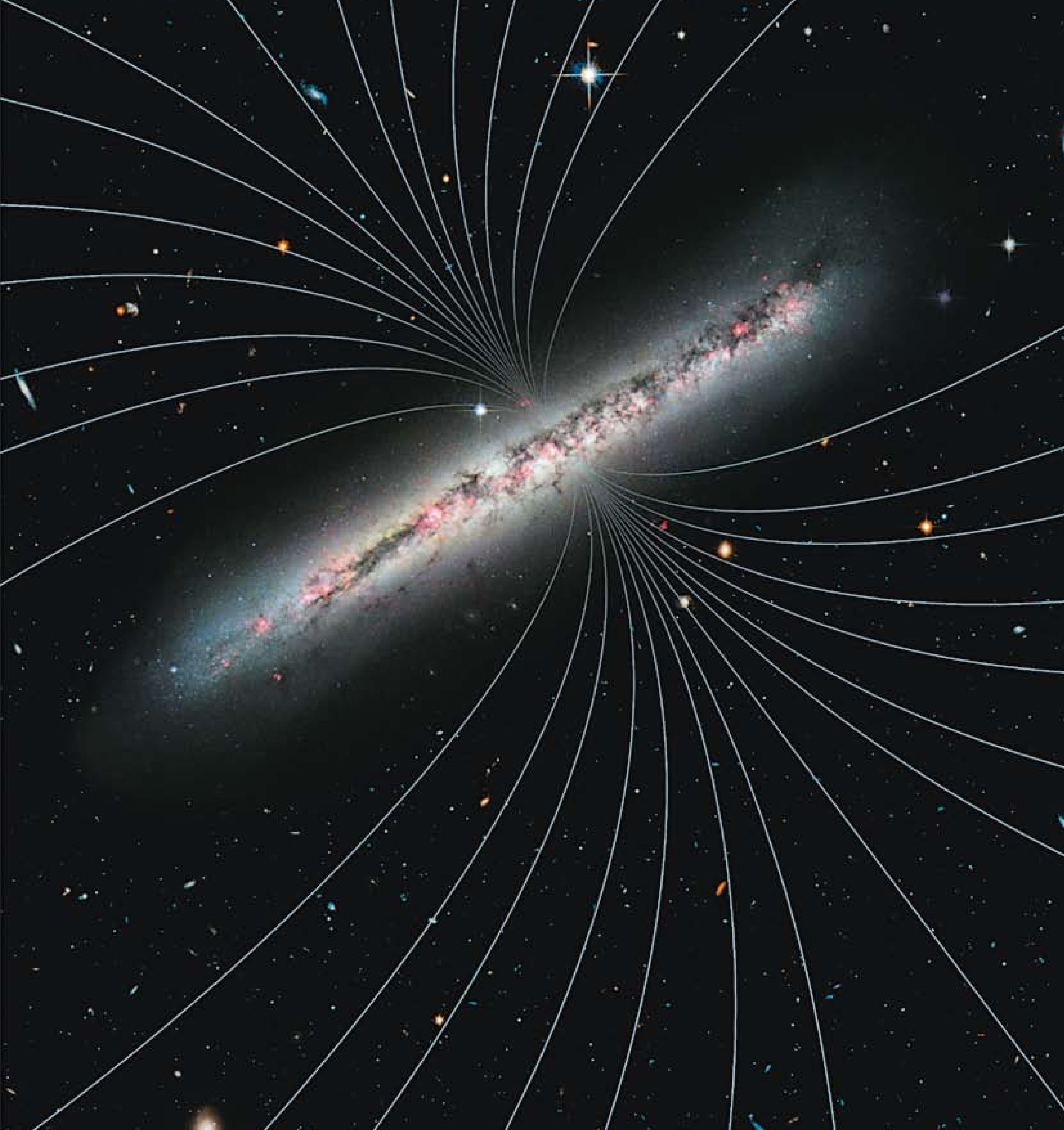
HIPPARCHOS

The Hellenic Astronomical Society Newsletter
Volume 2, Issue 9

ISSN: 1790-9252



Contents

HIPPARCHOS

Volume 2, Issue 9 • February 2013

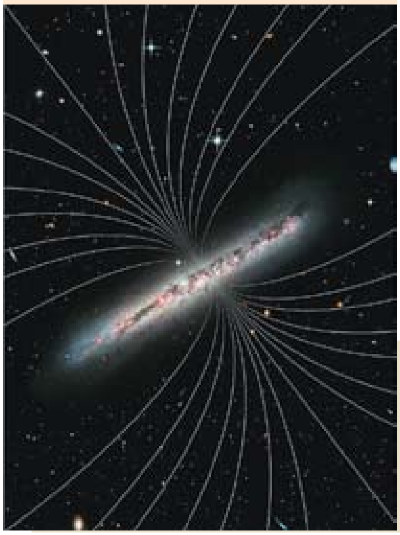
ISSN: 1790-9252

Hipparchos is the official newsletter of the Hellenic Astronomical Society. It publishes review papers, news and comments on topics of interest to astronomers, including matters concerning members of the Hellenic Astronomical Society.

Contact person

Christos Efthymiopoulos
Academy of Athens
Research Center for Astronomy
& Applied Mathematics
Soranou Efessiou 4
Athens, GR-11527, Greece
Tel: +30-210-6597513
Fax: +30-210-6597602
E-mail: cefthim@academyofathens.gr

Printed by ZITI Publications • www.ziti.gr



Message from the President 3

WORKSHOPS

1st "Thalis" school/workshop on "Space Weather" 4

The Role and the Origin of Magnetic Fields in Astrophysics 5

BRIEF SCIENCE NEWS

Celebrating 50 years of X-ray Astronomy: a conference in Mykonos 6

ARTICLES

Jet dynamics in gamma-ray burst sources
by Nektarios Vlahakis 7

The question of cosmic magnetism
by Christos G. Tsagas 11

REVIEWS

The Magnetic Origin of Solar Eruptions
by Alexander Nindos 15

Astrophysical Jets from Black Holes
by Ioannis Contopoulos 21

Herschel Space Observatory: Looking through cosmic dust
by Manolis Xilouris 27

CONFERENCE ANNOUNCEMENT

Massive Stars: From α to Ω 35
June, 10-14, 2013
Rhodes, Greece

Image description:

Schematic representation of a so-called antisymmetric (or odd-parity) galactic magnetic field configuration scenario. The origin of galactic and cosmic magnetic fields is an important open problem of astrophysics.

Message from the President

Dear friends,

As with every year, 2013 comes with good and bad things. Being optimistic, I will start with the good ones.

This year, our Society celebrates its 20^{th} anniversary. We are not an old Society, but we are maturing, and it shows. Our biannual conferences have become major events for our members. They are well attended, with excellent Plenary and Invited Speakers. The contributed talks and the posters have nothing to envy from the corresponding ones in Societies that are larger and older than ours. The 11^{th} Hellenic Astronomical Conference, 9-12 September 2013, will be celebratory (albeit with a limited budget) and it promises to be longer in duration and with more participants than the previous ones. The facilities of the Biomedical Research Foundation of the Academy of Athens, where the 11^{th} Hellenic Astronomical Conference will take place, are excellent and the Local Organizing Committee has already been working hard to secure a first rate conference in all respects. I expect to see most of you, preferably all, in Athens in September. Please visit the website of Hel.A.S. for details about our upcoming conference.

The bad things are that Astronomers in Greece suffer, like the rest of the population in the country, due to the economic crisis. The consequences are hard and they affect our everyday life, except possibly one aspect of it: our research ideas! Governments can manage and mismanage countries, but they cannot interfere with our research work. The reduced salaries, budgets, and resources make things more difficult, but they should not be an excuse for reduced research productivity, both in quantity and quality; at least for those of us, who can operate with limited resources. I encourage our young Astronomers to try to "stay alive" in research, even if they have to spend a few years abroad. Several of us older Astronomers will retire in the next few years and good scientists must be around to take the positions that will open. At the moment no positions are opening, but this will change. It is not the first time that Greece has gone through a trough.

And a lighter thing before closing: I am sure you have all read many papers which stated that "the effects of the magnetic field will not be taken into account in this work". The reason is not that magnetic fields are not important, but rather because they are difficult to handle. I am happy to see that four articles in the present issue of IPPARCHOS deal exclusively with magnetic fields, showing that members of our Society have really "tamed" astrophysical magnetic fields. No economic crisis can reverse this!

Happy reading of HIPPARCHOS!

Nick Kylafis
President of Hel.A.S.

Programme of 1st "Thalis" school/workshop on "Space Weather"

February 25-27, 2013, Portaria, Pelion, Greece

Hellenic National Space Weather Research Network

The term "space weather" refers to conditions on the Sun and in the solar wind, Earth's magnetosphere, ionosphere, and thermosphere that can influence the performance, efficiency, and reliability of space- and ground-based infrastructure and can endanger unprotected humans in space conditions or above the Earth's poles.

Monday, February 25, 2013	
09:00-12:30	Arrivals
12:30-14:00	Lunch
14:00-15:30 [E]	M. Georgoulis: *Emergence and Evolution of Solar Active-Region Magnetic Fields*
15:30-16:15 [E]	C. Gontikakis: *Study of the Transition Region Using Spectral Lines*
16:15-17:45 [E]	A. Nindos: *The Magnetic Origins of Solar Eruptions*
17:45-18:30 [R]	PhD student/Post doc short presentations (Smyrli, Dimitrakoudis, Kouloumvakos)
18:30-19:00	Coffee break
19:00-20:00 [D]	Discussion (Coordinators: Georgoulis, Nindos)
20:00-21:00	Dinner
21:00-23:00 [G]	Small group discussions

Tuesday, February 26, 2013	
09:00-10:30 [E]	S. Patsourakos: *The Genesis of CMEs*
10:30-11:00	Coffee break
11:00-12:30 [E]	L. Vlahos / A. Anastasiadis (45 min each): *Complexity and Magnetic Reconnection in Solar and Heliospheric Environments*
12:30-14:00	Lunch
14:00-15:30 [E]	K. Tsinganos / V. Archontis (45 min each): *MHD theory and MHD Numerical Codes / Modeling Magnetic Flux Emergence and Related Phenomena in the Solar Atmoshere*
15:30-17:00 [E]	A. Vourlidas: *CME Evolution in the Corona & Heliosphere*
17:00-17:30	Coffee break
17:30-18:00 [R]	PhD student/Post doc short presentations (Dimitropoulou, Podladchikova)
18:00-19:30 [D]	Discussion (Coordinators: Vourlidas, Anastasiadis, Archontis, Patsourakos)
19:30-21:00	Dinner
21:00-23:00 [G]	Small group discussions

Wednesday, February 27, 2013	
09:00-10:30 [E]	M. Sarris / G. Anagnostopoulos: *Energetic Particles in the Sun-Magnetosphere-Ionosphere-Atmosphere-Lithosphere-Technoshere Coupling*
10:30-11:00	Coffee break
11:00-12:30 [E]	I. Daglis: *Waves, Particles and Storms in Geospace*
12:30-14:00	Lunch
14:00-15:00 [E]	T. Sarris: *ULF Waves in the Magnetosphere: Excitation mechanisms, Structure, Spatial Distribution and their Role in Energetic Particle Populations*
15:00-15:45 [E]	G. Balasis: *Simultaneous Observations of ULF Waves in the Earthís Magnetosphere, Topside Ionosphere and Surface*
15:45-16:30 [E]	D. Sarafopoulos: *Ion Jets and Magnetic Flux Ropes in the Earthís Magnetotail*
16:30-17:00	Coffee break
17:00-18:45 [R]	PhD student/Post doc short presentations (Metallinou, Bogiatzis, Iliopoulos, Athanasiou, Georgiou, Sponias, Papadimitriou)
18:45-20:15 [D]	Discussion (Coordinators: Daglis, Sarris T., Anagnostopoulos, Sarafopoulos, Balasis)
20:15-21:15	Dinner
21:15-23:00 [G]	Small group discussions

LEGEND

[E] Tutorial talks introducing the background necessary to follow the individual projects' description.

[R] Short (15-minute) presentations of the pre-doctoral and doctoral researches on their recent work.

[D] The coordinators of the individual projects will present the work planned for the National Space Weather Research Network.

[G] The groups meet after dinner (with a glass of beer or wine) to discuss their concrete plans.

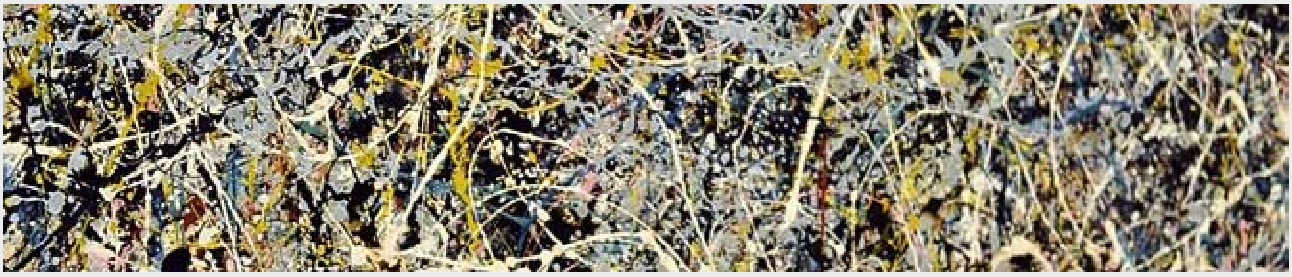
Location: Portaria Hotel & Spa • http://www.portariahotel.gr/index.php/el/

http://proteus.space.noa.gr/~hnswrn

The Role and the Origin of Magnetic Fields in Astrophysics

March 11-12, 2013, Athens, Greece

Workshop in the framework of Action Excellence of the GSRT of Greece and the ESF



Magnetic fields are present in all astrophysical scales, from stellar mass black hole scales of a few km, to galactic scales of several kpc, up to extragalactic scales of several Mpc. Indirect estimates of their strength through Faraday rotation, synchrotron emission, and polarization of optical starlight suggest that the energy content in the magnetic field is comparable to the energy content in the interstellar and intergalactic gas.

The Origin of astrophysical magnetic fields remains one of the most important unsolved questions in modern astrophysics. It is generally assumed that magnetic fields in stellar interiors, accretion disks, and spiral galaxies, arise from the combined action of convection, differential rotation and helical turbulence, the so-called hydro-magnetic dynamo. Another theory, the cosmic battery, proposes that astrophysical magnetic fields are continuously produced around accreting black holes in X-ray binaries and active galactic nuclei, and that they are stretched out to larger scales by astrophysical jets.

The aim of this one-and-a-half-day workshop is to bring together world renown experts who will review the role of magnetic fields in astrophysics and discuss their origin. There will also be a limited number of contributed talks. Registration is free and open to everyone, but in order to encourage discussions, attendance will be limited to about 50 participants.

The workshop is supported by the Academy of Athens, the General Secretariat for Research and Technology of Greece and the European Social Fund in the framework of Action 'Excellence'.

Preliminary Program

	Monday, March 11, 2013
	Welcome
9:20	**G. Contopoulos** (Academy of Athens)
	Morning Session
9:30 - 10:15	**D. Lynden-Bell** (Cambridge) *Origins and energy principles*
10:15 - 11:00	**K. Kokkotas** (Tubingen)
11:00 - 11:15	Coffee Break
11:15 - 12:00	**N. Vlahakis** (Athens) *Relativistic jet dynamics and the role of the magnetic field*
12:00 - 12:45	**D. Gabuzda** (Cork) *Monte Carlo simulations of transverse Faraday rotation gradients: new evidence that AGN jets carry helical magnetic fields*
12:45 - 13:00	Discussion
	Afternoon Session
15:00 - 15:45	**D. Kazanas** (NASA) *Toward a unified AGN structure*
15:45 - 16:30	**T. Font** (Valencia) *MHD simulations of stellar core collapse in general relativity*
16:30 - 16:45	Coffee Break
16:45 - 17:30	**M. Georgoulis** (RCAAM) *Heliophysics in the heliosphere: tales of solar magnetic fields and their defining role in the sun's sphere of influence*
17:30 - 18:15	**I. Contopoulos** (RCAAM) *The Cosmic Battery in X-ray binaries*
18:15 - 18:30	Discussion

	Tuesday, March 12, 2013
	Morning Session
9:30 - 10:15	**L. Rezzola** (Potsdam) *Magnetic fields in relativistic compact-object binaries*
10:15 - 11:00	**N. Stergioulas** (Thessaloniki)
11:00 - 11:15	Coffee Break
11:15 - 12:45	**Contributed talks**
12:45 - 13:00	Discussion

Location: Academy of Athens, Panepistimiou 28, Athens, 10679

http://astro.academyofathens.gr/mf2013/

Celebrating 50 years of X-ray Astronomy: a conference in Mykonos

In 2012 X-ray Astronomy became 50 years old. The first observations by means of sounding rocket experiments in X-ray wavelengths opened a new window in astrophysics. The first experiment was conducted by Riccardo Giacconi in 1962. For this first experiment which signaled the birth of X-ray Astronomy, Prof. Giacconi has been awarded with the Nobel Prize in 2003. The aim of this Aerobee rocket experiment was to detect X-ray emission from the Moon. X-ray radiation from the moon had not been detected at the time, but instead the first X-ray source outside the solar system was found. This is Scorpio X-1 a Low Mass X-ray binary. The same experiment detected a diffuse X-ray glow from the whole sky, the X-ray background. We know now mainly thanks to NASA's Chandra mission that the X-ray background is not really diffuse but consists of tens of thousands of Active Galactic Nuclei per square degree.

In X-ray wavelengths we observe the most energetic phenomena in the Universe, i.e. those revealing temperatures at least a few million degrees. These high temperatures, at least in the extragalactic Universe, are encountered in the vicinity of supermassive black holes and in the gas found in the large gravitational potentials of clusters of galaxies. The temperature and number density of clusters of galaxies at high redshifts provides crucial information about the mass density of the Universe.

The 50th birthday of X-ray Astronomy was celebrated with a conference at St. John hotel in Mykonos. The conference was organized by the National Observatory of Athens (I. Georgantopoulos and M. Plionis). More than 120 scientists attended this conference mainly from Europe and the United States, but also from Japan, China, Brazil, Mexico and Australia. This was the fourth in a series of X-ray Astronomy and Cosmology conferences, organized on a regular basis by the National Observatory of Athens. The bulk of the conference was occupied by recent results from ESA's XMM-Newton and NASA's Chandra X-ray mission both of which have completed now 13 years in orbit. A highlight of the conference were the opening talks by the pioneers of X-ray Astronomy Prof. R. Giacconi and Prof. K.A. Pounds describing the early days of X-ray Astronomy in the US and the UK respectively. Another highlight was the first results from the US NuSTAR mission which carries the first ever telescope to observe at hard X-ray energies above 10 keV. This energy band is dominated by Compton-thick Active Galactic Nuclei, i.e. those with very large obscuring column densities (>10^{24} cm^{-2}) equivalent to an optical reddening of AV~400 mag in the optical part of the spectrum and, hence, invisible at optical wavelengths.

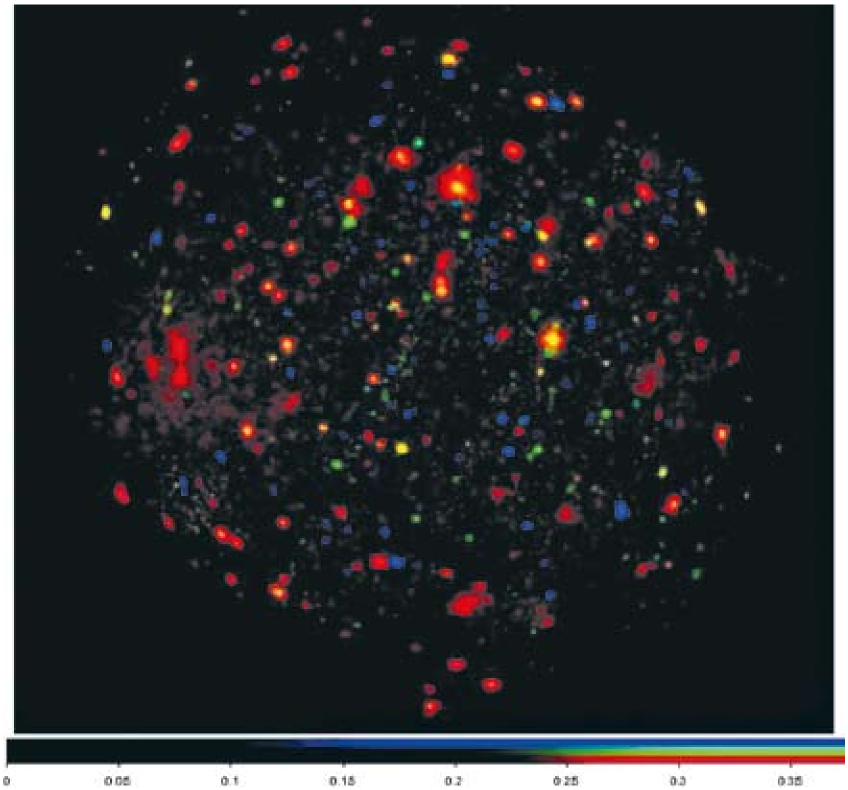


Figure: The most sensitive observation of the Universe obtained at X-ray wavelengths (0.5-10 keV) with ESA's mission XMM-Newton. This image was presented at the conference by A. Comastri and collaborators. The area covered is about 30×30 arcmin. The colour coding is such that absorbed (>10^{22} cm^{-2}) and unabsorbed sources (<10^{22} cm^{-2}) appear with blue and red colours, respectively.

by I. Georgantopoulos and M. Plionis
National Observatory of Athens

Jet dynamics in gamma-ray burst sources

by Nektarios Vlahakis

Section of Astrophysics, Astronomy and Mechanics, Department of Physics, University of Athens

Abstract

Gamma-ray bursts (GRBs) are among the most interesting laboratories of high energy astrophysics. Despite the strenuous efforts and steps in understanding made with the help of space telescopes many of their features still pose difficult problems. In the "standard" model they are associated with relativistic jets moving toward the observer with bulk Lorentz factors of the order of hundreds. Here I discuss the dynamics of these jets focusing on the role that the magnetic field plays in them, in extracting energy from the source and accelerating plasma to the required speeds.

