HIPPARCHOS

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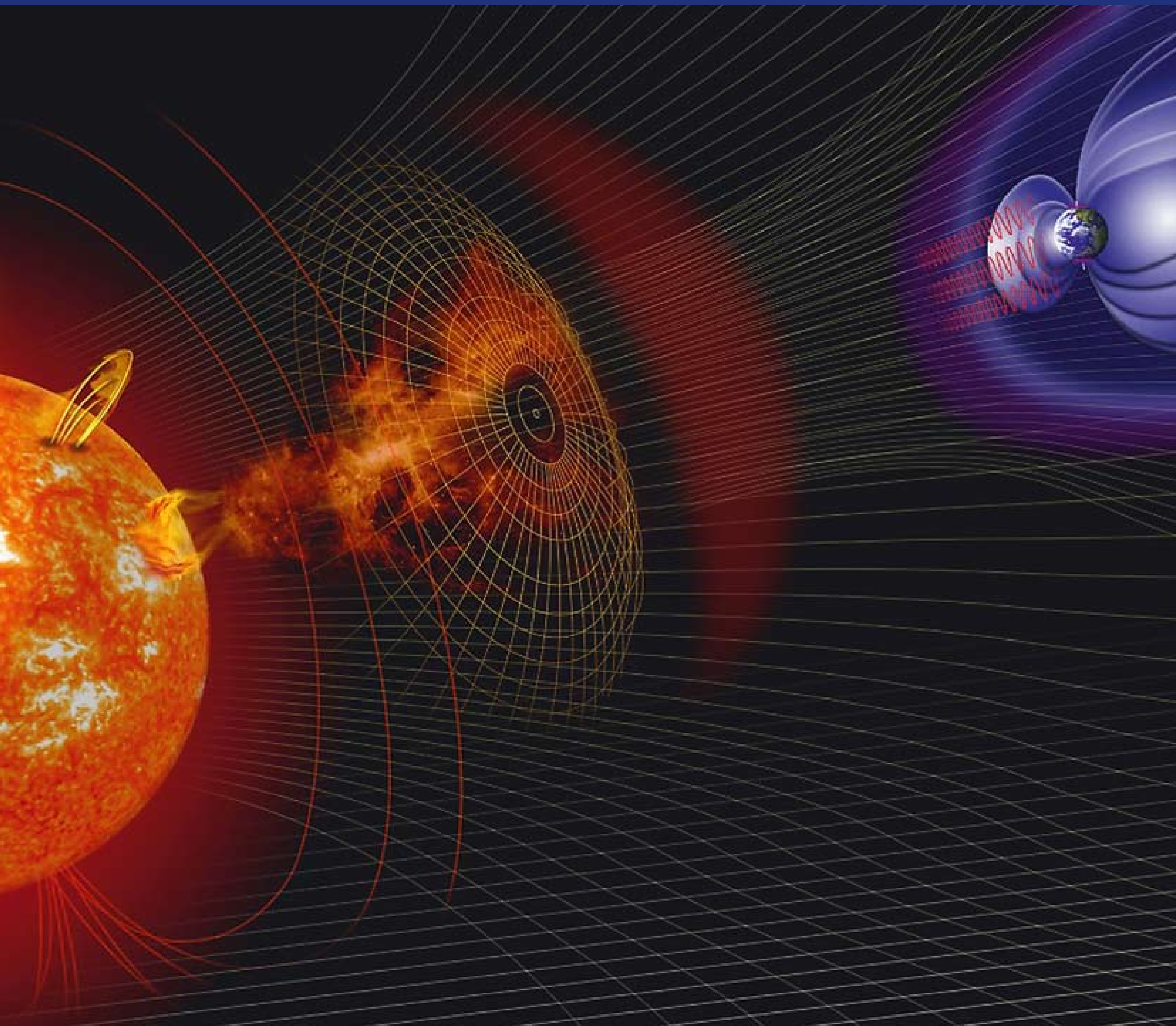

Contents

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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.

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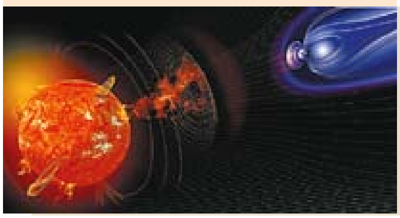


Cover Image:
Schematic representation of the effect of solar eruptions on the terrestrial magnetosphere and geospace

(Image courtesy: NASA). See page 6 for the First Hel.A.S. Summer School on "Physical Processes and Data Analysis in Heliophysics", to be held in Athens, September 1 to 5, 2014.

Message from the President

3 June 2014

Dear friends,

It is with pleasure that I am writing this message. My term as President of the Hellenic Astronomical Society comes to an end in ten days and I am leaving with very fond memories.

I believe that our Society is on a "curve of growth" and there is no sign that this will change in the future. Thanks mainly to our young colleagues, the quality and quantity of astronomical research in Greece is constantly improving. Our young members have had their fair share of the EXCELLENCE (ARISTEIA) grants of the General Secretariat for Research and Technology. Also, our members continue to be successful with international grants.

The economic crisis of the last four years has affected everyone, but our Society, again thanks to its members, has not done badly. A significant reserve has been established and the Society is able to guarantee to all Greek Astronomers free publication of their articles in Astronomy & Astrophysics, despite the change in the government's policy. Payment of page charges would be prohibitive to our members.

Last, but not least, I want to mention the establishment by our Society of a Summer School every even year. The first such School will take place this coming September and it will be on Physical Processes and Data Analysis in Heliophysics. I believe this is quite appropriate, since the study of Solar Physics is quite strong in Greece.

I would like to thank our members for entrusting me with the presidency of our Society in the past four years and I wish success to the new Council that will be elected on June 13. The departing Council is here to help in any way possible.

Nick Kylafis
President of Hel.A.S.

11th Hellenic Astronomical Conference

Under the Auspices of H.E. the President of the Hellenic Republic Dr. Karolos Papoulias

20 ΧΡΟΝΙΑ YEARS

ΕΛΑΣΕΤ ΕΛΛΗΝΙΚΗ ΑΣΤΡΟΝΟΜΙΚΗ ΕΤΑΙΡΕΙΑ HELAS HELLENIC ASTRONOMICAL SOCIETY

The Hellenic Astronomical Conference, organized by the Hellenic Astronomical Society (Hel.A.S.), is the major scientific event of the greek astronomical community. The Conference, which takes place every two years in a different part of Greece, brings together scientists with research interests in Astronomy, Astrophysics, and Space Physics.

The 11th Conference of Hel.A.S. was held in Athens, from 8 to 12 September 2013. The conference was co-organised by the Research Center for Astronomy and Applied Mathematics of the Academy of Athens. The conference took place at the main auditorium of the Biomedical Research Foundation of the Academy of Athens. The welcome reception was hosted in the historical central building of the Academy of Athens, while the official conference dinner was hosted in the gardens of the historical central building of the National Observatory of Athens, at the Nymphes hill (Lofos Nymfon), very close to the Acropolis.

Scientific Organizing Committee (SOC):
N. Kylafis (chair), A. Anastasiadis, A. Bonanos, C. Efthymiopoulos, I. Papadakis, K. Tsiganis and N. Vlahakis.

Local Organizing Committee (LOC):
C. Efthymiopoulos (Chair), C. Gontikakis, M. Harsoula, N. Delis, L. Tsigaridi, M. Katsanikas, G. Aggelopoulou and M. Zoulias.

We would like to gratefully acknowledge the support of the following **sponsors:** Academy of Athens, National Observatory of Athens, Biomedical Research Foundation of the Academy of Athens.

The official opening of the conference took place at the central building of the Academy of Athens. There was a **public outreach talk** (I. Contopoulos: *"Magnetic fields and Black Holes in the Universe"*). This was preceded by short addresses by all former presidents of Hel.A.S. (G. Contopoulos, J. Seiradakis, P. Laskarides, and K. Tsiganos), on the occasion of the **20th anniversary of Hel.A.S**.

The conference reached a record number of 178 registered participants. There were five **plenary talks**:

- A. Vourlidas: *Hurricane Season in the Inner Heliosphere: Observations of Coronal Mass Ejections during Solar Maximum*
- R-P. Kudritzki: *Supergiant Stars as Extragalactic Probes of Cosmic Abundances and Distances*
- T. Courvoisier: *Building up a European Astronomical Community*
- F. Combes: *Molecular gas in galaxies across the Hubble time*
- M. Plionis: *Recent developments in Cosmology*

The conference invited a **young astronomer** to give a *"Highlight Talk"*. This was delivered by A. Fragos: *The Origin of Black Hole Spin in Galactic Low-mass X-ray binaries*. Also, the Hel.A.S. continued the tradition of **"Best Ph.D Award"** Talk (E. Papastergis: *Statistical analysis of ALFALFA galaxies: insights in galaxy formation & near-field cosmology*).

Finally, there was a talk "in memory of John Hadjidemetriou" delivered by Hel.A.S. Honorary President G. Contopoulos.

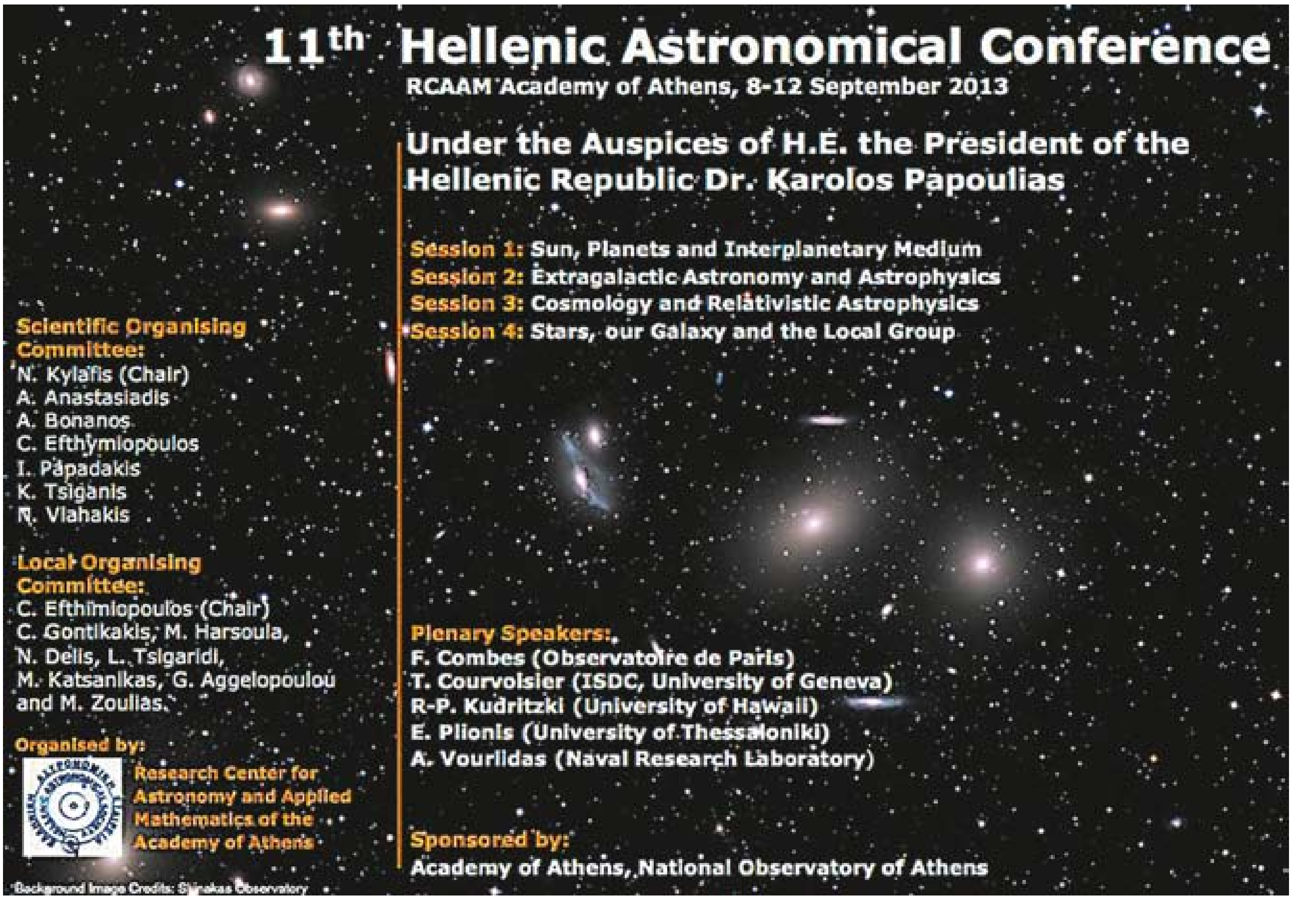
The conference hosted four scientific sessions, namely:

- **Session 1:** «Sun, Planets and Interplanetary Medium»
- **Session 2:** «Extragalactic Astronomy and Astrophysics»
- **Session 3:** «Cosmology and Relativistic Astrophysics»
- **Session 4:** «Stars, Our Galaxy and the Local Group»

There were in total 78 talks (23 in section 1, 29 in section 2, 14 in section 3, and 18 in section 4) and 68 posters (33 in section 1, 11 in section 2, 4 in section 3, and 20 in section 4) presented. The oral and poster presentations were made public (see http://www.helas.gr/conf/2013/presentations.php and http://www.helas.gr/conf/2013/posters_pres.php respectively). The abstracts of all presentations were linked to the ADS database.

We were very happy for the quality and high level of research results presented during the 11th astronomical conference. This only generates confidence and optimism for the future of Greek astronomy.

More details about the conference can be found at http://www.helas.gr/conf/2013/



Sponsored by: ACADEMY OF ATHENS BRFAA

11th Hellenic Astronomical Conference picture

The 1st Summer School of the Hellenic Astronomical Society

During the General Assembly of the Hel.A.S. in September 2013, the Hel.A.S. council proposed to organize a summer school on even years, when there are no Hel.A.S. Conferences. The purpose of the schools will be to offer training to the younger members of Hel.A.S., such as graduate students and young postdoctoral researchers, as well as the opportunity for them to meet and interact with more experienced researchers.

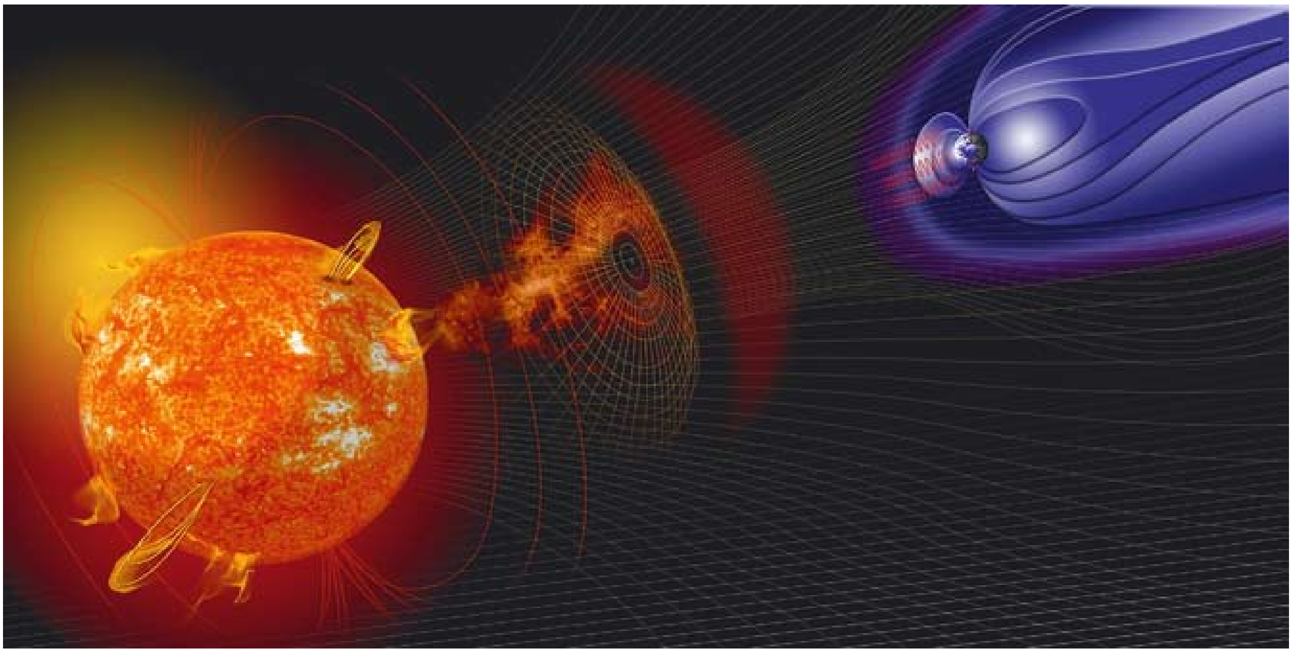
The 1st Hel.A.S. Summer School will take place in September 2014, in collaboration with the National Observatory of Athens (NOA) and the Research Center for Astronomy and Applied Mathematics (RCAAM) of the Academy of Athens. The central theme is:

"Physical Processes and Data Analysis in Heliophysics"

The School will be held in Athens, from the 1st until the 5th of September, 2014.

