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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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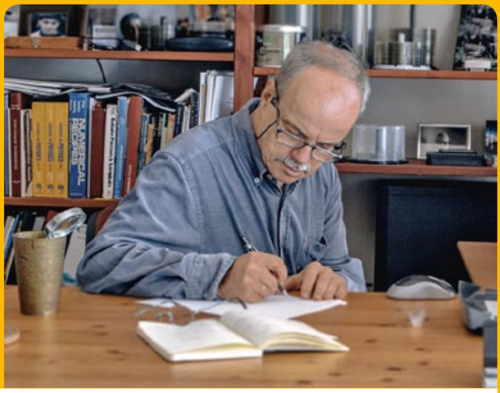
Cover Image:
The Orion nebula above the participants of the 1948 IAU GA in Zurich. A composition for the celebration of the 100 years of IAU.
Credit: IAU

Message from the President



The new issue of Hipparchos you are holding in your hands is, in many ways, a special issue as it celebrates the 100th anniversary of International Astonomical Union born on July 28, 1919. This important anniversary, known as "IAU 100 - Under One Sky" is celebrated around the globe, and in Greece, with a series of events – for more information see our Society's site:

http://www.helas.gr/IAU100.php

Therefore it comes as no surprise that the editor of Hipparchos decided that it would be very timely to dedicate most of this year's issue to this unique event.

It was thus very appropriate to ask Academician (and first President of our Society) Prof. Georgios Contopoulos to write a personal view of IAU as he served, amongst other positions of prominence, as its General Secretary from 1973-1976. Prof. Contopoulos's recollections are an amazing mosaic of the mid to late 20th century history showing that science, like all human activities, is closely related to its era. The Cold War globally, and the Greek Junta on a local level, set the stony stage where astronomers had to move in order to meet and discuss science in an epoch that international communication was not as easy as it is today and national barriers were setting sometimes high obstacles. Still the language of the scientists proves to be much more universal than this of the politicians.

On the second installment concerning the anniversary, Prof. Kanaris Tsinganos, also former President of Hel.A.S. and, at present, the National Outreach Coordinator for IAU 100, undertakes the difficult task to present us with the major discoveries that marked these last 100 years of Astronomy. The task is achieved as the author does not try to cover everything – which would have been exhausting for author, readers and editor alike – but focuses instead on some selected, hand-picked topics. This works very well and the combination of about fourty photographs/diagrams accompanied by an informative text on topics ranging from the Sun/Solar System to Cosmology conveys the width and spread of the last 100 years of astronomical discovery.

The current issue of Hipparchos contains also two review articles not directly connected to IAU 100 but having interest on their own. Dr Christophe Sauty (Observatoire de Paris) gives us a very clear, from a theoretical standpoint, review of MHD disks and jets. The story behind the science is also very interesting, since Dr. Sauty is one of the very few examples of people who came from abroad to work on their PhD in Greece and in the process he developed strong ties to the country – as well as to Hel.A.S. The other review article is by our Secretary, Dr. Kostis Gontikakis (KEAEM, Academy of Athens) and deals, in a brief but concise way, with the upper solar atmosphere, a fascinating topic that is still far from understood.

I hope that all the above prove that the present issue of Hipparchos is indeed special. It gives us, from the authors' personal perspectives, the tremenduous growth of Astronomy during the last 100 years and makes us wonder what the future might bring. Furthermore, the "IAU 100 - Under One Sky" anniversary is a perfect opportunity for demonstrating to the public the richness and depth of the science we all practice and love. It is also an opportunity to bolster the scientific methods against the various branches of pseudo-science which, thanks to their sheer ultra-lightness and enigmatic support, have become undeservedly fashionable. And, last but not least, it gives us the opporunity to demonstrate, in these high tension times, that we indeed live under one sky and the study of this sky breaks down the barriers imposed not only on us, but also on all of humanity.

Apostolos Mastichiadis
President of Hel.A.S.

100 years of the International Astronomical Union (IAU)

by **George Contopoulos**
Former General Secretary of the IAU

This year is the hundredth anniversary of the International Astronomical Union (IAU).

The IAU forms the most important collaboration of the astronomers of the world. It has more than 13000 members, from more than 100 countries. Its members are at least doctors of astronomy or of related fields. It contains about 50 Commissions on various subjects and its governing body is the Executive Committee that consists of the President, the General Secretary, the Assistant General Secretary and 5 more members.

Every Commission has its Organizing Committee, that includes its President and Vice President. The Commissions deal with particular subjects, like the dynamical astronomy, the planets, the spectroscopy of the stars, the stellar evolution, the Galaxy and other galaxies, the cosmology, the high energy astrophysics, etc.

The term of the Executive Committee and of all the Commissions' officers is three years. Every 3 years there is a General Assembly of the Union, that brings together thousands of astronomers. During the General Assembly there are many scientific meetings and meetings on various organizational subjects, like the introduction of new members and countries, the election of the new Presidium, and the ratification of the decisions of the various Commissions. E.g. the General Assembly ratifies the names of the various structures of the moon and the planets, the basic parameters of stellar astronomy and of cosmology, the future Symposia etc.

I had the opportunity to participate in many General Assemblies of the IAU and to be elected President of the Commission 33 on the Structure and Dynamics of the Galaxy (1967), Assistant General Secretary (1970) and General Secretary of the IAU (1973).

Here I will mention some of my reminiscences from my participation in the IAU.

The first time that I participated in a General Assembly was in Dublin, Ireland (1955). There I had the opportunity to meet many leading astronomers, like Ryle (Nobel prize for his work in radio-astronomy, Fig. 1), Profs. Oort and Lindblad, leading specialists in galactic dynamics etc. The General Assemblies give us a unique opportunity of contact with astronomers from all around the world. The most important result of these contacts for me, was the invitation by Prof. Lindblad (Fig. 2), to go for one month in Stockholm, the following year. I met also

Figure 1: *General Assembly of the IAU in Dublin (1958). Talking with Prof. Ryle (Nobel prize).*

Figure 2: *Professor and Mrs. Lindblad at the Dublin General Assembly.*

the Dutch Professor Oort, who was at that time President of the Commission on the Structure and Dynamics of the Galaxy (Commission 33) and was then succeeded by Professor Blaauw and later by Professor Bok.

