DARK focuses on dark matter, dark energy, the "dark ages", and cosmic dust through interaction between observational and theoretical/numerical studies in cosmology and astroparticle physics. DARK has already injected much new blood and scientific vitality in Danish astronomy and shows considerable potential for further growth. The field is also experiencing a significant boost at AU, especially in the area of astroparticle cosmology, and it is one of the key strategic priorities of the DNSC.

3.2 The life cycle of matter in gas, stars and planets

The universe we see today is the result of many cycles of processing and reprocessing of the matter left over from the Big Bang. Nuclear burning of the primordial hydrogen and helium deep inside stars has gradually produced all the chemical elements we now take for granted. The violent death of stars recycles the freshly synthesised elements into the interstellar gas, the raw material for new stars and planets. From the enriched gas, new stars and galaxies are formed, and the life cycle of

The spiral galaxy NGC 1232 © ESO

matter is closed again. In a very real sense, this process also underlies our own evolution, through the formation of planets that may host life and the synthesis of the elements from which life arose.

Stars are the central engine of the chemical evolution of the Universe, and understanding their formation and evolution is a key research topic. Among the most important issues are the formation of stars of very high or very low mass and the origin of the distribution of stellar masses – now and in the early Universe when conditions were quite different. The structure and properties of collapsing protostellar cores and the associated jets and accretion disks are other key issues, crucial for understanding the initial conditions for planet formation.

Effects of rotation, turbulence and magnetic fields on mixing processes in stars are central for a proper understanding of their evolution and the way they synthesise new chemical elements and deliver them to the interstellar matter. Proper modelling of mixing in stars also plays a major role in understanding the primordial production of lithium.

The study of stellar evolution is making a major advance through the development of asteroseismology, with important contributions impending from space missions and ground-based observations.

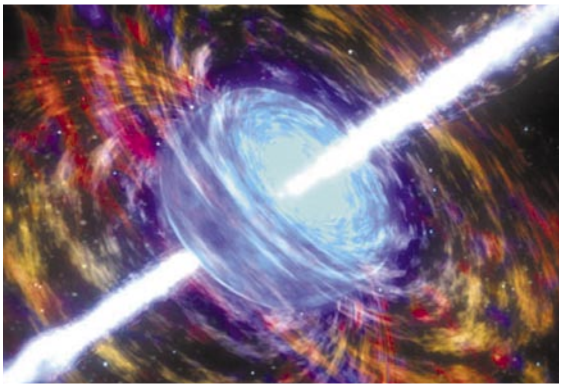
Efficient data analysis techniques are a major challenge, but a matching development of the models of stellar structure is also required. A Danish team will play a major coordinating role in the use of data from the Kepler mission for asteroseismology.

Stars are the central engine of the chemical evolution ...

Progress in planet formation studies is driven primarily by new observations in the infrared and submm radio regime, and by theoretical work and supercomputer simulations focusing on the formation of protoplanetary disks, the roles of core accretion and gravitational collapse in planet formation, and the possible role of planet migration.

Our own solar system provides important constraints on mechanisms for forming planets and moons within a large range of distances from the Sun, including the recently reclassified Pluto and similar objects in the outermost reaches of the solar system. In parallel, ground-based surveys continue to discover extra-solar planets of ever lower masses and greater variety, including a recent detection (with Danish participation) of a 5 Earth-mass planet. Impending space missions will detect even larger numbers of exoplanets, greatly improve the statistical basis for understanding the formation and evolution of extra-solar planetary systems, and may even find true Earth analogues in a habitable zone around the parent stars. Complementary ground-based studies are needed to fully exploit these data.

Danish astrophysicists are well prepared to make decisive contributions in all of these areas. ALMA as well as impending ESA and NASA space missions will bring a wealth of new data that will revolutionise our understanding of the life cycle of matter in our own galaxy as well as in others, and we can expect a similar revolution in our understanding of the structure and formation of planetary systems as well. Specific projects in all of these areas are being planned, in tandem with the further development of the leading Danish position in the theoretical description and numerical modelling of the underlying physical processes, as described above.



Exploding star producing a gamma-ray burst © NASA/ SkyWorks Digital

3.3 Extreme Astrophysics

Many astrophysical environments – from the surface of the Sun to giant black holes in distant galaxies – exhibit extreme physical conditions, where 'non-classical' processes produce X-rays, γ-rays, high-energy particles, or gravitational radiation. The diagnostic content of such signals is unique and opens new windows into these extreme settings. Interpreting the signals and understanding the physical processes is challenging, but potentially also very rewarding.

A forefront topic is the formation and propagation of jets from accreting systems, which are observed in different contexts covering an enormous range of physical dimensions. The most powerful and enigmatic jets are those presumed to initiate Gamma-Ray Bursts (GRBs). Observational evidence associates the most common (long-duration) type of GRBs with the death of very massive stars, while short GRBs may originate from mergers of compact objects. Recent observations of prompt radiation and details of the transition to the afterglow phase, for both types of GRB, have put further constraints on the underlying physics.