More information can be found at:

http://www.helas.gr/school/2014



Organizing Committees

Scientific Organizing Committee

Chair: A. Anastasiadis (NOA)

Members: I.A. Daglis (UoA), M. Georgoulis (RCAAM), S. Patsourakos (UoI), K. Tsinganos (NOA-UoA), G. Tsiropoula (NOA) and L. Vlahos (AUTH)

Local Organizing Committee

Chair: M. Georgoulis (RCAAM)

Members: C. Gontikakis (RCAAM) and G. Tsiropoula (NOA)

Registration

The School participation is limited to 30-35 persons. A registration fee of 60 € has been set to cover writing material and coffee break costs. The registration fee will be paid in cash upon arrival. Participants are encouraged to complete the Registration Form available from the School website (before July 15, 2014).

http://www.helas.gr/school/2014/register.php

Venue

The 1st Summer School of Hel.A.S. will take place at the "Kostis Palamas" Building of the University of Athens (Akadimias 48 & Sina Street, entrance from Akadimias).

Star Formation: a Persistent Mystery

by Konstantinos Tassis
Department of Physics, University of Crete

Abstract

Despite its central importance in developing a predictive theory of star formation, the initiation of star formation has been one of the most persistent problems in modern astrophysics. The main open questions revolve around the interpretation of the low efficiency of star formation: why are molecular clouds supported against gravity? and what drives small fragments of these clouds to form, lose their support, and collapse to form protostars? Here, the two main contestant theories (magnetic support and fragmentation, and turbulent support and fragmentation) are reviewed, together with promising observational tests that may help us distinguish between them.

Introduction

Stars have monopolized the interest of astronomers for centuries while more recently the focus has been shifted to galaxies as the fundamental unit making up the cosmic web. But at the foundation of modern astrophysics lies the process of the formation of stable, hydrogen-burning stars, the building blocks of galaxies, from rarified gas. Star formation is a complex physical process, which has operated over most of cosmic time and is not yet fully understood. While the study of star formation is a fundamental and exciting topic on its own, the development of a predictive theory of star formation is essential for many other fields, like galaxy formation and evolution and cosmology.

A successful theory of star formation should be able to provide, from first principles, the stellar initial mass function (what fraction of stars are born at each mass interval) and its dependence on local conditions, the efficiency of star formation in different environments (the rate at which stars form from a specific amount of gas) and the stellar multiplicity. All these quantities are critical inputs for simulations of both galaxy formation and evolution, as well as planetary formation – but, lacking a star formation theory, they are supplied by simplified empirical recipes. If we are therefore to be able to claim true understanding of how galaxies evolve in the cosmos, and of how planets, the hosts of life, are formed, we have to first understand how stars form.

The raw material out of which stars are formed exists in the space between stars, which is not empty. Rather, it consists of gas (mostly hydrogen, with about 25% by mass helium and traces of heavier elements), dust grains, cosmic rays, and it is permeated by magnetic fields and photons. These ingredients are collectively referred to as the *interstellar medium* (ISM). The ISM is not uniform: it exhibits a wide range of densities. ISM condensations are known as interstellar clouds. Newborn stars are observed in the densest, coldest of these clouds. In these stellar nurseries the bulk of hydrogen gas is in molecular form – hence the name *molecular clouds*.

Star formation is driven by the self-gravity of the gas and its interplay with other forces associated with thermal pressure, turbulence, and magnetic fields (since the molecular gas is weakly ionized by cosmic-ray interactions). In the interstellar medium, the energy density associated on average with turbulence, magnetic fields, thermal pressure, cosmic rays, and the interstellar photon field is in rough equipartition, around 1 eV per cc each (Draine 2011). In developing a theory of star formation, therefore, none of these ingredients can be ignored; instead, all have to be treated as potentially important players. This makes star formation an inherently complex and difficult to study process.

Under certain conditions, self-gravity overpowers all opposing agents. If this occurs, the formation of one or more stars is inevitable. In this review, we will focus on the initiation of star formation: the processes through which gravity manages to dominate and force the formation of a protostar. Although the open questions on what happens from that point on are enough to fill books rather than review articles, here we will only tackle the onset of star formation – partly for the sake of brevity, but also because these first stages provide the initial conditions for everything that follows.

In this review, we will first discuss the properties of molecular clouds as they are known to us by different types of observations, and we will then briefly review the main theoretical ideas on the onset of gravitational collapse in molecular clouds, emphasizing the still - open questions. Despite its central importance, the initiation of star formation has been one of the most persistent problems in modern astrophysics.

Observations of Molecular Clouds

I. Mass Distribution and Kinematics

Molecular clouds **consist** mostly of molecular hydrogen (H_2). However, H_2 in molecular clouds cannot be directly observed: the two nuclei in the H_2 molecule are identical, so the molecule does not have any permanent dipole moment nor any dipolar rotational transitions. Rather, the lowest energy transitions are purely quadrupole rotational ones, which are not excited in gas with temperature lower than about 100K – much higher than typical temperatures of molecular clouds (~10K). Thus, the bulk of the gas in molecular clouds does not emit radiation.

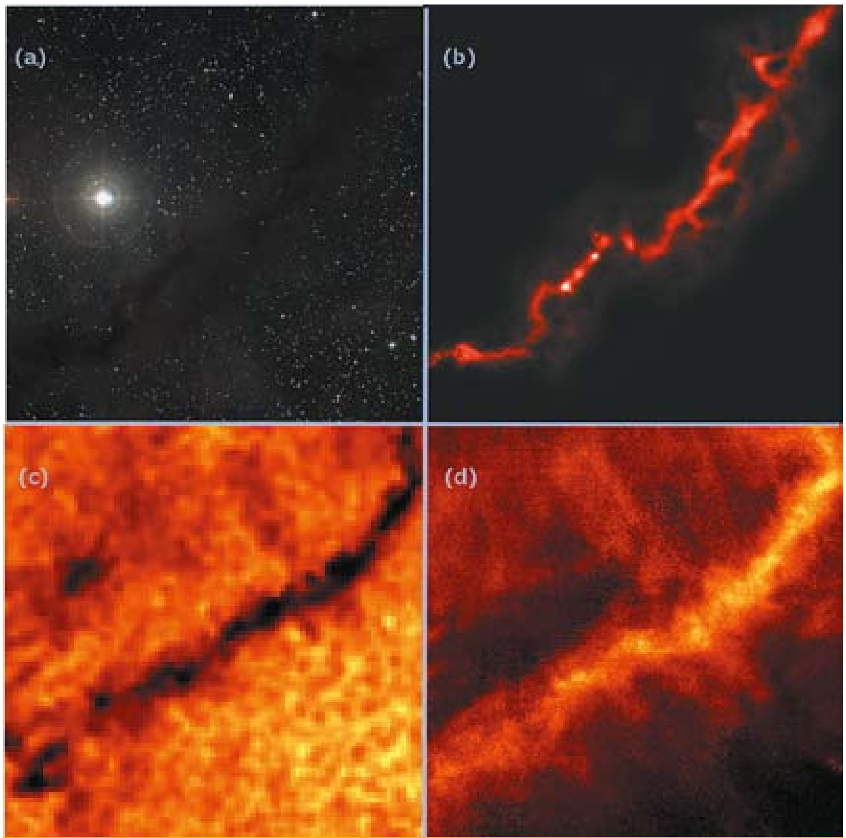


Figure 1: A region in the Taurus molecular cloud as seen in optical emission (a), far infrared (b), through an extinction map (c), and in CO emission (d).
Credit: (a),(b): ESO/APEX (MPIfR/ESO/OSO)/A. Hacar et al./Digitized Sky Survey 2. Acknowledgment: Davide De Martin. (c),(d): J. Pineda.

Then, how does one go about observing molecular clouds? By relying on constituents other than H_2: interstellar dust, and tracer molecules.

Interstellar dust comprises about 1% by mass of molecular clouds. It absorbs light of background stars, and as a result molecular clouds are seen in the optical as dark patches on the sky obscuring starlight (Figure 1a). The absorbed starlight heats the dust, and it is thus re-emitted in submillimeter wavelengths as thermal radiation (Figure 1b). The morphology traced by submillimeter emission, as expected, correlates very well with *extinction maps* that rely on measuring the amount of starlight absorption to quantify the amount of intervening dust (Figure 1c).

The morphology of molecular clouds revealed in this way is complex. The gas within a molecular cloud is distributed in a very non-uniform manner, with variations between low- and high-density regions. On large scales, the clouds appear filamentary. A good example is shown in Figure 2, which depicts a dust thermal emission map of the Polaris Flare cloud as revealed by ESAís Herschel Space Observatory. The spider-webólike structure is striking.

Protostars appear inside smaller-scale, more compact overdensities, known as *molecular cloud cores*. Cores frequently reside along filaments. The mass distribution of cores is similar in shape with the mass distribution (initial mass function) of stars (Könyves et al. 2010). Thus they are the fundamental unit of the star formation process, and understanding the way that cores are formed is central in understanding star formation.

H_2 is not the only molecule present in molecular clouds. Chemical processes in the interstellar medium combine hydrogen and higher mass atoms, including C, N, O, and heavier elements, into a variety of molecular species, including complex and organic compounds. A particularly abundant and commonly observed molecule that is very frequently used to trace molecular gas is CO (Figure 1d). In contrast to H_2, CO and other non-homonuclear tracer molecules used in molecular cloud observations have rotational transitions with low excitation temperatures and thus emit even at the low temperatures and densities characteristic of molecular clouds.

While dust extinction and continuum emission can only offer information about the mass and morphology of the gas traced by the dust, the presence of tracer molecules allows us to study line emission and thus open a window into molecular cloud kinematics and dynamics. This is achieved through the Doppler effect and the velocity information that we can extract from it. Such studies have revealed two crucial pieces of information regarding the initial stages of star formation.

First, molecular clouds are not collapsing *as a whole*. Star formation is a battle between gravity and the forces that oppose it, and, while gravity has to eventually win if we want a star to form, *this battle is not won at the molecular cloud scale*. Rather, most of the mass of a molecular cloud is supported against gravity, and the efficiency of the star formation process is low. Stars are only formed within molecular cloud cores, which represent a small fraction of the mass (a few percent) of the entire cloud (e.g., Johnston et al. 2004).

Second, molecular cloud linewidths are supersonic, and clouds on large scales exhibit random, turbulent motions. In contrast, molecular cloud cores appear detached from the parent cloudsís turbulent field (Goodman et al. 1998) and are observed to be collapsing. Even then, though, core lifetimes are observed to be longer than a free-fall time (Enoch et al. 2008, Evans et al. 2009): even when gravity has won and the formation of a protostar is on its way, the forces opposing it still play an important role in the process of star formation.

Molecular spectral lines are thus an invaluable source of information in molecular clouds. However, the interpretation of such observations is complicated by the fact that molecular tracer species are not a fair tracer of the H_2 distribution, because of the complex and nonlinear effect of interstellar chemistry. Molecular abundances are determined not only by the local gas density but also by the dynamical evolution of a particular molecular cloud region. As a result, all information that is obtained by molecular cloud observations is viewed through a "chemical lens", rendering the study of interstellar chemistry a critical ingredient in developing a theory of star formation. Figure 3 (from Bering & Tafalla 2007) shows a characteristic example of

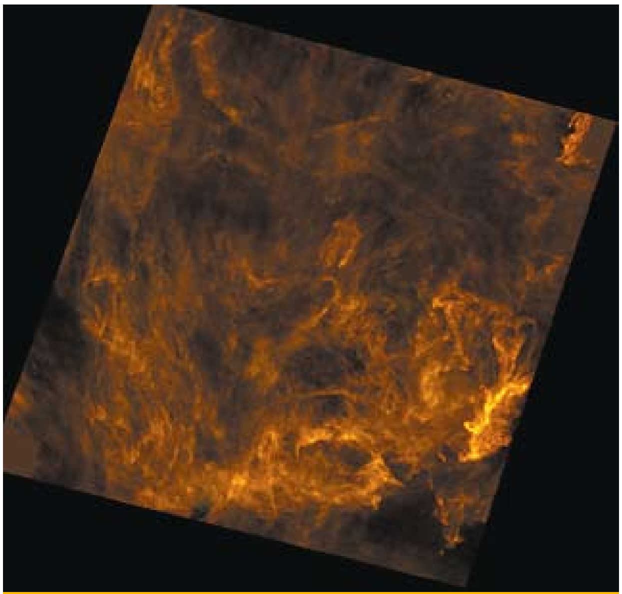


Figure 2: Filamentary structure in the Polaris Flare molecular cloud. Credit: ESA and the SPIRE & PACS consortia, Ph. André (CEA Saclay) for the "Gould's Belt survey" Key Programme Consortium.

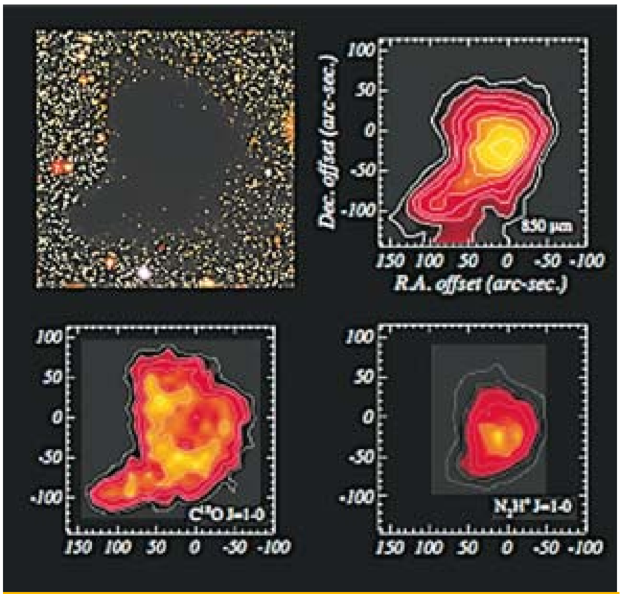


Figure 3: Core B68 in optical (upper left), dust continuum emission (upper right), and viewed through the chemical lens ($C^{18}O$ and N_2H^+ molecular transitions, lower left and right respectively).
Credit: Bergin & Tafalla 2007.

a core seen through the "chemical lens". In the lower two panels, core B68 (seen in the upper panels in the optical and dust continuum emission) is mapped through $C^{18}O$ and N_2H^+ molecular line emission. CO is anticorrelated with the dust continuum peak as it mainly traces the lower density parts of a core, while N_2H^+ is only excited at higher densities and traces the high-density parts.

2. Magnetic Fields

The presence of dust and molecules other than H_2 in molecular clouds enable us to also study the magnetic field in these structures.