Gamma-ray bursts (GRBs) are the most powerful explosions in the universe. They involve the release of a huge amount of energy, equivalent to a significant proportion of the rest mass energy of the Sun, in very short time periods, from milliseconds to several minutes.

GRBs were first discovered in the late 1960s by the Vela satellites[1], as flashes of gamma-rays coming from random directions in space. The second important step was the Burst and Transient Source Experiment (BATSE) on board the Compton Gamma-Ray Observatory (CGRO) that detected several thousand GRBs between 1991 and 2000 with a rate of approximately one per day, and showed a uniform distribution in galactic coordinates suggesting a cosmological origin. The next crucial observation was done in 1997 by the BeppoSAX[2], which allowed the detection of counterparts to GRBs in other wavelengths, the so-called afterglow. The prompt emission in gamma-rays is followed by a much longer emission (that lasts typically for many days to months) in lower energies, from X-rays, ultraviolet, optical, up to radio. The sufficiently accurate localization of GRBs with BeppoSAX allowed follow-up observations using ground-based telescopes. The identification of the host galaxy was possible for a number of GRBs, and redshift measurements confirmed that their sources are indeed at cosmological distances.

In our days two satellites, Swift and Fermi, continue to observe GRBs. Swift, launched on November 2004, is a mission dedicated to the multi-wavelength observations of GRBs in gamma-rays, X-rays, ultraviolet, and optical. One of its major achievements is that it gives for the first time information on the transition phase between the prompt emission and the afterglow. Fermi Gamma-ray Space Telescope, launched on June 2008, measures the GRB prompt emission spectrum over a large energy range, for the first time up to 300 GeV, unveiling their high-energy emission behavior.

According to the most commonly accepted scenario, the prompt GRB as well as the afterglow energy is stored before the emission, as kinetic energy of a relativistically moving jet. We cannot directly observe this motion; bulk Lorentz factors of the order of a few hundreds are inferred from the requirement that the flows must be optically thin to photon-photon annihilation. Recent Fermi observations of prompt GeV emission from several GRBs infer even higher values of bulk Lorentz factors, >1000.

Jet opening angles – typically a few degrees – are deduced from panchromatic breaks in the light curves of some afterglows (see Piran 2005 for a review). Although recent Swift observations have revealed that panchromatic breaks are not that common (Racusin et al 2009), it is widely accepted that GRB outflows are collimated, and this significantly lowers their energy budget. Actually a more careful study of jet-break mechanisms shows that they are expected to be chromatic (van Eerten et al 2011). More work needs to be done in order to connect the jet opening angle with the observed chromatic breaks.

Depending on the duration of the prompt emission, GRBs are divided in two categories, long (with duration >2s) and short. Long bursts are observed in star-forming galaxies and are thus associated with the death of massive stars. According to the collapsar model (McFadyen & Woosley 1998) which is considered almost as certain mostly due to the established connection of some bursts with Type Ic supernovae (e.g. Levesque et al 2012), the jet originates in a rapidly accreting stellar mass black hole that is formed from the collapse of the iron core of the massive star.

On the other hand, short GRBs are thought to be connected to the merging of two stellar mass compact objects (neutron stars or black holes), the result of which is again a stellar mass black hole surrounded by a debris disk. In both cases the initial conditions for the production of the jet are similar (black hole and accretion disk), although the progenitors differ. The duration of the prompt gamma-ray emission corresponds to the activity of the central engine (milliseconds to minutes). Nevertheless, the outflow can be considered steady-state, since this duration is much longer compared to the dynamical timescale of a stellar mass black hole.

1 Vela (from "velador", meaning watchman in Spanish) was a group of satellites developed by US to monitor compliance with the Partial Test Ban Treaty by the Soviet Union, during the cold war.

2 "Beppo" in honor of the Italian physicist Giuseppe Occhialini. SAX stands for "Satelite per Astronomia X".

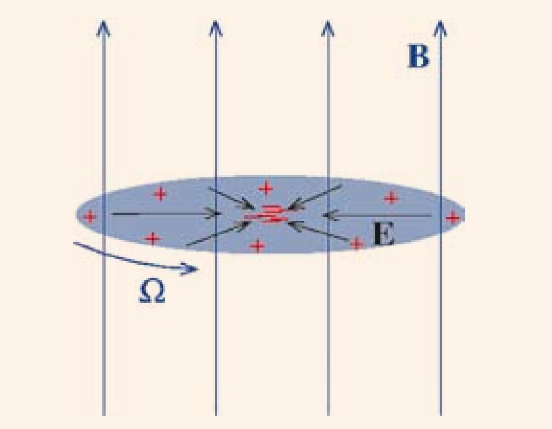


Figure 1: A unipolar inductor (or Faraday disk). An electromotive force is created when a conducting disk is rotated inside a magnetic field. The Lorentz force induces negative charges at the central region of the disk close to the rotation axis, and positive charges at its perimeter. The charge density and electric field is shown in the figure.

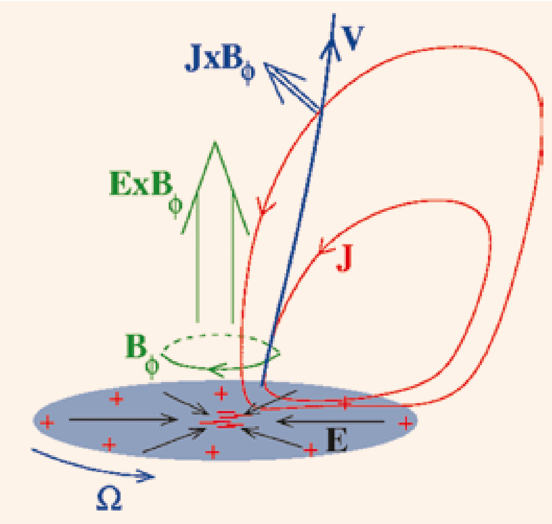


Figure 2: A "wire" of plasma charges closes the circuit. The current J and its associated azimuthal magnetic field B_φ is shown in the figure. An outflowing Poynting flux ExB_φ is naturally formed, and thus energy and angular momentum is extracted from the disk. If the streamlines are more collimated than the current lines, the JxB_φ force (shown in the figure) has a component along the bulk speed, accelerating the outflow, and a component normal to it, affecting its collimation.

In both progenitor scenarios we end up with a baryonic flow originating from the vicinity of a compact object and its surrounding accretion disk, similarly to the relativistic AGN and the nonrelativistic YSO jets.

A question arises on how the GRB outflow is accelerated to such high bulk Lorentz factors. One possible answer is related to a thermal fireball produced by viscous dissipation inside an accretion disk and subsequent escape of neutrinos. However, it is unlikely that thermal driving alone can explain the terminal speeds of relativistic GRB jets. The lack of detection of a thermal component in the spectra of some GRBs implies an upper limit in the initial temperature and points towards an initially magnetically dominated outflow (Zhang & Pe'er 2009). Magnetic fields can tap the rotational energy of the compact object or disk, providing the most plausible mechanism of energy extraction. The extraction mechanism is acting like a unipolar inductor, see figures 1 and 2, with the rotating "disk" being the accretion disk, or the central object. Qualitatively it works in the same way no matter if the central source is a protostar and/or its accretion disk, a stellar mass compact object and/or its accretion disk – as in the GRB and microquasar cases – or an active galactic nucleus. The only requirement is to have a rotating conducting source threaded by a large scale magnetic field. In the case of a rapidly rotating black hole the spacetime itself plays the role of the "disk"; this is the so-called Blandford & Znajek (1977) process.

Guided by the Blandford & Payne (1982) model of nonrelativistic jets one could expect that magnetic forces could efficiently accelerate the outflow, reaching a kinetic energy flux comparable to the ejected Poynting flux at Alfvénic distances. It turns out, however, that a relativistic flow is still Poynting flux dominated at these distances and the magnetic acceleration should work at much larger scales. In fact, there was a general belief for decades, based on a model of Michel (1969) on conical flows, that the mechanism of magnetic acceleration is in general inefficient. This corresponds to an outflow with streamlines along the current lines, the so-called force-free case, in which the Lorentz force JxB_φ has no component along the flow (see figure 2). The extracted energy remains in the electromagnetic field up to large distances from the source and a dissipation mechanism (e.g. reconnection or instabilities) is needed in order to somehow transfer the energy to the observed radiation. Works in this direction include Lyutikov & Blandford (2002); Giannios & Spruit (2006); McKinney & Uzdensky (2012).

An alternative way to transfer the energy to radiation is through shocks (and associated particle acceleration in them, e.g., Petropoulou et al 2011), or some instability (e.g., Mastichiadis & Kazanas 2009) after first creating a relativistically moving jet. This requires to accelerate the plasma by efficiently transferring the Poynting flux to matter kinetic energy flux. The first works showing that this is indeed possible were based on self-similar solutions of the magnetohydrodynamic (MHD) equations in the cold limit, Li et al (1992); Contopoulos (1994), and including a hot electron/positron/photon fluid, Vlahakis & Königl (2003). Komissarov et al (2009) generalized these results with the help of numerical simulations, giving also analytical scalings that relate the spatial distribution of the Lorentz factor and the flow shape with the pressure of the environment of the jet. As explained in that work, the role of the external pressure is crucial in controlling the magnetic acceleration efficiency. In the absence of external pressure the streamlines and the frozen in magnetic field freely expands creating a force-free flow which remains Poynting-flux dominated, since the current J and flow speed V are parallel and the Lorentz force JxB_φ has no component along the flow. On the contrary, if the external pressure is nonnegligible, the collimation of the flow leads to the situation sketched in figure 2. The streamlines are more collimated than the current lines and the JxB_φ force is able to efficiently accelerate the plasma. Such an external pressure is naturally expected in the case of GRB jets which are formed and initially propagated inside the progenitor star. Numerical simulations indeed show that the magnetic acceleration is efficient, reaching Lorentz factors ~0.5 E/Mc^2, where E is the extracted energy flux (that initially resides in the electromagnetic field) and M is the baryonic mass flux of the jet. Figure 3 shows a numerically simulated MHD jet, from Komissarov et al (2009).

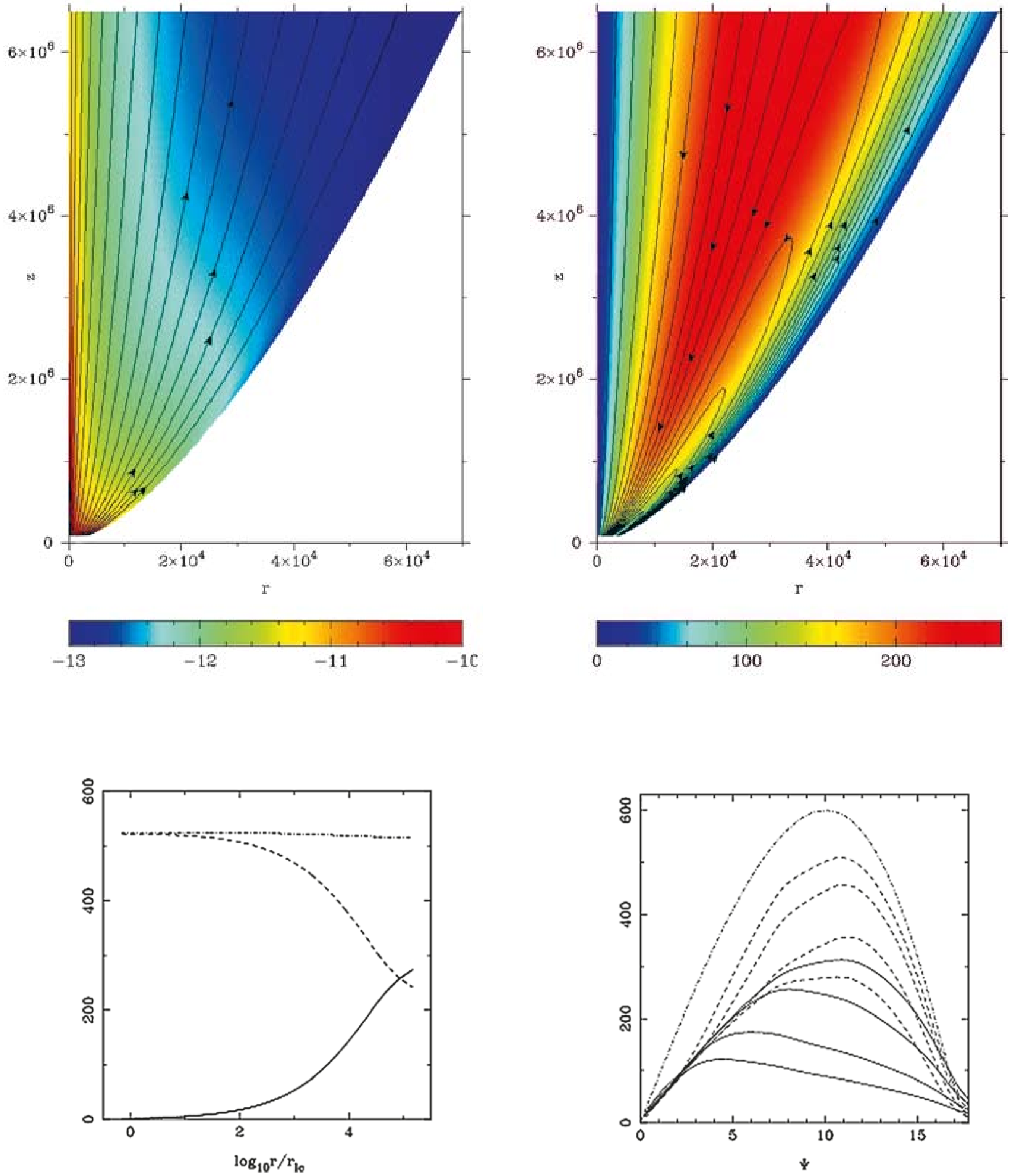


Figure 3: A numerically simulated MHD jet, from Komissarov et al (2009). A poloidal cross section of the jet is shown in the top row. Top left panel: density (color) and magnetic field lines. Top right panel: Lorentz factor (color) and current lines. The bottom row shows the evolution of the two parts of the energy-to-mass flux ratio (matter and electromagnetic) with distance. Bottom left panel: the Lorentz factor Γ (solid line), the Poynting-to-mass flux ratio Γσ (dashed), and their sum E/Mc^2 (dash-dotted), as functions of the cylindrical distance along a particular streamline. At small distances the flow is Poynting flux-dominated (Γσ>>Γ), while at large distances Γ~Γσ, meaning that half of the energy has been transferred to the matter. Bottom right panel: the distribution of the same quantities for all streamlines, from the rotation axis (Ψ=0) to the boundary of the jet (maximum Ψ), at various distances. In particular, solid lines show Γ at z = 5×10^4, 5×10^5, 5×10^6, 5×10^7 (increasing upward), dashed lines show Γσ at the same locations (increasing downward), and the dash-dotted line shows their constant sum E/Mc^2.

The collimation/acceleration paradigm for the jet formation seems to successfully work in jets of all scales. However, for the relativistic ones, it produces outflows with half-opening angles of the order of 1/Γ (see Komissarov et al 2009 for details). This is problematic in the GRB case since high Lorentz factors go along with very narrow jets, whose opening angles are significantly smaller than the ones inferred from the observations (typically a few degrees). A solution to this problem for long collapsar GRBs can be given by carefully studying the dynamics at the region where the jet comes out from the progenitor star, and its external pressure drops to practically zero. Tchekhovskoy et al (2010) and Komissarov et al (2010) simulated this transition and found that it is accompanied by a spurt of acceleration, which can be interpreted as rarefaction acceleration. The loss of external support induces a sideways expansion of the jet, and consequently a strong rarefaction wave that is driven into the flow and accelerates it. The increase of the Lorentz factor without further collimation has a strong impact on the resulting opening angle of the jet, making it a few degrees, i.e., much greater than the inverse of the terminal Lorentz factor.

Sapountzis & Vlahakis (2013) developed a semi-analytical model describing the rarefaction acceleration in GRB jets, successfully explaining previous simulation results. Figure 4 shows an example.

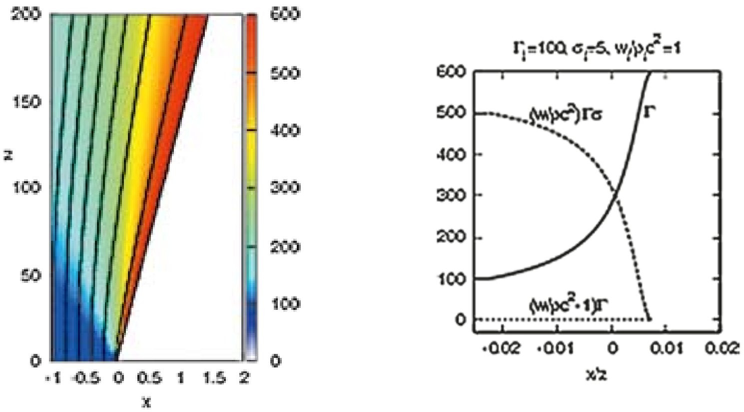


Figure 4: A rarefied jet solution, from Sapountzis & Vlahakis (2013). The left panel shows the Lorentz factor (color) and the streamlines (white on the right is void space). The bending of the streamlines (which are initially vertical) start at the front of the rarefaction wave, a cone starting from the origin and passing through the point (x = –1, z~50). The Lorentz factor increases from 100 (its assumed initial value when the jet breaks out of the star) to 600 near the boundary of the jet. The right panel shows the Lorentz factor Γ (solid line) and the Poynting-to-mass flux ratio (dashed line) as functions of the angle x/z (in each streamline). Evidently, the jet becomes matter dominated near its boundary.

In principle, MHD could explain jet dynamics in GRBs in a similar way as in other astrophysical settings, notably in AGN. In fact the similarity of the two classes of objects seems to be extended in the properties of their emission (Nemmen et al 2012).

The GRB-related physics is full of puzzles and surprises. To model and understand the involved mechanisms – in progenitor types, jet dynamics, emission mechanisms, to name just a few interrelated subtopics – is a continuous challenge, definitely one of the most fascinating area of research in modern astrophysics.

References

Blandford R. D., Payne D. G. 1982, MNRAS, 199, 883
Blandford R. D., Znajek R. L. 1977, MNRAS, 179, 433
Contopoulos J. 1994, ApJ, 432, 508
Giannios D., Spruit H. C. 2006, A&A, 450, 887
Komissarov S. S., Vlahakis N., Königl A., Barkov M.V. 2009, MNRAS, 394, 1182
Komissarov S. S., Vlahakis N., Königl A. 2010, MNRAS, 407, 17
Levesque E. M. et al 2012, ApJ, 758, 92
Li Z.-Y., Chiueh T., Begelman M. C. 1992, ApJ, 394, 459
Lyutikov M., Blandford R. 2002, astro-ph/0210671
MacFadyen A., Woosley S. 1998, AAS, 30, 1311
Mastichiadis A., Kazanas D. 2009, ApJ, 694, 54
McKinney J. C., Uzdensky D. A. 2012, MNRAS, 419, 573
Michel F. C. 1969, ApJ, 158, 727
Nemmen R. S., Georganopoulos M., et al 2012, Science, 338, 1445
Petropoulou M., Mastichiadis A., Piran T. 2011, A&A, 531, 76
Piran T. 2005, Rev. Modern Phys., 76, 1143
Racusin J. L. et al 2009, ApJ, 698, 43
Sapountzis K., Vlahakis N. 2013, MNRAS submitted
Tchekhovskoy A., Narayan R., McKinney J. C., 2010, NewA, 15, 749
van Eerten H. J., et al 2011, MNRAS, 410, 2016
Vlahakis N., Königl A. 2003, ApJ, 596, 1080
Zhang B., Pe'er A. 2009, ApJ, 700, L65

The question of cosmic magnetism

by Christos G. Tsagas

Section of Astrophysics, Astronomy and Mechanics, Department of Physics
Aristotle University of Thessaloniki

Abstract

Magnetic fields seem to be everywhere in the universe, but we still know little about their origin, their evolution and their implications. It is generally believed that, at least the galactic fields, have been amplified and supported by some kind of dynamo action. However, the galactic dynamo requires and initial seed-field in order to operate. So, for decades, researchers have been looking for physical mechanisms which could produce the magnetic seeds that will supply the dynamo. Nevertheless, despite the large number and the variety of the proposed scenarios, the issue remains open. Besides solving the problem of cosmic magnetogenesis, we also want to know how these fields have evolved in time, whether they have left any imprints of their presence and if they have played a role in the formation of the structure that we see in the universe today. In fact, these questions become increasingly pressing as the detection of magnetic fields in remote parts of our universe keeps going on.