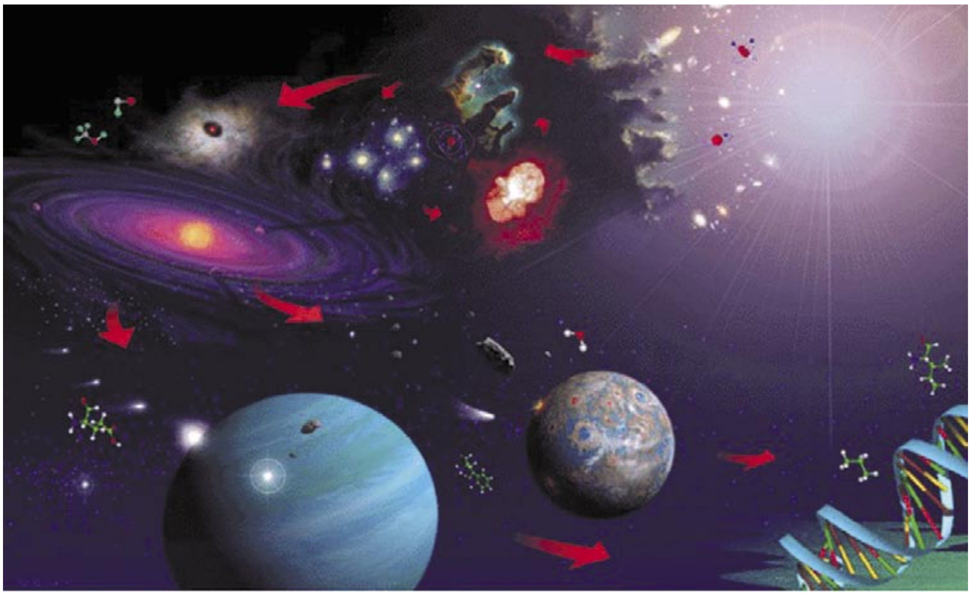
This has, however, not yet led to consensus on the jet acceleration and radiation mechanisms; the new observations are in fact to some extent inconsistent with earlier interpretations and modelling, which indicates that even more sophisticated models are needed. Some inspiration towards more detailed jet modelling may come from the much smaller and better-understood sub-relativistic jets from accreting proto-stars.

X-ray and γ-ray sources in our own galaxy are generally associated with compact objects – the black hole at the centre of the Galaxy, and neutron stars and black holes created by the gravitational collapse of massive stars in supernova explosions. The creation or coalescence of such compact objects creates powerful gravitational waves, soon to be detected by large experiments now under construction. Accretion of matter, e.g. from a binary companion onto a compact object, generates X- and γ-rays as observable diagnostics of the physical conditions where extreme gravitational and electromagnetic forces are at work.

Danish astrophysicists are actively involved in interpreting such observations. They have also developed expertise in modelling such extreme physical environments, using fluid and particle dynamics under special and general relativistic conditions. Notably, huge relativistic charged-particle models with associated particle-photon interactions and radiation diagnostics have become available. Applications in the solar context, where excellent time and spatial resolution is available, provides an invaluable testing ground and is attractive because of the substantial European expertise and potential for network collaborations. “Extreme astrophysics” thus remains a promising growth area for Danish astronomy.

3.4 Astrophysics and other sciences

Astrophysics interfaces with many other sciences. Atomic, nuclear and particle physics provide insight in the fundamental astrophysical processes. Conversely, astrophysics yields data that cannot be obtained in the laboratory, on topics ranging from particle physics or the nature of gravity under extreme conditions to biology. Astrophysics also interacts with computer science in large-scale simulation methods for a wide range of physical processes.



The life cycle of matter in the Universe © NASA

Many new developments are likely to come from these areas. Astroparticle physics is being strengthened in Denmark, but better links to geology/geophysics, planetary science, relevant laboratory physics groups, and biology at all the major universities are also needed. These booming fields will be particularly important for the longer term.

The coupling between astrophysics and particle physics has been especially fruitful in recent years. Precise and detailed measurements of the cosmic microwave background (CMB) have provided important information on key particle physics parameters. The recent papers on CMB anisotropies from the WMAP satellite are among the most cited across all the sciences, not least by particle physicists, and the Nobel Prize in physics for 2006 was awarded in this field. The upcoming Planck mission will provide even more detailed observations of the CMB anisotropies than the WMAP mission.

At the highest energies, cosmic rays will become an important tool for studying both extreme astrophysical sites and the extent and origin of intergalactic magnetic fields. At the other end of the energy scale, the discovery of extrasolar planets has spurred huge interest in the formation of planetary systems and the conditions for life elsewhere in the Universe (astrobiology). Such studies need input from chemistry, geology, and biology; in turn, they provide valuable information on the evolution of our own Solar System.