Dust grains can reveal information about the magnetic field through the alignment of their angular momentum vector with magnetic field lines. Needle-like grains acquire angular momentum through thermal collisions or non-thermal processes (such as interaction with photons), in rough rotational energy equipartition along their principal axes. The angular momentum is then greatest in the direction of the shortest axis. The presence of the magnetic field subsequently leads to an alignment of the angular momentum (and thus, the shortest axis) along magnetic field lines (Figure 4). Grains in such a configuration act like a polaroid with respect to light passing through the cloud: they preferentially absorb the polarization component that has the E-vector parallel to their longest axis (perpendicular to the magnetic field). The transmitted light (optical) is thus partially polarized in the direction of the magnetic field. In emission (far infrared), on the other hand, grains act like tiny dipolar antennae, emitting light that is partially polarized in the direction of their longest axis (perpendicular to the magnetic field). Thus linear polarization studies of molecular clouds trace the plane-of-the-sky component of the magnetic field, both in emission and absorption, with the polarization direction of emitted and transmitted light being perpendicular to each other.

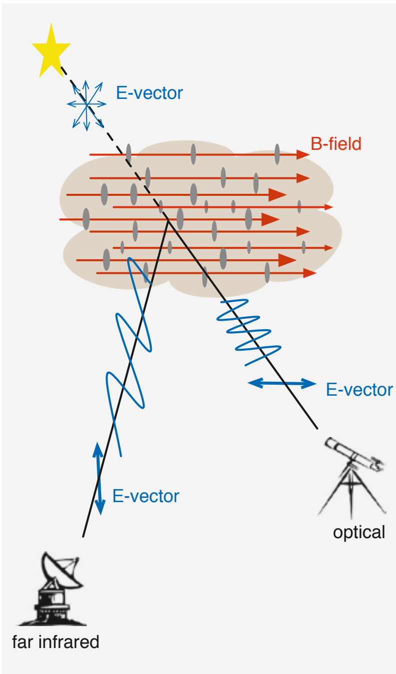


Figure 4: Linear polarization in molecular clouds. Emitted light is polarized along the longest axis of the dust grains (perpendicular to the magnetic field). Transmitted radiation from background stars is polarized perpendicular to the long axis of dust grains (parallel to the magnetic field).

Another way to study the plane-of-the-sky magnetic field relies on the study of polarization of molecular line emission (Goldreich-Kylafis effect, Goldreich & Kylafis 1981, 1982). The component of the magnetic field that lies along the line of sight can be studied through the Zeeman effect. In the latter case, it is the strength of the magnetic field along that specific direction that is measured.

Linear polarization maps have revealed that a large-scale ordered magnetic field component exists in molecular clouds, indicating that the turbulent flows are not sufficient to completely tangle up the field and eliminate all of its ordered structure. An example is shown in Figure 5, which depicts a linear polarization map of the transmitted light from background stars for the Pipe nebula (Alves et al. 2008).

Detailed maps of magnetic fields surrounding molecular cloud cores have revealed the so-called hourglass-shape morphology, caused when an ordered large-scale field is "pinched" toward the center by the dynamical contraction of a collapsing core (Figure 6, Girart et al. 2006).

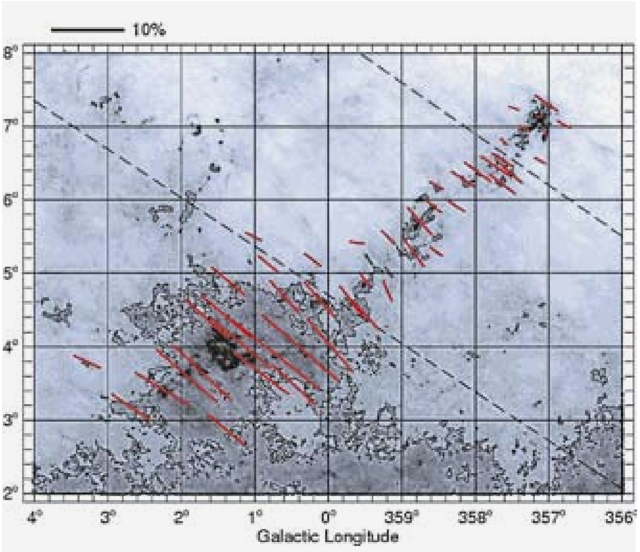


Figure 5: Magnetic field in the Pipe molecular cloud as traced by opto-polarimetry of background stars.
Credit: Alves et al. 2008.

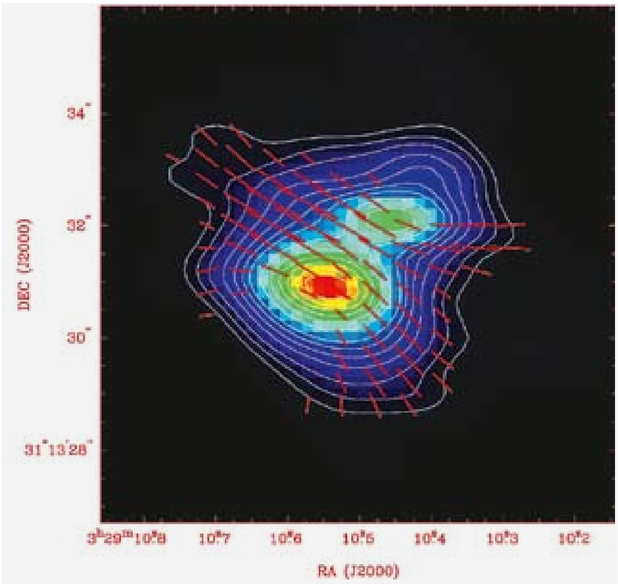


Figure 6: Hourglass morphology of the magnetic field in NGC1333, observed through studies of polarization of dust continuum emission.
Credit: Girart et al. 2006.

How do cores form? Theoretical ideas

In the previous section we reviewed the evidence that point toward a low efficiency for the star formation process: most mass of the cloud is supported against gravity, as clouds are not collapsing as a whole; only a small percentage of the cloud mass resides in cores where stars will form; and the lifetimes of cores are longer that the free-fall timescale. The question then that naturally arises is: why is the efficiency low, and what is the mechanism that regulates the star formation process?

At the heart of this problem lie the mechanisms by which molecular clouds (a) are supported against gravity as a whole and (b) fragment to form cores which will then go on to collapse.

Regarding the first question, there is one contestant that certainly does *not* enter the competition for cloud support: thermal pressure. The reason for this lack of effectiveness of thermal pressure in battling gravity is the very low temperatures of molecular clouds. Thermal pressure can only support structures of up to a certain mass, known as the *Jeans mass*. For typical molecular cloud temperatures, the Jeans mass is about $5M_{\odot}$. This means that any structure more massive than this limit cannot be thermally supported and, in absence of other means of support, will collapse under its own self-gravity. Molecular clouds however have masses between a thousand and a million solar masses – much higher than the Jeans mass. So whatever supports them, it is not thermal pressure.

Another in principle plausible mechanism for support against gravity is rotation. Interstellar clouds carry angular momentum at the very least because of their participation to the Galactic rotation. In fact, that specific angular momentum by itself is so large that it exceeds by at least two orders of magnitude the specific angular momentum associated with single and binary stars – so a centrifugal barrier would certainly form long before contraction would bring the density up to protostellar densities. A mechanism is therefore needed to transfer angular momentum from a collapsing core to the surrounding medium if stars are to form in the first place (this requirement is known as the *angular momentum problem* of star formation). It is now generally accepted that this mechanism is *magnetic breaking* (Mouschovias & Paleologou 1979): magnetic field lines connect dense with more diffuse, larger-scale material, and transfer angular momentum away from the dense, contracting part. It turns out that magnetic breaking is so fast and efficient that rotation does not contribute substantially to the support of a molecular cloud as a whole against gravity.

What is then the main agent that opposes gravity on molecular cloud scales? Two mechanisms have been proposed: the effective pressure associated with random motions of turbulent eddies, and magnetic fields. As we have seen, the presence of both turbulent motions and magnetic fields has been observationally confirmed in molecular clouds. Determining which of the two mechanisms *dominates* in different cloud types is still a matter of active research and heated debate in the field. The answer to the second question – how do clouds fragment to form cores – also depends on whether it is turbulence or magnetic fields that dominate on large scales.

Let us first consider the case where turbulence is dynamically more important that the magnetic field, and the molecular cloud as a whole is supported predominantly by turbulence (Mac Low & Klessen, 2004 Elmegreen & Scalo 2004). The velocities corresponding to the supersonic linewidths in such clouds are thought to be super-Alfvenic (higher than the Alfven speed, which is the characteristic speed of propagation of a certain type of magnetohydrodynamic waves). As a result, the magnetic field does not have time to react to disturbances caused to it by the turbulent velocity field of the gas. The magnetic field is then relatively weak and magnetic field lines can be dragged around by the random turbulent motions, so they are expected to appear rather tangled. In this case, overdensities are created by compression in regions where turbulent flows converge. Some of these overdensities have enough mass to exceed the Jeans limit, and these go on to collapse and form stars. Others are below the Jeans limit, and as a result eventually re-expand – these are known as "transient clumps".

Next, let us consider the case where the magnetic field is dynamically more important than turbulence (Mouschovias & Ciolek 1999, Mouschovias, Tassis, & Kunz, 2006). In this case, it is important to first take a close look at the microphysics of how the magnetic field "communicates" with the gas.

The magnetic field can of course only directly "talk" to the charged particles in a molecular cloud: ionized atoms and molecules, free electrons, and charged dust grains. The magnetic field is well coupled to the charged components of the cloud and the magnetic field lines follow the motion of the charged particles. The magnetic force is communicated to the bulk of the molecular cloud mass, which is in the form of neutral H_2 molecules, through collisions between charged particles and neutrals. If the degree of ionization in a cloud is high, then these collisions are frequent, the magnetic field and the neutrals are well-coupled, and the magnetic field lines and the neutral fluid move together. This state is known as "magnetic flux freezing."

Molecular clouds, however, do *not* have a high degree of ionization. They are self-shielded against ionizing radiation from massive stars (outer layers of the cloud attenuate the high-energy photons and protect the inner layers), so they can only rely on the more penetrating cosmic rays (relativistic charged nuclei) to provide some ionization. As a result, the coupling between magnetic field lines and neutral particles is imperfect, and a drift can develop between magnetic field lines and the neutral gas towards centers of gravity. This process is known as *ambipolar diffusion*, and it allows the slow increase of mass associated with a region of fixed magnetic flux (Figure 7).

Let us now go back to thinking about a molecular cloud that is globally supported by the magnetic field, which dominates over turbulence. The velocities associated with turbulent flows in this case are sub-Alfvenic or Alfvenic, and the magnetic field lines cannot be dragged around effectively by turbulent flows, so the magnetic field appears rather ordered. The quantity that determines

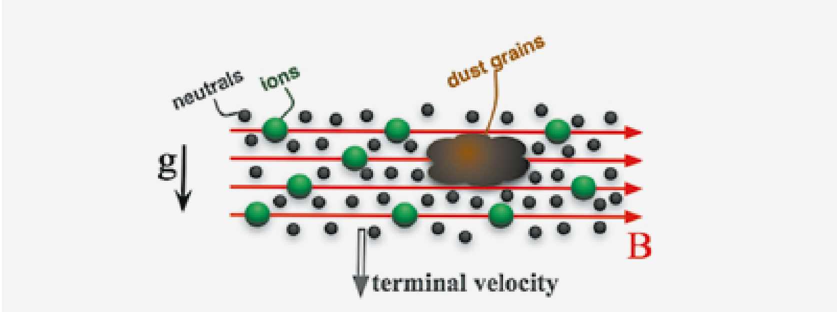


Figure 7: Microphysics of magnetic molecular clouds. Magnetic forces are felt by charged particles and communicated to the bulk of the gas through collisions. Because the degree of ionization is low, a drift can develop between field lines and charged particles on the one hand, and the neutral fluid on the other. As a result, neutrals can diffuse through field lines towards centers of gravity (ambipolar diffusion).

the effectiveness of the magnetic field in opposing gravity is the ratio between mass and magnetic flux (Mouschovias & Spitzer, 1976). If the mass-to-flux ratio in a region is below a critical value (the region is *magnetically subcritical*), the magnetic field wins, and the region is supported against gravity. If the mass to flux ratio however exceeds the critical value (the region is *magnetically supercritical*) then gravity wins, and the region collapses due to its self-gravity. Thus, in this scenario, clouds (which are not collapsing) are magnetically subcritical as a whole, while cores are magnetically supercritical. The question in this case is how one can form supercritical fragments within a subcritical parent cloud. The answer is provided by ambipolar diffusion: because of the imperfect coupling between the magnetic field and the neutral gas, neutral molecules can diffuse between field lines and increase the mass-to-flux ratio around centers of gravity, until it exceeds the critical value, at which point a supercritical fragment is formed. Cores that are dense enough to be observable in magnetically supported clouds are generally already magnetically supercritical, and they are in the process of collapsing dynamically until a hydrostatic protostar is formed at their center.

Distinguishing between these two paths to core formation is presently the focus of great theoretical and observational efforts by researchers of the early phases of star formation. A few promising approaches in this direction are discussed below.

Magnetically supercritical or subcritical clouds? The mass-to-magnetic-flux ratio quantifies the relative importance between magnetic field and gravity. If molecular clouds as a whole are found to be subcritical, then magnetic forces alone are adequate to support them against their self-gravity, and turbulent effective pressure is not necessary, even if it is present. Measuring this important quantity requires separate knowledge of the mass and magnetic field strength of a particular region. Important obstacles in obtaining reliable measurements of the mass-to-flux ratio are geometrical projection effects, difficulty to measure magnetic field strengths in low-density regions, and the effect of chemistry – since magnetic fields can only be assessed through molecular line observations (Crutcher, Hakobian & Troland 2009, Mouschovias & Tassis 2009).

Super-Alfvenic or sub-Alfvenic turbulence? The Alfven speed in a cloud, as compared to the characteristic speed of random motions (determined from the supersonic linewidths of molecular lines) characterizes the relative strength between magnetic field and turbulence, and could in principle by itself be indicative of which of the two scenarios discussed above is more likely to occur in specific clouds. However, knowledge of the Alfven speed requires knowledge of the magnetic field and the density of a region, quantities which are affected by all the observational uncertainties discussed for the mass-to-flux ratio above. Thus, indirect methods have been developed (Hildebrand et al. 2009, Houde et al. 2009, Heyer et al. 2008)

Ordered or tangled magnetic field? The degree of entanglement of magnetic field lines is another measure of the relative importance between magnetic field and turbulence in a molecular cloud. This information can be accessed through polarimetric mapping of the plane-of-the-sky component of the magnetic field (Dotson et al. 2010, Clemens et al. 2012). However, once the first stars are formed within the cloud, their energy output can significantly alter the magnetic field geometry of the parent cloud. For this reason, mapping of quiescent clouds that do not host any protostars yet are the most promising targets for such studies.

Orientation of magnetic fields in clouds and cores. Because magnetic forces only act perpendicular to the magnetic field, clouds and cores in regions with dynamically important magnetic fields will tend to be more compressed in the direction parallel to the field where there is no magnetic support. As a result, the mean magnetic field will be preferentially oriented parallel to the shortest axis of the molecular cloud or core. If magnetic fields are dynamically unimportant compared to turbulence, then magnetic fields are dragged around by turbulence and the mean magnetic field has a random orientation with respect to the molecular cloud or core principal axes. However, projection effects can make observations of this effect difficult to interpret (Tassis 2007, Tassis et al. 2009, Chapman et al. 2013).

Molecular abundances. The abundances of specific molecular species depend on the dynamical evolution of a cloud. The rate of a chemical process depends on the local density, and therefore the resulting abundances of any specific molecule in some region depend on the amount of time it has spent at a specific density. Magnetic forces keep mediating the rate of collapse of cores even after a supercritical fragment is formed, while once turbulence decays, and in the absence of a significant magnetic field, collapse proceeds on a free-fall timescale. In this way, even cores of similar total lifetimes will exhibit different molecular abundances if they have reached a certain evolutionary stage through the turbulent or magnetic paths. However, other parameters, such as temperature, elemental abundances, and the cosmic ray ionization rate can significantly affect the cloud chemistry and the resulting abundances (Tassis, Willacy, Yorke & Turner 2012a,b, Tassis, Hezareh & Willacy 2012). As a result, chemodynamical studies of molecular clouds are complex and time-consuming.