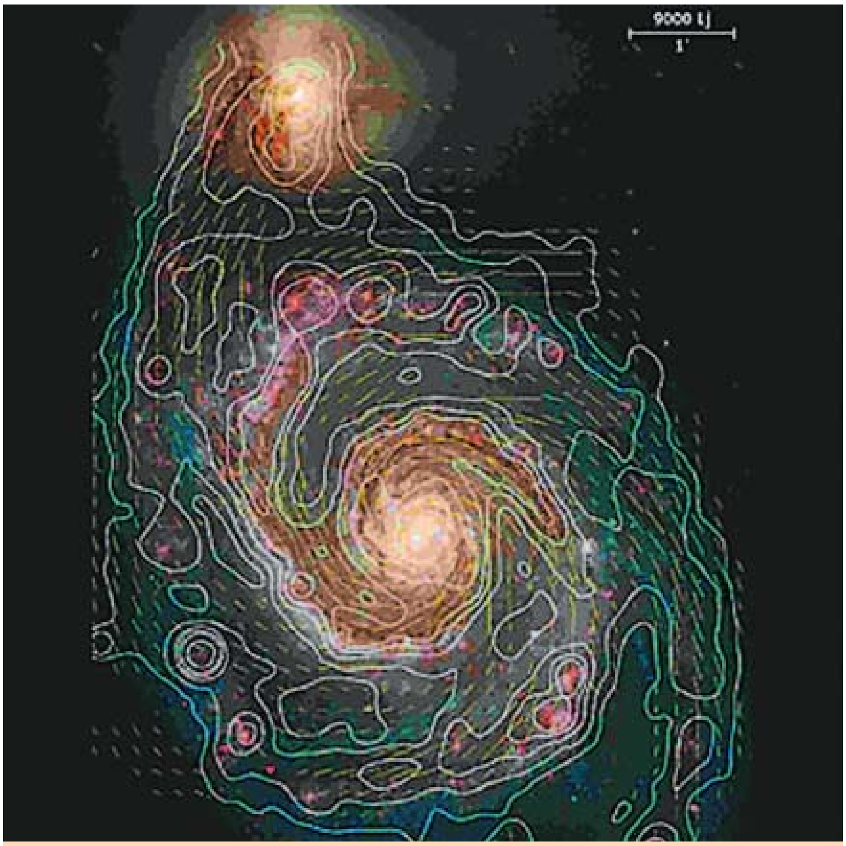


Figure: Image of the Whirlpool galaxy (M51) with the radio intensity contours and the magnetic field lines (credit: MPIfR Bonn and Hubble Heritage Team).

The widespread presence of large-scale magnetic (*B*) fields in the cosmos is a well established observational fact [1]. Actually, as our detection methods improve, magnetic fields appear everywhere in the universe. The Milky Way disc, for example, is permeated by a coherent *B*-field with strength of the order of 10^{-6} G, which makes it a major component of the interstellar medium. Magnetic fields of analogous magnitude and size have also been found in other spiral and barred galaxies. In addition, observations have repeatedly confirmed the magnetic presence in galaxy clusters and in remote protogalactic clouds. For instance, organised *B*-fields of μG strength have been reported at redshifts close to 1.3. It is generally believed that these fields have originated from week magnetic seeds, which were amplified to the observed strengths by the galactic dynamo. As yet, however, we do not know the origin of the seed-fields. They might be the result of astrophysical processes operating at late times, namely after recombination, or remnants of a primordial field [2, 3]. In addition, the detection of *B*-fields in young proto-galaxies, similar in strength with those in fully formed galaxies, has put the standard dynamo paradigm under scrutiny. It is possible, for example, that the dynamo does not need as much time as expected to built up a coherent magnetic field. On the other hand, as mentioned before, it is also conceivable that these high-redsift *B*-fields are of cosmological origin. Strong support for the idea of primordial magnetism may come from recent reports claiming the first ever detection of magnetic fields in intergalactic voids, with strengths close to 10^{-15} G [4]-[6]. It is therefore fair to say that the more we look for magnetic fields in the universe, the more ubiquitous we find them to be. Nevertheless, the origin, the evolution and the role of the large-scale cosmic magnetic fields remain open questions.

Detection methods: Polarised emission is the key to the detection of ordered magnetic fields. Optical polarisation, for example, is triggered by extinction along the line-of-sight, which itself is caused by dust grains aligned by an interstellar *B*-field. Although of limited value, optical polarisation has revealed the magnetic structure in the Milky Way and in other close-by galaxies. Further out, one can appeal to Faraday rotation measurements to establish the presence of coherent *B*-fields. Faraday rotation occurs when polarised radiation from background sources goes through a magnetised plasma, which then changes the orientation of the polarisation plane. The rotation angle depends on the strength and the direction of the magnetic force-lines (the line-of-sight component) and multi-wavelength observations of Faraday rotation can provide the three dimensional picture of the *B*-field. This way, rotation measurements of polarised radiation have led to the detection of magnetic fields in galaxy clusters, such as the Coma cluster [12].

A lot of information about galactic and intergalactic magnetic fields comes from radio signals. The Zeeman splitting of radio spectral lines, for example, has allowed us to measure the magnetic strength inside the gas clouds of the Milky Way, as well as inside dense HI clouds in other distant galaxies [8]. Typically, however, the Zeeman splitting is weak and for this reason it usually works only for interstellar magnetic fields. The total strength of the galactic fields can be measured from the intensity of the overall synchrotron emission. There is a proviso, however, that the magnetic energy density and that of the cosmic rays are in equipartition. Measurements based on this assumption, have led to magnetic strengths of approximately 5 μG in radio-faint galaxies and to *B*-fields close to 15 μG in gas-rich, star-forming galaxies. Even stronger magnetic fields (between 50 and 100 μG) have been found in starburst and merging galaxies [9].

In addition to the more conventional detection methods, there are also novel techniques that attempt to exploit the magnetic effects on highly energetic photons coming from active background sources. For instance, TeV-level photons from distant Active Galactic Nuclei (AGN) can lead to γ-ray production, as they interact with low-frequency background photons. What is important is that the profile of the resulting γ-ray spectrum can be affected by an intervening magnetic field (even by a weak one). In particular, the *B*-field can cause an extended halo around the AGN's γ-ray image. The detection of such halos has recently led a number of independent groups to claim, for the first time, the presence of magnetic fields in empty intergalactic space [4]-[6]. In all cases, the reported strengths were around 10^{-15} G.

Generation mechanisms: As mentioned in the beginning, despite the established ubiquitous presence of large-scale magnetic fields in the universe, their origin remains as yet unanswered. Over the years, there have been many attempts by many researchers to address the issue of cosmic magnetogenesis. The proposed scenarios are typically classified into those operating at late times (after recombination) and those advocating a cosmological origin for the large-scale magnetic fields seen in the universe today. In both cases, the aim is to generate the initial seed-fields that will feed the galactic dynamo once galaxy formation starts in earnest [10].

Late-time magnetogenesis usually employs battery-type mechanisms to create the initial seed fields. The Biermann-battery, which was originally proposed to address the question of stellar magnetism, has also been suggested as a mechanism of generating the galactic *B*-fields. The Biermann effect exploits differences in the ion and the electron acceleration to generate electric currents that will subsequently induce magnetic seeds of astrophysically interesting size and magnitude. Several variations of the Biermann-battery have been suggested as possible ways of magnetic generation during the post-recombination era (e.g. see [11]-[13]). The scenarios also involve supernovae explosions and AGN jets, which can in principle supply the interstellar plasma with *B*-seeds strong enough to feed the galactic dynamo. Turbulent motions and shocks developed during the collapse of a proto-galaxy, or thermal-battery processes that occur in reionisation fronts, could do the same as well (see [14] for a brief review). There are still obstacles to overcome however. Although battery-type mechanisms can explain the galactic *B*-fields, they face problems when applied to galaxy clusters. Even more difficult is to engage battery effects (or other known astrophysical processes) to explain the magnetic fields that were recently claimed to exist in intergalactic voids, where presumably no dynamo amplification can operate.

Alternatively, one could appeal to primordial magnetogenesis. The latter is attractive because it makes it easier to explain the *B*-fields found in young proto-galactic clouds and those recently claimed to exist in empty intergalactic space. Nevertheless, generating large-scale magnetic fields before recombination has proved a rather difficult theoretical exercise. The problems have to do with the scale, as well as the strength of the original seed-field. In particular, magnetic fields created before recombination and after the end of inflation are too small in size and will destabilise the dynamo. The latter requires seeds coherent on (comoving) scales no less than ~10 Kpc [10]. Typically, however, *B*-fields generated between inflation and recombination have much smaller lengths. This is so because the scale of the generated seed cannot exceed (due to causality) the size of the particle horizon at the time of magnetogenesis. The latter is well below the required 10 Kpc. For instance, at the electroweak phase transition, the horizon is close to the current size of our Solar System. One can increase the coherence scale of the original *B*-field by appealing to a mechanism known as "inverse cascade". In particular, magnetic helicity, a conserved quantity that reflects the topology of the field lines and measures their degree of withering and twisting, inverse-cascades from smaller to larger scales. As a result, helical magnetic fields can in principle enhance their original size [15]. Nevertheless, to achieve that, one requires *B*-seeds with rather large amounts of helicity.

Inflation can easily solve the scale problem, since it naturally produces superhorizon sized correlations. In addition, inflation provides a mechanism of generating magnetic seeds, by pushing electromagnetic quantum fluctuations outside the horizon, where they (presumably) freeze-out as classical electromagnetic fields. There is, however, a serious strength issue. The galactic dynamo requires seeds between ~10^{-22} G and ~10^{-12} G, depending on its efficiency [10]. Typically, however, the residual strength of a magnetic field that went through a phase of de Sitter inflation is less than 10^{-50} G. The reason is the so-called "adiabatic decay" of magnetic fields in Friedman-Robertson-Walker (FRW) universes. The belief, in other words, that

B-fields in FRW cosmologies always decay as $B \propto a^{-2}$, where a is the cosmological scale factor. This causes the catastrophic dilution of essentially all inflationary magnetic seeds. Solutions to the above described strength problem are usually sought outside classical electromagnetism or standard cosmology. These typically involve breaking the conformal invariance of Maxwell's equations, which slows down the magnetic decay-rate and can lead to B-fields with astrophysically relevant final strengths. The process of slowing down the adiabatic magnetic decay is commonly known as "superadiabatic amplification". Analogous effects can be obtained by abandoning standard cosmology, modifying General Relativity, or by introducing some other kind of new physics (see [3] for an extensive review). Success, however, is typically achieved at a cost. In addition to breaking away from standard physics and introducing extra free parameters, the proposed scenarios usually require a considerable amount of fine tuning.

Observational limits: Magnetic fields introduce new ingredients to their physical environment and for this reason the strength of any cosmological magnetic field is subject to constraints imposed by observations. Typically, the main limits come from primordial nucleosynthesis and from the isotropy of the Cosmic Microwave Background (CMB) spectrum.

As far as primordial nucleosynthesis is concerned, three are the main magnetic effects. The first has to do with the proton-to-neutron conversion ratio. In particular, the rate at which neutrons converse to protons increases when a magnetic field is present [16]. This means that the neutron-to-proton ratio freezes-out at a lower temperature, which makes it more difficult to produce the observed abundances of ^{4}He nuclei (as well as those of the heavier elements). A magnetic presence can also affect primordial nucleosynthesis because its extra energy boosts the expansion rate of the universe. The latter determines the timescale of the weak interaction and thus the temperature at which the proton-to-neutron ratio will freeze out [17]. A third magnetic effect comes from the fact that the B-field increases the electron pressure. This delays the electron-positron annihilation and generally leads to lower ^{4}He abundances [18]. When all of the above are taken into account, one finds that magnetic fields stronger than 10^{11} G at the time of nucleosynthesis are inconsistent with the observed abundances of the light elements. Redshifted to the present, the aforementioned constraint translates into $B \leq 10^{-7}$ G today.

Stronger constraints are imposed by the Cosmic Microwave Background. Magnetic fields are generically anisotropic sources and their presence should affect, to a greater or lesser degree, the isotropy of the CMB spectrum. Currently, the high isotropy of the Cosmic Microwave Background (of the order of 10^{-5}) appears to exclude all homogeneous cosmological magnetic fields that are stronger than $\sim 10^{-9}$ G (in today's values) [19]. The same limit seems to include stochastic fields as well. One could also look for magnetic imprints in the acoustic peaks of the CMB. In principle, the location and magnitude of these peaks changes because of the extra pressure that the B-field adds to the system [20]. This can lead to potentially observable effects. Magnetic fields can also source tensor modes, but their signal is similar to that coming from inflationary gravitational waves and therefore difficult to distinguish. Finally, the CMB polarisation, as well as non-Gaussianities in the CMB temperature maps, are additional areas where one could look for magnetic related imprints in the future.

Implications for structure formation: In addition, to their effects on nucleosynthesis and the CMB, cosmological B-fields can also affect the standard (non-magnetised) picture of structure formation. The latter is believed to be the result of a mechanism known as "gravitational, or Jeans, instability". According to this view, small inhomogeneities in the density distribution of the matter (like those seen in the CMB) grow slowly, under the effect of their own gravity, to give the galaxies, the galaxy clusters and the voids that we see today. The current concordance cosmological model, the ΛCDM paradigm, does not account for B-fields, despite their established widespread presence. Typically, the magnetic effects on the highly conductive cosmological plasma propagate via the Lorentz force. The latter carries the combined action of the field's pressure and tension, which means that the overall magnetic influence depends on whether the pressure or the tension component of the Lorentz force dominates.

It has long been known that the magnetic presence will generally source all three types of density inhomogeneities, namely scalar, vector and tensor. However, the way the B-field affects the evolution of these distortions seems to depend on which part of the Lorentz force (the pressure or the tension) plays the major role. To linear order, scalar inhomogeneities (those we usually call density perturbations) are typically affected by the field's pressure only. This means that the overall stability of the system against gravitational contraction is enhanced by the extra magnetic pressure. As a result, magnetised density perturbations grow slower than their magnetic-free counterparts. On small enough scales, in particular, the field's pressure increases the effective Jeans length (during the radiation era), or establishes a purely magnetic Jeans scale (during the dust epoch). In fact, for B-fields of $\sim 10^{-7}$ G, like those seen in many clusters of galaxies, the associated magnetic Jeans length is of the order of 1 Mpc, which is approximately the size of a typical galaxy cluster (see [21] for a review). Recall that the Jeans length defines the scale below which the pressure stops the perturbations from growing and forces them to oscillate. Therefore, the overall magnetic effect on (scalar) density perturbations seems rather negative. The B-field either slows down the growth rate of these distortions, or increases the size of the area inside which the perturbations no longer grow due to pressure support.

Density perturbations of vector nature are rotational inhomogeneities in the distribution of the matter component. A magnetic presence will generally switch-on such density vortices, as well ordinary kinematic vorticity. In this case, however, the magnetic influence comes mainly from the field's tension rather than its pressure. As a result, the overall magnetic effect on this type of distortions differs. More specifically vorticity decays slower in magnetised cosmologies than in magnetic-free models. During the dust era, for example, vorticity decays like a^{-1}, instead of following the standard a^{-2}-law (recall that a is the cosmological scale factor). In other words, the magnetic presence seems to create a favourable environment for the survival of rotational perturbations. One could then argue that magnetised cosmologies should contain more residual vorticity than their non-magnetised partners.

Magnetic fields can also source tensor perturbations. These include pure-tensor modes, namely gravitational waves, as well as trace-free shape distortions. The latter monitor changes in the shape of the perturbation (e.g. from a spherically symmetric configuration to something more complicated) under constant volume. Nevertheless, although it has long been known that the *B*-fields can generate such distortions, the magnetic role and implications for their evolution is still essentially unknown. It would be interesting to examine, for example, whether a particular magnetic configuration inside a young proto-galactic cloud, could favour a specific final shape for the galaxy itself.

The answers to the questions raised by the widespread presence of magnetic fields in the universe still elude us, despite the ongoing efforts. As far as the origin is concerned, two are the main schools of thought. The first advocates a late-time epoch of magnetogenesis, while the second appeals to primordial magnetism. The recently claimed (first) magnetic detections in intergalactic voids have probably given a boost to the latter approach. It is very likely, however, that the origin issue will not settle unless a magnetic imprint is found in the CMB. The data from the PLANCK satellite mission, which measure the temperature anisotropy of the CMB with unprecedented precision, might help in this respect. Analogous are the expectations from other ongoing and planned experiments, such as BICEP2/Keck, POLARBeaR and SPIDER, which focus on the CMB polarization. It is also encouraging that magnetohydrodynamic numerical codes have been gradually incorporated into structure formation models, in order to deal with the high complexity of the nonlinear regime (e.g. see [22]). Although magnetic fields are not included in the "concordance cosmological model", namely in the ΛCDM paradigm, this might happen sooner rather than later. Then, one hopes to have structure formation scenarios with fewer free parameters and more physics.

References

1. Vallée J.P. "Magnetic fields in the galactic Universe, as observed in supershells, galaxies, intergalactic and cosmic realm" *New Astronomy Reviews* 55 (2011) 91-154.
2. Widrow L.M. "Origin of galactic and extragalactic magnetic fields" *Reviews of Modern Physics* 74 (2002) 775-823.
3. Kandus A., Kunze K.E. and Tsagas C.G. "Primordial magnetogenesis" *Physics Reports* 505 (2011) 1-58.
4. Neronov A. "Evidence for strong extragalactic magnetic fields from Fermi observations of TeV blazars" *Science* 328 (2010) 73.
5. Tavecchio F., Ghisellini G., Foschini L., Bonnoli G., Ghirlanda G. and Coppi P. "The intergalactic magnetic field constrained by Fermi/Large Area Telescope observations of the TeV blazar 1ES0229+200" *Monthly Notices of the Royal Astronomical Society Letters* 406 (2010) L70-L74.
6. Ando S. and Kusenko A. "Evidence for gamma-ray halos around active galactic nuclei and the first measurement of intergalactic magnetic fields" *Astrophysical Journal Letters* 722 (2010) L39-L44.
7. Kim K.-T., Kronberg P.P., Dewdney P.E. and Landecker T.L. "The halo and magnetic field of the Coma cluster of galaxies" *Astrophysical Journal* 355 (1990) 29-35.
8. Wolfe A.M., Jorgenson R.A., Robishaw T., Heiles C. and Prochaska J.X. "An 84-G magnetic field in a galaxy at redshift z = 0.692" *Nature* 455 (2008) 638-640.
9. Chyzy K.T. and Beck R. "Magnetic fields in merging spirals - the Antennae" *Astronomy and Astrophysics* 417 (2004) 541-555.
10. Brandenburg A. and Subramanian K. "Astrophysical magnetic fields and nonlinear dynamo theory" *Physics Reports* 417 (2005) 1-209.
11. Pudritz R.E. and Silk J. "The origin of magnetic fields and primordial stars in protogalaxies" *Astrophys. J.* 342 (1989) 650-659.
12. Kulsrud R.M., Cen R., Ostriker J.P. and Ryu D. "The protogalactic origin for cosmic magnetic fields" *Astrophys. J.* 480 (1997) 481-491.
13. Xu H., O'Shea B.W., Collins D.C., Norman N.L., Li H. and Li S. "The Biermann battery in cosmological MHD simulations of population III star formation" *Astrophys. J.* 688 (2008) L57-L60.
14. Ryu D., Schleicher D.R.G., Treumann R.A., Tsagas C.G. and Widrow L.M. "Magnetic fields in the large-scale structure of the universe" *Space Sci. Rev.* 166 (2012) 1-35.
15. Brandenburg A., Enqvist K. and Olesen P. "Large-scale magnetic fields from hydromagnetic turbulence in the very early universe" *Physical Review D* 54 (1996) 1291-1300.
16. O'Connell and Matese J.J "Effect of a constant magnetic field on the neutron beta decay rate and its astrophysical implications" *Nature* 222 (1969) 649-650.
17. Cheng B., Schramm D.N. and Truran J.W. "Constraints on the strength of a primordial magnetic field from big bang nucleosynthesis" *Physical Review D* 49 (1994) 5006-5018.
18. Kernan P.J., Starkman G.D. and Vachaspati T. "Big bang nucleosynthesis constraints on primordial magnetic fields" *Physical Review D* 54 (1996) 7207-7214.
19. Barrow J.D., Ferreira P.G. and Silk J. "Constraints on a primordial magnetic field" *Physical Review Letters* 78 (1997) 3610-3613.
20. Adams J., Danielsson U.H., Grasso D. and Rubinstein H. "Distortion of the acoustic peaks in the CMBR due to a primordial magnetic field" *Physical Review D* 388 (1996) 253-258.
21. Barrow J.D., Maartens R. and Tsagas C.G. "Cosmology with inhomogeneous magnetic fields" *Physics Reports* 449 (2007) 131-171.
22. Dolag K., Grasso D., Springel V. and Tkachev I. "Constrained simulations of the magnetic field in the local Universe and the propagation of ultrahigh energy cosmic rays" *Journal of Cosmology and Astroparticle Physics* 01 (2005) 009.