During my visit to Stockholm in 1956 I had the opportunity to calculate with the help of an electronic computer, for the first time in international astronomy, some 3-dimensional orbits of stars in a galaxy. The forms of these orbits were quite unexpected at that time. I presented these orbits at the next General Assembly of the IAU in Moscow (1958). I was the only Greek representative in this General Assembly (see the Greek flag in front of the University of Moscow (Fig. 3) because the travel from Greece to the Soviet Union at that time was not permitted, and I got a special permission with great difficulty.

At my lecture in Moscow there was present Professor Dirk Brouwer, who invited me to Yale University as a visiting professor. Thus, Moscow opened for me the road to the United States, where I have been many times as visiting professor in several universities.

The next General Assemby was in Berkeley, California (1961). There we had the first meeting of the specialists in Stellar and Galactic Dynamics. In this meeting there were the American Ivan King, the French Michel Hénon, the British Donald Lynden-Bell, the German Sebastian von Hoerner, and a few more, and we decided to have in Greece the first International Symposium in Dynamical Astronomy. This took place in Thessaloniki in 1964. This Symposium brought together for the first time people that were working in Celestial Mechanics and those that were working on Stellar and Galactic Dynamics. After that meeting the field of Dynamical Astronomy had a spectacular development.

Then there was the General Assembly in Hamburg (1964). During this Assembly Professor Bok, President of the Commission on the Structure and Dynamics of the Galaxy (Commission 33) of the IAU, proposed me as his successor as President of the Commission. But the Presidium of the IAU had objections. As Prof. Bok told me, I had a basic drawback: the fact that I was not Dutch, as all the previous Presidents of this Commission. But Dr. Bok convened the Organizing Committee of Commission 33 and all of them unanimously, declared that they did not want any other person as President, besides Contopoulos. After that the Presidium of the IAU gave in. Thus, I became Vice President of the Commission and after 3 years I became its President.

The main job of the President of the Commission was to write a Report on the activities in the field of the Structure and Dynamics of the Galaxy during the last three years. In this particular occasion I prepared, besides the usual abridged review required by the IAU, a big volume describing the recent scientific developments in Dynamical Astronomy. This volume had a considerable impact internationally.

The next big change for me came in 1970. The President of the IAU at that time, was the German Professor Otto Heckmann. Dr. Heckmann invited me to Hamburg to give a lecture and then he proposed to me to become the next General Secretary of the Union. I felt very honored, but I was skeptical if I should accept, because Greece was under a Junta, and I was not certain whether I would be free to travel frequently abroad as required. I was remembering the case of a colleague of mine who despite the fact that he had the required permission to travel abroad, he was taken out of a plane that he had boarded. I told that to Dr. Heckmann, but he assured me that the Junta would not dare to stop me if I had this prestigious international position. Thus, I accepted, and I was elected Assistant General Secretary in 1970, at the Brighton, England General Assembly of the IAU.

During this General Assembly I made a proposal to the representatives of the United Kingdom, France, Germany and the Soviet Union to form a European Astronomical Society. All were very favorable, but when the Soviet delegates returned to Moscow they were not allowed to participate in such a Society. Thus, my project failed at that time and it was realized only after a number of years when the international conditions were better.

Then I proposed a different project, namely to have every year a large local meeting in Europe, under the auspices of the International Astronomical Union. This idea was quite successful and the first European Meetings took

Figure 3: *The flags of the participant countries at the Moscow General Assembly of the IAU (1958) in front of the Moscow University.*

Figure 4: *The first European Meeting under the auspices of the IAU in Athens (1972). We see Prof. Chandrasekhar (Nobel prize) [right] and Prof. Oort [center].*

place in Athens (1972) and Tbilisi, Georgia (USSR) in 1975. Later on, there were many similar "Continental" Meetings not only in Europe but also in Asia, in Australia - New Zealand, and in Latin America.

The first European IAU Meeting in Athens was very successful. (Fig. 3 shows two leading astronomers, Prof. S. Chandrasekhar (Nobel prize) and J. Oort, that attended our Meeting). Among other participants there were many people from the Eastern countries, the Soviet Union, Poland, Czechoslovakia, Yugoslavia, Romania and Bulgaria. But most of them were provided with only one dollar per day for their expenses. Thus, we provided free lodging and most of the meals for them and they all were enthusiastic. This we could do because the Ministry of Education had provided some money for our expenses.

But the Minister of Education was angry because in the booklet that described the Program of the Meeting we were not stating that the Meeting was co-authored by the IAU and the Greek Ministry of Education. I replied that the IAU does not co-author Meetings with local organizations. Then the Minister threatened that he would cancel the Meeting. But how this could be done when many participants were already arriving? Thus, I proposed a compromise solution. To write that the Meeting was organized by the IAU with financial support from the Greek Ministry of Education. This was accepted, but reluctantly.

The next General Assembly took place in Sydney, Australia, in 1973. There I took over as General Secretary. But before that Meeting there was a serious controversy in the IAU because the Polish representative wanted to have this General Assembly in Poland, because this year was the 500th anniversary of Copernicus. And the Soviets threatened that they would withdraw if we would not accept the Polish proposal. Thus, we decided to have an Extraordinary General Assembly in Poland, immediately after the General Assembly in Australia. Thus, many people travelled directly to Poland from Australia.