Although all tests discussed above are being actively pursued, the results tend to be no more than a factor of two away from agreeing with either scenario. The key therefore to resolving this controversy is entering the era of *precision interstellar medium observations*. The timing to be studying star formation physics is particularly good, because of the upcoming torrential flood of data through current and upcoming instruments and missions, including Herschel, ALMA, SOFIA, SKA, and the JWST.

The astrophysics group at the University of Crete is pioneering such studies in two distinct fronts: chemodynamical modeling and optopolarimetric mapping of molecular clouds in transmitted light from background stars, using the RoboPol optopolarimeter, which is an instrument specifically designed and built for the 1.3m telescope at the Skinakas Observatory, and represents a collaborative effort between FORTH and the University of Crete, Caltech, the Max-Planck Institute for Radioastronomy in Bonn, the Nicolaus Copernicus University in Poland, and the Intra-University Center for Astronomy and Astrophysics in Pune, India.

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Orbital Evolution in Extra-solar systems

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Abstract

Nowadays, extra-solar systems are a hot research topic including various aspects, as observation, formation, composition etc. In this paper, we present the main orbital and dynamical features of these systems and discuss the evolution of planetary orbits in multi-planet systems. Particularly, we consider the dynamics of a two-planet system modeled by the general three body problem. Complicated orbits and chaos due to the mutual planetary interactions occur. However, regions of regular orbits in phase space can host planetary systems with long-term stability.

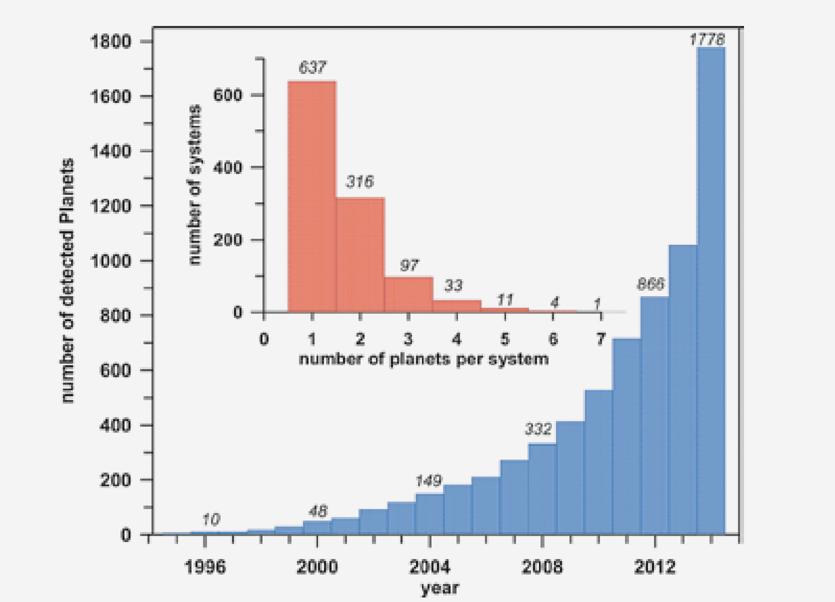

Figure 1: The blue histogram shows how many exoplanets have been discovered until the indicated year. The abrupt increase of the number in 2014 (although this number refers to March, 6th) is due to the addition of a set of 702 planets discovered by the KST. The red histogram shows how the 1778 planets are arranged in the 1099 planetary systems.

1. Introduction

After the detection of the first three planets orbiting the pulsar *PSR B1257+12* in 1992 and the first planet orbiting the main-sequence star *51 Pegasi* in 1996, a significant growth of detected exoplanets took place, which currently seems to be rather exponential. One of the most reliable catalogs of exoplanets is given by the *Extrasolar Planets Encyclopedia* (EPE) [1]. Very recently, on 6th March 2014, a set of 702 new planet candidates, observed by the Kepler Space Telescope (KST), were added in this catalog, which now includes 1778 planets arranged in 1099 planetary systems[1]. In the blue histogram of figure 1, we present how the number of discovered exoplanets increases year by year and in the red one how the planets are distributed in the planetary systems. A number of 637 systems contains only one planet, while the rest 1141 planets are arranged in 462 multi-planet systems most of them consisting of two planets. The most "populated" system is *Kepler-90* (around the star *KOI-351*), which seems to consist of seven planets[2].

The first detection method used was the method of *radial velocity* or *Doppler method* and most of the known exoplanets have been discovered by this method, which is still widely used. The *transit method* has also been proved efficient, mainly after its application by the KST. Gravitational microlencing, reflection/emission methods, polarimetry e.t.c. can also be used as detection methods [2]. *Direct imaging* has given few yet spectacular results, firstly, with the discovery of the planet *Formalhaut b* by the Hubble telescope and, recently with the discovery of *Beta Pictoris b* by the Gemini Planet Imager (see figure 2). The region of observations has a radius of about 10^3 l.y. and it is estimated that our galaxy contains 400 billion planets. The closest exoplanet to our Solar system is the *Epsilon Eridani b* in a distance of 10 l.y.

Most exoplanets are classified as *hot Jupiters*, namely gas giant planets that are very close to their host star, e.g. *HD 102956 b* which has mass equal to Jupi-

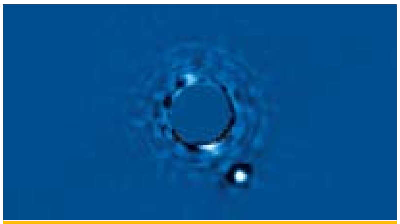

Figure 2: The first light image of an exoplanet (Beta Pictoris b) by the Gemini Telescope (announced in 7 January 2014 by NASA JPL, http://planetquest.jpl.nasa.gov/news/144)

1. This number changes day by day, including new discoveries or excluding planets for which a confirmation study had failed.

2. In 2013 it was announced that the system *HD10180* **has 10 planets, but today only six planets have been confirmed**

ter's mass ($1M_J$), semimajor axis 0.08*AU* and period 6.5 days. Very massive planets have been found, either close to their host star (e.g. *Kepler-39 b* with mass $20M_J$, semimajor axis 0.15 AU and period 21 days), or very far from their host star (e.g. *HIP 78530 b* has mass $24M_J$, semimajor axis 710*AU* and period 12*Ky*). As detection techniques are improved, smaller planets are detected. Many of them have masses equal to 10-20 times the mass of the Earth, are possibly gaseous and are called *Mini-Neptunes*. Nevertheless, planets with mass of the order of the Earth's and of similar radius can be detected by the KST. They are possibly terrestrial (rocky) planets and become very interesting for detailed study, when they are located in a habitable zone, e.g. the *Gliese 667C c* [3].

Studying the general structure of the known extrasolar systems we can certainly argue that our Solar system is an exception. Thus, the proposed mechanisms for formation and evolution of planetary systems should be revised and generalized. In the following, we focus on the orbital characteristics of multi-planet systems, the conditions required for their long-term stability and the role of planetary resonance.

2. Orbital and dynamical features

Considering a system consisting of a star and a planet (assumed as point masses) we expect Keplerian elliptic planetary orbits around the star with period *T*, semi-major axis *a*, eccentricity *e* and inclination *I*. From the observations and after applying particular fitting methods (see e.g. [2]) these orbital parameters can be estimated approximately for each observed planet. In figure 3, we plot the distributions *a-e* and *T-e* of 623 planets for which we have an estimation of the orbital parameters in the list of EPE. The fact that the majority of planets appears with small semi-major axes and periods is possibly caused by an observational selection bias, since large and close to the star planets are more easily detectable. Most of these close-to-star planets have also small orbital eccentricities possibly caused by tidal circulation [4].

An important orbital feature that is clearly seen from the plot of figure 3 is that we obtain the existene of many planets with large eccentricities. E.g. an extreme planet is *HD 20782 b* with a=1.38*AU* and e=0.97. High eccentric orbits are also observed in multi-planet systems. E.g. in the two-planet system around the star *HD 7449* the inner and the outer planets have eccentricity 0.82 and 0.53, respectively (see figure 4). The formation of such highly eccentric planetary systems is not sufficiently supported by the current theories. However, long-term evolution stability is possible and can be proved as we explain in the last section.

The inclination I_o of the orbital plane with respect to the observer is defined as the angle between the normal to the planet's orbital plane and the line of the observer to the star. Most observational methods, and mainly the transiting method, can observe planets only with inclinations $I_o \approx 90°$. For radial-velocity observations the inclination is very important for the computation of the planetary mass because the particular measurements provide us with an estimation of the quantity $m \times \sin I_o$.

The inclination *I* defined between the normal of the orbital plane and the stellar rotational axis is the most important from a dynamical point of view. In this sense, particular studies indicate that most planetary systems are inclined [5]. Cases where $I \approx 180°$, i.e. planets moving around the star in a direction opposite to the spin of the star, have also been indicated in observations making the puzzle of planetary formation quite complicated. Generally, it seems that in multi-planet systems, planets are almost coplanar, i.e. the *mutual* inclination $\Delta I = I_1 - I_2$ between two planets is close to zero. However, cases of high mutual inclination between planets have also been observed, e.g. the planets c and d around *Upsilon Andromeda* seem to have mutual inclination larger than 30°.

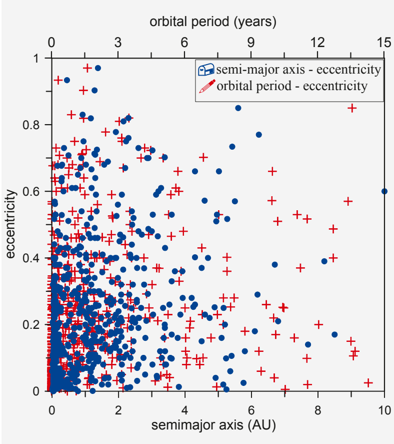

Figure 3: The distribution of exoplanets in the planes a-e (blue dots) and T-e (red crosses). Most of the planets have small semi-major axis (or period) and small eccentricity. There are few more planets, which are located outside the axis' limits of the plot and they are not shown.

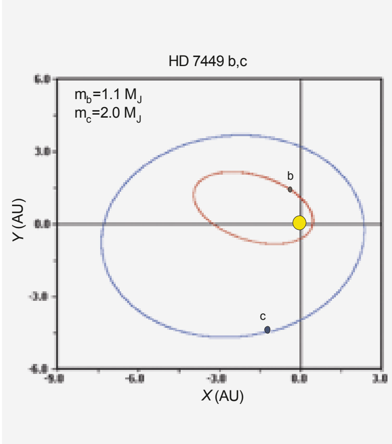

Figure 4: The orbits of the giant planets around the star HD 7449. The eccentricities of the inner and the outer planet are 0.82 and 0.53, respectively. The semimajor axes are 2.3*AU* and 4.96*AU*, respectively.

Mean motion resonances (MMR) in multi-planet systems appear frequently. Two planets (1 and 2) are in a MMR, when the ratio $\rho = T_1/T_2$ of their orbital period is close to a ratio $r = p/q$ of two (small) integers. Computing the ratio ρ of all planet pairs appearing in the multi-planet systems of the EPE list we obtain a significant number of resonant pairs. Certainly this number depends on the divergence $\delta = (\rho - r)/r$ that we set as a threshold. For divergence less than 5%, 2% or 1% we find respectively 419, 174 or 83 resonant planetary pairs. Their distribution to each value *r* is shown in figure 5.

3. The three body model and orbital evolution

A two-planet system can be modeled by a system of three point masses m_0, m_1 and m_2 representing the star, the inner and the outer planet, respectively. Thus $m_0 >> m_{1,2}$ and initially it holds $a_1 < a_2$. Although the planetary masses are very small, the mutual planetary interaction is not negligible if we want to study the orbital evolution for moderate or long time intervals and during such an evolu-

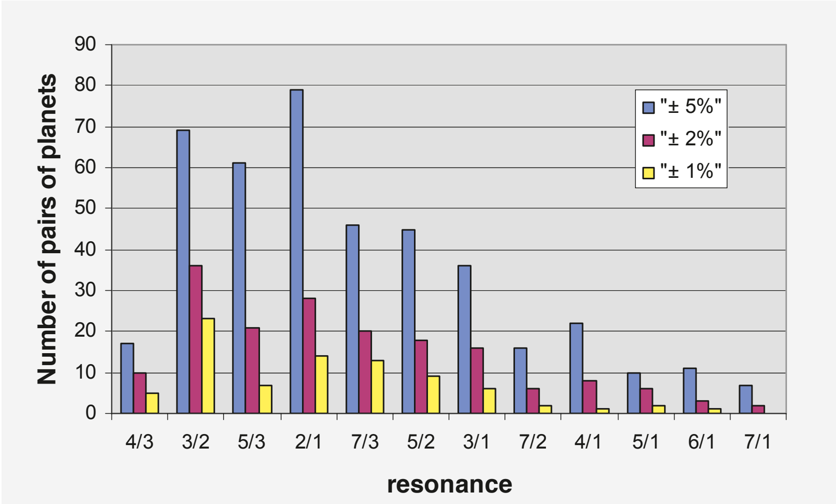

Figure 5: The distribution of resonant planetary pairs at each resonance p/q. Different color bars correspond to different threshold values of the difference of the ratio T_1/T_2 from the ratio p/q. For each pair we have set as T_1 the greater orbital period.

tion the inner planet may become outer and vice versa.

Let X_i be the position vector of the three bodies in an inertial frame. Following Poincaré, we can consider for the planets the astrocentric position vectors $r_i = X_i - X_0$ and the barycentric momenta $p_i = m_i(dX_i/dt)$ and write the Hamiltonian of the system in the form $H = H_0 + H_1$, where

$$H_0 = \sum_{k=1}^{2}\left(\frac{p_k^2}{2\beta_k} - \frac{\mu_k \beta_k}{|r_k|}\right)$$

$$H_1 = -\frac{Gm_1m_2}{|r_1 - r_2|} + \frac{p_1 p_2}{m_0}$$

$$\mu_k = G(m_0 + m_k), \quad \beta_k = \frac{m_0 m_k}{m_0 + m_k}.$$

The term H_0 describes the evolution of the planets in the framework of the two body problem (unperturbed star-planet system). The second term includes the planetary interactions and is a perturbation term for the integrable part H_0. Subsequently, we have a nonintegrable model of 6 degrees of freedom and the corresponding canonical equations of motion are integrated numerically. In this system we have the conservation of energy and the three components of the angular momentum vector [6].

A second formalism for the planetary three-body model results if we express the Hamiltonian in orbital elements[3]

$$H = -\sum_{k=1}^{2}\frac{Gm_0m_k}{2a_k} - \frac{Gm_1m_2}{a_2}R(a_i, e_i, I_i, \omega_i, \Omega_i, \lambda_i)$$

where ω_i is the argument of periastron, Ω_i is the longitude of ascending node and λ_i is the mean longitude (index $i=1,2$ refers to the particular planet) [7]. From the above Hamiltonian simplified models can be constructed by the *method of averaging*.

By averaging that fast motion on the ellipse, given by the angles λ_i, we obtain the secular model. Up to second order in masses we obtain that the phase space structure depends on the planetary mass ratio m_1/m_2. Also, it turns out that the semimajor axes remain almost constant and in a coplanar system the eccentricities e_1 and e_2 oscillate slowly with opposite phases. Actually, in a 3D system the conservation of angular momentum is expressed as

$$\alpha_1\sqrt{1-e_1^2}\,\sin I_1 + \alpha_2\sqrt{1-e_2^2}\,\sin I_2 \approx const.$$

where α_i are almost constants, which depend on the masses and semimajor axes of the planets. Another feature of secular dynamics is also the libration of the difference $\Delta\varpi = \varpi_2 - \varpi_1$ of the longitude of pericenter of the two planets [8].

When the system is close to a MMR, the averaging should exclude slow "angle combinations" [7][8]. For a resonance $r = p/q$ we can define the resonant (slow) angles $\sigma_i = q\lambda_1 - p\lambda_2 + (p-q)\varpi_i$. If σ_1 or σ_2 librates we argue that the planetary system involves inside the resonance. The center of a resonant domain or the "exact resonance" is given by the stable stationary solutions i.e. the minima of the averaged Hamiltonian where σ_i=const. In resonant evolution, the semimajor axes are not invariant (as in the secular evolution), but we can derive the constraint

$$\beta_1 a_1^2 + \beta_1 a_2^2 = const.,$$

where β_i are almost constants and depend on the masses and the resonance.