The Magnetic Origin of Solar Eruptions

by Alexander Nindos

Section of Astrogeophysics, Physics Department, University of Ioannina

Abstract

The structure of the solar atmosphere results from the interaction between plasma and magnetic field. The same holds for the Sun's largest explosive phenomena – flares and coronal mass ejections (CMEs). In this article, I discuss the role of the magnetic field in the initiation of these phenomena. I present the standard concepts for the occurrence of flares and CMEs, and I highlight recent advances in the subject.

I. The Sun is a Magnetic Star

The Sun is made up of plasma and magnetic field and the structure of its atmosphere is the result of their interaction. Almost everywhere in the solar atmosphere the magnetic Reynolds number is much larger than unity. The behavior of the plasma and the magnetic field then depends upon their relative energy density. If the energy density of the plasma is much smaller than that of the field, then the field dominates and the plasma flows along the field lines. This is the case in the chromosphere, the corona and in sunspots. In the opposite case, the plasma dominates and drags/deforms the field. This happens in the photosphere (outside sunspots) and in the solar wind. The distribution of magnetic flux at any given layer of the solar atmosphere is not uniform; regions with large amounts of magnetic flux are called active regions (ARs).

In the low layers of the solar atmosphere the magnetic field is measured by employing the Zeeman effect; the resulting maps of the magnetic field are called magnetograms. In the corona, quantitative information on the magnetic field is difficult to obtain because of the weak intensity of coronal lines and their large thermal broadening. Alternatives based on observations[1] suffer from serious difficulties. Usually we take the photospheric magnetic field measurements as boundary condition for numerical calculations of the coronal magnetic field. The magnetic field extrapolation methods rely on various assumptions made about the physical conditions in the corona and, despite recent progress, their robustness is still a subject of active research[2].

II. Flares and Coronal Mass Ejections

Flares and coronal mass ejections (CMEs) are the most violent transient phenomena in the Sun. Both phenomena release energies of a few $\times 10^{32}$ ergs. A flare is a relatively localized sudden flash of radiation across virtually the entire electromagnetic spectrum. This happens because large amounts of energy are released. Its typical time scale is of the order of one minute. The explosion happens in ARs, initially in the low corona, but very soon practically all heights of the atmosphere below and above the explosion region are affected. In a typical flare, plasma is heated and particles are accelerated to relativistic energies on short time scales. A large flare may require the acceleration of 10^{37} electrons s^{-1} to energies >20 keV for periods of tens of seconds.

A CME is a large-scale expulsion of coronal magnetized plasma into the interplanetary medium. CMEs are detected in white-light coronagraphs by Thompson scattering of the photospheric light by the coronal electrons in the ejected mass. In an average event, 10^{14}-10^{16} g of plasma is ejected into the heliosphere with speeds ranging from 100 to 2000 km s^{-1}. An example of a CME appears in Figure 1. Since coronagraphs occult the solar disk, supplementary data are required for the determination of the on-disk sources of CMEs.

Not all flares are accompanied by CMEs and vice versa. Flares without CMEs are called confined flares, while those accompanied by CMEs are called eruptive flares. We note, however, that the strongest events practically always show both a CME and a flare.

Eruptive events come from surface regions of strongly sheared/twisted magnetic fields. Flares occur close to polarity inversion lines which are the regions that concentrate most of the AR's shear. Furthermore, CMEs may show a relatively dark region below their leading edge (e.g. see Figure 1). Such regions are assumed to be magnetic flux ropes seen edge-on (with the term flux rope we mean a set of magnetic field lines that wind at least one full turn about an axial field line). Note, however, that reconnection may cause flux ropes to form from erupting sheared arcades, so the observation of a flux rope CME does not necessarily imply that a flux rope was part of the initial configuration.

III. The "Standard" Flare-CME Model

Since the initiation of both flares and CMEs occurs in the corona, they both extract their energies from the magnetic field energy stored in the corona. The minimum energy of the magnetic field occurs when the field is potential, i.e. there are no electric currents ("current-free" field) and from such field, energy cannot be extracted. Energy from the magnetic field can be extracted and converted to other forms only when the field deviates from the potential state. This happens only when electric currents are present; the field must be

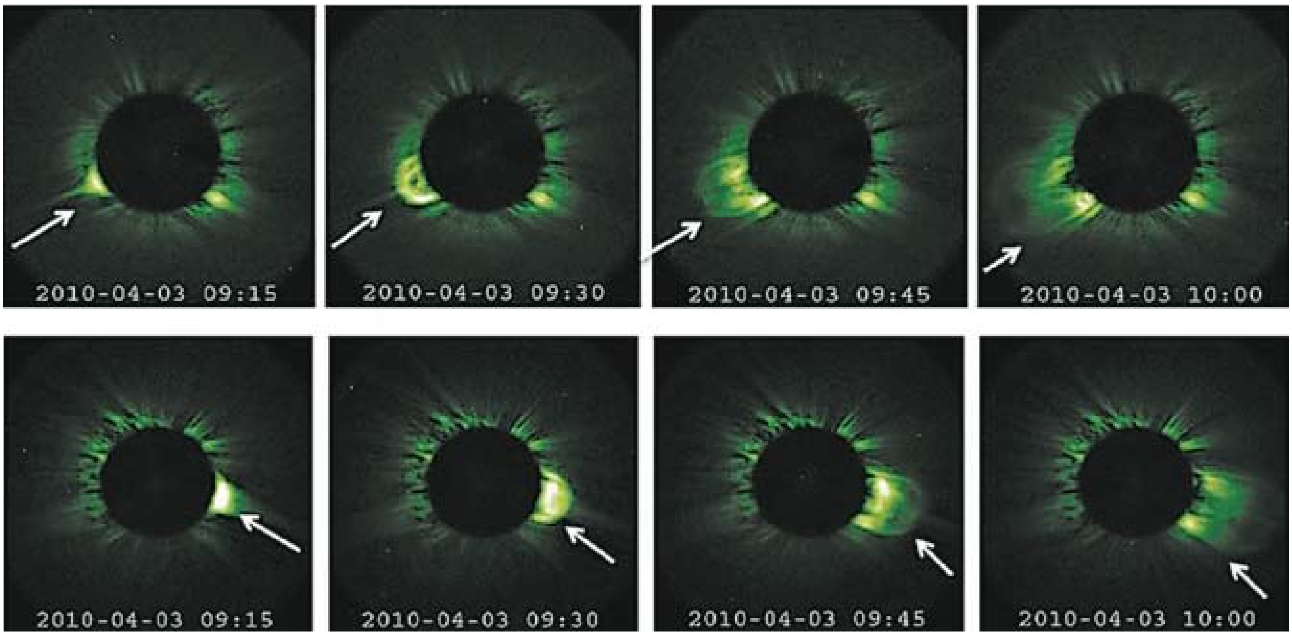


Figure 1: SECCHI/STEREO COR1 Ahead (up) and COR1 Behind (down) images showing the evolution of a CME from two different vantage points. The CME location is indicated by an arrow in each image.

stressed. The degree of linkage and/or twistedness in the magnetic field is quantified by the magnetic helicity.

It is generally believed that the energy that drives transient solar activity is *stored* in the coronal magnetic field *prior* to eruption. The characteristic time scale for magnetic energy transfer through the photosphere is much longer than the time scale for transfer through the corona. Observations show[e.g. 3] that the buildup process may take several hours to several days before sufficient energy to power a flare/CME is stored into the corona. The energy buildup process yields a concentration of strongly non-potential field around the polarity inversion line of the AR. This sheared field is held down by the overlying background field which is almost potential.

An eruption occurs when the force balance breaks down. In the corona the field dominates the plasma and therefore, we may consider the Lorentz force only. The two competing forces are the components of the Lorentz force, i.e. magnetic pressure and magnetic tension. Due to their enhanced magnetic pressure, structures of strong magnetic field tend to expand into regions of weak field. Equilibrium is preserved if the tension provided by the overlying background field is sufficient to hold in place the structure that tends to expand. Confinement fails when the energy trapped in a coronal structure is sufficient to drive an outward expansion against the overlying field. The explosive outward expansion of the field yields a CME. Below the eruption, field lines reconnect to a less-stressed configuration. Then a flare is produced if strong fields exist in the erupted region, otherwise we obtain a "CME without flare". If the overlying field inhibits a global eruption, then we obtain a "confined flare".

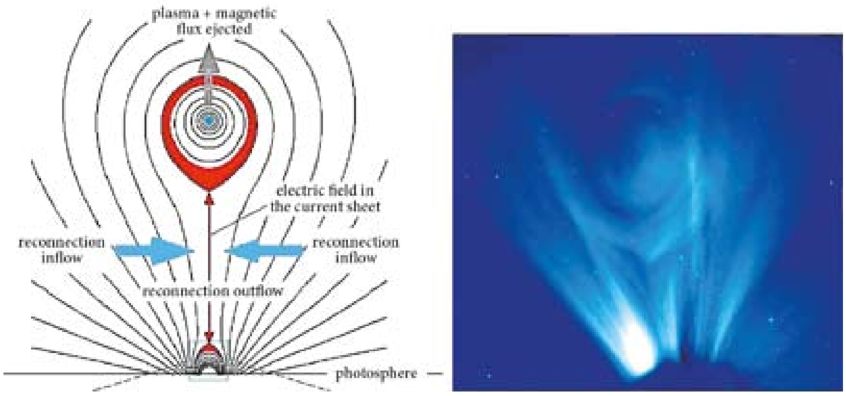


Figure 2: Left: Cartoon of the standard model of solar eruptions. Right: White-light image observed on November 4, 2007, by the SECCHI/STEREO COR2 Ahead instrument with features that resemble the standard model.

The standard model of an eruptive event appears in Figure 2 (left panel). A brief summary is as follows. A loss of equilibrium or instability triggers the explosive release of energy. The closed coronal field is so stretched by the catastrophic loss of equilibrium of the flux rope that the field effectively opens up and a vertical current sheet forms in the wake of the flux rope. Reconnection enabled by plasma instabilities inside the current sheet creates the separating Hα/EUV flare ribbons and the growing coronal flare loop systems observed in eruptive flares. Reconnection may also help the extended part of magnetic structure, including the flux rope, escape into the outer corona, resulting in a CME. Therefore, CMEs and flares are related phenomena; they represent different manifestations of processes of magnetic restructuring and associated energy release. The reported close temporal coincidence between the acceleration phase of several CMEs[e.g. 4,5] with the rise phase of the related flares strengthens this conclusion.

This picture is more likely to account for a major event that manifests an eruptive prominence, a CME, and a flare. Several old and recent observations have been interpreted in terms of the above model, and sometimes the morphological similarity is striking (e.g. in Figure 2, compare the cartoon of the left panel with the coronagraphic image of the right panel). However, any treatment in the framework of the simple version of the standard model presented here, will have trouble with self-consistency because of the strong effects of particle acceleration. Recent studies have emphasized the complexity of the magnetic configurations that erupt (the standard model refers to a simple bipolar configuration), the 3D nature of the phenomena, the role of statistical sub-processes working in a self-organized manner, and the physics of magnetic helicity.

IV. Beyond Cartoons

The subject of this article is large but the pages allocated to it are restricted. Thus, I will discuss only a few topics which, in my opinion, open new avenues of research.

Sites of energy release

Reconnection is intimately related to the process of conversion of the magnetic energy. Since the magnetic Reynolds number is much larger than unity in the corona, magnetic energy dissipation can occur efficiently when small spatial scales are created in the magnetic field. This can happen by the development of MHD turbulence or by the formation of thin current layers as the configuration evolves (both processes are related). Therefore, the topology of the coronal field is extremely important to understand where energy could be released.

A consensus has been reached[e.g. 6] that the most obvious magnetic configurations, where current layers can form, are the ones with complex topologies. These configurations may involve *separatrices*, i.e. magnetic surfaces where the field line linkage is discontinuous. Separatrices are associated with regions where the coronal field vanishes (null points)

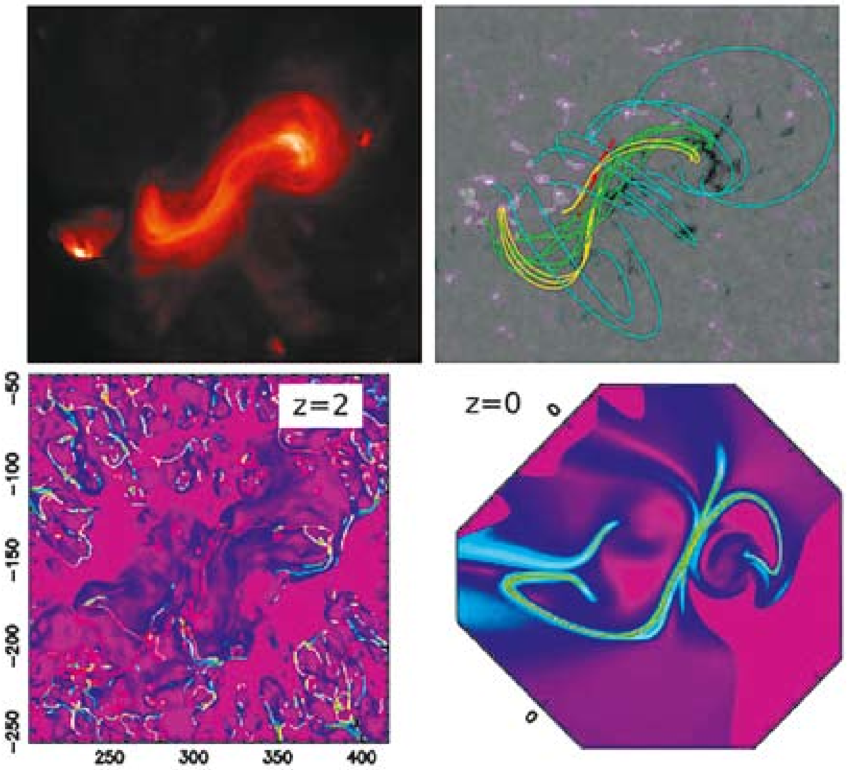


Figure 3: Top row, left: soft X-ray image of a sigmoidal AR observed by XRT/Hinode on February 12, 2007. Top row, right: selected field lines from the best-fit magnetic-field extrapolation model overlaid over a photospheric magnetogram. Bottom row: distribution of logQ in different horizontal slices for the extrapolation model (left) and the simulation (right). Q, the squashing factor, quantifies the strength of QSLs (modified from[8]).

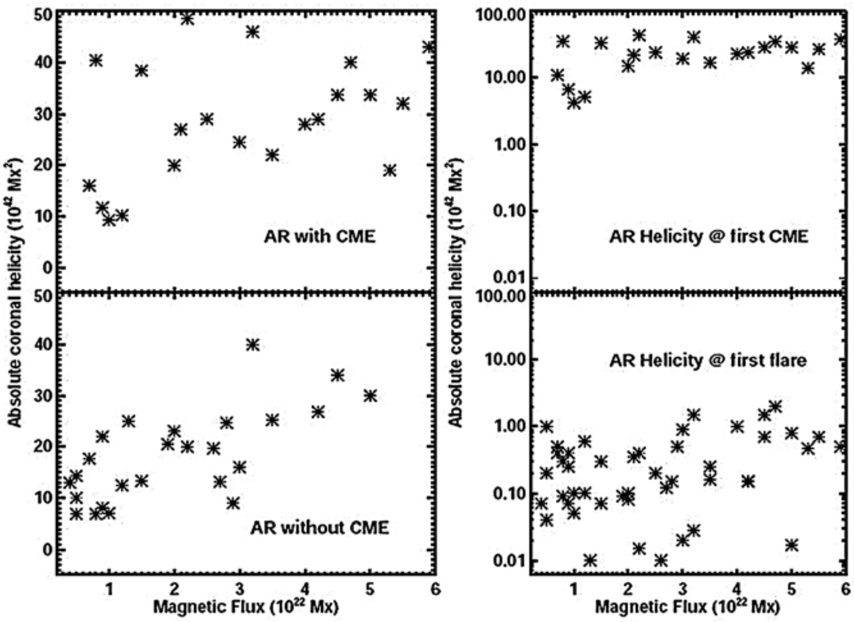


Figure 4: Left column, top: scatter plot of coronal helicities of emerging ARs just before their first CMEs as a function of the ARs' magnetic fluxes. Left column, bottom: same as top panel, but for ARs when they cross W45° without producing any CME. Right column, top: same as left column, top. Right column, bottom: same as top panel, with the exception that the helicities were calculated just before the first confined flare of each AR.

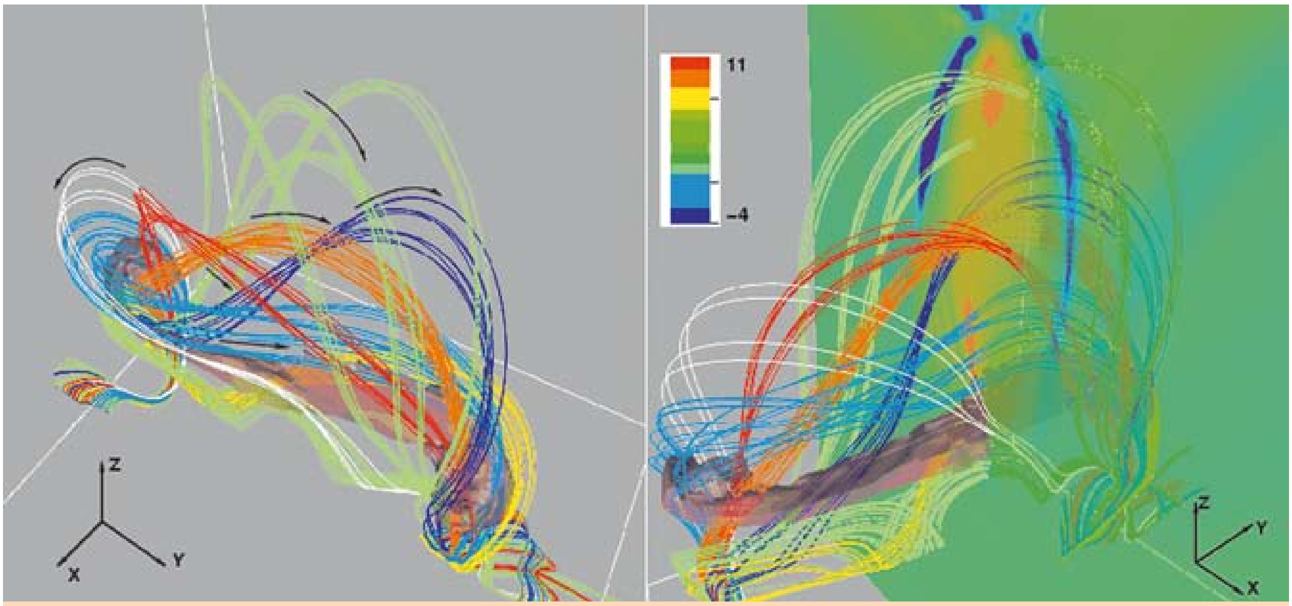


Figure 5: Left: eruption of flux rope (orange lines) and topology of field lines around the flux rope. The arrows show the direction of the magnetic field. Right: side view of the same sets of field lines. The color map shows the vertical velocity plane in the y=0 plane[13].

or with field lines tangent to the photosphere (bald patches). The concept of separatrices has been generalized with the introduction of "quasi-separatrix layers (QSLs)"[7], i.e. regions where there is drastic change in the field-line linkage (not necessarily a discontinuity). The strongest electric field and current are generated at, or close to where QSLs are thinnest.