In summary, Danish astrophysics research must maintain a focus on interdisciplinary aspects. Interdisciplinarity should also be a driving force on the educational side: Astrophysics has become very popular with physics students in general and also acts as a spearhead in recruiting new students, who seem to prefer a mix of physics with other subjects such as life sciences. Astrophysics courses could also be beneficial for students in chemistry, biology, etc. – and even outside the natural sciences and engineering (see p. 20).

4. Staffing, Recruitment, Education, and Outreach

Staffing, structure, and education in Danish astronomy have changed greatly since 2003. New teaching initiatives have already resulted in a significant increase of the enrolment in astronomy courses at all levels, at the same time as the faculty available to teach them has been shrinking. The net trend is very positive and encouraging, but may not be sustainable in the long term. The related issues are closely linked and are discussed together here.

4.1 Renewing the Tenured Scientific Staff

Half the generation change in the scientific staff is already behind us, but with significant loss: As found by IDA *(http://www.astrofysik.dk/content/docs/DK_astro_ressource_05.pdf)*, the tenured scientific staff dropped by 6 FTEs from 2003 to 2005. A couple of positions have been filled recently, but the declining overall trend counteracts the growing scientific and educational contributions of astronomy (see Sect. 4.2) and must be reversed. An orderly renewal of the tenured research staff must be instituted if we are convince the best young scientists to consider a career in Denmark. A further 13 senior staff will retire within the decade covered by this report, and their replacement should be planned so as to maintain a healthy evolution of the field, balancing the needs for breadth vs. specialisation.

Universities will seek scientists who will enhance their research and teaching portfolios and be able to attract external funding, and they will select outstanding candidates when they appear. The policy of adding staff in the research fields described above has been very successful in all of these respects and strengthened our recommended priority fields as well. The profile of the new staff is also well matched to the science cases of the ma-

Astronomy then and now

A: Galileo Galilei ca. 1625

B: Tamara Davis 2007 © DARK

jor new infrastructure projects included in the ESFRI and ASTRONET roadmaps (see Sect. 5). We therefore recommend a continued focus on these strategic priorities, while keeping in mind the need to maintain a broad teaching programme in astrophysics up to the MSc level.

The development of space- and ground-based astronomical instrumentation is a separate, but related issue. The integration of DNSC in DTU offers an opportunity to anchor the strong Danish record in space and ground based instrumentation for astronomy in an even stronger basis of modern technology. E.g., the development of X-ray instrumentation at DNSC is leading to many invitations to participate in (pre-studies for) space-missions.

DAC finds that a requirement for successful participation in major instrumentation projects is a commensurate effort to exploit the related science opportunities, and notes the Solar System Physics Group at DNSC as a successful example of an instrumental development complemented effectively by a strong scientific group recruited to exploit the resulting data. DAC recommends that DNSC follow a similar a policy for astrophysics when renewing the tenured scientific staff, especially in times of increasing involvement in space astronomy missions.

For the immediate future, we recommend that NBI fill a full professorship in "The life-cycle of matter in the Universe" or a similarly broad theme, and that both NBI and IFA announce associate professorships in (preferably complementary) fields that can exploit the capabilities of ALMA. At DTU, the faculty renewal plans for astrophysics at DNSC should include an appropriate complement of full professorships. Later tenured positions at all universities should be announced in broad areas within the priority scientific fields, so as to attract the most qualified candidates, and further strengthening of the staff should be considered if the positive trend in student enrolment is to continue. Given the large number of retirements during the next decade, options for recruiting exceptionally talented individuals promptly when opportunities arise should be held in reserve in this period.

4.2 Education and enrolment

Society needs more people trained in the physical sciences, and astronomy has a key role in attracting students. At the BSc level, ~50% of the physics students at NBI and IFA (40-50 students each) already now choose astronomy as part of their first-year curriculum, and ~15 attend the third-year courses. Much of this is due to the recent improvements in the courses, which continue with more project based teaching, more hands-on observing courses, etc. At the PhD level, a national graduate school in astrophysics was funded in 2006 (the *Danish Astrophysics Research School*, or DARS). In combination with the other externally funded centres, a national PhD and postdoc programme has de facto been created, and the number of PhD students has increased by ~50% over the last three years, to ~25 today.

NORDFORSK sponsored summer school at La Palma, 2006. © C. Thöne

Hands-on experience with astronomical observations, especially at observatories abroad, has great attraction for students and has also proved to enhance their opportunities for taking employment outside astronomy. Well-organised group courses at telescopes in the Canary Islands have proved to be very successful, as have the opportunities to conduct experimental thesis projects at all levels. Remote observing is being introduced as a more cost-effective alternative for large student groups. We recommend that these initiatives be strengthened and organised in a systematic and cost-effective manner, e.g. through Nordic collaboration.

These measures have already shown a very positive effect on student enrolment at all levels. There is good prospect for an additional increase, but further efforts will probably be better spent ensuring that the students also complete their degrees in a timely manner – primarily through more individual attention and supervision.