The conservation of the angular momentum can be used for reducing further the degrees of freedom by two. This is achieved by choosing a suitable *rotating frame* Oxyz, where the star and one of the planets (say planet 1) are always located on the plane Oxz and Oz axis is chosen to coincide with the vector of angular momentum. In this rotating frame, the planet 2 is given by the components $(x,y,z) = (x_2,y_2,z_2)$, but only the component $\chi = x_1$ is required for the determination of the planet 1. Thus the system is described by four degrees of freedom and Hamiltonian

$$H = H(\chi, x, y, z, p_\chi, p_x, p_y, p_z)$$

where p_χ, p_x, p_y and p_z are the conjugate momenta [9]. In this formalism, we can obtain directly the well known circular restricted three body problem, if we set $m_2 = 0$, χ = const. and n = const., where n is the angular velocity of the rotating frame.

Hamiltonian, *H,* written for the rotating frame is convenient, when we want to study the dynamics through the periodic orbits of the system. The families of periodic orbits of the restricted three body problem, generally, are continued to the general three body problem and can be computed in a systematic way [10][9]. Periodic orbits are associated with the stationary solutions of the approximate averaged Hamiltonian mentioned above. Families of periodic orbits are either "circular" or "elliptic". Along a circular family the ratio $\rho = T_2/T_1$ of planetary periods varies. Families of elliptic orbits bifurcate from the circular family, when $\rho = p/q$ (i.e. at resonances). Along these bifurcating families ρ remains almost constant. Thus, all elliptic periodic orbits are resonant and, actually, present the "exact" dynamical resonance [11]. Linear stability analysis can be performed classifying the periodic orbits as stable or unstable.

3. More precisely we use canonical Delaunay-like variables

4. Orbital Evolution of HD 82943b,c

In this section, we present an example of the dynamical analysis of the orbital evolution of the extra-solar system around the star HD 82943 (with mass $1.18 M_{Sun}$). Three planets have been discovered for this star, the planets b,c and d with period 442, 219 and 1078 days, respectively. The first two planets have masses ~$4.8 M_J$ and the third one is quite smaller with mass $0.29 M_J$. So, we can neglect the interaction of the third planet to the other two heavy planets and study the evolution in the framework of the three body model with inner planet (P_1) the planet c and outer planet (P_2) the planet b. The orbital parameters are the following

	m (M_J)	a (AU)	e	ϖ (°)
P_1	4.78	0.75	0.425	133
P_2	4.80	1.20	0.203	107

No estimation is given for the position of the planets in their elliptic orbits. The two planets are coplanar with I_0=19°. Also the system is resonant with $T_2/T_1 \approx 2.0$.

For the planetary ratio $m_2/m_1 \approx 1$ and for the region of the given eccentricity values, we find that there exists a family of periodic orbits, which is symmetric and corresponds to a planetary configuration with aligned planets, i.e. $\Delta\varpi = 0°$, and when the inner planet is at periastron the outer planet could be found at apoastron, i.e. $\sigma_1 = 0°$. Thus, we will consider for our analysis two planetary initial configurations: *configuration A* with $\Delta\varpi = 0°$ and *configuration B* with $\Delta\varpi = -26°$ (the value given in the list). We consider that P_1 is initially located at periastron and P_2 at apoastron[4].

In Figure 6, we present the evolution of the eccentricities and the apsidal difference $\Delta\varpi$ for configurations A and B. When the planets are aligned (configuration A) the system evolves regularly, $\Delta\varpi$ librates indicating the resonant evolution and the eccentricities show small (anti-phase) oscillations. However, if we consider the configuration B, we see that $\Delta\varpi$ rotates. Although, the evolution initially seems regular, after 1.2 *Ky* the system is destabilized. Small planetary encounters occur and the outer planet increases its eccentricity to values almost up to 1 (collision with the star).

In order to understand the underlying dynamics of the above evolution, we depict the qualitative type of evolution of all orbits in particular domains of the phase space by constructing *dynamical maps of stability*, namely we consider plane grids of initial conditions and for each grid point we evolve the orbits and classify them as regular or chaotic by computing a chaoticity index e.g. the DFLI in our case [12]. In the maps presented below, light (yellow) colors indicate chaotic motion while dark ones (blue-green) corresponds to regular evolution.

In panels (a) and (b) of figure 7, we consider all possible eccentricities of the two planets (keeping the rest orbital parameters as it is defined in the two configurations A and B, respectively). We obtain that in configuration A (panel a) there is a strip of regular orbits. The backbone of this region is the stable 2:1 resonant family of periodic orbits for the particular planetary masses (the gray characteristic curve). If we

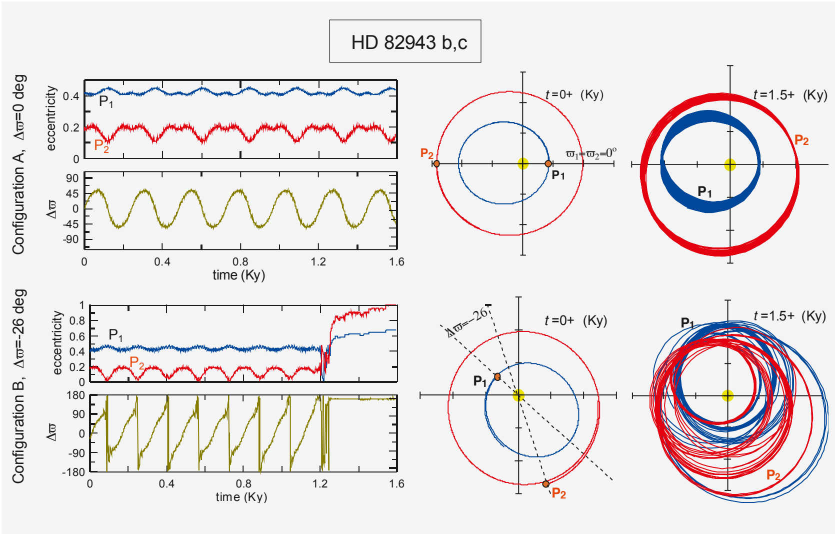

Figure 6: The evolution of planets c (P1) and b (P2) of the system HD 82943 for the two different initial configurations A and B (see the text). In the left panels, the time evolution of the eccentricities and the planetary apsidal difference is presented. In the middle, we show the initial configuration of the system and the orbit in its first moments of evolution. In the right, the planetary orbits at about 1.5Ky are shown. The destabilization in the configuration B is obvious.

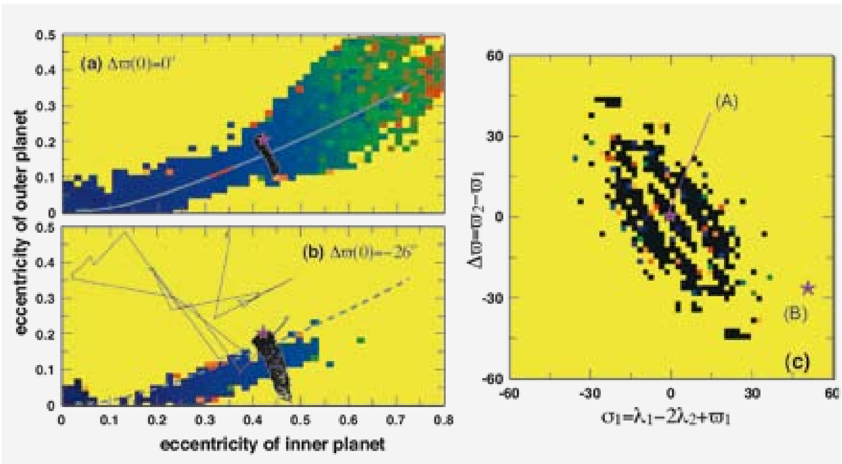

Figure 7: Dynamical maps of stability for the system HD 82943. a) map in the plane of initial eccentricities for the configuration A, b) map in the plane of initial eccentricities for the configuration B, c) map in the plane of initial resonant angles (σ_1, $\Delta\varpi$) at (e_1,e_2)=(0.425, 0.16). Yellow regions indicate chaos while dark colors correspond to regular orbits. The star shows the starting point of the system.

4 This is the better configuration with respect to stability

project the planetary evolution in the plane of eccentricities, we obtain oscillations centered at the eccentricity values of a periodic orbit at about $(e_1,e_2) = (0.42,\ 0.16)$. When the planets are not initially set to be aligned ($\Delta\varpi \neq 0°$), the regions of regular orbits in the dynamical stability maps shrink and show a shift from the characteristic curve of periodic orbits. Subsequently, for $\Delta\varpi = -26°$ the system seems to be located in the chaotic region (but close to the regular one). Thus, the system destabilizes and shows diffusion in the wide chaotic sea of the phase space, where the evolution is strongly irregular. In these dynamical regions, the system suffers from close encounters, which possibly lead one of the planets to a collision with a star or to escape or to a planet-planet collision.

In panel (c) of figure 7, we consider the eccentricity values (0.42, 0.16), mentioned above, and construct a dynamical map for a grid of initial conditions with all possible planetary alignments $\Delta\varpi$ and initial angle positions (presented by the resonant angle σ_1). The central regular region is associated with the periodic orbit, located in this map at (0,0). Again, we see that the configuration B locates the system in the chaotic region. We may conclude from the above analysis that the orbital parameters given in the EPE list should be revised. Namely, stability is guaranteed for $|\Delta\varpi|<26°$. Also, if we assume slightly smaller planetary masses, then the regular region is expanded and the system can be located in the regular region. Possible planetary mutual inclination may also be a stabilization factor.

When two planets have large enough eccentricities, then planetary close encounters (and subsequently destabilization) are, generally, unavoidable unless the system is in resonance. Resonances can offer a phase protection, i.e. although orbits are close (or intersect), the planets cannot be found close to each other. It has been shown that stable resonant periodic orbits can exist for very large eccentricities and therefore, regions of stability can be located. However, as eccentricities increase, the stability domain around the central periodic orbit shrinks. Thus, a real planetary system with large eccentricities may be found only very close to a stable resonant periodic orbit. This, for example, should be the case for the system HD 7449 presented in figure 4.

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Superluminous Supernovae

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The discovery of a new class of Supernovae

Supernovae are some of the most spectacular phenomena in the Universe, marking the explosive deaths of massive stars ($M_* \geq 8\ M_\odot$; Type II and Type Ib/c SNe and subtypes), or the thermonuclear explosions of white dwarfs that exceed the Chandrasekhar mass (~1.4 $M_\odot$; Type Ia SNe). The exceptional luminosity produced by Type Ia events, typically reaching peak absolute visual magnitudes of M_V~-19, allow us to detect them at great, cosmological distances yielding information about the very nature of the Universe. Typical Type II SN events are not nearly as luminous as Type Ia events but are important in that they provide information about the evolution and mass-loss history of massive stars as well as heavy nucleosynthesis and the chemical enrichment of the interstellar medium.

Some of the main early supernova search projects, such as the Supernova Cosmology Project [1] and the High-Z Supernova Search Team [2] were focusing on the discovery of Type Ia events due to their importance as cosmological standard candles. The basic characteristic of these surveys is that they were targeted searches; the telescopes used had relatively small fields of view and focused on large bright spiral galaxies in the Virgo and Coma clusters. Therefore these searches were biased in the sense that they ignored potentially interesting transient events occurring in other, lower luminosity environments.

The first untargeted, unbiased supernova search, the Texas Supernova Search Project (TSS; later RSVP: ROTSE Supernova Verification Project, [3]) uses four fully automated, unfiltered, large field of view telescopes, the ROTSE-III telescopes (ROTSE: Robotic Optical Transient Search Experiment) that scan large portions of the sky in a nightly basis

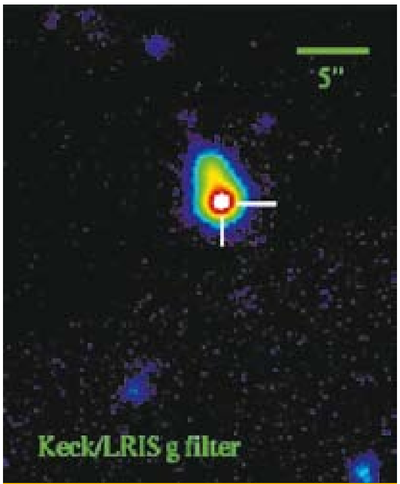

Figure 1: Discovery image of SN 2008am showing its position in its host galaxy [44].

looking for new transients by comparing images taken in previous scans (dynamically comparative photometry). The most productive of these telescopes, ROTSE-IIIb that is installed at the McDonald Observatory in West Texas led to the prompt discovery of a large number of new transients. Targets of interests discovered by ROTSE are then passed to the observing queue of the Hobby-Eberly Telescope where spectra are obtained by the Low Resolution Spectrograph (HET-LRS) instrument allowing for the final classification of the transients.

In 2005 the TSS project discovered the first of what was going to be a new, unique and rare class of supernovae explosions, the Superluminous Supernovae (SLSN) events. At the redshift of $z = 0.2832$, SN 2005ap [4] reached peak unfiltered absolute magnitude in excess of -22 within 1-3 weeks after explosion followed by a rapid decline. Consequently, the corresponding peak luminosity for this event was greater than 10^{44} erg/s, or comparable to the total luminosity of the whole Milky Way galaxy! The exceptional luminosity, the unprecedented light curve shape and the unique spectra of this event did not resemble any of the characteristics of SN explosions discovered to date.

The following year, TSS discovered yet another SLSN with a very broad light curve shape, SN 2006 gy [5,6,7]. SN 2006 gy has been one of the most well observed SLSN with photometric observations spanning from the ultraviolet (UV) to the infrared (IR) and high quality contemporaneous spectra for hundreds of days after the explosion, until the transient became dimmer than detection limits. SN 2006gy possessed optical spectra dominated by narrow emission lines of hydrogen reminiscent to those of Type IIn SN explosions ("n" for "narrow" indicating the presence of narrow lines). The origin of these lines is believed to be a shock propagating in the circumstellar medium (CSM) around the explosion, produced by the interaction of the SN ejecta with that medium. The LC of SN 2006gy took about 70 days to rise to peak luminosity at the rest frame of the event indicating a large diffusion mass associated with it. The combination of high peak luminosity and slow LC evolution led to the theory that SN 2006gy was powered by either the result of the explosion of an extremely massive star ($M_* \geq 100\ M_\odot$) or the interaction of massive SN ejecta with an also massive CSM shell, thought to have been ejected by the progenitor star in the years prior to explosion [6]. The TSS has discovered a dozen more SLSN up to date (Figure 1) including some unclassified transient phenomena.

The TSS project was later complemented by more efficient and high response transient search projects such as the Palomar Transient Factory [8] and Pan-STARRS that, altogether account to the discovery of more than 30 SLSN events up to date [9]. This sample of SLSN has a revealed a great degree of diversity as the main striking characteristic of this class of events: a variety of LC shapes, peak luminosities, decline rates as well as spectroscopic characteristics that raise intriguing questions about the nature of these events, the implications for massive star evolution as well as their potential role in the chemical enrichment of the Universe.

The observed properties of SLSNe

The LCs of SLSNe exhibit differences in terms of peak luminosity, rise time to maximum light, general LC shape and late time decline rate with some being consistent with the radioactive decay rates of ^{56}Ni and ^{56}Co, in a similar manner with Type Ia and some Type II events, while many are not. Therefore, classification of SLSN based on the LC alone is incomplete and it does not capture the physics since in some cases the LC shows a "linear" decline in logarithmic (in luminosity) plots similar to that of Type IIL SNe (SN 2006gy) and in other cases the LC are characteristic of Type II and Ib/c events.