The way to proceed for case studies is to combine data from the latest space missions with state-of-the art magnetic field extrapolations and/or MHD simulations, analyze the topological features of the AR, and determine the physical causes for the eruption. An example is given in Figure 3: the analysis showed that the most probable site for reconnection was identified under the flux rope that appeared in both the magnetic field extrapolation and the MHD simulation.

The role of magnetic helicity

The importance of storage and release of magnetic free energy is almost universally acknowledged for solar eruptions. However, the role of magnetic helicity is still under debate. Contrary to magnetic energy, helicity cannot be efficiently removed by magnetic reconnection. Furthermore, on the global scale, helicity emerges predominantly negative in the northern hemisphere and predominantly positive in the southern hemisphere, and this pattern does not change from solar cycle to solar cycle. Therefore, it has been proposed that CMEs are the primary agents through which the Sun gets rid of its excess helicity.

Despite the difficulties in the calculation of magnetic helicity, a few publications have shown that, statistically, the pre-flare coronal helicity of ARs producing CME-associated flares is larger than the helicity of those that produce confined flares[9,10,11,12]. As an example, in Figure 4 I show the results of a study of the helicity evolution of several emerging ARs. The left column of Figure 4 shows that, statistically, the coronal helicity of the ARs that produced a CME before crossing W45° was larger than the coronal helicity of those that crossed W45° without producing a CME. The right column of Figure 4 shows the coronal helicities at two different times in the evolution of the ARs: the bottom panel shows them when the ARs produced their first confined flare while the top panel shows them when the ARs produced their first CME. The segregation of the two sets of helicity values is almost complete. This result implies that, unlike CMEs, confined flares may occur without the prior accumulation of significant amounts of helicity.

MHD simulations

Over the years, significant effort has been put toward the numerical investigation of the nature of coronal eruptions. To this end, MHD simulations have been used widely. In most models the pre-eruption configuration is either a sheared arcade or a flux rope. Generally speaking, all MHD models need to be checked against observations in order to understand how realistic they are. We should keep in mind that all models are highly simplified compared to what really happens in the Sun. Their most severe limitation is that most of them assume a bipolar magnetic configuration, whereas, it is well-established from observations that eruptions occur more frequently in multi-polar configurations.

Having said the above, recent state-of-the-art simulations treat self-consistently the whole chain of events, from the formation of flux ropes all the way to the eruption, and capture, qualitatively, important aspects of the eruptive process. An example is given in Figure 5[13]. In this simulation a sub-photospheric twisted flux tube rises from the solar interior and expands into the corona. A flux rope is formed within the expanding field, due to shearing and reconnection of field lines at low atmospheric heights. If the tube emerges into a non-magnetized atmosphere, the flux rope rises, but it remains confined inside the expanding magnetized volume. In contrast, if the expanding tube is allowed to reconnect with a pre-existing coronal field, the flux rope experiences a full eruption with a rise profile that is in qualitative agreement with erupting filaments and CMEs.

V. Future Work

The ultimate goal of the research in the subject is to determine where, why, and when an eruption will occur. Despite the significant progress that has been achieved in recent years, there is much work still to be done. Non-incremental progress cannot be achieved without the efficient coupling between observations and theory. Given the importance of magnetic free energy and helicity, it is necessary to improve the accuracy of the relevant calculations. The topology is also an important issue because if we determine it accurately, we will be able to determine possible sites of reconnection. To this end, non-linear force-free field extrapolations need to mature and become faster. Effort needs to be made to develop fully 3D theoretical models. The MHD simulations should try to incorporate boundary conditions provided by vector magnetograms, as well as evolution of the photospheric field consistent with observations. Moreover, we need to find pre-eruption/eruption observational signatures and compare them against the models. The current and future generation of space-borne and ground-based instruments, as well as the development of new sophisticated codes and the increase of computer power have been and will be providing solid ground for the accomplishment of these tasks.

Acknowledgments

I thank the editors of Hipparchos for giving me the opportunity to present this review. My work has been partly co-financed by the European Union (European Social Fund – ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF) – Research Funding Program: "Thales. Investing in knowledge society through the European Social Fund".

References

1. Alissandrakis, C.E., 2013, Lect. Notes in Phys., in press.
2. Wiegelmann, T., & Sakurai, T. 2012, Living Rev. Solar. Phys., 9, 5.
3. Schmieder, B., Forbes, T.G., Malherbe, J.M., & Machado, M.E. 1987, ApJ, 317, 956.
4. Zhang, J., Dere, K.P., Howard, R.A., Kundu, M.R., & White, S.M. 2001, ApJ, 559, 452.
5. Temmer, M., Veronig, A.M., Kontar, E.P., Krucker, S., & Vršnak, B. 2010, ApJ, 712, 1410.
6. Démoulin, P., 2007, Adv. Space Res. 39, 1367.
7. Démoulin, P., Henoux, J.C., Priest, E.R., & Mandrini, C.H. 1996, A&A, 308, 643.
8. Savcheva, A., Pariat, E., van Ballegooijen, A., Aulanier, G., & DeLuca, E. 2012, ApJ, 750, 15.
9. Nindos, A., & Andrews, M.D. 2004, ApJ, 616, L175.
10. LaBonte, B.J., Georgoulis, M.K., & Rust, D.M. 2007, ApJ, 671, 955.
11. Nindos, A., Patsourakos, S., Wiegelmann, T. 2012, ApJ, 748, L6.
12. Tziotziou, K., Georgoulis, M.K., & Raouafi, N. 2012, ApJ, 779, L4.
13. Archontis, V., & Török, T. 2008, A&A, 492, L35.

Jets of high-energy particles extend from a supermassive black hole. Image of Centaurus A taken by the Chandra X-Ray Observatory.
Image courtesy of NASA, Chandra X-Ray Observatory, Harvard-Smithsonian Center for Astrophysics, and R. Kraft et al.
Source: https://lasers.llnl.gov/multimedia/photo_gallery/images/photo_week/large/cena.jpg

Astrophysical Jets from Black Holes

by Ioannis Contopoulos

Research Center for Astronomy and Applied Mathematics of the Academy of Athens

REVIEWS

Abstract

Astrophysical jets are collimated plasma outflows observed in systems of all mass scales that far exceed the dimensions of their host. The current paradigm for the launching, acceleration, collimation, and radiation of relativistic jets involves the electro-magnetic extraction of rotational energy from a spinning black hole and the accretion disk around it. We present recent theoretical and observational evidence that challenges the conventional black hole jet paradigm.

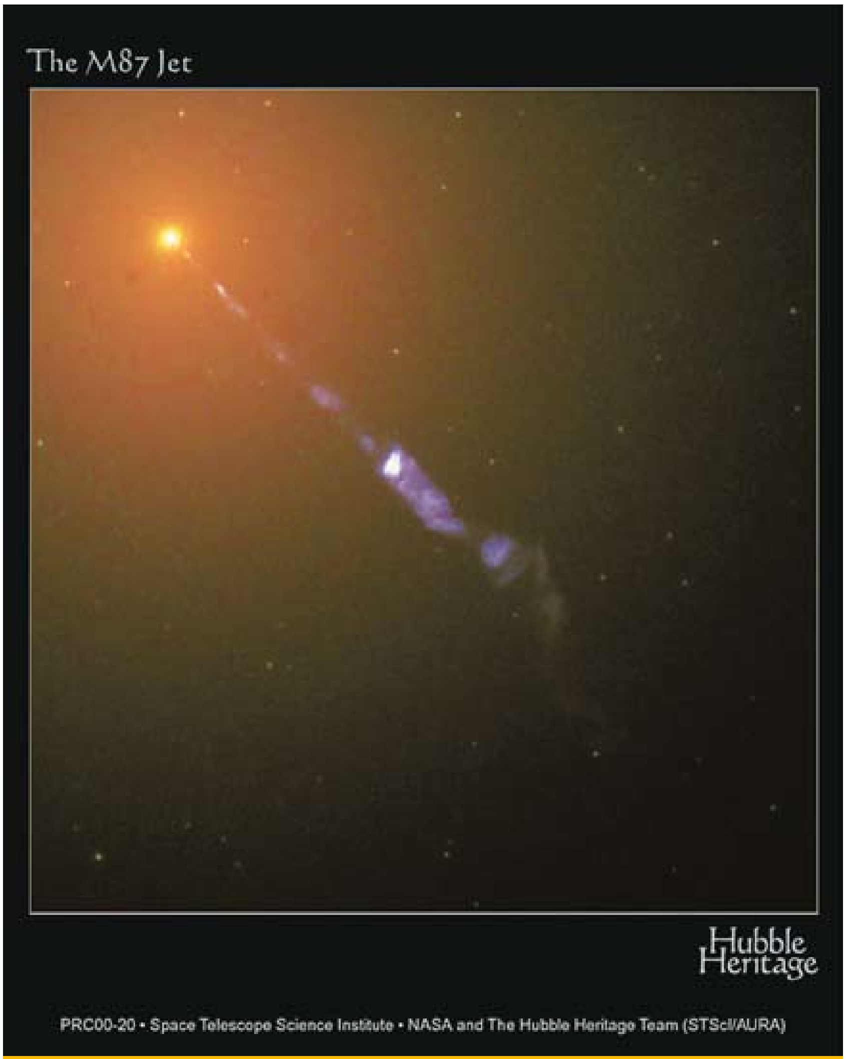


Figure 1: Hubble Space Telescope image of a black hole jet emanating from the center of giant elliptical galaxy M87 in the Virgo cluster of galaxies. Credit: J. A. Biretta et al., Hubble Heritage Team (STScI/AURA), Nasa.

The conventional paradigm

The generation of double opposite-directed fast collimated outflows from the immediate vicinity of a collapsed astrophysical object is one of the most impressive phenomena in astrophysics. Jets are observed in systems of all astrophysical mass scales. Characteristic examples are non-relativistic proto-stellar jets in classical T-Tauri stars, ballistic outflows in stellar mass microquasars, relativistic jets in giant radio galaxies and quasars that harbor super-massive black holes, hyper-relativistic jets in gamma-ray bursts during the collapse of massive stars to a black hole, etc. (see Pudritz, Hardcastle & Gabuzda 2012 for a review). The spatial dimensions of these outflows far exceed the dimensions of their host, and extend from a few to a million light years (Figure 1).

At the origin of the jet, matter accretes onto a central compact object (proto-star, neutron star, black hole). It is intriguing that all these very different systems release a significant part of their gravitational potential energy in the form of collimated outflows with very similar characteristics. At its base, the outflow is magnetically dominated, but as in most astrophysical systems, the source of energy is not magnetic. The magnetic field acts as an "intermediary" that channels the potential energy released in the accretion to directed energy in the outflow. It is set in rotation by the accreting plasma and the rotating central compact object, and thus transfers angular momentum to the plasma above. As a result, the field is wound into a helical structure, and plasma is flung outward by the coordinated action of rotation (centrifugal driving, Blandford & Payne 1982) and the "spring" pressure of the helical magnetic field (astrophysical plasma gun, Contopoulos 1995; magnetic towers, Lynden-Bell 1996). In black hole jets, the outflow slowly accelerates to relativistic velocities (Li, Chiueh & Begelman 1992, Contopoulos 1994), while the final Lorentz factor depends on the mass loading in the jet. Fast relativistic acceleration is also expected in the super-fast-magnetosonic regime of gamma-ray burst jets as they escape through the envelopes of their progenitor stars (Tchekhovskoy, Narayan & McKinney 2010a, Komissarov, Vlahakis & Königl 2010). Further downstream, magnetic fields provide collimation and stability up to the jet termination (e.g. Ferrari, Mignone & Campigotto 2011). They are also responsible for the synchrotron radiation emitted by relativistic electrons that spiral around magnetic field lines.

The latest state of the art magneto-hydrodynamic supercomputer simulations further strengthen the above theoretical picture (e.g. McKinney, Tchekhovskoy & Blandford 2012), but in fact, more than three decades of analytical and numerical research simply confirm the results of the early magneto-hydrodynamic numerical simulations of Uchida & Shibata (1985). We have thus reached the following paradigm:

> *Jets naturally form whenever a compact astrophysical object is surrounded by a rotating plasma disk, while both are immersed in a large scale ordered magnetic field.*

Several implications are readily derived from this paradigm. Jets over all astrophysical scales are re-scaled versions of a universal magneto-hydrodynamic jet model. The main re-scaling parameter turns out to be the mass of the central gravitating compact object. In the case of black-hole jets, another important parameter is the spin of the black hole. Furthermore, whenever one of the above three constituents is missing, jets do not form. For example, an isolated magnetized compact object (e.g. a pulsar), or un-magnetized accretion alone will not generate collimated outflows. An isolated black hole cannot even be magnetized (without a surrounding disk "holding" the magnetic field that permeates the black hole event horizon), and therefore it too cannot form a jet. Finally, the large scale environment may influence the morphology of the jet (shape, termination, radiation), but plays a secondary role in its formation.

Unfortunately, observations of the physical constituents of astrophysical jets have not kept up with our theoretical models. Hubble Space Telescope observations of proto-stellar jets have shown their general association with accretion disks, but the innermost disk is not directly observable. Furthermore, the recent discovery of differential rotation in the jet (Bacciotti et al. 2002) confirms that proto-stellar jets indeed carry a significant amount of their associated accretion disk's angular momentum. The presence of black holes at the origin of X-ray binary and extragalactic jets is also confirmed indirectly, as is the presence of dynamically significant magnetic fields. What is more difficult to confirm is the large scale helical magnetic field structure because it is easily destroyed as the outflow "plows through" its surroundings. Nevertheless, recent observations of transverse gradients in the Faraday rotation measure distribution across jets from Active Galactic Nuclei (Asada et al. 2002, Zavala & Taylor 2005, Gabuzda et al. 2008, Contopoulos et al. 2009, Kronberg et al. 2011, etc.) have tentatively confirmed the helical magnetic field structure proposed theoretically (Blandford 1993).

The conventional jet paradigm leaves two fundamental issues unanswered, namely what is the origin of the large scale magnetic field, and why astrophysical systems that contain all of the above physical elements sometimes do not produce jets. These issues are particularly pressing in the case of black hole jets where a) the magnetic field is certainly not generated by the black hole but is generated/brought in and held in place by the surrounding accretion disk, b) jets are an intermittent and not persistent feature of X-ray binaries, and c) most galaxies with rotating super-massive black holes at their centers do not form prominent jets (radio quiet). We will address these issues in the following two sections.

The origin of the black hole magnetic field

Weak random magnetic fields are present in the accretion disk and do contribute significantly to the disk dynamics through the Magneto-Rotational Instability (Balbus & Hawley 1991), but this is not what is needed to form jets. What is needed is an ordered magnetic field of uniform polarity, and it can be shown that this is impossible to emerge from local processes in the accretion disk. Magnetic flux of one polarity is either brought in from large distances, or both polarities are generated in situ through some dynamo or battery process but the two polarities must then be spatially separated from each other (Spruit 2010). Furthermore, during the past several years, it has become possible to measure the spin of accreting black holes by modeling the X-ray emission from their accretion disks. The two methods employed so far (continuum-fitting, and Fe Kα line reflection) show significant discrepancies among themselves (McClintock et al. 2011) which implies that we may be missing an important parameter of the black hole accretion system. This may very well be *the accumulated magnetic flux*, and our theories must account for its role and origin.

Most recent numerical simulations focus on the inward advection of an ordered magnetic field from a "reservoir" of uniform magnetic flux (companion star or the interstellar medium) at large distances (e.g. McKinney, Tchekhovskoy & Blandford 2012, and references therein). There are two problems with this scenario. Firstly, astrophysical accretion flows are known to be turbulent, and turbulence generates viscosity and magnetic diffusivity of similar magnitude. This inhibits the inward advection of ordered magnetic flux, and the accumulated magnetic field is negligible compared to what is needed to form a jet (see Spruit 2010 for details). Notice that most recent magneto-hydrodynamic numerical simulations are ideal (non-diffusive), and therefore they miss this important physical effect. Secondly, even if there was a way to suppress magnetic diffusivity, the source of the required "reservoir" of uniform magnetic flux in galactic nuclei accretion disks is not known.

The hydro-magnetic dynamo can certainly amplify a pre-existing magnetic field to very high values, only the problem of polarity separation cannot be solved in a natural way (Cattaneo 2007). Even if the dynamo were found to be a valid physical theory, it becomes problematic when applied in the magnetic fields of extragalactic jets. Existing theories predict extremely weak primordial "seed" fields (Biermann 1950; Ichiki et al. 2006), and fast exponential amplification is needed to account for the ordered magnetic flux observed in extragalactic jets.

We will here discuss a previously unaccounted for player in the ongoing study of astrophysical disks and jets proposed by Contopoulos & Kazanas (1998), the so called ***Cosmic Battery***. This works as follows: The accretion disk plasma around a black hole reaches temperatures up to 10^7 °K and emits copiously in X-rays. Plasma electrons and protons at the inner edge of the disk scatter off the X-ray photon field and thus feel a radiation pressure against the direction of rotation[1]. The Thomson cross-section of the electron is a million times greater than that of the proton, and therefore the electrons feel a much higher decelerating force, leading to their lagging behind the protons as they both move around the centre in the azimuthal direction. This generates an azimuthal electric current along the direction of rotation, and therefore naturally a large scale dipolar magnetic field through the centre. Technically, the growth of the magnetic field is governed by the induction equation, and the radiation pressure manifests itself as a novel electric field component opposite to the direction of rotation in the induction equation. The time needed for the energy density in the ordered magnetic field to grow to a level comparable to the rest mass energy density of the accreting matter is hours to weeks in a stellar mass black hole, and several hundred million years in a super-massive black hole. The axial part of the field will be held around the black hole by the inner conducting accreting plasma, whereas the outer return part of the field will diffuse outward through the dissipative turbulent disk. Each field component will generate its own collimated outflow, and therefore the jet will consist of an axial and a more extended outer component.

The Cosmic Battery makes a definite prediction about the direction of the axial electric current *along the jet*, unique to this model: The electric current generated at the inner edge of the disk flows along the direction of rotation, and the axial magnetic field points in the direction of omega. As seen in Figure 2, rotation twists the axial field into a helical structure with an axial electric current flowing toward the origin. The exact opposite happens with the return magnetic field that diffuses out through the disk. The axial electric current in the outer magnetic helical structure flows away from the origin. Only very recently did we manage to observe the directions

1 An analogous effect, the Poynting-Robertson effect, is known to be in action on interplanetary dust grains in our solar system.

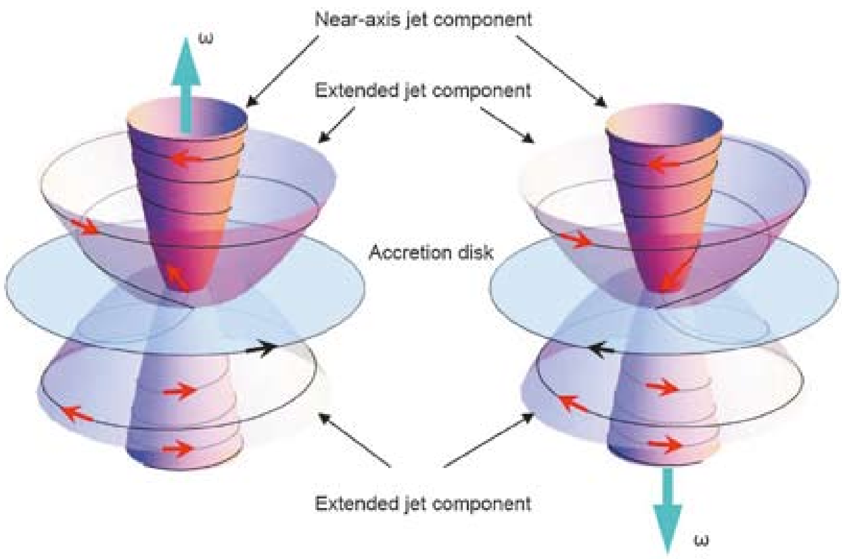


Figure 2: Sketch of the magnetic field generated by the Cosmic Battery (black lines with red arrows) near the axis and periphery of a black hole jet. The direction of disk rotation is shown by the black arrows in the disk and the corresponding angular velocity vector by the cyan arrows (after Contopoulos et al. 2009).