The potential for growth will, however, soon be limited by saturation of the teaching staff. Adding students at first-year lectures takes little extra effort, but they also need to complete the course. Hands-on laboratory or observing courses or closer supervision of MSc and PhD student, while effective, are time-consuming and cannot be expanded *ad ifinitum*; these courses are already greatly oversubscribed. Junior staff on soft money can assist with some tasks, but the responsibility for supervising thesis projects and courses abroad must rest with the tenured staff, who already now struggles to cope with the demand. The potential is great, however, and a few extra staff positions here would be a very cost-effective investment.

As a specific goal, the annual number of astronomy-related MSc's should increase to at least 1 per faculty scientist in 2009 and 1.5 in 2012 (including MSc' who go on to take a PhD). Our main recommendations towards this goal follow below, with further details in Appendix B.

Society needs more people trained in the physical sciences ...

At the BSc level, courses traditionally target the theoretical foundations of astronomy, but many students are also attracted by the observational aspects. More "hands-on" experience with data from archives or from on-site or remote observing runs (e.g. at NOT) should be offered, in combinations suited to the content and attendance of the courses. Collaboration between the universities in developing and offering these opportunities is essential; a specific initiative is under way on a Nordic basis. Astronomy also has ample potential to offer BSc projects that include exciting science, original research, and a realistic schedule.

At the MSc level, an attractive suite of astronomy courses is needed, including modules that will help candidates to find jobs outside astronomy. Examples are digital image analysis, analysis of large data sets, technology and instrumentation, project management, outreach skills, etc. Better coordination of the course programmes at all universities is needed, and interested astronomy students should be encouraged to take engineering courses at DTU or Aalborg University (AAU), and vice versa – of course with proper credit. MSc thesis projects should emphasise the use of own and archival data from ESO, NOT, space observatories, and/or Danish supercomputing facilities; better opportunities for MSc projects at the interface between astronomy and technology should be provided as well.

Given the small total size of the teaching staff, collaboration and synergy between all groups must be strengthened as much as possible, so as to deploy the available teaching resources more efficiently without sacrificing quality. The different structure, volume, and requirements for (astronomy) courses at the different universities at the BSc and MSc levels is a particularly severe impediment to attempts to coordinate the teaching effort, improve student mobility, and optimise the use of scarce teaching resources for the benefit of all. We strongly recommend that the faculties work together to facilitate national synergy in science education – especially where good will exists already, as in astronomy.

At the PhD level, the small numbers of students and teachers make a common set of courses especially important, and DARS will offer a suite of dedicated PhD courses in all major focus areas of Danish astrophysics, including courses given by high-calibre lecturers from abroad. The intention is to increase the number of PhD students in astrophysics from the current ~25 to 30-35 within five years, hopefully adding a number of astronomy-related engineering PhD students as well.

Astronomy courses for a wider community. In some countries, an "Astronomy 101" course for non-science majors (i.e. students in law, humanities, etc.) is an established success, helping to foster a scientifically literate public and generating income for the astronomy departments. Such courses for students outside physics and astronomy should also be organised in Denmark; both IFA and NBI are taking steps to do so, and plans are under way at DTU. Courses leading to a Master's degree in Space Science and Technology are also popular and attract foreign students in several countries (e.g. Sweden), and should be considered in Denmark as well.

... exciting science, original research, and a realistic schedule.

Finally, astronomy has special potential in life-long education for Gymnasium and other teachers, as astronomy offers many attractive opportunities to demonstrate the laws of physics at work in the Universe. A new initiative focused towards Gymnasium teachers is a specialised "Master" degree in astronomy (60 ECTS credit points). We recommend that the potential of this degree be fully used to ensure that many teachers receive a formal astronomy degree. The opportunities for and potential of astronomy education for a broader and more general audience should be further explored in cooperation with the relevant authorities and professional organisations.

4.3 Outreach

Astronomy holds a special attraction for the public, and the market for outreach initiatives is insatiable. The Danish community struggles to cope with this task (estimated to take about 1 FTE/year) within existing staff resources, and with little professional assistance. IDA has been able to improve the situation within its limited resources, and DARS now offers a course in professional communication techniques to PhD students, including elements of professional standards of ethical conduct in scientific publication, but the overall outreach effort is subcritical.

Recent developments suggest that outreach units of critical mass may soon form at the faculty level. We recommend that contact persons for astronomy be identified everywhere, and that they coordinate closely for maximum overall impact. The 100th anniversary of the birth of Prof. Bengt Strömgren in 2008 and the *International Year of Astronomy* in 2009 will offer rich opportunities to bring the fascination and potential of astronomy to the general public if a professional effort can be planned and supported.

The observatory on La Palma © A. Kjær

5. Research Infrastructures, Instrumentation, and Technology Development

Progress in astronomy happens by synergy between observation, theory, and computation. Danish astronomy has access to front-line observing facilities primarily through ESA and ESO. The observational effort is appropriately focused on these facilities, with essential and highly effective support from IDA. It is of paramount importance that the full Danish participation in ESO and ESA and their front-line projects be maintained and supported.