Figure 2 shows a collection of SLSN LCs. The observed differences in peak luminosity as well as total energy radiated (10^{51}–10^{53} erg) hint that the power source is not standard but comes in varying degrees of intensity. The differences in the timescales to rise to maximum luminosity on the other hand are indicative of different diffusion masses associated with the SLSN ejecta. More specifically, the SN ejecta (or diffusion) mass can be estimated by the following formula [10, 11, 12]:

$$M_{ej} = \frac{3\beta\, c}{10\kappa} v_{ej}\, t_d^2$$

where β = 13.8 is a constant coming from integrating characteristic SN ejecta density profiles, c is the speed of light, κ is the optical opacity of the SN ejecta (0.38 for hydrogen rich, 0.2 for helium rich and 0.1 for H/He poor material), v_{ej} is the typical ejecta velocity and can be measured by spectroscopic features and t_d is the diffusion time and is characteristic of the rise time to maximum light.

The dependence of M_{ej} to the second power of t_d is the reason why there is a variety of diffusion masses characteristic to SLSN since their rise times to maximum can be as low as <10 days in some cases (SN 2005ap) while they can exceed 100 days in other cases (CSS 100217; [13]). Such a variety of SN ejecta mass could translate to either a variety of progenitor masses or even a variety of circumstellar masses around the progenitor star as we will discuss in the next section.

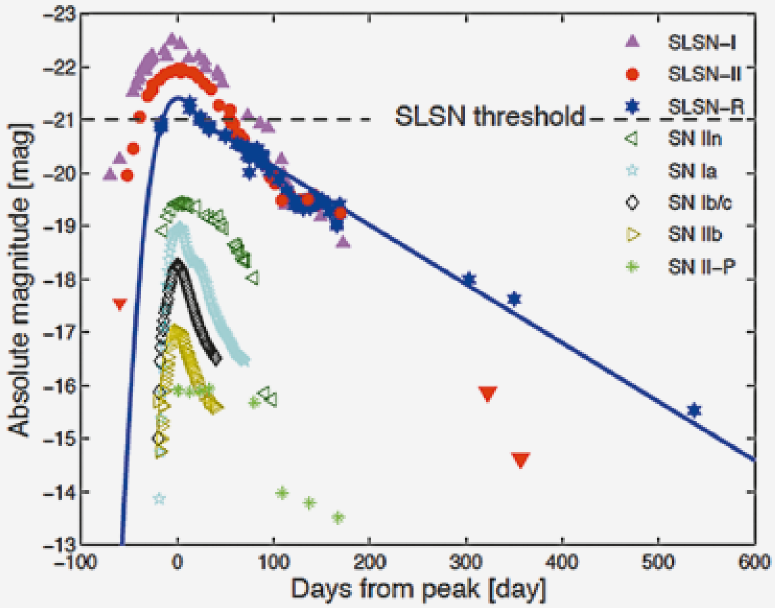

Figure 2: LCs of different types of SNe as compared to SLSNe [9].

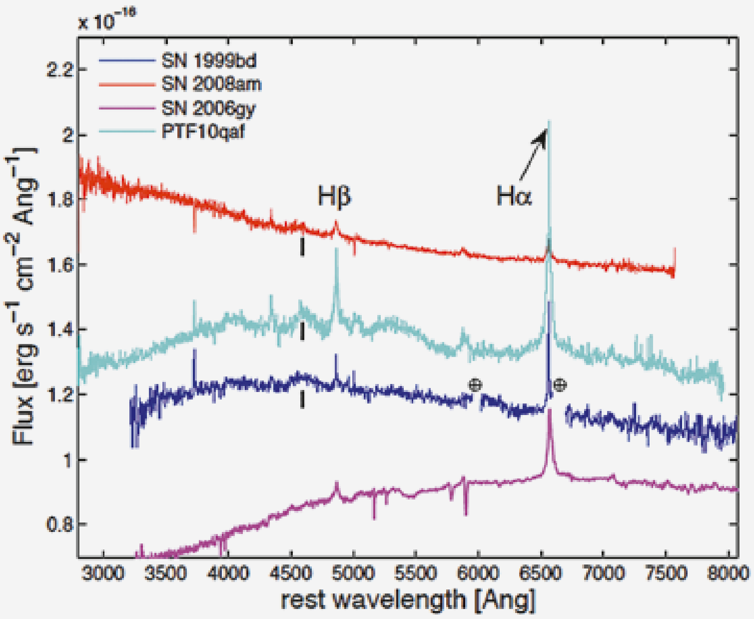

Figure 3: Spectra of SLSN-II [9].

The spectra of SLSNe also show differences amongst them but they can be generally classified in two categories: hydrogen-rich spectra that show emission Balmer lines of H and hydrogen-poor spectra that lack H and, in some cases, He as well. Based on this observable alone the SLSNe are categorized in SLSN-II and SLSN-I in accordance with the categorization of normal luminosity SNe [9]. Some SLSN-I like SN 2007bi [14] show Fe, Co and Ni lines at the very late

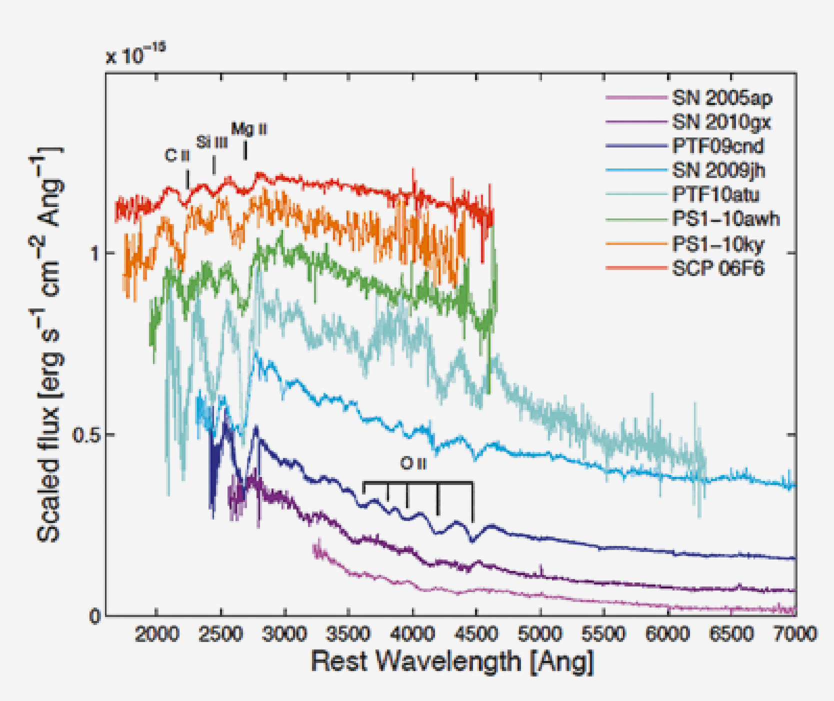

Figure 4: Spectra of SLSN-I [9].

times that might be indicative to the radioactive decays of ^{56}Ni and ^{56}Co and are referred to as SLSN-R where "R" stands for "radioactive". This subclass is of particular interest as it has raised the question of whether those events are related to the long theorized Pair Instability Supernova explosions (PISNe) that represent the deaths of extremely massive stars (>120 $M_\odot$) producing several solar masses of ^{56}Ni powering their LCs to superluminous levels. We return to this topic in the next section. Figures 3 and 4 show some examples of SLSN-II and SLSN-I spectra accordingly. The lack of H-features in SLSN-I events can be indicative of the lack of H overall in their ejecta meaning that the progenitors of these events lost their H/He envelopes maybe in a similar manner than the progenitors of SN Type Ib/c did.

SLSNe, especially SLSN-I are also unique in that they are usually discovered in low luminosity, sub-solar metallicity dwarf host galaxies [15]. In some cases for SLSN-I SNe the hosts are not even detected [16]. Figure 5 shows the metallicity of some known SLSN hosts.

Finally, the most apparent characteristic of SLSNe is that they are a particularly rare phenomenon, with an average discovery of one SLSN a year during the first years of TSS that increased to a few with the introduction of PTF and PanSTARRS. More formally, it is estimated that SLSN-I are the most rare SLSN events with a rate of ~32 events / Gpc^3 /year while SLSN-II have a rate of ~151 events / Gpc^3 /year assuming a Hubble constant of 71 km/s/Mpc [17]. This amounts to approximately just 1 SLSN event for every 400 to 1300 core-collapse SNe (Type II or Ib/c).

How are SLSNe powered?

The unique diversity of the observed properties of SLSNe has triggered intense theoretical work with the purpose to unveil what powers these events. The debate today rests on the two main hypotheses that either the SLSN diversity is due to a unique power input mechanism that involves many parameters or to a different power input mechanisms. Up to date, three main mechanisms have been proposed as the power inputs of SLSNe: Pair-Instability Supernovae, massive SN ejecta – circumstellar matter (CSM) interaction and magnetar spin-down.

Pair-Instability Supernova explosions have been theorized since the late 1960s [18, 19, 20, 21, 22, 23] and result from the collapse of the carbon/oxygen cores of very massive stars (M_{ZAMS} > 120 $M_\odot$) that encounter the electron-positron pair instability. More specifically, very massive stars naturally develop massive C/O cores (M_{CO} > 60 $M_\odot$) during the late stages of their evolution that are characterized by high temperatures ($T_{core} > 10^9$ K) but relatively low densities ($\rho_c > 10^4 – 10^5$ g/cm^3). At this thermodynamical regime rapid production of electron-positron pairs is favored in the core. Under such conditions, the rate of the electron-positron pair production can even exceed the rate of gamma-ray generation by nuclear fusion and a large fraction of gamma-rays can be absorbed by the newly generated pairs before those annihilate. This process softens the equation of state and the adiabatic index falls below 4/3 such that radiation pressure support is removed and the C/O core begins to collapse under the influence of gravity. The collapse leads to higher core temperatures and densities and due to the high (steep power law) sensitivity of pair-production and nuclear reaction rates to the temperature the overall process becomes a runaway effect leading to the continuous contraction of the core up to the point where the available carbon and oxygen fuel is ignited and explosively burns releasing > 10^{51} ergs of energy and leading to the formation of several solar masses of ^{56}Ni in some cases. The decay of this very large amount of radioactive ^{56}Ni, that can be 10-100 times more than that produced in typical CCSNe and Type Ia SNe, can provide the input heating to power the PISN LC to superluminous levels.

From the available set of SLSNe only a very limited number of events have been discussed as PISNe candidates based on the properties of their LCs and late time spectra. Some notable examples are SN 2007bi [14] and SN 2010hy [24, 25]. The most widely debated PISN candidate is SN 2007bi. Some authors [14,26] have presented radiation hydrodynamics modeling of the LC of SN 2007bi and concluded that a PISN resulting from a He-rich core of about ~110 $M_\odot$ can adequately reproduce the observed pseudo-bolometric LC. A caveat to this result is the lack of a large number of data points during the rising part of the PISN LC that does not allow for an accurate estimate of the explosion date and, therefore, the real rise-time of the LC that is related to the ejecta mass deduced. Another concern is raised by recent results from non-local thermodynamical equilibrium (n-LTE) spectroscopic modeling of PISNe [27] that find

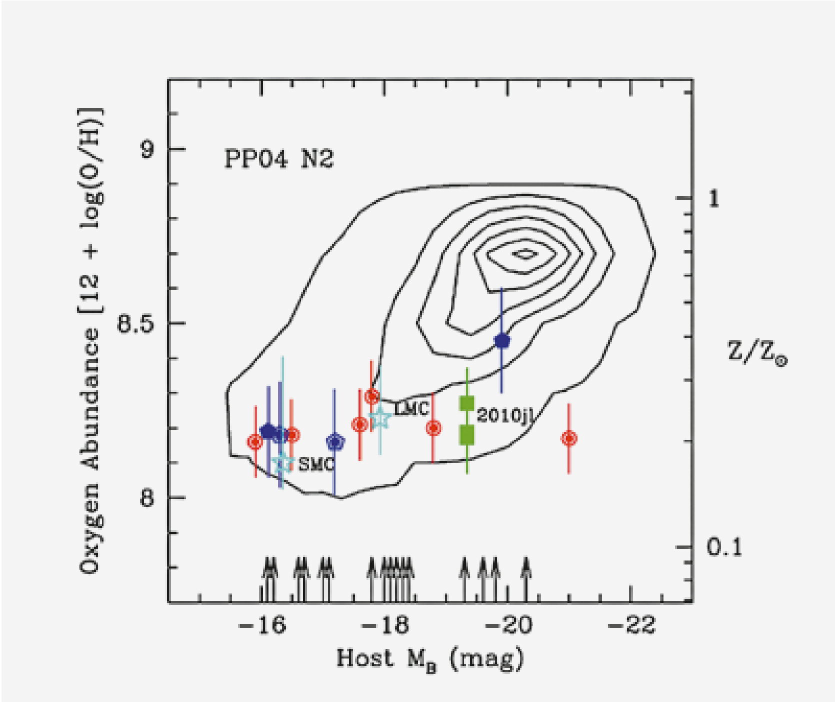

Figure 5: Metallicities of some known SLSN hosts [15].

that the spectral properties and color evolution of PISNe do not have any resemblance with that observed for SN 2007bi. More specifically, PISN are expected to be intrinsically red events while the color evolution of SN 2007bi, especially at early times is particularly blue in color. Yet another strong counter-argument against the PISN hypothesis for the case of SN 2007bi is the measured high metallicity of the host galaxy ($Z > 0.4\ Z_\odot$). At such high metallicity a massive star would experience extreme radiative driven mass-loss during the main-sequence that would drive the final mass of the star below the limits required for PISN to be encountered. A relevant parameter study has shown that the upper metallicity limit for PISNe to be encountered based on models of star formation and the known initial mass function (IMF) is $Z \sim 0.3\ Z_\odot$ and even in that case the progenitor would have to have a ZAMS mass in excess of 300 $M_\odot$ to become a PISN [28]. It's worth noting that the most massive stars ever detected have masses of that order [29].

As we will discuss below, other alternatives have been proposed to explain the nature of SN 2007bi including magnetar spin-down power [30] and H-poor CSM interaction [31].

The second power input mechanism proposed for the majority of SLSNe is that of violent, massive SN ejecta – CSM interaction [32, 33, 34, 35, 36, 37, 38, 39]. It is known that massive stars lose mass throughout the evolution either via steady state winds or via episodic mass-loss events. The exact properties of mass-loss in massive stars during their very late stages of evolution leading to supernova are not well known but a variety of mechanisms have been proposed including mass-loss due to gravity waves originating from vigorous convective shell burning [40,41] or Luminous Blue Variable (LBV) – type mass loss from stars with luminosities close to their Eddington limit such as η – Carina [6] or even a "milder" form of pair-instability events (Pulsational PISNe) occurring at a narrow CO core mass range ($40\ M_\odot < M_{CO} < 60\ M_\odot$) that does not lead to the total disruption of the star but rather to multiple ejections of the outer, less gravitationally bound shells [31,34]. Such violent mass-loss eruptions have been observed around massive evolved stars (with η – Carina being the best example) or even recorded in the weeks prior to the actual SN explosion as in the case of SN 2009ip [42,43].

The pre-SN mass loss naturally sets the initial conditions of the environment within which the SN will occur. The SN ejecta will collide with the surrounding CSM formed by mass-loss leading to the formation of a strong radiative forward shock that propagates into the CSM and a reverse shock that propagates back into the SN ejecta (see Figure 6). This double shock structure will then evolve inwards in mass coordinates depositing shock kinetic energy into the SN ejecta that can be efficiently converted into luminosity powering the LC of a SLSN. The efficiency as well as magnitude of the luminosity that will be deposited by the shocks in the interaction region depends strongly on the original combination of the SN ejecta mass, the CSM mass, their density profiles as well as the SN energy and the radial separation between the CSM shell and the progenitor star. Efficiency is generally maximized for comparable SN ejecta and CSM masses [37] and the LCs SLSN events such as SN 2006gy, SN 2008am [44], SN 2010gx [45] and many others have been successfully modeled with this mechanism [37, 38, 39].