In Poland we were treated very nicely. Among other things the Polish provided us with a photocopy of the original manuscript of Copernicus under the title "De revolutionibus orbium coelestium". In this photocopy I noticed that there was a page in which Copernicus was referring to the Greek astronomer Aristarchus, who was the first to propose the heliocentric theory. However, this page was crossed out and it did not appear in the published book of Copernicus. I showed this page to the President of the IAU, Professor Leo Goldberg, and it made a strong impression on him. Then at the opening ceremony the next day, when the Polish organizers emphasized the original theory of Copernicus, when the time came for the President of the IAU to speak, Dr. Goldberg emphasized the fact that Copernicus, as a true scientist, he made the correct references to his predecessors, especially the Greek Aristarchus, who first proposed the heliocentric theory.

As Assistant General Secretary of the IAU I was supervising the Meetings of the IAU, in particular its Symposia and Colloquia, and the corresponding publications. During the 3-years period (1970-1973) I had to take care of 50 Symposia and Colloquia.

Later as General Secretary of the IAU, I had to take care of all the correspondence of the Union, thousands of letters with the National Committees (50 at the time), the 50 Commissions of the Union and a large number of other Organizations and Unions. One of my first efforts was the return to the Union of China, which had withdrawn after Taiwan was accepted as a member country. Finally China accepted to return under the condition that we should accept that there is only one China, but there are two groups of Chinese representatives, one from Beijing and the other from Taipei (capital of Taiwan). When later the Chinese representatives from Beijing came to our next General Assembly, they thanked me particularly for my efforts in their favor.

Besides my other duties, I was the representative of the IAU in ICSU (International Council of Scientific Unions), that had representatives from all the countries and International Unions, like the Unions of Physics, Mathematics, Chemistry, etc. The most important meeting of the ICSU at that time took place in Leningrad in 1974. There all the representatives of the Unions emphasized their wish to have more ample participation of scientists from the Soviet Union. But the President of the Soviet delegation, Professor Ambartsumian, disappointed us by stressing that the participation of scientists in International Meetings should be arranged inter-nations, which in his opinion means that only the National Academies should decide who should participate in such Meetings and it was not correct to send invitations to particular persons. After Ambartsumian's talk the atmosphere of the Meeting became chilly. Then I asked to speak and I made the following remarks: "The isolation of the scientists is an obstacle to the progress of Science. And I have personal experience of that because the Greek scientists are not free to travel abroad (at that time we had the restrictions of the Junta). The same is true for the scientific status of the Soviet Union, despite the fact that this is a great country". I am happy to state that despite my disagreement with Prof. Ambartsumian we remained good friends. And I will give an example of our relations.

When we had the Extraordinary General Assembly in Poland, Professor Ambartsumian was invited to give a basic invited lecture. But he had written this lecture in Russian and he expected someone to translate it to English during his talk. But we could not find any appropriate translator. Then Ambartsumian spent a night writing his lecture in English. But while the subject of his talk was important (it had to do essentially with the dark matter in the Universe) his English was not good enough and his pronunciation was worse. Thus the audience did not understand almost anything from his talk. But I got up after his talk and I said "I will tell you in a few words the main points of the lecture of Prof. Ambartsumian". The audience then became very attentive. And in the end the clapping of the hands was enthusiastic.

On a different occasion the President of the IAU Prof. Goldberg and myself sent a letter of support for a number of astronomers in the Soviet Union that had been persecuted by the government. After that I had a telephone call from Prof. Mrs. Massevich, Vice President of the Soviet Astronomical Committee, who proposed to give a lecture in our University. I was very happy to accept her proposal. After her talk, I took her to dinner, but there Mrs. Massevich criticized strongly the action of the President and of myself. She said "What is the importance of some reactionary scientists, like Sakharov and some others, when the large majority of the Soviet scientists are supporting our government? What do you want? To withdraw from the International Astronomical Union?" Then I replied "Now I understand why you came to Greece. You came just to tell me your criticisms. Therefore, when you return home tell "them" that I, as General Secretary of the IAU, I am obliged to help all the astronomers of the world, whether they support your government or not. And you cannot ignore the contributions of people like Sakharov, who promote the bright image of the Soviet Union internationally".

The most crucial event of my term of General Secretary of the IAU happened when the General Assembly of the ICSU took place in 1974, in Turkey. I applied for a visa to Turkey but the Turks did not give it to me (it was the time after the Turkish invasion of Cyprus). Then the President of the IAU, Prof. Goldberg, informed the President of ICSU, who replied "Why don't you send some other person, besides Contopoulos, to represent your Union?" But Goldberg replied "Contopoulos is the only legal representative of the IAU, and if the Turks do not give him a visa, then according to the statutes of ICSU, about the free circulation of scientists, you are obliged to cancel the ICSU General Assembly in Turkey". At the same time Goldberg informed the National Academies of the USA, England, Sweden etc. about this problem and some academies informed their representatives to depart from the ICSU General Assembly in protest if Contopoulos did not appear.

Thus, the last moment the Turks gave in. A day before the opening of the ICSU meeting they called me from the Turkish consulate of Thessaloniki, to go and get my visa. This day was a Saturday and the consulate was closed. But they opened it just to give me my visa. Thus, I left the next day and I flew to Constantinople (Istanbul) and Ankara. And there some representatives told me that if I did not appear at the meeting they had instructions to leave the ICSU meeting, in protest.

During my 3-year term as General Secretary a second Junta was established in Greece. The change happened a Sunday. This Sunday the secretaries of the General Secretariat, Mr. Jappel and Mrs. Dankova, started with their car an excursion to Chalkidiki. On their way they noticed many tanks in the streets, but they did not pay much attention. They thought that there were some maneuvers. But further on they were stopped by a company of soldiers and the leading officer told them "Verboten". "Why verboten?" asked Jappel and the officer replied in broken German "Wir haven revolution. Papadopoulos kaput. Andere Papadopoulos, andere demokratie." (We have a revolution. Papadopoulos is out. Another Papadopoulos has come, another democracy)! It was funny to call this second Junta a "democracy"! Nevertheless we survived, despite the terrible destructions caused by this so-called "democracy".