New observatories in space and on the ground are planned, covering the entire electromagnetic spectrum, and new particle and gravitational wave detectors will soon open yet other windows on the Universe. Supercomputers, grid computing, and faster networks will break new ground in numerical astrophysics and pave the way for the *International Virtual Observatory* – a global archive of data at all wavelengths and accessible to anyone. Progress in our four core scientific fields will require several of these facilities; Danish astronomers already work in the relevant scientific fields, and their track record shows that they can compete successfully for access to the largest international facilities.

5.1 International coordination

The largest mature ground-based European research infrastructure projects are included in the recent ESFRI Roadmap, while Europe's plans for space astronomy are embodied in ESA's *Cosmic Vision* report. Indeed, the most ambitious of these projects will only be feasible though global cooperation, but the issue of funding the construction and operation of new large facilities while maintaining even the most productive existing ones remains unsolved.

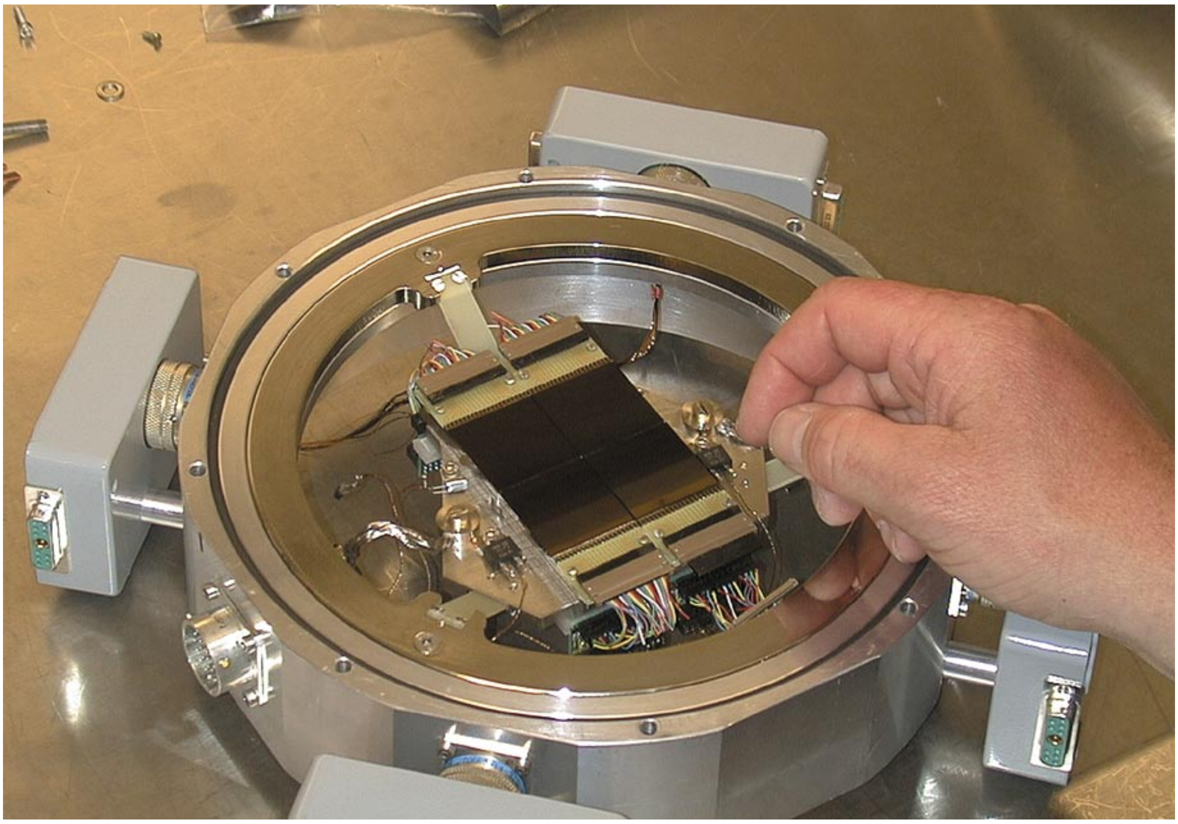
To address this issue, the ERA-NET ASTRONET has been formed by ESO, ESA, and the largest national funding agencies for astronomy in Europe with the aim to develop a comprehensive, yet financially realistic long-term plan for European astronomy. The ASTRONET *Infrastructure Roadmap*, unlike that by ESFRI, will address *all* of astronomy, at all wavelengths, from the ground and from space, operations as well as construction costs, theory and computing, as well as recruitment, education and other human resource issues over the next ~25 years. It will be released in late 2008 and, if successful, will revolutionise the way that Europe plans, builds, operates, and exploits both its large and medium-size facilities.