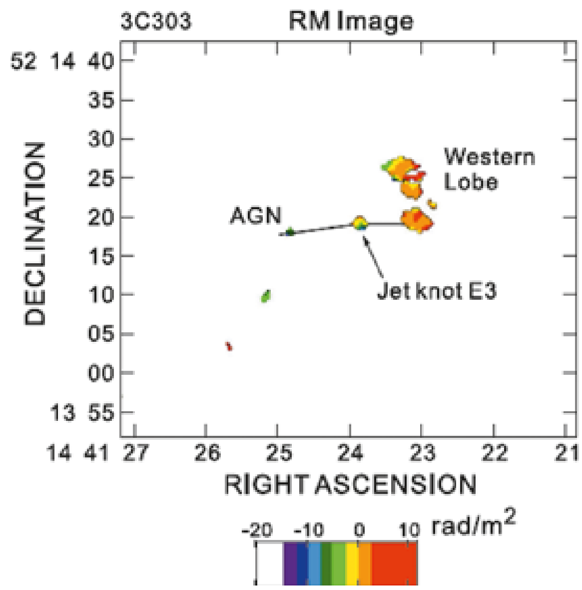


Figure 3: Faraday rotation image of the kiloparsec-scale radio jet of galaxy 3C303. Red/blue: line of sight magnetic field toward/away from observer. In jet knot E3, an electric current of 10^{18} A flows along the direction of the jet away from the central black hole, as predicted by the Cosmic Battery (after Kronberg et al. 2011).

of the axial and outer electric currents in Faraday rotation measure gradients across parsec-scale VLBI axial jets and kiloparsec-scale extragalactic outer radio jets. These observations are very hard to obtain, and a definite observational confirmation of our model will have to wait the operation of the next generation of radio telescopes. Still, current observations confirm our theoretical predictions, albeit only tentatively (Contopoulos et al. 2009, Christodoulou et al. 2011; see Figure 3). It is interesting that the hydro-magnetic dynamo has no preference for a particular direction of the magnetic field, nor the electric current, and therefore cannot account for this effect.

Electromagnetic energy extraction from rotating black holes

In 1977, Blandford and Znajek proposed that energy and angular momentum will be extracted electromagnetically from a spinning black hole embedded in a magnetic field, and most people today believe that this is the origin of the black hole radio jets observed in X-ray binaries and Active Galactic Nuclei. They argued that rotation induces an electric field which electrostatically accelerates any stray charged particle in the vicinity of the black hole, and if the magnetic field and black hole angular momentum are large enough, the accelerated particles will radiate, and the radiation will freely produce electron-positron pairs. Thus, the electromagnetic field in the vicinity of the black hole horizon will naturally be inundated with an approximately force-free charged outflowing electron-positron plasma, in direct analogy to the theory of pulsar electrodynamics proposed a few years earlier by Goldreich & Julian (1969). For years, people believed that the electromagnetic extraction of black hole energy had been overestimated (Livio, Ogilvie & Pringle 1999), and only very recently did numerical simulations derive a supposedly strong correlation between jet power and black hole spin as proposed by Blanford & Znajek (e.g. Komissarov 2005, McKinney 2005, Tchekhovskoy, Narayan & McKinney 2010b, Ruiz et al. 2012). Unfortunately, recent observations of black hole jets in X-ray binaries find no evidence for such correlation (Fender, Gallo & Russell 2010, Russell, Gallo & Fender 2012; see Figure 4; see however also Narayan & McClintock 2012 for the opposite point of view). A possible resolution of this disappointing result may be that one of the two observational methods that determine the black hole spin (the continuum-fitting method; Zhang, Cui & Chen 1997) hasn't taken into account the role of the accumulated magnetic flux in displacing the inner edge of the disk. It is conceptually possible that, when that displacement is taken into account (Contopoulos & Papadopoulos 2012), a jet power-black hole spin correlation will appear in the data.

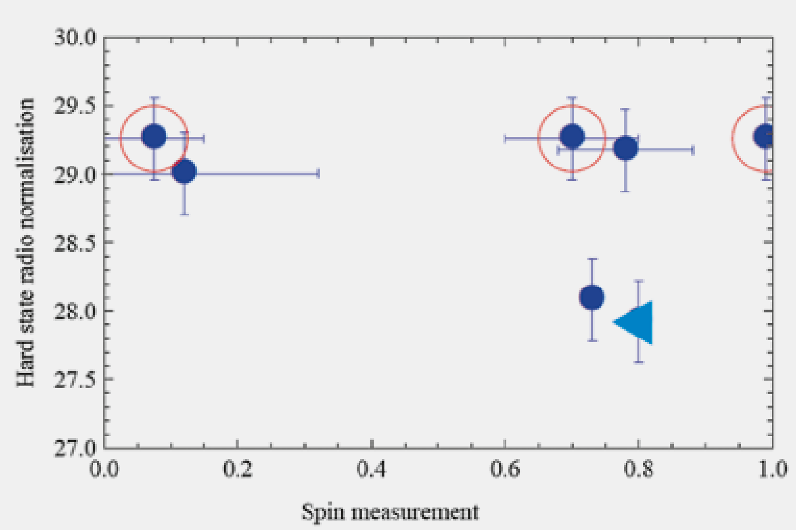


Figure 4: A comparison of estimated jet power with reported black hole spin in X-ray binaries. No correlation between the two is seen in the data. Adapted from Fender, Gallo & Russell 2010.

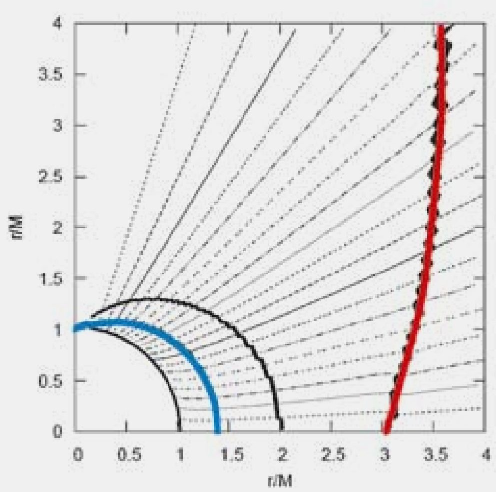


Figure 5: Poloidal magnetic field lines (thin lines) near the event horizon (inner solid black circle) of a maximally spinning black hole (a=0.9999M). The thick blue line represents the inner light-surface (inside the ergosphere). The thick red line represents the outer light-surface (the generalized light cylinder). Distances in units of GM/c^2. Adapted from Contopoulos, Kazanas & Papadopoulos 2013.

There is though one more interesting possibility that requires a deeper investigation of the steady-state black hole magnetosphere. The theory of the electromagnetic energy extraction from spinning black holes was developed in direct analogy to pulsars, but when it was first proposed, the structure of the pulsar magnetosphere was not yet known. That problem was solved several years later by Contopoulos, Kazanas & Fendt (1999) who showed that the electromagnetic energy extraction from pulsars is uniquely determined when magnetic field lines cross a critical surface, the so called "light-cylinder". In the case of a spinning black hole magnetosphere there exist two such critical surfaces, the inner and outer "light-surfaces". Therefore, *electromagnetic energy extraction from rotating black holes is uniquely determined only when magnetic field lines cross both light-surfaces, and in particular the outer one which is the generalized light-cylinder*[2]. The physical significance of the two light surfaces has only very recently been investigated by Contopoulos, Kazanas & Papadopoulos (2013) who also found that the structure of the spinning black hole magnetosphere is very close to a split monopole configuration (see figure 5).

Their results are in excellent agreement with the results of time-dependent numerical simulations obtained recently by several other authors (e.g. Tchekhovskoy, Narayan & McKinney 2010b, Lyutikov & McKinney 2011). All these works confirmed the high efficiency of the Blandford-Znajek process in extract-

2 Recent numerical simulations that show electromagnetic energy extraction without crossing of the generalized light cylinder require further investigation of the role of their boundary conditions (see Palenzuela et al. 2011).

ing electromagnetic energy from rotating black holes. However, in order to observe astrophysical jets, the extracted electromagnetic energy must somehow be transformed into the kinetic energy of the relativistic electron-positron plasma outflow. One possibility may be that, in direct analogy to pulsars, *the outflow Lorentz factor* Γ *in a monopolar magnetosphere increases linearly with cylindrical radius* R *as*

$$\Gamma \sim R/R_{LC}$$

beyond the light cylinder at $R=R_{LC}$ *and up to the fast magnetosonic point of the outflow* (Contopoulos & Kazanas 2002). It is, therefore, conceivable that, if the black hole magnetosphere is surrounded by a collimated disk wind, magnetic field lines that cross the black hole event horizon do not extend as far from the axis as uncollimated ones, and are thus expected to reach lower Lorentz factors. This theoretical result is in agreement with the observed anti-correlation between the presence of disk winds and the presence of radio jets in X-ray binaries (Neilsen & Lee 2009, Ponti et al. 2012), and may also account for the dichotomy between radio quiet and radio loud galaxies. Of course the final Lorentz factor of such outflows will also depend on the mass loading of a given magnetic field line, and the interrelation between the black hole and disk outflows merits further investigation.

Outlook for the future

The physical mechanism at the origin of the spectacular natural phenomenon of relativistic astrophysical jets is the electromagnetic extraction of energy from a spinning black hole, as proposed more than 35 years ago by Blandford and Znajek. Recent theoretical and numerical advances confirm the high efficiency of this mechanism. However, the efficiency of transforming electromagnetic energy into the kinetic energy of a collimated relativistic plasma outflow is still under intensive investigation. Recent observations suggest that the efficiency of this transformation is related to the presence or absence of a disk and/or disk outflows around the black hole magnetosphere.

The origin of the accumulated magnetic field is also under current intensive theoretical and numerical investigation. Future simulations of the innermost region around the central black hole will incorporate the Cosmic Battery, namely a novel source in the induction equation due to the radiation drag on plasma electrons, and new exciting results are expected soon. Further observational confirmation of the Cosmic Battery will have to wait the operation of the next generation of radio telescopes (ATA-256, EVLA, LOFAR, ASKAP, MeerKAT, SKA, VSOP-2; Gaensler et al. 2009, Law et al. 2011).

Acknowledgements

The author would like to acknowledge support by the General Secretariat for Research and Technology of Greece and the European Social Fund in the framework of Action `Excellence'.

References

Asada, K. et al. 2002, Proc. Astron. Soc. of Japan, 54, 39
Bacciotti, F. et al. 2002, Astrohysical Journal, 576, 222
Balbus, S.A. & Hawley, J. F. 1991, Astrophysical Journal, 376, 214
Biermann, L. 1950, Z. Naturforsch, 5a, 65
Blandford, R. D. 1993, Astrophys. Space Sc. Library, 103, 15
Blandford, R. D. & Payne, 1982, Monthly Notices, 199, 883
Blandford, R. D. & Znajek, R. L. 1977, Monthly Notices, 179, 433
Cattaneo, F. 2007, APS, 49th Ann. Meet. Div. of Plasma Physics, UT2.001
Christodoulou, D. M. et al. 2011, submitted to Astronomy & Astrophysics
Contopoulos, J. 1994, Astrophysical Journal, 432, 508
Contopoulos, J. 1995, Astrophysical Journal, 450, 616
Contopoulos, I. et al. 2009, Astrophys. J. Lett., 702, 148
Contopoulos, I. & Kazanas, D. 1998, Astrophysical Journal, 508, 859
Contopoulos, I., Kazanas, D. & Fendt, C. 1999, Astrophysical Journal, 511, 351
Contopoulos, I. & Kazanas, D. 2002, Astrophysical Journal, 566, 336
Contopoulos, I. et al. 2009, Astrophysical Journal, 702L, 148
Contopoulos, I. & Papadopoulos, D.V. 2012, Monthly Notices, 425, 147
Contopoulos, I., Kazanas, D. & Papadopoulos, D.V. 2013, Astrophysical Journal, in press
Fender, R. P., Gallo, E. & Russell, D. 2010, Monthly Notices, 406, 1425
Ferrari, A., Mignone, A. & Campigotto, M. 2011, Adv. Plasma Astroph., IAU Symp., 274, 410
Gabuzda, D. C. et al. 2008, Monthly Notices, 384, 1003
Gaensler, B. M. et al. 2009, IAUS, 259, 645
Goldreich, P. & Julian, W. H. 1969, Astrophysical Journal, 157, 869
Ichiki, K. et al. 2006, Science, 311, 827
Komissarov, S. S. 2005, Monthly Notices, 359, 801
Komissarov, S. S., Vlahakis, N. & Königl, A. 2010, Monthly Notices, 407, 17
Kronberg, P. P. et al. 2011, Astrophysical Journal, 741L, 15
Li, Z-Y, Chiueh, T. & Begelman, M. C. 1992, Astrophysical Journal, 394, 459
Livio, M., Ogilvie, G. I., Pringle, J. E. 1999, Astrophysical Journal, 512, 100
Law, C. J. et al. 2011, Astrophysical Journal, 728, 57
Lynden-Bell 1996, Monthly Notices, 279, 389
Lyutikov, M. & McKinney, J., C. 2011, Phys. Rev. D., 84, 4019
McClintock, J. E. et al. 2011, Classical and Quantum Gravity, 28, 114009
McKinney, J. C. 2005, Astrophysical Journal, 630, L5
McKinney, J. C., Tchekhovskoy, A. & Blandford, R. D. 2012, Monthly Notices, 423, 3083
Narayan, R. & McClintock, J. E. 2012, Monthly Notices, 419L, 69
Neilsen, J. & Lee, J. C. 2009, Nature, 458, 481
Palenzuela, C. et al. 2011, Classical and Quantum Gravity, 28, 134007
Ponti, G. et al. 2012, Monthly Notices, 422L, 11
Pudritz, R. E., Hardcastle, M. J. & Gabuzda, D. C. 2012, Space Sciences Reviews, Springer
Ruiz, M. et al. 2012, Monthly Notices, 423, 1300
Russell, D., Galo, E. & Fender, R. P. 2012, SS9 EWASS 2012
Spruit, H. C. 2010, Lecture Notes in Physics, 794, 233 (Springer)
Tchekhovskoy, A., Narayan, R. & McKinney, J. C. 2010a, New Astronomy, 15, 749
Tchekhovskoy, A., Narayan, R. & McKinney, J. C. 2010b, Astrophysical Journal, 711, 50
Uchida, Y. & Shibata, K. 1985, Pub. Astron. Soc. of Japan, 37, 515
Zavala, R. T. & Taylor, G. B. 2005, Astrophys. J. Lett., 626, 73
Zhang, S. N., Cui, W. & Chen, W. 1997, Astrophysical Journal, 482, L155

Herschel Infrared Observatory
Credit: European Space Agency
Source: http://solarsystem.nasa.gov/multimedia/gallery/herschel_IR_11.jpg

HERSCHEL SPACE OBSERVATORY
Looking through cosmic dust

by Manolis Xilouris

Institute for Astronomy, Astrophysics, Space Applications and Remote Sensing, National Observatory of Athens

Abstract

Launched by Ariane 5 in May 2009, the Herschel Space Observatory is the fourth «cornerstone» mission in the European Space Agency science program, along with Rosetta, Planck, and the Gaia missions. Its primary mirror, of 3.5 m in diameter, is more than four times larger than any previous infrared space telescope allowing Herschel to collect almost 20 times more light compared to previous missions. Herschel is the first observatory to cover the entire wavelength range from far-infrared to submillimetre studying otherwise invisible dusty and cold regions of the cosmos, both near and far. Operating for more than three years Herschel Space Observatory has delivered a tremendous wealth of imaging and spectroscopic observations, many of which have already lead to outstanding discoveries.

Figure 1: The Herschel space telescope stands on top of the Ariane 5 launch vehicle on 10 May 2009. Credit: ESA/CNES/Arianespace.

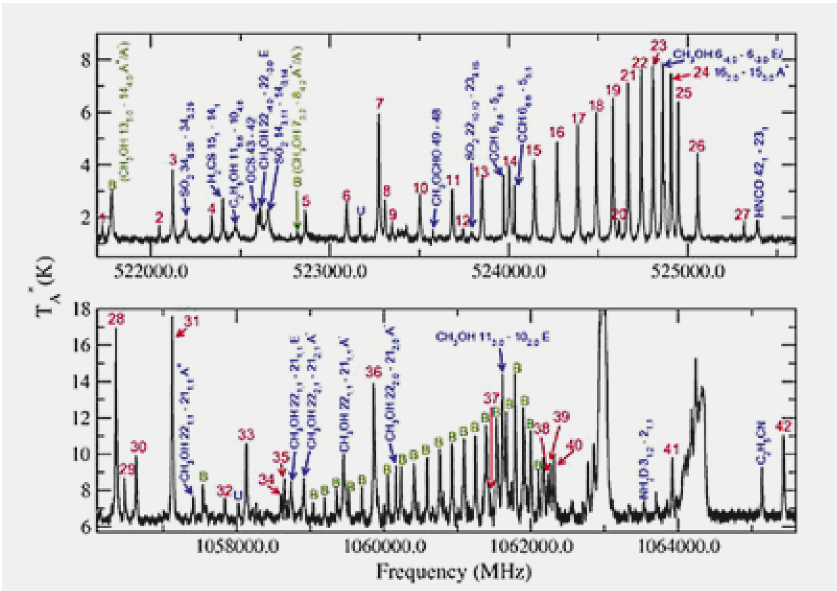


Figure 2: The HIFI spectrum of the Orion-KL region shows a multitude of lines from which many physical and chemical properties of the gas can be inferred. Red numbers denote isolated methanol transitions, blue text denotes transitions from other molecules and methanol transitions which are blended, green text and B denotes methanol lines which are blended with different parity states, and U denotes unidentified lines. The chemical compounds seen in this spectrum were known from ground-based observations, but these lines are seen with HIFI for the first time. From Wang et al. (2011).

1. Introduction

The launch of the Herschel Space Observatory (Fig. 1; Pilbratt et al., 2010) can be marked as a milestone in the area of infrared astronomy. With a mirror of 3.5 m in diameter, Herschel studies the Universe in the far-infrared and sub-millimeter wavelength ranges (60-670 μm) thanks to the capabilities of the three instruments on board: HIFI (de Graauw et al., 2010), PACS (Poglitsch et al., 2010), and SPIRE (Griffin et al., 2010). The infrared and sub-millimeter regions of the spectrum are of great scientific interest, not only because it is here that cool objects (10-100 K) radiate the bulk of their energy, but also because of their rich variety of diagnostic atomic, ionic, molecular and solid-state spectral features (see an example in Fig. 2). Measurements at these wavelengths permit determination

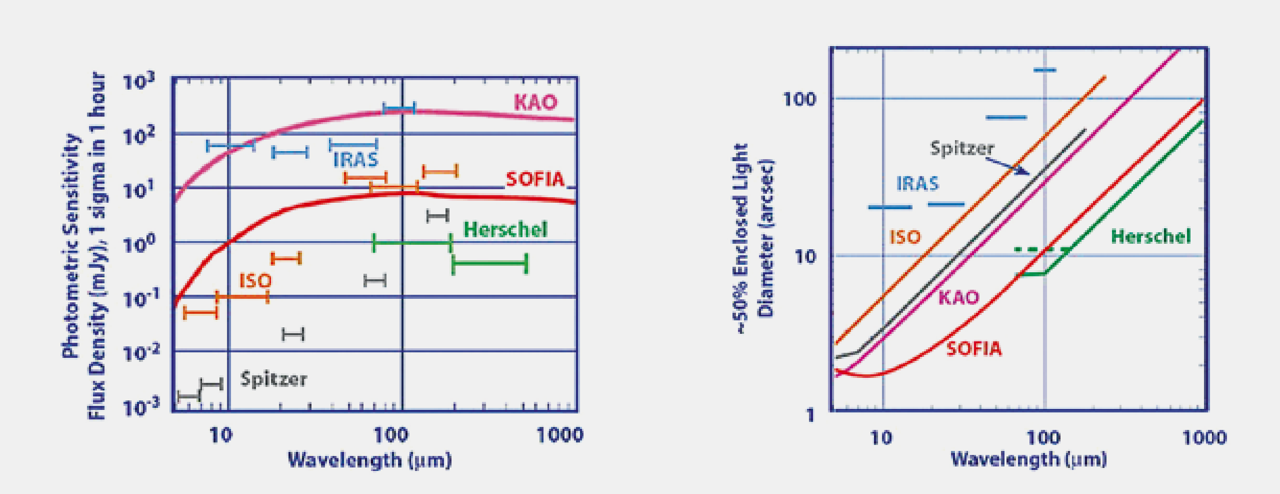


Figure 3: Photometric Sensitivity *(left)* and spatial resolution *(right)* of Herschel Space Telescope (green) in Comparison to other Missions [IRAS (blue), KAO (magenta), SOFIA (red), ISO (orange), Spitzer (grey)]. Credit: SOFIA Science Center (www.sofia.usra.edu).

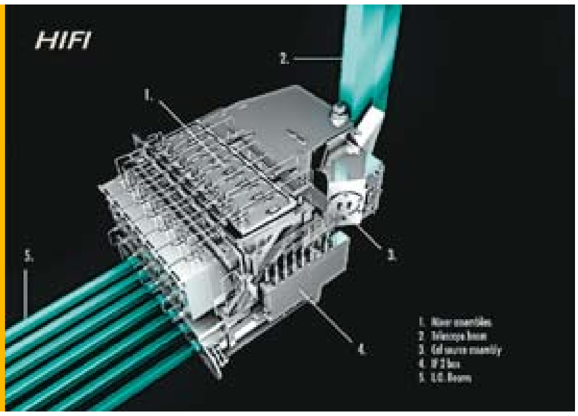
and evaluation of the physical processes taking place in astronomical sources, establishing the energy balance, temperature, abundances, density and velocity.