The CSM interaction is actually observed at least in the case of SLSN-II events in a matter similar to that for normal luminosity Type IIn SNe. These events often possess spectra that are dominated by Balmer intermediate width (~1000-5000 km/s) emission lines of Hydrogen. These are Case B recombination lines that are produced by the CSM shock ionizing the material which then quickly cools and recombines. It is unclear whether the measured width of these emission lines is characteristic of bulk kinematic motion, however, since single and multiple electron scattering effects can broaden these line profiles. In a similar manner one would expect intermediate with CSM lines in the spectra of H-poor events characteristic of other elements, such as carbon and oxygen. Such lines might have been observed in the first and second spectrum of SN 2007bi but also in other cases. The possibility that SN 2007bi and other SLSN-I events are powered by H-poor CSM interaction or by a combination of H-poor interaction and radioactive decay of ^{56}Ni is therefore worth considering [31]. LC models of SN ejecta – CSM interaction seem to well reproduce the majority, if not all, observed SLSN LCs albeit the naturally large number of parameters associated with this phenomenon [39]. Including the uncertainty of CSM composition (H-rich versus H-poor) and considering the complexity of CSM environments around some massive stars like η−Carina models of CSM interaction can naturally explain the diversity of SLSN characteristics.

Finally, the third proposed SLSN LC power input mechanism proposed is that of energy released by the spin-down of a newborn magnetar following a core-collapse SN explosion [46, 47]. Newly born highly magnetized (B ~ 10^{14} G) millisecond magnetars rapidly spin-down converting their magneto-rotational energy into radiation that can then heat the expanding SN ejecta. Although some n-LTE models of magnetar spin-down seem to accurately reproduce the spectra of SN 2007bi and the luminosities of many SLSNe (such as SN 2008es) concerns have been raised about whether the non-thermal magnetar radiation sufficiently thermalizes in the ejecta [48]. The magnetar spin-down model is still under debate but it has gained growing support amongst the community over the last year. Rigorous and self-consistent radiation hydrodynamics and n-LTE spectral evolution modeling is required to provide more insight to the question of what mechanism best describes the observables and this is an ongoing endeavor and a subject of debate amongst supernova astrophysicists.

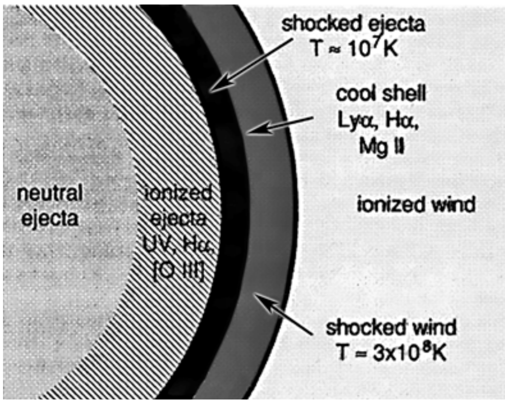

Figure 6:
Illustration of SN ejecta - CSM interaction [33].

Future prospects

The discovery of SLSN challenges our knowledge about massive stellar death and pre-SN mass-loss and opens new ways to probe energy generation by supernovae. The modern high cadence rapid response transient search projects led by two of the worldís leading astrophysics research institutions, the PTF at Caltech and PanSTARRS at Harvard University have increased the number of the discoveries of these events and further confirmed their striking diversity.

In addition to all that, SLSNe in the form of PISNe or CSM interaction powered SNe can also be an important probe of the early Universe. The first (Population III) stars are expected to be significantly more massive than contemporary stars therefore dying as energetic SN explosions [49, 50, 51]. The extreme luminosities and long durations of these events can allow them to be observed by the next generation space telescopes such as JWST and WFIRST at redshift above 20-30 [52, 53, 54, 55, 56, 57, 58]. Studying the properties of these Population III explosions can thus help us investigate the chemical enrichment of the primordial interstellar medium, which sets the stage for the future generations of stars to be born.

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Research Projects in Astronomy in Greece

Funded by the GSRT "Excellence I and II" (Aristeia) Action

In two successive calls, with deadlines expiring September 2011 and June 2012 respectively, the Greek General Secretariat for Research and Technology (GRST) invited researchers in universities and research institutes to submit proposals in the framework of the program "Excellence" (Aristeia). Aristeia is an action taking place within the framework of the Ministry of Education Operational Program for Education and Life-long Learning. It is a highly competitive program aiming to provide researchers, who have demonstrably met standards of excellence in their personal research, with the financial means to reach a state of so-called "autonomy". This is defined by the GSRT as the possibility to develop a principal investigator's own research group, in order to pursue and further expand the PI's scientific vision by carrying research hosted in a Greek university or research institute. The Hellenic Astronomical Society has gladly observed the vivid participation of the Greek astronomical community in the Aristeia calls. We would like to congratulate all those who took part in the process, and in particular our seven members who have won an Aristeia grant. These are: **A. Bonanos** (IAASARS, National Observatory of Athens), I**. Contopoulos** (RCAAM/Academy of Athens), **V. Pavlidou** (Department of Physics, University of Crete), **M. Xilouris** (IAASARS, National Observatory of Athens), for Aristeia I, and **P. Boumis** (IAASARS, National Observatory of Athens), **I. Papadakis** (Department of Physics, University of Crete), and **G. Tsiropoula** (IAASARS, National Observatory of Athens) for Aristeia II.

The following is a brief account of the astronomy research projects funded under Aristeia.

GSRT
GENERAL SECRETARIAT FOR RESEARCH AND TECHNOLOGY

Hellenic Republic

Ministry of Education and Religious Affairs

Revealed by their own Dust: Identifying the Missing Links in Massive Star Evolution - MissingLinks

Principal Investigator: A. Bonanos
Institute for Astronomy, Astrophysics, Space Applications and Remote Sensing, National Observatory of Athens

We have undertaken a systematic study of rare, luminous dusty massive stars in nearby (D<10 Mpc) galaxies, which correspond to progenitors of future core-collapse supernovae and possibly transients. Luminous blue variables (LBVs), supergiant B[e] (sgB[e]), some Wolf-Rayet stars and red supergiants (RSGs) belong to this class of dusty objects, their rarity implying a very short but perhaps critical stage in the evolution of massive stars. The role of mass loss from massive stars, especially episodic mass loss in evolved massive stars, is one of the outstanding open questions facing stellar evolution theory, and the proposed research has the potential to dramatically transform this field by providing crucial data on the properties and statistics of systems most obscured by their own mass loss.

What is new about our approach is that we propose a systematic study of these very interesting objects, "missing links in massive star evolution". We take advantage of the abundant mid-IR imaging data of nearby galaxies existing in the Spitzer archive to identify the luminous mid-IR population of stars in the star-forming spiral and dwarf irregular galaxies of the Local Group and in more distant galaxies, such as M83. Follow-up spectroscopy has so far revealed several candidate luminous blue variables (LBVs), red supergiants (RSGs) and yellow supergiants (e.g. Britavskiy et al. 2014, A&A, 562, 75).

The proposed research program will address a number of important scientific questions, such as: Can the presence of significant mid-IR excess be used as a hallmark of being a LBV? Is the mass loss from LBVs mostly episodic, or can it be also in the form of a continuous wind? What is the frequency of major mass ejection events, similar to eta Car? Does every massive star have one such event in its lifetime, one in a hundred stars, or are such events even less common? Does that frequency depend on the metallicity? Do massive stars have a major mass ejection episode before they explode as supernovae? What is the evolutionary status of sgB[e] stars? The proposed research is an exploratory study of a new regime, and the investigators fully "expect to find the unexpected" and in fact they already discuss some of their "unexpected" findings for luminous dusty stars.

A.Z. Bonanos, N. Britavskiy, S.J. Williams, M. Kourniotis, P. Boumis (National Observatory of Athens, Greece), A. Mehner (ESO, Chile), J.L. Prieto (Princeton, USA) (including postdocs, students & collaborators).

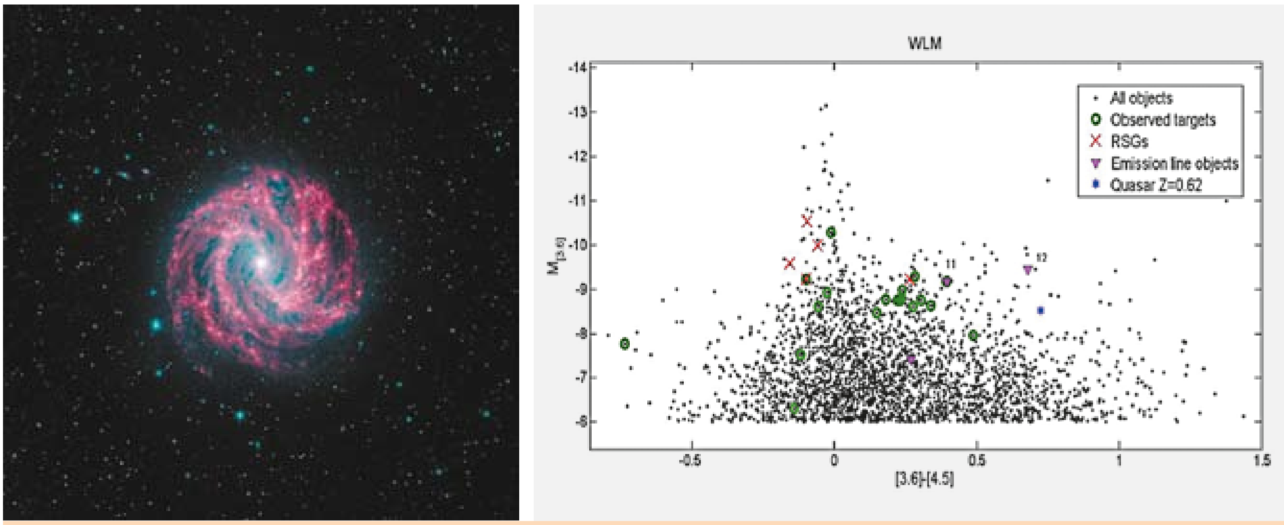

Figure: Left: Spitzer/IRAC image of M83, located at 4.5 Mpc (3.6 μm in blue, 4.5 μm in green and 8 μm in red; NASA/JPL-Caltech). We have analyzed these archival mid-infrared data along with near-infrared follow-up images to select dusty obscured candidates (Williams et al., in prep.). Right: [3.6]-[4.5] color magnitude diagram for WLM, one of the dwarf irregular galaxies under investigation. All targets we have followed up with spectroscopy are labeled. We have discovered 5 red supergiants (RSGs), 3 emission line objects (candidate LBVs and supergiant B[e] stars) and a quasar at z=0.62 (Britavskiy et al., in prep.).

The origin of astrophysical magnetic fields - CosmicBattery

Principal Investigator: I. Contopoulos
Research Center for Astronomy and Applied Mathematics, Academy of Athens

Magnetic fields are an important element of the Universe, their origin, however, remains one of the most fundamental unsolved questions of modern astrophysics. A few years back, we proposed the mechanism of the Cosmic Battery for the generation of astrophysical magnetic fields in the vicinity of the accretion disk around stellar mass black holes and active galactic nuclei. Recent observations of galactic X-ray binaries and extragalactic radio sources attest to the important role of this mechanism in astrophysics. Our Proposal aims to give a final answer to the question on whether the Cosmic Battery can indeed account for the origin of magnetic fields in the Universe. The astrophysical problem that we are investigating combines General Relativity, non-ideal Magneto-Hydrodynamics, and Radiation Transfer. Our core research team consists of the Principal Investigator, a main member, one postdoctoral researcher, and two graduate students. Our effort encountered great bureaucratic hurdles which resulted in the non-implementation of the numerical simulation part of the Proposal. Fortunately, its theoretical part is proceeding normally, with very important results up to now:

i) We obtained the general structure of Kerr black hole magnetospheres and emphasized the physical significance of the inner and outer light cylinders in the electromagnetic extraction of the black hole rotational energy,

ii) We proposed a new mechanism for the generation of high energy radiation in Gamma Ray Bursts (GRB) through the electromagnetic spin-down of the maximally rotating black hole that forms during the collapse of its supermassive stellar progenitor,

iii) We proposed a GRB sub-category (tentatively named «100sec GRB») which may function as «Standard Candles» in Cosmology,

iv) We calculated numerically the radiation field of the accretion disk around a rotating Kerr black hole and the resulting magnetic field generated through the mechanism of the Cosmic Battery.

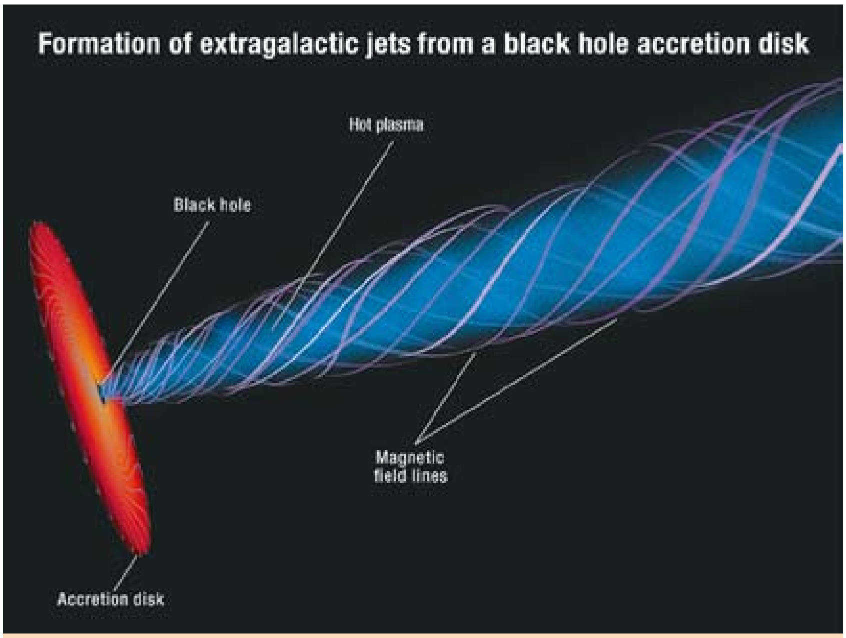

Figure: The accretion disk of hot plasma swirling around a supermassive black hole generates powerful magnetic fields. The disk's rotation twists the field into a funnel shape. These field lines constrict and direct the outflow of high-speed plasma from the black hole's vicinity. The result is a narrow, tapered, extragalactic jet. Credit: NASA, ESA, and A. Feild (STScI)

Our results to date have been presented in the form of scientific papers in the Astrophysical Journal, a chapter in a special volume (Springer), seminars at research Institutes in Greece (Athens, Thessaloniki, Crete) and abroad (Cornell, Princeton, Purdue, Southampton), presentations at international conferences (Madrid, Granada, Les Houches, Dallas, Potsdam, Athens, etc.), and a special Workshop (Academy of Athens, March 2013). Completion of the Program is expected by the end of September 2015.

Unveiling the Physics of Supermassive Black Holes and Relativistic Jets with Optical Polarization Observations of Blazars - RoboPol

Principal Investigator: V. Pavlidou
Department of Physics, University of Crete

Blazars are the most active galaxies known. They are powered by relativistic jets of matter speeding towards us almost head-on at the speed of light, radiating exclusively through extreme, non-thermal particle interactions, energized by accretion onto supermassive black holes. Despite intensive observational and theoretical efforts over the last four decades, the details of blazar astrophysics remain elusive. The launch of NASA's Fermi Gamma-ray Space Telescope in 2008 has provided an unprecedented opportunity for the systematic study of blazar jets and has prompted large-scale blazar monitoring efforts across wavelengths. In such a multi-wavelength campaign, a novel effect was discovered: fast changes in the optical polarization during gamma-ray flares. Such events probe the magnetic field structure in the jet and the evolution of disturbances responsible for blazar flares. Their systematic study can answer long-standing questions in our theoretical understanding of jets; however, until recently, optical polarimetry programs were not adequate to find and follow similar events with the efficiency and time-resolution needed.

Figure: RoboPol Comissioning at the Skinakas 1.3m telescope.

The RoboPol program, a collaboration between the University of Crete, Caltech, the Max-Planck Institute for Radioastronomy, the Inter-University Centre for Astronomy and Astrophysics in India, and the Nicolaus Copernicus university in Poland, was envisioned as a focused, legacy project aimed to settle this question by providing blazar optopolarimetric data of unprecedented volume and quality. To this end, the RoboPol instrument was specifically designed for the 1.3m telescope of the University of Crete's Skinakas Observatory, and it was successfully commissioned in May 2013, while its first, very successful observing season, was concluded in November of the same year. Since April 2014. RoboPol has been observing blazars as part of its second observing season, monitoring over 100 blazars with a dynamical observing schedule, using a large amount of telescope time: 4 nights a week, on average.