Danish astronomy continues to contribute considerably to the field …

Smaller instruments remain necessary to prepare projects for the large facilities and conduct unique science that would not be possible at the largest telescopes. Recent examples include GRB afterglow detections, planet searches, Galactic surveys, and asteroseismology as carried out at NOT, the Danish 1.5m telescope, and other medium-size instruments. Cost-effective options for continued access to such facilities should be pursued at the European level, through the OPTICON network.

In this context, we note that Greenland may offer similarly unique meteorological conditions as the Antarctic for certain studies: Extremely stable air, low temperatures, and uninterrupted darkness for several months. We consider it a national obligation to ascertain whether such conditions really do exist in Greenland, and recommend that a professional test programme be conducted in cooperation with groups experienced in polar site testing.

Human resources are the main limiting factor in the Danish use of the international facilities. Adequate staff should be assigned to exploit new facilities, but based on realistic deployment schedules so they can work effectively (see Appendix A). Providing PhD student and postdoc support for P.I.s who have won access through



Detector systems at the Niels Bohr Institute © A.N. Sørensen

competition to a NASA facility or a precursor project has proved very effective in the USA; IDA has followed this policy successfully since 2004, and DAC endorses its intention to reinforce it in the future.

5.2 Astronomy and technology in Denmark

As a rule, creative astronomers get the front-line tools they need by contributing innovative and feasible designs. A certain level of technical competence is needed to even make such proposals, but cannot be created instantly when needed. The current lack of training in technical disciplines and project management for astronomy students is an impediment for an effective Danish participation in such projects, and for innovative Danish initiatives in telescopes and instrumentation. We have addressed this aspect in Sect. 4.2.

Front-line telescopes on the ground and in space need equally advanced instruments. Indeed, in many space missions, participation in an instrument consortium is mandatory for privileged access to the data. Danish astronomy continues to contribute considerably to the field, currently through several space experiments and the “X-shooter” spectrograph for the ESO VLT, designed and built in part by the NBI instrumentation group with participation from DNSC. Given the advanced technology used in modern astronomical instruments and the potential spin-offs, a continued effective Danish presence in this field is of general interest.

Lack of resources and inadequate national coordination are severe obstacles in trying to reach this goal, however. Front-line instrumentation for the large ground and space-based facilities of the future will demand technical and management expertise and financial resources at a level that is now only attained by large, well-funded groups such as those in France, the UK, Netherlands, or Italy. Even now, Danish groups can only participate in consortia, but not undertake major projects independently. This trend will be further amplified in the future, and options for collaborations, both within Denmark and e.g. at the Nordic level, should be actively pursued. Increased investments will be needed to achieve any real impact in this field.

The issue is complex, as it involves both scientific, technical, staffing, and institutional policies of many potential partners. DAC recommends that a working group be formed with members from the astronomical research groups, the technical universities, and industry, with the task to review the needs and options in this area and recommend suitable actions. In particular, the group should address the following issues:

- Future projects offering favourable opportunities for Danish participation
- Key technologies that need to be developed in Denmark or deployed in astronomy
- Core and complementary expertise in Danish universities and industry
- Opportunities for synergy between ground and space based instrumentation projects
- Opportunities and obstacles for spinoff and commercialisation of new techniques
- Training requirements and opportunities for scientific and technical staff and students
- Potential new funding sources for astronomical instrumentation projects
- Opportunities for international, including Nordic, cooperation

6. Organisation and Resources

The organisational structure of Danish astronomy has recently undergone radical change. Research and education are now distributed between various astronomy groups at the three universities, all embedded in larger physics and/or technology departments. DAC is appointed by the faculties at AU and CU and the DNSC Director to advise them on joint long-term strategies for Danish astronomy. DAC also serves as a "Forum for Astronomy" of the *Danish Space Consortium*, but (unlike IDA) has no mandate or resources to implement its recommendations, advise other entities, or represent any other groups than itself.

Since DAC was formed, new externally funded centres have appeared, notably IDA, DARK, DASC, and DARS, each with their independent boards or steering committees. DAC has no formal connection to these centres; yet, their substantial funding gives them a key role in shaping the future. The new astrophysics section of the *Danish Physical Society* and the *National Committee for the IAU* under the Royal Danish Academy of Sciences and Letters are formally free-standing entities as well.

... their substantial funding gives them a key role in shaping the future ...

Given the small community, good coordination is maintained through personal contacts, but this diffuse structure is sometimes inconvenient. E.g., no single entity can represent Danish astronomy to such authorities as the *Danish Natural Science Research Council* (FNU) or Ministries (VTU, UVM), e.g. regarding membership of ESO/ESA committees. This applies to the EU-funded astronomy networks as well (e.g., Denmark is now represented in both OPTICON and ASTRONET by NOTSA), and to professional societies such as the *European Astronomical Society* or the *European Physical Society*. Proliferation of committees is to be avoided, but with updated Terms of Reference and membership, DAC might become a plausible candidate.