The far-infrared and submillimeter part of the spectrum is well suited to study the origin of galaxies, stars and planets, because gas and dust clouds emit the bulk of their radiation in this range. In particular, continuum observations readily probe the mass and the temperature of the clouds. Here, the advantage over mid-infrared or shorter-wavelength observations is that the radiation is mostly optically thin, so that it traces the entire volume of the clouds rather than just their surfaces. Furthermore, the large number of atomic fine structure and molecular rotational transitions spanning a wide range of excitation energies (from ~1 to ~1000 K) and radiative decay rates provides a powerful tool to measure the densities, temperatures and masses of interstellar clouds (Fig. 2). The goal of far-infrared and submillimeter astronomy is therefore a basic understanding of the physics and chemistry of interstellar clouds, star-forming regions, protoplanetary disks, the envelopes of evolved stars, planetary atmospheres, normal galaxies, active galactic nuclei, and starburst galaxies.

2. The telescope and the science payload

The Herschel spacecraft is approximately 7.5 metres high and 4×4 metres in overall cross section, with a launch mass of around 3.3 tonnes (Fig. 1). The spacecraft comprises a service module, which houses systems for power conditioning, attitude control, data handling and communications, together with the warm parts of the scientific instruments, and a payload module. The payload module consists of the telescope, the optical bench, with the parts of the instruments that need to be cooled, i.e. the sensitive detector units and cooling systems. The payload module is fitted with a sunshield, which protects the telescope and cryostat from solar visible and infrared radiation and also prevents Earth straylight from entering the telescope. The sunshield also carries solar cells for the electric power generation.

Figure 4: Artist's impression of the Heterodyne Instrument for the Far Infrared's (HIFI) focal plane unit. Credit: ESA.



The mission builds on earlier infrared space missions with cryogenic telescopes [IRAS (Neugebauer et al. 1984), ISO (Kessler et al. 1996), Spitzer Space Observatory (Werner et al. 2004), and AKARI (Murakami et al. 2007)] and is designed to offer a larger telescope and to extend the spectral coverage further into the far-infrared and submillimetre providing the highest, to date, sensitivity and resolving power capabilities (see Fig. 3).

Herschel's operational orbit is located 1.5 million kilometres away from the Earth in a direction diametrically opposite to the Sun, at the second Lagrange point of the Sun-Earth system (L2). By orbiting at L2, Herschel avoids problems caused by infrared radiation from the Earth interfering with observations. The L2 orbit also prevents the occurrence of temperature changes due to the spacecraft moving in and out of eclipse in an Earth orbit, which are a particular problem for infrared instruments requiring extreme thermal stability.

In order to fully exploit the favorable conditions offered by being in space Herschel is equipped with three scientific instruments (HIFI, PACS, and SPIRE) designed to perform imaging and spectroscopic observations in the wavelength range from 60 to 670 μm.

2.1 The Heterodyne Instrument for the Far Infrared (HIFI)

HIFI is a high-resolution heterodyne spectrometer (Fig. 4). The heterodyne detection principle involves translating the frequency range of the signal observed by the telescope to a lower frequency where it is easier to perform the required measurements. This is done by mixing the incoming signal with a very stable monochromatic signal, generated by a local oscillator, and extracting the difference frequency for further processing. HIFI observes in seven bands covering 480 to 1910 GHz. It was developed by a consortium led by the SRON Netherlands Institute for Space Science.

2.2 The Photoconductor Array Camera and Spectrometer (PACS)

The Photoconductor Array Camera and Spectrometer (PACS) contains a camera and a low to medium resolution spectrometer (Fig. 5). It operates at wavelengths between 55 and 210 μm. PACS contains four detector arrays, two bolometer arrays and two Germanium:Gallium photoconductor arrays. The bolometer arrays are dedicated for wideband photometry, while the photoconductor arrays are to be employed exclusively for medium-resolution spectroscopy. PACS can be operated either as an imaging photometer, or as an integral field line spectrometer. It was developed by a consortium led by the Max-Planck-Institut für extraterrestrische Physik, Germany.

2.3 The Spectral and Photometric Imaging REceiver (SPIRE)

The Spectral and Photometric Imaging Receiver (SPIRE) comprises a three-band imaging photometer and an imaging Fourier Transform Spectrometer (FTS, Fig. 6). The three-band imaging photometer is centred at 250, 350 and 500 μm, and the imaging FTS covers the range 200-670 μm. The detectors are arrays of feedhorn-coupled NTD spider-web bolometers cooled to 0.3 K. SPIRE was developed by a consortium led by Cardiff University (UK).

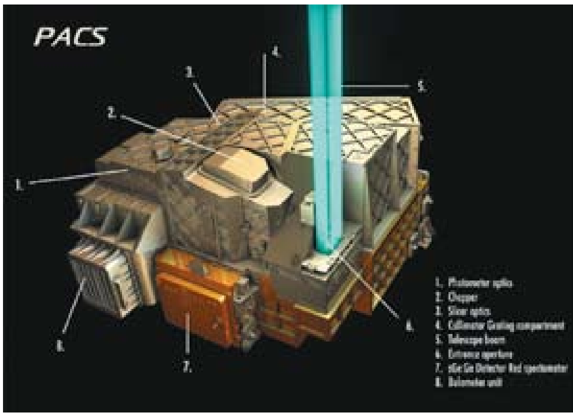


Figure 5: Artist's impression of the Array Camera and Spectrometer (PACS) focal plane unit. Credit: ESA.

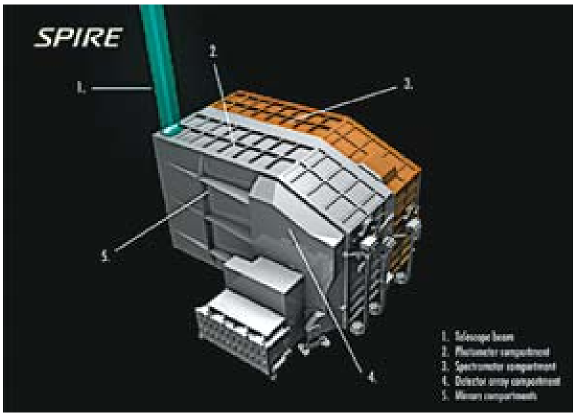


Figure 6: Artist's impression of the Spectral and Photometric Imaging Receiver (SPIRE) focal plane unit. Credit: ESA.

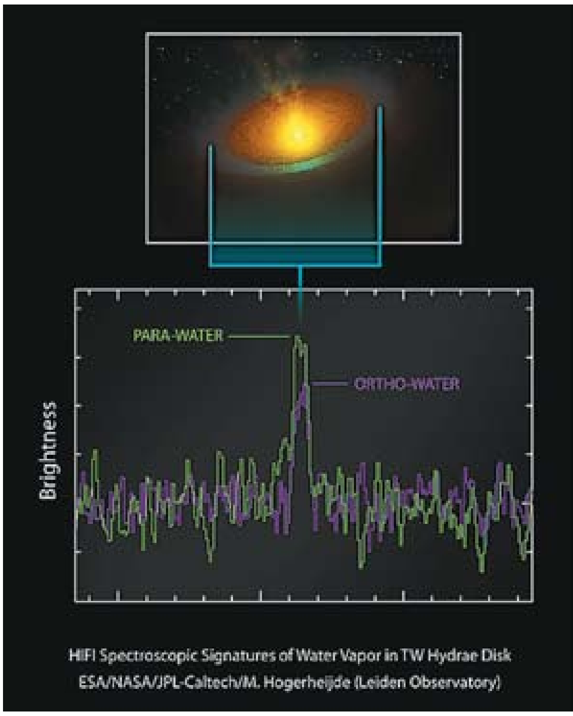


Figure 7: An artist's impression of the icy protoplanetary disc around the young star TW Hydrae *(upper panel)* and the spectrum of the disc as obtained using the HIFI spectrometer on ESA's Herschel Space Observatory *(lower panel)*. Credits: ESA/NASA/JPL-Caltech/M. Hogerheijde (Leiden Observatory).

3. Science Highlights

The prime science objectives of Herschel are intimately connected to the physics of and processes in the interstellar medium (ISM) in the widest sense: near and far in both space and time, stretching from Solar System objects and the relics of the formation of the Sun and our Solar System, through star formation and the feedback by evolved stars to the ISM, to the star formation history of the Universe, galaxy evolution, and cosmology. Observations from Herschel have already shown its strong impact on research in these fields, as exemplified by the major following observational results.

3.1 Detection of the water reservoir in a forming planetary system

Icy bodies may have delivered the oceans to the early Earth, yet little is known about water in the ice-dominated regions of extra-solar planet-forming disks. The HIFI spectrometer has detected emission lines from both spin isomers of cold water vapor from the disk around the young star TW Hydrae (Fig. 7; Hogerheijde et al., 2011). The vapor arises when highly energetic UV radiation from the central star interacts with icy grains in the disc. The detected water vapor, resulting from photodesorption, implies an ice reservoir in the giant planet formation zone and beyond. Simulations of water chemistry and line formation indicate that the 7.3×10^{21} g of detected water vapor (equivalent to 0.005 times the mass of Earth's oceans) originate from a total ice reservoir of 9×10^{27} g (or several thousands of Earth's oceans) throughout the disk. The ratio of ortho-to-para water observed in TW Hydrae's protoplanetary disc (see Fig. 7) falls well below that of solar system comets, suggesting that comets contain heterogeneous ice mixtures collected across the entire solar nebula during the early stages of planetary birth.

3.2 The origin of H_2O on the early Earth

A key result of HIFI concerns the D/H ratio of cometary water. The origin of water on Earth is a long-standing question because the early Earth was too warm to retain such volatile species. Delivery by comets during the Great Bombardment is an attractive solution, except that the isotopic composition, in particular the D/H ratio, of water in well-known comets such as Halley, Hale-Bopp and Hyakutake is at least twice the value of 1.56×10^{-4} for the Earth's oceans (Fig. 8). Therefore, the "Nice" model for the evolution of the Solar system has most of the volatiles, including H_2O, coming from asteroids (Morbidelli, 2010). However, the measured comets all stem from the Oort cloud, where they were expelled by gravitational interaction with the giant planets. The D/H ratios of such long-period comets thus may not reflect pristine conditions but be affected by processing in the inner Solar system. With HIFI, the first measurement has been obtained of the D/H ratio of water in a short-period comet from the Kuiper belt, which should reflect pristine conditions in the outer Solar system. The measured ratio of $(1.61 \pm 0.24) \times 10^{-4}$ (Hartogh et al., 2011) is consistent with the value for terrestrial ocean water (Fig. 8), implying that comets may have delivered at least some of the water to the early Earth.

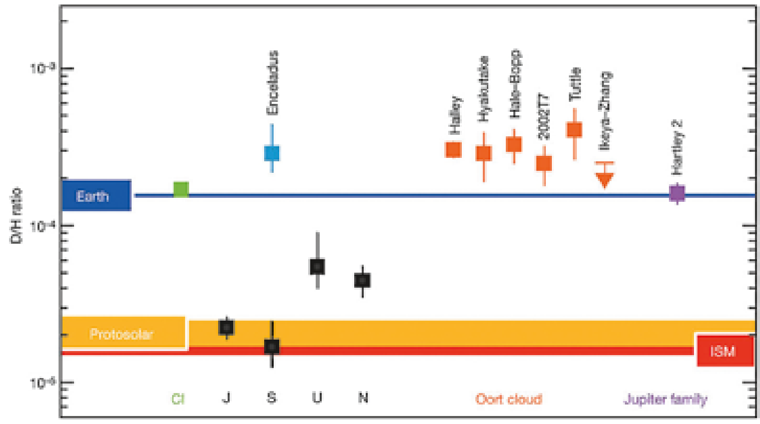


Figure 8: D/H ratios in the Solar System. Orange squares, values measured for water in the Oort-cloud comets 1P/Halley, C/1996 B2 (Hyakutake), C/1995 O1 (Hale-Bopp), C/2002 T7 (LINEAR) and 8P/Tuttle. Arrow (for 153P/Ikeya-Zhang), upper limit. Purple square, present measurement in the water of 103P/Hartley 2. Black symbols, D/H ratio in H_2 in the atmosphere of the giant planets—Jupiter (J), Saturn (S), Uranus (U) and Neptune (N). Light blue and green symbols, D/H values for water in the plume of Saturn's moon Enceladus and in CI carbonaceous chondrites, respectively. Error bars, 1σ. The D/H determinations in comets originating from the Oort cloud are twice the value for the Earth's ocean (blue line) and about a factor of ten larger than the protosolar value in H_2 (broad yellow line), the latter being comparable to the value in atomic hydrogen found in the local interstellar medium (ISM, red horizontal line). The D/H ratio in the Jupiter-family comet 103P/Hartley 2 is the same as the Earth's ocean value and the chondritic CI value. Uranus and Neptune have been enriched in deuterium by the mixing of their atmospheres with D-rich protoplanetary ices (Hartogh et al., 2011).

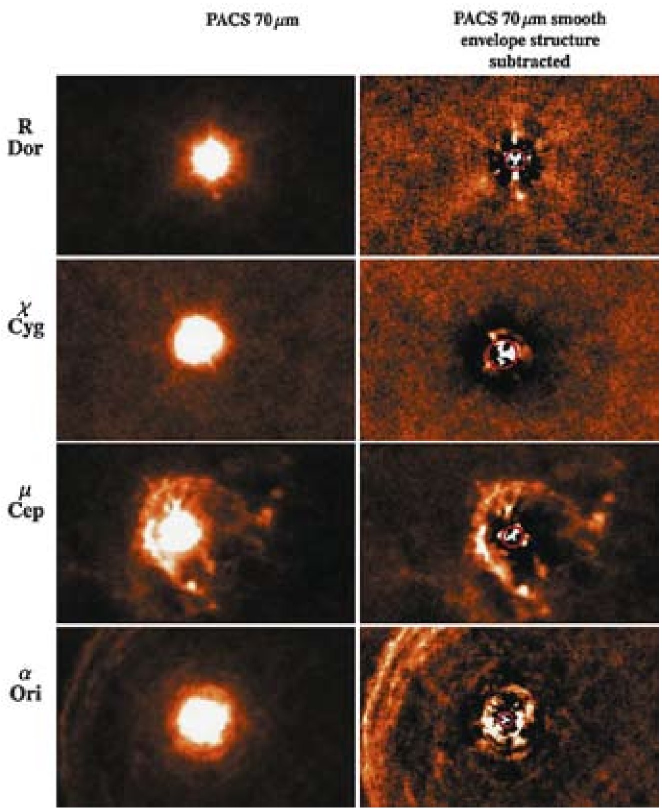


Figure 9: PACS images of four evolved stars before *(left)* and after *(right)* subtraction of the smooth halo of the circumstellar envelope. North is to the top, east is to the left. The six radial spikes (visible in the image of R Dor) are due to the support spider structure of the secondary mirror. The red circle with a radius of 15" marks the region where some PSF artifacts are still visible. These data were obtained in the framework of the *Herschel* MESS Guaranteed Time Key Programme (Groenewegen et al., 2011).

3.3 Inner envelope structure of AGB stars

The PACS image capabilities for nearby evolved stars are tremendous. Thanks to their high spatial resolution (of ~1"), one is able to map the structure of the inner envelope surrounding these evolved stars in quite some detail. To emphasize the shell morphology in the inner envelope, one can remove the extended envelope halo by subtracting a smooth, azimuthally averaged profile represented by a power law *r–a* (see Fig. 2 of Decin et al., 2011). An illustration for a point-like source is shown in the upper panels of Fig. 9: for the oxygen-rich semi-regular pulsating AGB star R Dor, experiencing a low mass-loss rate of ~1.2×10^{-7} $M_\odot$/yr (Schöier et al., 2004) no indications can be found for deviations from a smooth spherically symmetric envelope at scales >15". *χ Cyg* is the prototype of a S-type (C/O ratio slightly lower than 1) Mira variable with a period of 408 days at a distance of ~150 pc and a mass-loss rate of ~5×10^{-7} $M_\odot$/yr (Schöier et al., 2011). The PACS image shows some clear intensity enhancements in the north-western and south-eastern direction. *μ Cep* is an oxygen-rich supergiant at a distance of 390 pc (Cox et al., 2012). The PACS 70 μm image is dominated by the bow shock structure situated at ~50". Some asymmetries at ~20" away in the envelope are seen in the PACS image, although it is not clear if this is related to a turbulent mass-loss history or due to the large instabilities in the bow shock. *α Ori* is also an oxygen-rich supergiant at a distance of 197 pc (Harper et al., 2008). The *Herschel* images show the first evidence for a high degree of clumpiness of the material lost by the star beyond 15", which even persists until the material collides with the ISM. Very pronounced asymmetries are visible within 110" from the central star, although some weaker flux enhancements are visible until ~300" away. The typical angular extent ranges from ~10° to 90°. Indeed, four examples of evolved AGB and supergiant stars, and four different mass-loss histories. There is one common denominator: the emission we see is (almost completely) caused by dust – there might be some minor contribution from some atomic or molecular lines in the photometer bands as [O I] at 63 μm. This means that we are the direct witnesses of the role of dust in creating the envelope structure around these evolved stars.

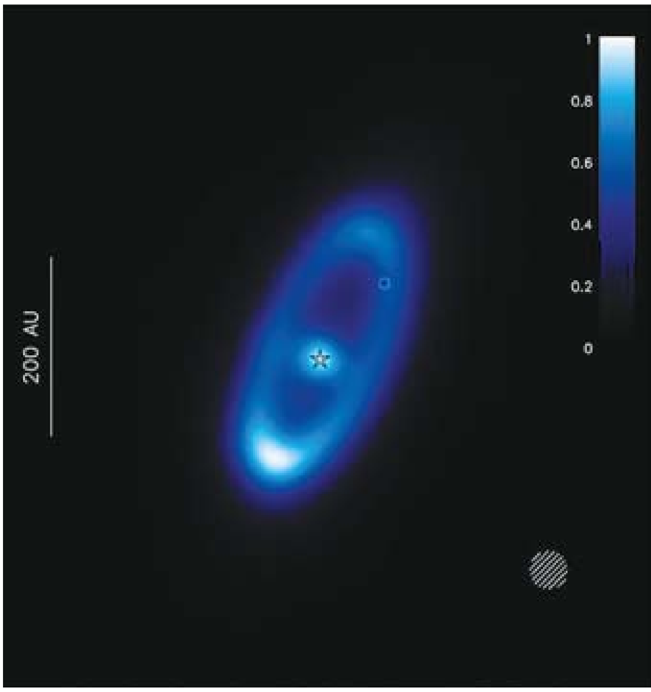


Figure 10: Herschel PACS 70 μm image of Fomalhaut (Acke et al. 2012). The positions of the star and of the planet candidate Fomalhaut b are indicated. The hatched circle indicates the spatial resolution (5.7"). The black-blue-white color scale is linear. North is up, east to the left.

3.4 Herschel images of Fomalhaut

Fomalhaut is a young ($2\pm1\times10^8$ years), nearby (7.7 pc), 2 $M_\odot$ star that is suspected to harbor an infant planetary system, interspersed with one or more belts of dusty debris. Herschel images show the main debris belt in great detail (Fig. 10). Even at high spatial resolution, the belt appears smooth. The region in between the belt and the central star is not devoid of material; thermal emission is observed here as well. Also at the location of the star, excess emission is detected. The appearance of the belt points toward a remarkably active system in which dust grains are produced at a very high rate by a collisional cascade in a narrow region filled with dynamically excited planetesimals. Dust particles with sizes below the blow-out size are abundantly present. The equivalent of 2000 one-km-sized comets are destroyed every day, out of a cometary reservoir amounting to 110 Earth masses. From comparison of their scattering and thermal properties, we find evidence that the dust grains are fluffy aggregates, which indicates a cometary origin. The excess emission at the location of the star may be produced by hot dust with a range of temperatures, but may also be due to gaseous free-free emission from a stellar wind.

3.5 Markarian 231 as seen by Herschel: black hole accretion or star formation?

Herschel SPIRE/FTS observations of the nearby ultraluminous infrared galaxy Mrk 231 reveal a total of 25 lines, including CO J=5–4 through J=13–12, 7 rotational lines of H_2O, 3 of OH^+ and one line each of H_2O^+, CH^+, and HF (van der Werf et al., 2010, 518, 42; see Fig. 11). The excitation of the CO rotational levels up to J=8 can be accounted for by UV radiation from star formation. However, the approximately flat luminosity distribution of the CO lines over the rotational ladder above J=8 requires the presence of a separate source of excitation for the highest CO lines. Through X-ray and Photon Dominated Region (XDR/PDR) modeling the most favoured model consists of a star forming disk of radius 560 pc, containing clumps of dense gas exposed to strong UV radiation, dominating the emission of CO lines up to J=8. X-rays from the accreting supermassive black hole in Mrk 231 dominate the excitation and chemistry of the inner disk out to a radius of 160 pc, consistent with the X-ray power of the AGN in Mrk 231. The extraordinary luminosity of the OH^+ and H_2O^+ lines reveals the signature of X-ray driven excitation and chemistry in this region.