My last duty as a General Secretary of the IAU was the organization of the General Assembly of Grenoble, France, in 1976. I had an enormous correspondence with the Local Organizing Committee, the National Committees, all the Commissions of the Union, the official representatives etc. During this General Assembly I had to organize about 250 special meetings, scientific and organizational.

Two things made me happy during the closing session of this General Assembly, when there was the final Report of the IAU.

First was the recognition by the President, Prof. Goldberg, of the huge work that I had completed during my three-year service. In particular he mentioned the tact I had shown in our contacts (meaning our disagreements), when I had to indicate him his duties. He also stressed that he was impressed that, despite my important organizational work, I did not stop my scientific work, and that he was particularly impressed by a recent seminar of mine that he had attended.

Second: After the closing session came to me the Soviet delegation with Mrs. Massevich on top, to thank me for all I had done to them. And in fact I had done a lot of services to the Soviet astronomers, independently of political attitudes, like scholarships, travel expenses, free books and journals etc.

This ended in principle my office as General Secretary of the IAU. However, my service to the IAU continued in different ways. I remained as Consultant to the Executive Committee for 3 more years. Thus I participated in the Executive Committee of the next General Assembly in Montreal, Canada, in 1979. I arrived at the Committee's meeting a little late and as I entered the President told me "Mister Contopoulos. We just decided to have the next General Assembly in Greece". "No kidding", I replied, because I knew the next General Assembly was scheduled to take place in Bulgaria. But the President said "It is not kidding. Look at the telegram in front of you." It was a telegram from the Bulgarian representatives saying that it was impossible for them to organize the General Assembly in Bulgaria. Thus, we started an incredible correspondence and finally the 1982 General Assembly took place in Patras, Greece.

My participation in this General Assembly was rather small. But I had the basic responsibility to organize a related Symposium on Cosmology in Kolymbari, near the town of Chania, Crete.

During the General Assembly of Patras, the most important Soviet delegate was Prof. Zeldovich, who gave an excellent lecture on cosmology. He stressed that the theory of Big Bang is as certain as the heliocentric theory of the Solar System (At that time it was not expected that a Soviet astronomer would support the Big Bang theory). Zeldovich urged all the interested participants to go to the cosmological Symposium in Crete. When I went to congratulate him he told me a few words in Russian. Then an English participant nearby smiled. And Zeldovich told him "Do not laugh. Contopoulos and I understand very well each other, because we are both Orthodox Christians". I was quite impressed.

The Cosmological Symposium in Crete took place in the Orthodox Academy of Crete and had a great success. There were present some of the leading cosmologists of the world. Among them there were the Soviet cosmologists Shklovsky, Novikov and Einasto, who were very happy.

After two years, in 1984, we had a similar Symposium in Toulouse, France. At the closing session all were praising the organizers of the Symposium for their work. But when it was the turn of Shklovsky to speak he said "This Symposium was very good. But it cannot reach the level of the Symposium organized by Contopoulos in Crete".

Later the IAU had even greater influence on the International Astronomy, that continues today. And I must stress that the participation of the Greek astronomers is always important. I hope and wish this active participation to be continued in the future.

For more details see my book "Adventures in Order and Chaos. A Scientific Autobiography", Kluwer, 2006 (Fig. 5).

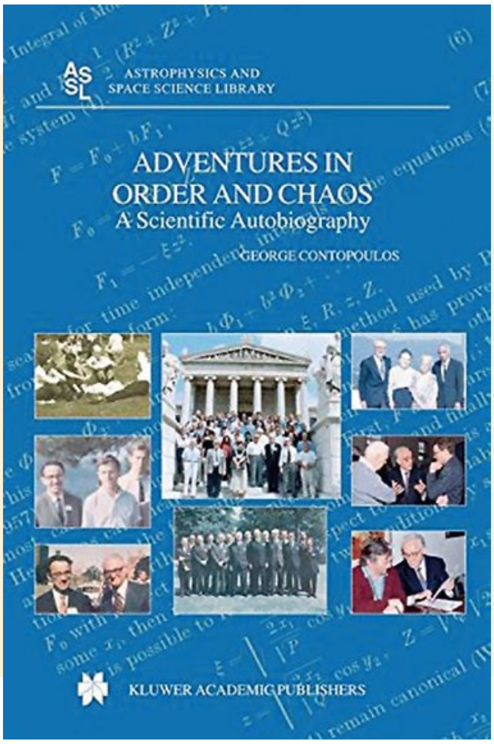


Figure 5: *The book "Adventures in Order and Chaos. A Scientific Autobiography", Kluwer, 2006.*

Visit our website

http://www.helas.gr

The above web server contains information, both in greek and english, about the Hellenic Astronomical Society (Hel.A.S.), the major organization of professional astronomers in Greece. The Society was established in 1993, it has more than 250 members, and it follows the usual structure of most modern scientific societies. The web pages provide information and pointers to astronomy related material, 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.

1919-2019: a century of the International Astronomical Union, an era of splendid astronomical discoveries

by Prof. Kanaris Tsinganos

National & Kapodistrian University of Athens, IAU National Outreach Coordinator for Greece

In 2019, the International Astronomical Union (IAU) is celebrating its 100th anniversary, as it was founded on the 28th of July 1919, at the Constitutive Assembly of the International Research Council (now International Council for Science) held in Brussels, Belgium. The 7 initial member states of the IAU were Belgium, Canada, France, Great Britain, **Greece**, Japan, and the United States. The first General Assembly, took place in Rome, Italy, 2-10 May 1922.

The mission of the International Astronomical Union is to promote and safeguard the science of astronomy in all its aspects, including research, education, communication and development through international cooperation. To commemorate this milestone, in 2019 the IAU is organizing a year-long celebration to increase awareness of a century of astronomical discoveries.

In particular in Greece, a number of events have been already taken place while many others are planned in the coming months. These centennial celebrations are aimed to stimulate nationwide interest in astronomy and science and to reach out to the global astronomical community, national science organizations and societies, policy-makers, students, families and the general public.