Given the diffuse organisational structure and variety of funding sources, it is also difficult to obtain an overview of the human and financial resources of Danish astronomy, as increasingly sought by national and international bodies, e.g. for research activities co-funded by the EU. Relevant information is, e.g., numbers, grades, and salaries of scientific and technical staff, numbers of graduates and their later careers, annual fees to international organisations and related national funding, and other project specific funding from public and private sources.

No comprehensive compilation of such information exists so far. At our request, IDA made a first survey of the human resources in Danish astronomy and the changes from 2003 to 2005 (see *http://www.astrofysik.dk/content/docs/DK_astro_ressource_05.pdf*). It demonstrates how the staffing of Danish astronomy changed quite significantly in just a couple of years. It would be of considerable interest to complement this with a similar survey of overall financial resources and with a publication and citation analysis for Danish astronomy in ~1988 (the first strategy report for Danish astronomy), 1997 (the year before first light of the VLT), and now. We recommend that the renewed IDA be given the resources to perform such an analysis.

Supernova blasts in the young Universe © A. Schaller (STScI)

7. Summary of Recommendations

The main recommendations developed in this report are summarised in the following, roughly in order of priority:

- An orderly programme to renew and strengthen the scientific staff at all three universities is a top priority if the rapidly increasing productivity of Danish astronomy in research and teaching is to fully benefit Danish science. New staff should primarily be recruited within the research areas described in Chap. 3, but maintaining a broad overall teaching profile. For the near future, we specifically recommend that NBI fill a full professorship in "The life-cycle of matter in the Universe" or similar theme; that both NBI and IFA announce associate professorships in (complementary) science fields that can exploit ALMA; and that DNSC complement the effort in space astronomy instrumentation with the scientific staff needed to exploit the investments effectively, including some at the level of full professor. Replacement of the 13 senior staff to retire during the decade will need careful planning.

- The continued full Danish participation in ESO and ESA and their frontline projects is of paramount importance for Danish astronomy, also in the future. The *Instrument Center for Danish Astrophysics (IDA)* is providing vital and effective underpinning of the scientific returns from ESO, ESA, and NOT, also in recruiting the most competitive young scientists for Danish astronomy, and should continue to develop this important role.

- Improved coordination and synergy are needed to create more effective teaching programmes at the BSc and MSc levels and optimise the use of faculty time. To do so, the present incompatibilities between study structures at the universities must be alleviated. A stronger component of hands-on experience should be introduced, including better opportunities for students to exchange courses in astronomy, space science, and related technologies.

- The ability of Danish research teams to participate in developing the next generation of large research infrastructures and/or instrumentation for them will require a new level of cooperation between the astronomical and engineering communities at AU, CU, and DTU, and with industry, as well as substantially increased investment. We recommend that a broadly-based working group be appointed to develop a specific action plan to secure the Danish technological returns from these opportunities.

- Good informal coordination exists in Danish astronomy, but we identify a need for a single advisory committee that can represent the whole community towards national and international partners across the various research groups, centres, and other actors.

APPENDIX

Appendix A: Acronyms and Large Projects

For reference, acronyms used and projects mentioned in this report are explained briefly here:

NAME	EXPLANATION
AAU	Aalborg University
ALMA	Atacama Large Millimetre Array, new submm radio array in Chile
APEX	ALMA Precursor EXperiment, 12m submm radio telescope in Chile
ASTRONET	ERA-NET preparing long-term plans for European astronomy
AU	University of Aarhus
Chandra	X-ray space observatory (NASA)
CMB	Cosmic Microwave Background
UC	University of Copenhagen
DAC	Danish Astronomy Committee (Astronomisk Udvalg)
DARK	Dark Cosmology Centre (Danish National Research Foundation, 2005)
DASC	Danish Asteroseismology Centre (FNU, 2004)
DNSC	Danish National Space Center
DTU	Technical University of Denmark
ELT	Extremely Large Telescope, a proposed 30-100m optical telescope
ESA	European Space Agency
ESFRI	European Strategy Forum for Research Infrastructures
ESO	European Southern Observatory
FDA	"The Future of Danish Astronomy", DAC report, 2003
FNU	Forskningsrådet for Natur og Univers
GAIA	ESA mission to study the Milky Way and nearby galaxies
GLAST	Gamma-ray Large Area Space Telescope (NASA, 2007)
GRB	Gamma-Ray Burst, violent explosions in distant galaxies
Herschel	Infrared space observatory (ESA, to be launched 2008)
HST	Hubble Space telescope (NASA/ESA)
IDA	Instrumentcenter for Dansk Astrofysik, funded by FNU
IFA	Institute of Physics & Astronomy, AU
INTEGRAL	Gamma-ray space observatory (ESA)
JDEM	Joint Dark Energy Mission (2010+) NASA
JWST	James Webb Space Telescope (NASA/ESA, to be launched 2013)
Kepler	Space mission to detect transiting exoplanets (NASA, 2008)
LIGO	Laser Interferometry Gravitational wave Observatory
LISA	Laser Interferometry Space Antenna NASA/ESA, 2017+)
NASA	National Aeronautics and Space Administration (USA)
NBI	The Niels Bohr Institute, CU
NOT	Nordic Optical Telescope, La Palma, Spain
NOTSA	Nordic Optical Telescope Scientific Association (operates NOT)
OPTICON	EU-funded coordination network for optical/infrared astronomy