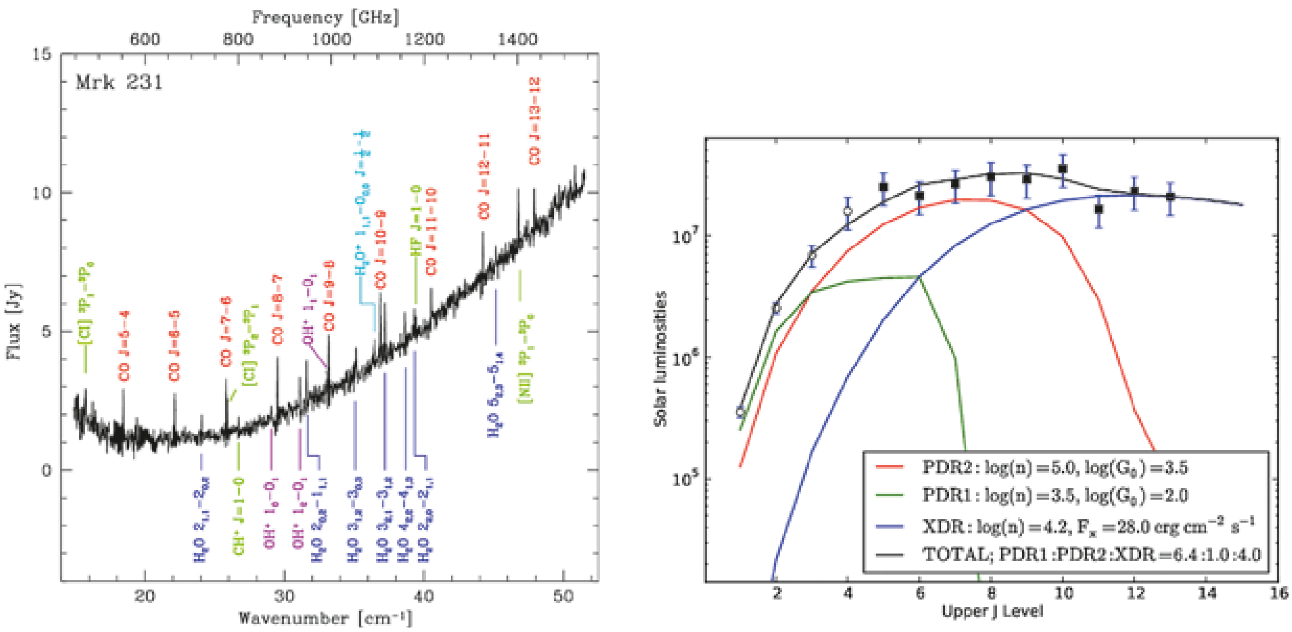


Figure 11: *Left:* D SPIRE FTS spectrum of Mrk 231. Line identifications are given in red for CO lines, in blue for H_2O, in magenta for OH^+, in cyan for H_2O^+, and in green for the remaining lines. Credits: ESA/Herschel/HerCULES consortium/Paul van der Werf. *Right:* Luminosities of CO lines from Mrk 231. Filled symbols represent measurements from the SPIRE FTS spectrum, while ground-based measurements are denoted with open symbols. Coloured lines indicate two model PDR components (red and green lines) and an XDR component (blue line). The sum of these three components is indicated by the black line and fits the CO measurements. In the legend, n denotes the number density of hydrogen nuclei ($n=nH+2nH_2$) in cm^{-3}, G0 denotes the incident UV flux in units of 1.6×10^{-3} erg s^{-1} cm^{-2} for the PDRs, and Fx the incident X-ray flux for the XDR. The legend also indicates the relative emitting areas of the three components.

3.6 Nearby galaxies as seen by Herschel

The Herschel Space Observatory (Pilbratt et al. 2010) provides an unprecedented view of the far-infrared and submillimetre emission from nearby galaxies. This waveband, however, is vital for astronomical studies as this is where dust in the interstellar medium (ISM) radiates. This is important for studies of galaxy evolution as star formation regions tend to be dusty, and therefore the use of UV and optical measurements to trace the star formation rate (SFR) can lead to it being underestimated (see Kennicutt 1998; Blain et al. 1999; Calzetti 2001; Papovich & Bell 2002; Calzetti et al. 2010). At wavelengths of 70-160 μm, the PACS instrument (Poglitsch et al. 2010) can produce images with resolutions of 6"-12" that are superior to what can be achieved with the Spitzer Space Telescope. At 250-500 μm, the SPIRE instrument (Griffin et al. 2010) produces images with unprecedented sensitivities to diffuse and point-like submillimetre emission. These data can be used to construct spectral energy distributions (SEDs) that sample the peak and Rayleigh-Jeans side of thermal dust emission, thus allowing to probe the coldest dust components

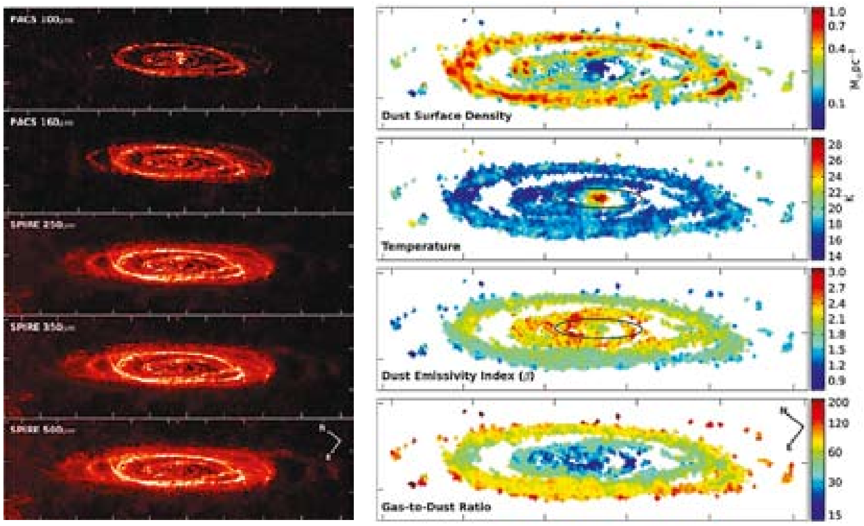


Figure 12: *Left:* Herschel images of M31 at 100, 160, 250, 350, and 500 μm (top to bottom). The images have dimensions of approximately 4.5×1.3 degrees, with a tick spacing of 30' and centered on 10h43m02s, +41°17'42". These images are all at their original resolution (Smith et al. 2012). *Right:* Distribution of dust surface density, temperature, the dust-emissivity index (β), and the distribution of the gas-to-dust ratio obtained by modeling the Spectral Energy Distribution (SED) of the galaxy. The temperature and β images include a black ellipse showing a radius of 3.1 kpc. The ticks are plotted at 30' intervals.

in nearby galaxies and place superior constraints on dust temperatures and masses. The unique resolution and sensitivity capabilities of Herschel are nicely demonstrated by studying the PACS and SPIRE maps of Andromeda galaxy (M31; Fig. 12). By fitting a modified-blackbody model to the observations the variation of temperature, dust mass, dust-emissivity index (β) and gas-to-dust ratio can be mapped across the galaxy with a spatial resolution of ~140 pc (see Fig. 12).

3.7 Massive Black Holes halt star birth in distant galaxies

Measuring star formation in galaxies containing powerful AGNs has long been a problem, because the radiation from the AGN outshines that from star formation in almost all wavebands. The combination of deep X-ray and submillimetre observations therefore offers the best prospects for studying the association of star formation and accretion during the 1<z<3 epoch (2-6 billion years after the Big Bang) when star formation and black hole growth in massive galaxies were at their most vigorous. Submillimetre observations (by the SPIRE instrument on the Herschel Space Observatory) of the Chandra Deep Field North (CDF-N) as part of the Herschel Multi-tiered Extragalactic Survey (HerMES) programme imply that the most prodigious episodes of star formation are common in the host galaxies of 1<z<3 AGN, but avoid powerful AGN in which accretion is at its peak (see Fig 13). The most likely explanation is that the incredibly strong winds from around these very powerful black holes are preventing the gas and dust in the rest of the galaxy from forming stars (Page et al. 2012).

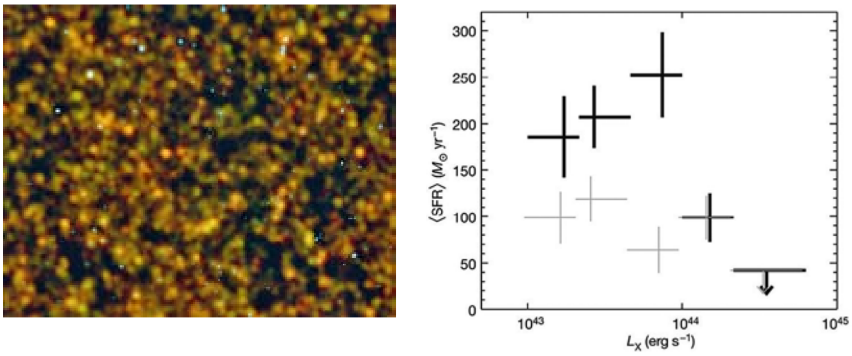


Figure 13: *Left:* Composite X-ray/submillimetre image of the Chandra Deep Field North (credit: ESA/Herschel/HerMES; NASA/CSX). The Chandra Deep Field North lies in the constellation of Ursa Major, Green and red correspond to the Herschel SPIRE 250 and 350 μm images showing the sky crowded with submillimetre-bright, dusty galaxies. Blue shows the X-rays recorded by Chandra, most of which come from active galactic nuclei. *Right:* Average star formation rates, <SFR>, derived from averaged far-infrared luminosities of 1<z<3 AGN, as a function of L_X. Through stacking analysis for the 1<z<3 AGN the average star formation rates were calculated for five bins of L_X from 1043 to 1045 erg s^{-1}. The mean star formation rate in AGN with L_X of 10^{43}–10^{44} erg s^{-1} is 214±25 M⊙/yr, compared to a mean star formation rate for AGN with L_X>10^{44} erg s^{-1} of 65±18 M⊙/yr.

3.8 The Cosmic Infrared Background

The Cosmic Infrared Background (CIB, Puget et al. 1996) accounts for roughly half of the total Extragalactic Background Light (EBL, Hauser & Dwek 2001), i.e., half of the energy radiated by all galaxies, at all cosmic epochs, at any wavelength (Dole et al. 2006). It is therefore a crucial constraint on modes and times of galaxy formation. At CIB peak wavelengths (100-200 μm), the nature of individual galaxies building up the EBL is poorly known. Past surveys produced limited samples of distant far-IR objects (e.g. Frayer et al. 2009), mainly due to the small apertures of the available instruments and the low sensitivity in the farinfrared. With the favorable diffraction limit of the large Herschel 3.5 m mirror (Pilbratt et al. 2010), and the high sensitivity of its Photodetector Array Camera and Spectrometer (PACS, 70, 100, 160 μm; Poglitsch et al. 2010), confusion and blending of sources are much less of a limitation. Herschel is now able to resolve a large fraction of the CIB at its peak into individual galaxies (Fig. 14). Exploitation of the Herschel/PACS observations of the GOODS-N, Lockman Hole, and COSMOS fields in the PACS Evolutionary Probe (PEP) guaranteed-time survey revealed that the total CIB surface brightness emitted above PEP 3σ flux limits corresponds to 58±7% and 74±5% of the COBE/DIRBE CIB direct measurements at 100 and 160 μm. Employing the "probability of deflection" statistics [P(D) analysis], these fractions increase to ~65% and ~89% (Berta et al. 2010; 2011). More than half of the resolved CIB was emitted at redshift z≤1. The 50%-light redshifts lie at z = 0.58, 0.67 and 0.73 at the three PACS wavelengths. The distribution moves towards earlier epochs at longer wavelengths: while the 70 μm CIB is mainly produced by z≤1.0 objects, the contribution of z>1.0 sources reaches 50% at 160 μm.

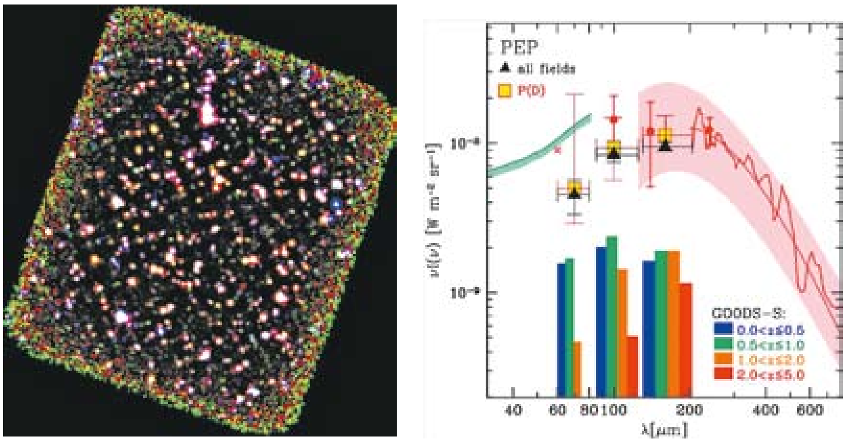


Figure 14: *Left:* A composite, three-colour image of the GOODS-South field, observed with Spitzer/MIPS at 24 micron (blue) and with Herschel/PACS at 100 micron (green) and 160 micron (red). The field size is 10'×10'; North is up and East to the left. Copyright: ESA/NASA/JPL-Caltech/GOODS-Herschel consortium/David Elbaz. *Right:* The Cosmic Infrared Background (CIB). Black filled triangles represent the total CIB emitted above the PACS Evolutionary Probe (PEP) flux limits, based on resolved number counts in GOODS-S, GOODS-N, Lockman Hole and COSMOS. Yellow squares belong to the P(D) analysis in GOODS-S. Histograms denote the contribution of different redshift bins to the CIB, over the flux range covered by GOODS-S. Literature data include: DIRBE measurements (filled circles, 1σ errors, Dole et al. 2006), FIRAS spectrum (solid lines above 200 μm, Lagache et al. 1999, 2000), Fixsen et al. (1998) modified Black Body (shaded area), 60 μm IRAS fluctuation analysis (cross, Miville-Deschênes et al. 2002), and γ-ray upper limits (green hatched line below 80 μm Mazin & Raue 2007).

References

Acke, B., Min, M., Dominik, C., et al. 2012, A&A, 540, 125

Berta, S., Magnelli, B., Lutz, D., et al. 2010, A&A, 518, L30

Berta, S., Magnelli, B., Nordon, R., et al. 2011, A&A, 532, 49

Blain, A. W., Smail, I., Ivison, R. J., Kneib, J.-P. 1999, MNRAS, 302, 632

Calzetti, D. 2001, PASP, 113, 1449

Cox, N.L.J., Kerschbaum, F., van Marle, A.-J., 2012, A&A, 537, 35

Decin, L., Royer, P., Cox, N.L.J., et al. 2011, A&A, 534, 1

De Graauw, T., Helmich, F. P., Phillips, T. G., et al. 2010, A&A, 518, L6

Dole, H., Lagache, G., Puget, J., et al. 2006, A&A, 451, 417

Fixsen, D., Dwek, E., Mather, J., Bennett, C., & Shafer, R. 1998, ApJ, 508, 123

Frayer, D.T., Sanders, D. B., Surace, J.A., et al. 2009, AJ, 138, 1261

Griffin, M., Abergel, A., Abreu, A., et al. 2010, A&A, 518, 3

Groenewegen, M.A.T., Waelkens, C., Barlow, M.J., et al. 2011, A&A, 526, 162

Harper, G.M., Brown, A., Guinan, E.F. 2008, AJ, 135, 1430

Hartogh, P, Lis, D.C., Bockelée-Morvan, D., et al. 2011, Nat, 478, 218

Hauser, M. G. & Dwek, E. 2001, ARA&A, 39, 249

Hogerheijde, M. R., Bergin E. A., Brinch C., 2011, Sci, 334, 3

Kennicutt, Jr., R. C. 1998, ARA&A, 36, 189

Kessler M. F., Steinz, J.A., Anderegg, M.E., et al. 1996, A&A, 315, L27

Lagache, G., Abergel, A., Boulanger, F., Désert, & Puget. 1999, A&A, 344, 322

Lagache, G., Haffner, L., Reynolds, R., & Tufte, S. 2000, A&A, 354, 247

Mazin, D. & Raue, M. 2007, A&A, 471, 439

Miville-Deschênes, M., Lagache, G., & Puget, J. 2002, A&A, 393, 749

Morbidelli, A. et al. 2000, Meteorit. Planet. Sci. 35, 1309

Murakami, H., Baba, H., Barthel, P., et al., 2007, PASJ, 59, 369

Neugebauer, G., Habing, H. J., van Duinen, R., et al. 1984, ApJ, 278, 1

Page, M.L., Symeonidis, M., Vieira, J.D., et al. 2012, Nat., 485, 213

Papovich, C., & Bell, E. F. 2002, ApJ, 579, L1

Pilbratt, G.L., Riedinger, J.R., Passvogel, T., et al. 2010, A&A, 518, L1

Poglitsch, A., Waelkens, C., Geis, N., et al. 2010, A&A, 518, 2

Puget, J., Abergel, A., Bernard, J., et al. 1996, A&A, 308, L5

Schöier, F.L., Olofsson, H., Wong, T., et al. 2004, A&A, 422, 651

Schöier, F.L., Maercker, M., Justtanont, K., et al. 2011, 530, 83

Smith, M.W.L., Eales, S.A., Gomez, H.L., et al. 2012, ApJ, 756, 40

van der Werf P. P., Isaak K. G., Meijerink R., et al. 2010, A&A, 518, 42

Wang, S., Bergin, E.A., Crockett, N. R., et al. 2011, A&A, 527, A95

Werner, M.W., Roellig, T.L., Low, F.J., et al. 2004, ApJS, 154, 1

Visit our website

http://www.helas.gr

The above web server contains information, both in greek and english, about the Hellenic Astronomical Society (Hel.A.S.), the major organization of professional astronomers in Greece. The Society was established in 1993, it has more than 250 members, and it follows the usual structure of most modern scientific societies. The web pages provide information and pointers to astronomy related material which would be useful to both professional and amateur astronomer in Greece. It contains a directory of all members of the Society, as well as an archive of all material published by the Society such as the electronic newsletters, past issues of "Hipparchos", and proceedings of Conferences of Hel.A.S. The server is currently hosted by the University of Thessaloniki.

Massive Stars: From α to Ω

The 'Massive Stars' meetings have enjoyed more than 40 years of startling success since the first meeting in Argentina in 1971. Held every 4 to 5 years, these meetings aim to encapsulate the current state-of-the-art of our understanding of the physics of Massive Stars and their role in the Universe. For this 10th meeting in the Massive Stars series the Institute of Astronomy, Astrophysics, Space Applications and Remote Sensing of the National Observatory of Athens, invites you to the island of Rhodes, once home to one of the greatest astronomers of antiquity, Hipparchos, who is generally acknowledged as the founder of trigonometry, discoverer of precession and publisher of the first star catalog around 135 BC.

The conference will build on results from ongoing large-scale multi-wavelength surveys of massive stars which are being coupled with new theoretical advances dealing with stellar evolution and the processes which affect that evolution: mass-loss, rotation, convection, magnetic fields, multiplicity and environment. It will tackle important problems from birth, through main sequence evolution and until core collapse.

There will be a strong focus on relating the major theoretical uncertainties afflicting stellar evolution through these phases to the current observational picture. The impetus for this focus is derived from the realization that our understanding of massive star evolution is severely challenged by new observations powered largely by technological advances in telescopes and instrumentation. This has enabled new ways of looking at old long-standing problems enabling large-scale high-quality surveys of resolved stellar populations. As theoretical approaches try to keep pace with this increase in information the cracks in our assumptions concerning stellar evolution have become more apparent, even glaring. Whereas before it might have been possible to understand some of the stars some of the time it is now clear that understanding stellar populations is a considerable challenge and will require substantial efforts to resolve.

This is an exciting time as observations have revealed large gaps in understanding of the formation and evolution of massive stars. The huge impact that massive stars have on their immediate environment, parent galaxies, and through the Universe, demands better understanding of massive star evolution from alpha to Omega.

Looking forward to seeing you in Rhodes!
The Local and Science Organizing Committees

http://a2omega-conference.net

Back issues of Hipparchos

Hipparchos is the official newsletter of the Hellenic Astronomical Society. It is distributed by post to the members of the society.

You can download back issues from:

http://www.helas.gr/news.php