After the second World War, Astronomy exploded in the 1950s and 1960s. New technology that had been developed for military purposes in the Second World War and the Cold War enabled astronomers to open and observe new parts of the electromagnetic spectrum. For example, radio astronomy made an entirely new kind of the universe visible. Then, the Space Race made it possible to observe X-ray, γ-ray and ultraviolet radiation and to visit other bodies in the Solar System. New discoveries followed each other at dizzying speed: the expansion of the universe and the cosmic background radiation, radio galaxies, quasars, blazars and active galactic nuclei, neutron stars and pulsars, white dwarfs, gamma-ray bursts, the solar wind and relativistic cosmic jets, gravitational lenses, dark matter in galaxy clusters, the Moon landing, robotic exploration of Mars and the epic crossing of the Heliopause, the accelerating expansion of the Universe, the detection of gravitational waves and supermassive black holes, etc. Thirteen Nobel prizes in Physics have been awarded to astrophysicists since 1921 when Einstein extended Newton's theory of gravity to the General Theory of Relativity.

This article aims to present a flavor of representative discoveries in solar and heliospheric physics, astrophysics and cosmology which took place during the last century. The list of astronomical discoveries is very long and by no means exhaustive, as it cannot present all revolutions that have happened in Astronomy since the turn of the 20th century. In fact today, our understanding of the Universe we live in has changed dramatically since the founding of the IAU, just one century ago (1919). The Universe is (several billions of

Figure 1: *First IAU General Assembly in Rome, Italy (1922). Credit: IAU.*

Figure 2: *The distribution of the 82 national IAU members.*

light years!) larger since the Big Bang, it is more diverse and more dynamic than anybody could have ever imagined. And much is still unknown. The recent detection of gravitational waves just opened another new window — who knows what we will see from there. Just this month of April (2019) from such a new window we were able to see the shadow of a several billion solar masses black hole in the center of the distant giant galaxy M87.

The following two tables of discoveries in the period 1905-1921 (Table A) and 1921-1933 (Table B) are indicative of the last 100 year's astronomical discoveries. The remaining several tables covering the period 1933-2019 cannot be displaced in the present article, due to lack of space. The interested reader may find them in the book *Above and Beyond* which is published in Greek by the author (2019).

Let us start with **Solar and Heliospheric Physics**. In the late 1950s, **Eugene Parker** proposed the idea of the supersonic solar wind and predicted the so-called Parker spiral shape of the solar magnetic field in the outer solar system. Parker also theorized an explanation for the superheated solar atmosphere, the corona, which is –contrary to what was expected by physics laws– hotter than the surface of the sun itself. Specifically, he proposed (1987) that the solar corona might be heated by a myriad of tiny "nanoflares", miniature brightenings resembling solar flares that would occur all over the surface of the Sun. His books, especially *Cosmical Magnetic Fields*, have been read by generations of investigators.

Figure 3: *From the visit of Henry Norris Russell to the National Observatory of Athens (1937). Credit: NOA.*

Table A

Important discoveries/breakthroughs: 1905-1915

Discovery of:	Year	Researcher(s):
The Special Theory of Relativity	1905	Albert Einstein, Swiss Patent Office, Bern, Switzerland
The first astrophysical jet from the elliptical galaxy M87	1908	Heber Curtis, Lick Observatory, California, USA
Strong magnetic fields in Sunspots	1908	George Hale, Mount Wilson Solar Observatory, USA.
The White Dwarfs	1910	Williamina Fleming, Edward Pickering, Henry Norris Russell, Cambridge MA,USA
Measurement of stellar masses and diameters	**1912**	Henry Norris Russell, Harlow Shapley, Princeton, USA
Observation of first redshifts in the spectral lines of «spiral nebulae»	1912	Vesto Slipher, Lowell Observatory, AZ, USA
The period/luminosity relation in the Cepheid variable stars	1912	Henrietta Leavitt, Harvard College Observatory, Cambridge, MA, USA
The Hertzsprung – Russel diagram	1914	Ejnar Hertzsprung, Potsdam, Henry Norris Russel, Princeton, USA
The stellar mass-luminosity relationship	1915	Jacob Halm, Cape South Observatory, Ejnar Hertzsprung, Potsdam

Important discoveries/breakthroughs: 1915-1921

Discovery of:	Year	Researcher(s)
The General Theory of Relativity	1915	Albert Einstein, Germany **(Nobel prize in Physics 1921)**
A model for a static Universe	1917	Albert Einstein, Germany
Shapley's model of the Galaxy using glaobular clusters	**1918**	Harlow Shapley, Διευθυντής του Harvard College Observatory 1921-1952
Gravitational deflection of light during the 1919 total solar eclipse	1919	Arthur Eddington, Cambridge, UK
The Shapley–Curtis Debate	1920	Harlow Shapley, Harvard Observatory, Heber Curtis, Lick Observatory, USA
Thermonuclear fusion as the energy source of the Sun	1920	Arthur Eddington, Cambridge, UK
The Saha ionization equation	1921	Megh Nad Saha, Ινδία
Interferometric measurement of the diameter of red giant stars	1921	Albert Michelson, USA **(Nobel prize in Physics 1907)**, experimental determination of the speed of light

Table B

Important discoveries/breakthroughs: 1921-1925

Discovery of:	Year	Researcher(s)
Photoexcitation and photoionization of the interstellar medium	1921	Henry Russel, USA, (1921), D. Menzel, USA, (1924), B. Stromgren, Δανία, (1939)
Friedmann's model of the Universe	1922	Alexander Friedmann (1922, 1924), ΕΣΣΔ
Distribution of stars in the Galaxy and the mass density in the disk of the Galaxy	1922	Jacob Kapteyn, Ολλανδία
Ionization states of ions in stellar atmospheres	1923	Ralph Fowler, UK (introduced Dirac, Lennard-Jones, Birkhoff, to quantum theory), Edward Milne,UK, (1923, 1924)
The theory of stellar internal structure and evolution	1924	Arthur Eddington, Cambridge, UK (1916-1924)
The spiral nebulae are extragalactic systems	1925	Knut Lundmark, Σουηδία, Edwin Hubble, USA (1920, 1925)
The rotation of the Galaxy	1925	Bertil Lindbland, Σουηδία
The composition of the stars	1925	Cecilia Payne-Gaposhkin, Harvard, USA