During the 2013 season, RoboPol performed the largest single-epoch survey of optopolarimetric properties of gamma-ray—loud blazars; it established that the polarization properties of gamma-ray—loud blazars differ significantly from those of gamma-ray—quiet blazars (gamma-ray—loud blazars are more polarized); and it detected 13 new polarization angle rotation events (compared to 17 such events ever observed with all other optopolarimetric efforts combined). Additional science that was performed wit the RoboPol instrument included the detection of polarization in one gamma-ray burst afterglow; the complete mapping of the magnetic field of a translucent interstellar cloud (the Polaris Flare) that was recently mapped by the Herschel Space Observatory; and the unexpected discovery of high degree of polarization from Be/X-ray binaries.

A Step in the Dark: The Dense Molecular Gas in Galaxies - DeMoGas

Principal Investigator: M. Xilouris
Institute for Astronomy, Astrophysics, Space Applications and Remote Sensing, National Observatory of Athens

Various types of galaxies are spread out throughout the Universe. The basic components of galaxies are stars, gas and dust. During their evolution these three components are interacting with each other. There are regions in the galaxies, the so-called molecular clouds, with large quantities of dust and gas (mostly atomic and molecular hydrogen) providing ideal conditions for the creation of new stars. Stars are forming, live their lives and die. During the last stages of their lives they «donate» their materials (gas and metals) to the interstellar space (via stellar winds or violent explosion events) and as a result, conditions for birth of new stars are set. This cycle between star formation and enrichment of the interstellar medium is keeping the galaxies as live entities that evolve with time.

There is a special group of galaxies that emit strongly at infrared wavelengths. These galaxies are called Luminous Infrared Galaxies (LIRGs) and have infrared luminosities (L_{IR}) higher than 10^{11} L⊙ (they are called ULIRGS –Ultra Luminous Infrared Galaxies– when $L_{IR}=10^{12}$ L⊙). Over the last decade comprehensive observations from X-rays through radio wavelengths have produced a consensus picture of local LIRGs, showing that they are mergers between gas-rich galaxies, where the interaction triggers some combination of dust-enshrouded star-formation and Active Galactic Nuclei (AGN) activity.

Left: Composite image of NGC6240 (HST/ACS B-band in blue, HST-ACS I-band in green and Spitzer/IRAC 8 μm in red. Right: The Spectral Line Energy Distribution (SLED) of the CO molecule decomposed in two dense components (A) and (B) (red and blue dotted lines) and a lower density component (C) (pink) which accounts for the low-J CO line emission (Papadopoulos, et al. 2014, ApJ, in press).

In our study we analyzed observations of this specific group of galaxies obtained through a long-term campaign during the past ~10 years. These observations (at far-infrared and sub-millimeter wavelengths) mainly reflect the presence of the molecule of carbon monoxide (CO) through its various transition states but also other important molecules such as ^{13}CO and HCN. Due to limitations due to Earth's atmosphere we can only observe the low transitions of this molecule from ground-based facilities. We have done so by using the JCMT telescope in Hawaii and the IRAM-30m telescope in Spain. For the higher transition states we made use of the Herschel Space Observatory of the European Space Agency. This effort provided us with a unique database for exploring the properties of the gas in dense molecular clouds. It is worth mentioning that studies so far have mostly been limited to the first two transitions of CO (J = 0-1 and 1-2). With our database we can, for the first time, study transitions up to J = 13-12. This provides us with the tools to probe deep into the molecular clouds and determine the conditions in the densest environments of the interstellar medium in galaxies.

The «DeMoGas» group is composed of the following members: Manolis Xilouris *(PI; NOA)*, Ioanna Leonidaki *(NOA)*, Padelis Papadopoulos *(Cardiff University)*, Paul van der Werf *(Leiden Observatory)*, Thomas Greve *(University College London)*, Zhi-Yu Zhang *(Royal Observatory, Edinburg)*, Panos Boumis *(NOA)*, Alceste Bonanos *(NOA)*.

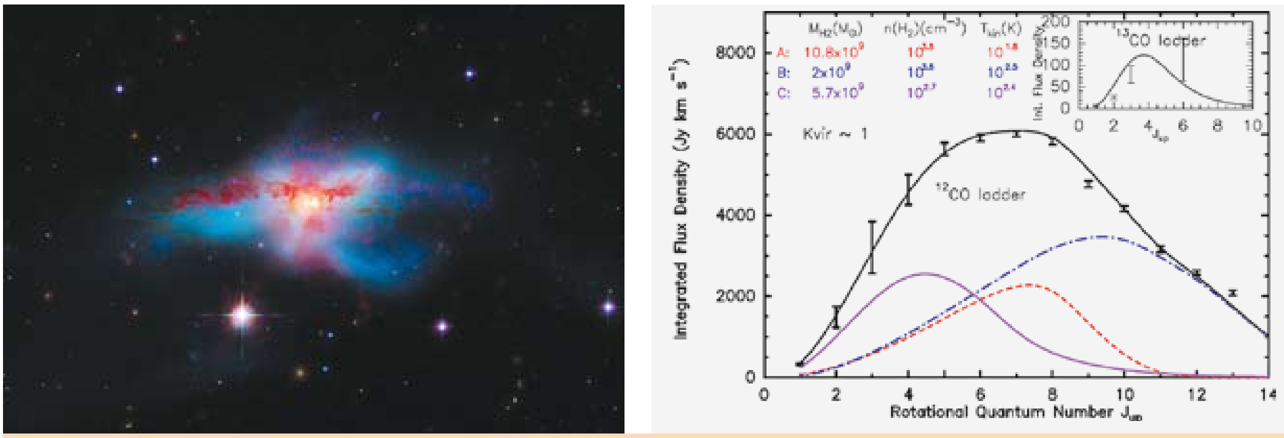

Figure: Left: Composite image of NGC6240 (HST/ACS B-band in blue, HST-ACS I-band in green and Spitzer/IRAC 8 μm in red. Right: The Spectral Line Energy Distribution (SLED) of the CO molecule decomposed in two dense components (A) and (B) (red and blue dotted lines) and a lower density component (C) (pink) which accounts for the low-J CO line emission (Papadopoulos et al. 2014, ApJ, in press).

The Manchester-Athens Wide-Field (narrow-band) Camera:

A Deep Sky-Survey of the Extensive Line Emission Regions at High Galactic Latitudes - MAWFC

Principal Investigator: P. Boumis

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

The sky at high galactic latitudes is host to a wide range of extensive phenomena that emit faintly in optical lines over a range of excitations. These features remain largely unexplored for the overwhelming majority of the observing programmes of the World's largest telescopes, which have been concentrated on achieving high angular resolution over small fields. First of all, the foreground, very diffuse, line emission from the galactic plane needs accurate evaluation down to a resolution of 1 arcmin to improve the interpretation of the Cosmic Microwave Background (CMB). Then there is the 100 degree long non-thermal radio spur apparently projecting from the Galactic centre. The question still remains as to whether or not this is a nearby supernova remnant or the more dramatic ejection of relativistic particles from the Galactic nucleus into the Galactic halo. Remarkably, no optical identification has yet occurred. In addition, the northern end of the huge HI Magellanic stream, which is certainly partially ionized, is yet to be explored at optical wavelengths although it is expected to emit Hα and [OIII] lines. The complexity of the nearest HII 30 degree diameter, `bubble' in Eridanus also needs evaluating with far deeper emission line observations to distinguish between its radiatively ionized and more filamentary, collisionally ionized components. It is the extremely large angular sizes of these phenomena that inhibits their observation.

The proposed project is to design and construct a state-of-the-art, wide-field (~30 degree diameter), narrow-band, optical filter camera - The `Manchester-Athens Wide Field Camera' (MAWFC). The standalone camera will be the first scientific instrument for astronomy that will be constructed and tested completely in Greece and will conduct a large-area sky survey that will provide maps at less than 1 arcmin resolution, in order to investigate the very extensive, but faint, line emission regions over the whole sky. We will make deep observations of the northern sky in the optical emission lines of Hα, [OIII] and Hβ, from astronomical sites. The successful outcome will have a significant impact on topical astronomical areas of research e.g. subtracting the foreground for the cosmic microwave background; estimating the electron temperature of the warm ionized gas by comparison with radio data; investigating the giant, high latitude, radio filaments from the Galactic center or very close objects in the Galactic plane of extreme angular extent; detecting the northern end of the LMC/SMC HI stream; investigating the Fermi/WMAP haze/bubbles.

Note that this new camera is a 10 times more sensitive upgrade of a prototype (Fig.1 left), it is an enhanced version of the one used very successfully several years ago (MWFC; Johnson et al. 1978, Boumis et al. 2001, Dickinson 2002). Figig.1 (right) illustrates successful use of the prototype device where the faint but extremely extensive Eridanus nebulosity has been imaged in the light of Hα (Boumis et al. 2001).

Team Members:
- Prof. John Meaburn *(Jodrell Bank Centre for Astrophysics, UK)*
- Dr. Alexandros Chiotellis *(postdoc, IAASARS, NOA)*
- Dr. Joan Font *(postdoc, IAASARS, NOA)*
- Mr. Vassilis Loizos *(IT specialist, IAASARS, NOA)*
- Dr. Clive Dickinson *(Jodrell Bank Centre for Astrophysics, UK)*
- Dr. Alceste Bonanos *(Associate Researcher, IAASARS, NOA)*
- Dr. Manolis Xilouris *(Senior Researcher, IAASARS, NOA)*

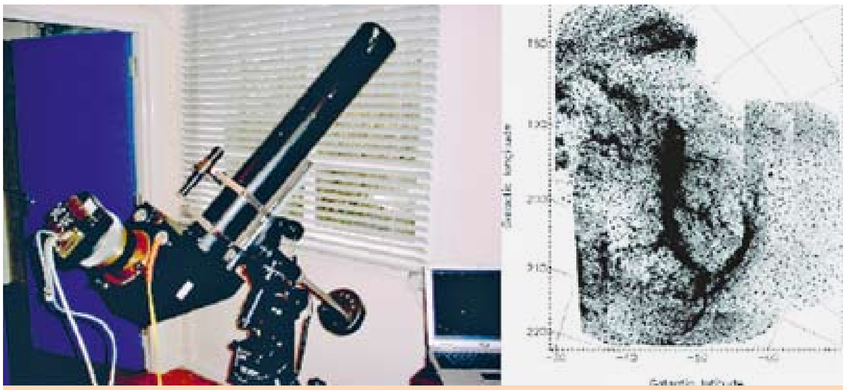

Figure 1: Left: Photo of the prototype Manchester Wide-Field Camera, being tested in the lab (circa 2001). The original design was large and bulky.
The Apogee Ap7-p CCD was not entirely adequate (pixels too large, array too small, dark current too high and filters only 50 mm diam.).
Right: Deep, mosaic Hα image of the high Galactic latitude Eridanus shells, made with this early version of the camera. Note the large field-of-view of the image (coordinates are in degrees; Boumis et al. 2001).

The Quest for Relativistic Signals in the X-Ray Light Curves of Active Galactic Nuclei - AGNQUEST

Principal Investigator: I. Papadakis
Department of Physics, University of Crete

Active Galactic Nuclei (AGN) are the most powerful persistent sources in the Universe. It is currently thought that energy in these objects is liberated by the accretion of matter onto a super-massive black hole (BH) at their center. The AGN emission is highly variable at all wavelengths, with the X-ray flux showing the fastest, and largest amplitude variability in any of the wavelength ranges. This fact implies that X-rays originate from a small region very close to the central source, and could be as small as ~ 10 gravitational radii, R_g. If the X-ray source illuminates optically thick cold matter, we expect to observe a Compton reflection spectral component containing a series of fluorescent lines. The most prominent line is the K_α line emitted by neutral iron at 6.4 keV. If Compton reflection originates in the inner accretion disc it will be affected by the black hole's strong gravitational field and the line profile will be "relativistically" skewed and asymmetric, with a red wing extending towards low X-ray energies due to gravitational redshift and transverse Doppler redshift.

By the end of the 1990s, it was believed that the relativistically broadened iron line was a common feature in AGN. The situation became less clear after the results from the first studies with XMM-Newton were published. In fact, the fraction of AGN which show this line in their spectra is currently rather unknown. Furthermore, "warm absorbers" and/or partial-covering of the central source from very "thick" absorbers, can introduce significant complexities into the iron K_α band, which prevents the accurate determination of their intrinsic width and shape.

However, recent detections of X-ray "negative" time lags in a few AGN support the view of X-ray reverberation across the inner accretion disc in these objects. For example, the radius of the X-ray reprocessing region in MCG -6-30-15 may be less than ~ $5R_g$, i.e. smaller than the radius of ISCO around a non-rotating BH. On the other hand, global simulations of thin discs where magnetorotational instabilities operate, indicate that they should be strongly inhomogeneous. When combined together, these results imply that the line emission in AGN may originate from dense accretion disc filaments, which rotate around the central source with relativistic velocities. If this is the case, the reprocessed emission from these filaments (i.e. the broad iron line) will be periodically modulated due to various relativistic effects, like Doppler boost for example. As a result, we expect significant periodic or "quasi-periodic oscillations" (QPOs) to appear in the power spectral density functions (PSDs) of AGN light curves in the 5-6.3 keV band light curves, i.e. energy bands where the reflection components constitute a significant percentage of the observed flux.

«AGN-QUEST» is a research project which was recently awarded an «Excellence II» («Aristeia II») grant for the GSRT, to study the flux variability of the iron line in a carefully selected sample of ~ 15 AGN with known Black Hole mass. The main objective is to construct light curves in the 5-6.3 keV band, using the vast amount of data that exist in the archive of current and previous X-ray missions (i.e. ASCA, XMM-Newton and Suzaku), and to use Fourier techniques to search for periodic/quasi-periodic signals at frequencies which are representative of the Keplerian orbital time scale at the ISCO radius for a Schwarzschild and a Kerr black hole. Hopefully, the project results will help us better understand the picture of the innermost gravitational radii around BHs, which is currently one of the most active research fields in High Energy Astrophysics.

Solar small-scale events and their role in the heating of the solar atmosphere - SOLAR

Principal Investigator: G. Tsiropoula

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

Solar small-scale structures are of pivotal importance because they intermittently connect the photosphere and chromosphere to the corona through their magnetic fields. Extensive past observations aimed at gaining clues on their true nature, and many attempts were made to provide theoretical models for processes responsible for their generation and sustain. Despite these developments, the state of our present understanding of these structures, as well as their interrelationship and the role they play in the heating and mass balance of the solar chromosphere and corona, remains far from satisfactory.

The aim of the funded research under the ARISTEIA II Action is the derivation of accurate physical parameters of small-scale events, the comprehension of their dynamical behavior, of their interrelationship, of their association with the magnetic field, of their formation mechanism(s), and of their role in coronal heating. These goals will be achieved by using high spatial and temporal resolution multi-wavelength and magnetic field observations of the Sun obtained by space and ground-based instruments and with advanced 3D MHD numerical simulations, inversion techniques for the line profiles and magnetic field extrapolation codes. These studies are crucial to reveal how the Sun's magnetic field drives the dynamics of its atmosphere and how this atmosphere is heated.

More specifically, the scientific objectives of the funded project are the following:

- The study of the short term dynamics of solar small-scale events observed in different wavelengths by several ground-based and space instruments that observe in a range of temperatures,
- The determination of their physical parameters (3-D morphology, temperature, density, velocity) and changes of these parameters during their lifetime,
- The comprehension of their interrelationship,
- The derivation of a relationship between their morphology and dynamics and the three-dimensional magnetic field structure,
- The determination of their driver mechanism(s) through 3D MHD numerical simulations and forward modeling,
- The study of their role in the energy and mass balance of the solar atmosphere.

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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, useful to both professional and amateur astronomers in Greece. It contains a directory of all members of the Society, as well as an archive of all material published by the Society, including electronic newsletters, past issues of "Hipparchos", and proceedings of Conferences of Hel.A.S. The server is currently hosted by the University of Thessaloniki.

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