2007-2017

Planck	Space mission to study the CMB (ESA, to be launched 2008)
RadioNet	EU-funded coordination network for radio astronomy
VISTA	4m wide-field infrared survey telescope in Chile (2008)
VLT	ESO's Very Large Telescope (four 8-m telescopes in Chile)
VLTI	VLT Interferometer, combining light from the 4 VLT telescopes
SKA	Square Kilometre Array, a proposed large radio telescope
WMAP	Wilkinson Microwave Anisotropy Probe; NASA CMB mission
XEUS	X-ray Evolving Universe Spectroscopy mission (ESA)
XMM-Newton	X-ray space observatory (ESA)

A rough deployment schedule for the major new research infrastructures is useful for planning the research staff effort needed to exploit them effectively. Currently, it is as follows:

Present:	ESO VLT/VLTI, HST, APEX, Chandra, XMM-Newton, INTEGRAL
2007-2010:	VISTA, ALMA stage I, Planck, Herschel, Kepler, GLAST
2010-2015:	GAIA, JWST, ALMA (full array), JDEM
2015 - :	ELT, LISA, XEUS

The future radio observatory ALMA in Chile © ESO

Appendix B: Recommended Initiatives in Astronomy Education

Astronomy is introduced at the BSc level in physics through a suite ("fagpakke") of courses, in competition with other physics disciplines. Students decide whether to remain in astronomy based on their experience with these initial courses. Their quality, coherence, and success must therefore be monitored closely, and hands-on experience with archival space or ground based data and/or real observing trips should be offered already at the BSc level (e.g. at NOT).

Equally importantly, astronomy can offer a broad spectrum of BSc projects that include exciting science, "hot" original research, and a realistic schedule. Information about such offers should be given already towards the end of the second year of study, and exchanges of project offers and experience between the universities is essential.

In order to recruit more BSc students and help them to complete their studies in time, several concrete steps can be taken, limited essentially only by available staff time:

- A vigorous outreach program at both Primary and High Schools (including HTX) should present astronomy as an exciting subject, with the network of Science High Schools as a particularly promising initial audience. Suitable initiatives include "erhvervspraktik", visits, talks, and focused projects (for a few students). Institutional homepages should be reorganised so as to allow potential future students to find us easily. "Astronomy days" at the institutes for potential students and for Primary and High School physics teachers, with talks, discussions, demonstrations etc., have also proved very effective.

- Observing courses, on-site in the Canary Islands or by remote observing, should be an integral part of the BSc program; funding for such activities is well invested.

- Some astronomy seminars should be held at a level suitable also for BSc students.

Many of these recommendations apply to the MSc level as well. Here, however, a suite of courses is needed which focus not only on astronomical research, but also on skills that will help candidates to find employment elsewhere in society. Examples are digital image analysis, statistics and analysis of large data sets, project and business management, outreach, etc. Interested astronomy students at AU and CU should be able to take courses in relevant areas of technology and instrumentation at DTU or AAU, and vice versa. A joint catalogue of MSc thesis projects and supervisors between the universities should be maintained, e.g. by IDA.

Appendix C:
Terms of Reference and Membership of the Committee

KOMMISSORIUM

Astronomisk Udvalg nedsættes af de naturvidenskabelige fakulteter ved Københavns og Aarhus Universitet samt Dansk Rumforskningsinstitut til at varetage følgende opgaver:

1. at udarbejde langsigtede aktivitetsplaner til fremme af faglig fornyelse, koordination og samarbejde i dansk astronomi, specielt vedrørende engagementer i længerevarende ressourcekrævende projekter, samt herudfra tage sådanne initiativer, som kan fremme et hensigtsmæssigt samarbejde mellem alle relevante fagspecialer.

2. at rådgive fakulteteter og institutter (NBIfAFG, IFA, DRI) om væsentlige emner vedrørende dansk astronomisk forskning i almindelighed, herunder om personaleressourcer, infrastruktur, opgavefordeling og engagementer i længerevarende, ressourcekrævende projekter.

2. at stå til rådighed med rådgivning til "Statens Forskningsrådgivende System" om væsentlige emner vedrørende dansk astronomisk forskning nationalt såvel som internationalt.

4. at aflægge en årlig rapport til fakulteter og institutter om udvalgets aktiviteter og aktuelle planer samt årligt fremlægge disse til bred diskussion ved de årlige astronomimøder eller lignende lejligheder.

8. april 2002

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