Important discoveries/breakthroughs: 1927-1933

Discovery of:	Year	Researcher(s)
The expansion of the Universe - «The Primeval Atom»	1927	Georges Lemaitre, Katholieke Universiteit Leuven, Belgium
The differential rotation of the Galaxy	1927	Jan Oort, Leiden, Ολλανδία
Identification of «Nebullium» lines as the «forbidden» lines of O^{2+}	1927	Ira Sprague Bowen, USA, first director of the Palomar Observatory
The theory of White Dwarfs	1929	S. Chandrasekhar, Un. of Chicago, USA **(Nobel prize in Physics 1985)**, Wilhelm Anderson, Estonia
The quantum barrier penetration in solar thermonuclear reactions	1929	Fritz Houtermans, Germany, Robert Atkinson, USA
The recession of the nebulae	1929	Edwin Hubble, Carnegie Institutions, Mount Wilson Observatory, California, USA
The dark matter in clusters of galaxies	1933	Fritz Zwicky, USA/Ελβετία

In 2017, NASA renamed the Solar Probe mission for Eugene Parker, the S. Chandrasekhar Distinguished Service Professor Emeritus, Department of Astronomy and Astrophysics at the University of Chicago. This is the first NASA mission that has been named for a living individual. The Parker Solar Probe (PSP) will swoop to within 6.4 million km of the Sun's surface, facing heat and radiation like no spacecraft before it. Launched in August 12th, 2018, the Parker Solar Probe has already started providing new data on solar activity and making critical contributions to our ability to forecast major space-weather events that impact life on Earth. The PSP aims to unlock the mysteries of the corona and also to protect our society that is increasingly dependent on technology from the threats of space weather.

A **solar prominence** (a filament when viewed against the solar disk) is a large, bright feature extending outward from the Sun's surface. Prominences are anchored to the Sun's surface in the photosphere, and extend outwards into the Sun's hot outer atmosphere, the corona. A prominence forms over timescales of about a day, and stable prominences may persist in the corona for several months, looping hundreds of thousands of kms into space. The red-glowing looped material is hot plasma, comprised of electrically charged hydrogen and helium. The prominence plasma flows along a tangled and twisted structure of magnetic fields generated by the sun's internal dynamo. An erupting prominence occurs when such a structure becomes unstable and bursts outward, releasing the plasma.

Another explosive solar structure is **solar jets**: we have shown via numerical simulations (Fig. 7) that they can be understood as the result of the interaction of emerging magnetic flux from the solar interior via magnetic buoyancy with preexisting magnetic flux in the solar atmosphere.

Figure 4: *Eugene Parker, professor emeritus at the University of Chicago, visiting the spacecraft that bears his name: NASA's Parker Solar Probe. Standing behind Parker is prof. S. Krimigis, former Head of the Space Department (1991-2004), Johns Hopkins University, Applied Physics Laboratory. Engineers in the clean room at the Johns Hopkins Applied Physics Laboratory in Laurel, Maryland, where the Probe was designed and is being built point out the instruments that will collect data as the mission travels directly through the Sun's atmosphere. Credit: NASA/Johns Hopkins APL/Ed Whitman.*

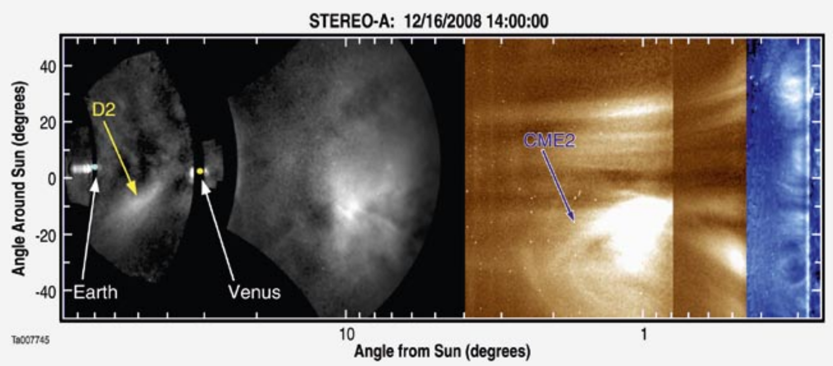


Figure 5: *One of the most significant results of the STEREO mission has been the 3-dimensional mapping of the solar wind inhomogeneities which are caused by coronal mass ejections (CMEs). These CMEs start from the solar base and move through the interstellar medium towards Earth and beyond it, shaping thus the conditions of* ***Space Weather****. Credit: picture kindly provided by Dr Angelos Vourlidas, from Howard et al, The Astrophysical Journal, 754, article id. 102, 10 pp. (2012).*

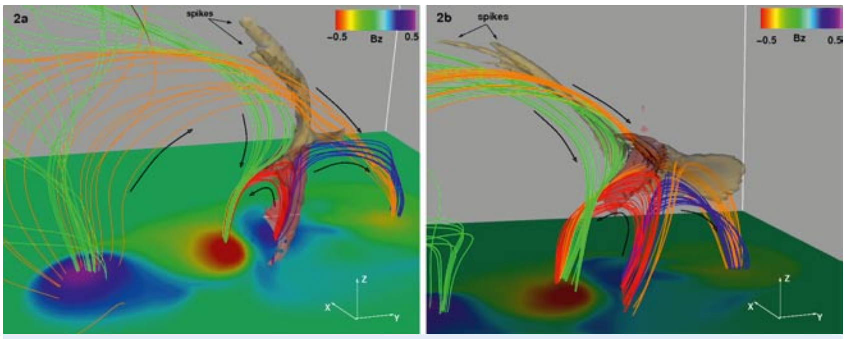


Figure 7: *A 3-dimensional visualization of the production of* ***solar jets****, via numerical simulations, from the article* Recurrent solar jets in active regions, *by V. Archontis, K. Gontikakis and K. Tsinganos, Astronomy & Astrophysics, Vol. 512, p. L2-L4 (2010). The blue lines represent the existing magnetic flux on the solar photosphere which interact with an emerging from the solar interior magnetic flux (green lines). After magnetic reconnection of these two magnetic flux systems, the red and orange magnetic lines are produced. The brown sheets represent the surfaces of equal velocity in the formed jets. The visualization corresponds at two times,* t = *144 (left) and* t = *184 (right).*

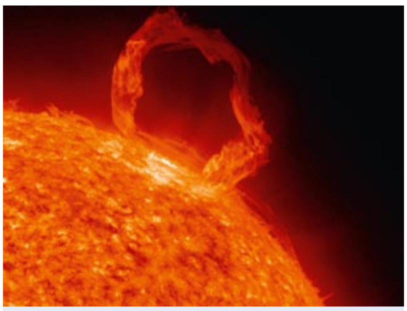


Figure 6: *A solar eruptive prominence as seen in extreme UV light on March 30, 2010. Credit: NASA/SDO.*

During the **solar eclipse** of March 29th, 2009, the path of totality of the Moon's shadow began at sunrise in Brazil and extended across the Atlantic to Africa, traveling across Ghana, the south-eastern tip of Ivory Coast, Togo, Benin, Nigeria, Niger, Chad, Libya, and a small corner of northwest Egypt and from there across the Mediterranean sea to Kastellórizo. From 1:51:59 till 1:55:00 pm the little island of Kastellórizo was immersed in the dark. A large group, including the author, from the Section of Astrophysics of the Dept. of Physics of the University of Athens, participated in the international expedition to observe this eclipse, taking therein this picture (Fig. 8).

On the 20th of July 1969, a historical milestone took place: Neil Armstrong became the first man to set foot on the **Moon**. There, he spoke the now-famous words: "That's one small step for [a] man, one giant leap for mankind." This memorable moment was broadcasted live around the world on television and radio. It became the most watched TV programming up to that date, with over 500 million viewers worldwide, and was covered heavily in the press. This event has also help a lasting impression in popular culture, including reference and portrayal in film, television, video games, folklore, literature and more. This moment was integral and influential for astronomy and space travel research. Not only does this event hold importance for the space industry, but also for humankind. Sending two astronauts into space, landing smoothly on the Moon and returning them safely to Earth was a dream many believed to be impossible. This huge achievement allowed for the conception and development of more human spaceflight missions.

The lightweight (10.6 kg) wheeled robotic Mars rover Sojourner (**Pathfinder**), became the first rover to operate outside the Earth–Moon system (Fig. 10). It is equipped with the *Alpha Particle X-ray Spectrometer* (APXS, developed by the team of Dr Thanasis Economou at the Un. of Chicago) to determine the composition of Martian rocks. It found all the elements except hydrogen, which constitutes just 0.1 percent of the rock's or soil's mass. The APXS works by irradiating rocks and soil samples with alpha particles. The results indicated that the rocks are much like Earth's andesites, confirming past volcanic activity. The Pathfinder marked the beginning of the robotic exploration of Mars which continues today with NASA's InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) mission which landed on Mars on November 26th, 2018.

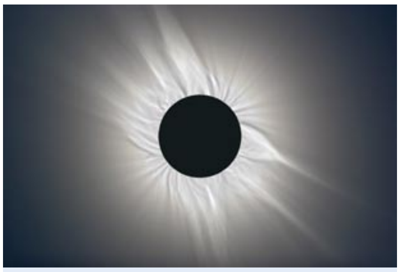


Figure 8: *The total solar eclipse of March 29th, 2006, as seen at Kastellorizo. Credit: Un. of Athens, Dept. of Physics, Section of Astrophysics.*

Figure 9: *The 20th of July 1969, Neil Armstrong becoming the first man to set foot on the Moon. Credit: NASA.*

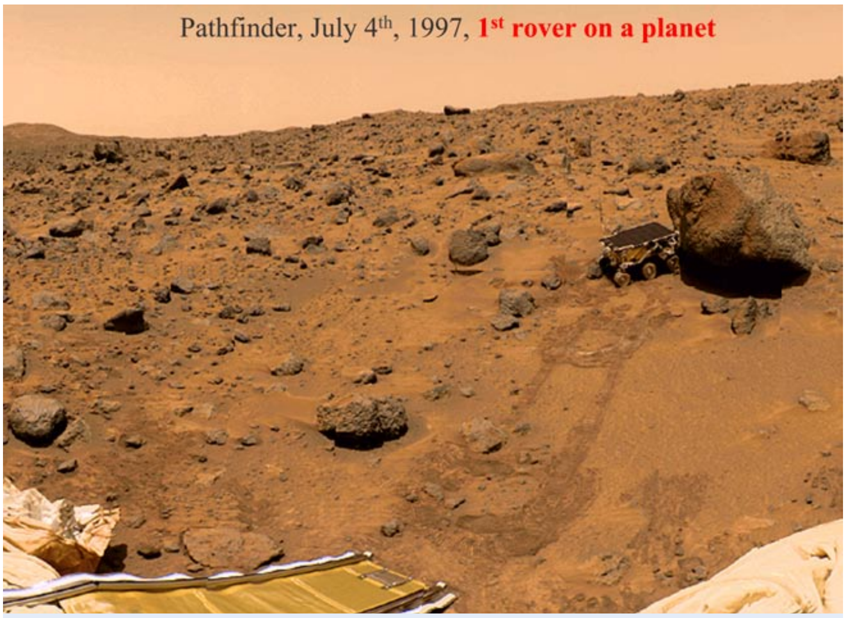


Figure 10: *NASA's Sojourner Rover on the Martian surface. Credit: NASA.*

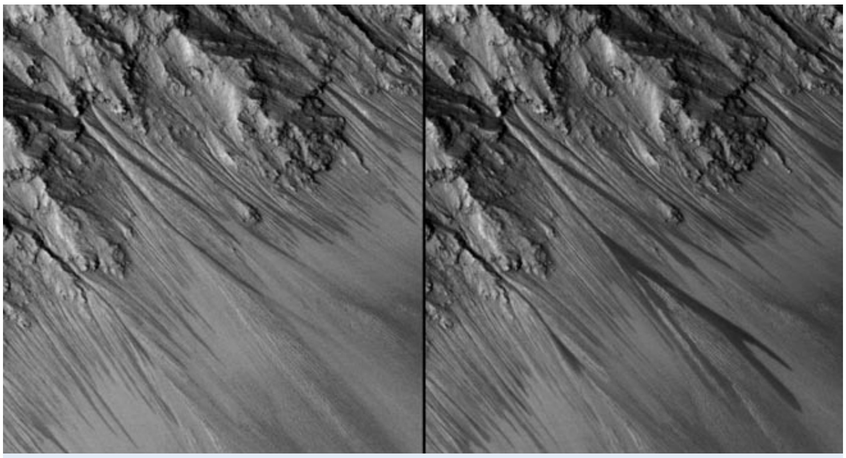


Figure 11: *Dark narrow streaks, called 'recurring slope lineae', emanate from the walls of Garni Crater on Mars. According to NASA, the above images captured about two weeks apart, show the growth of flows seen near the equator. Credit: NASA's Goddard Space Flight Center and NASA/JPL/University of Arizona.*

Mars is drier than the most arid deserts on Earth, yet we now know it harbors liquid water just beneath its surface. Images from the HiRISE camera aboard NASA's Mars Reconnaissance Orbiter spacecraft reveal seeps of moisture sliding down steep Martian cliffs that come and go with the seasons (Fig. 11). These dark streaks, called *recurring slope lineae*, appear on sun-facing hillsides, often inside craters. They usually advance slowly, over days or weeks, before fading away at summer's end. Dissolved salts lower the water's freezing point, perhaps explaining why flows are seen even at low temperatures. The water doesn't collect into streams or lakes like it might on Earth. Instead, it evaporates into the dry Martian air, leaving behind telltale traces of salt.

Jupiter, is best known for its colorful storms, the most famous being the Great Red Spot. By using the ultraviolet capabilities of NASA's Hubble Space Telescope, combined with the in situ measurements of the Juno mission, another beautiful feature of the planet, is its intense **auroras.** In fact, Jupiter's magnetosphere is 20,000 times stronger than Earth's. Not only are Jupiter's auroras huge in size, but they are also hundreds of times more energetic than auroras on Earth. It is useful to determine how Jupiter's auroras respond to changing conditions in the solar wind. For example, the Juno mission has observed signatures of powerful electric potentials, aligned with Jupiter's magnetic field, that accelerate electrons toward the Jovian atmosphere at energies up to 400 keV. This is 10 to 30 times higher than the largest auroral potentials observed at Earth, where only several keV are typically needed to generate the most intense auroras – known as discrete auroras – the dazzling, twisting, snake-like northern and southern lights seen in places like Alaska and Canada, northern Europe, and many other northern and southern polar regions. But, unlike those on Earth, Jupiter's auroras never cease. While on Earth the most intense auroras are caused by solar storms – when charged particles raining down on the upper atmosphere, exciting gases, and causing them to glow red, green, and purple – Jupiter has an additional source for its auroras: the strong magnetic field of the gas giant grabs charged particles from its surroundings (Fig. 12). This includes not only the charged particles within the solar wind, but also the particles thrown into space by its orbiting moon Io, known for its numerous and large volcanos.

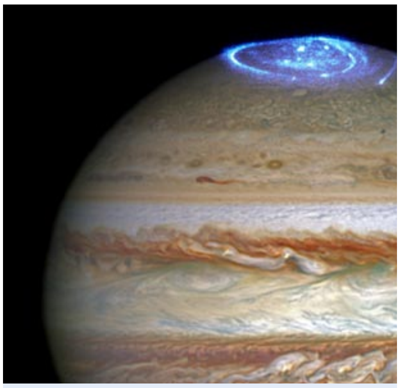


Figure 12: *The Jovian aurora captured by the HST and the planet Jupiter captured by the Juno spacecraft. Credit: NASA/HST.*

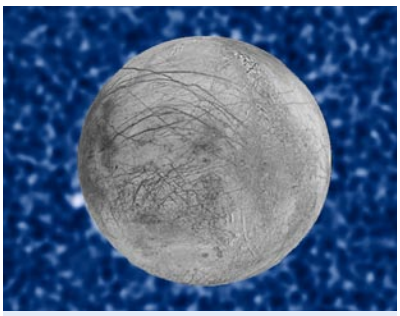


Figure 13: *A composite image showing plumes of water vapor erupting at the 8 o'clock position off the limb of Europa, photographed by NASA's Hubble's Space Telescope Imaging Spectrograph, superimposed on image of Europa assembled from data from the Galileo and Voyager missions. Credit: NASA/HSTScI.*

When Galileo discovered Jupiter's moon **Europa** in 1610, along with three other satellites whirling around the giant planet, he could have barely imagined it was such a world of wonder. This revelation didn't happen until 1979, when NASA's Voyager 1 and 2 spacecrafts flew by Jupiter and found evidence that Europa's interior, encapsulated under a crust of ice, has been kept warm over billions of years. The warmer temperature is due to gravitational tidal forces that flex the moon's interior — like squeezing a rubber ball — keeping it warm. At the time, it was speculated that the Voyagers might catch a snapshot of geysers on Europa. Such activity turned out to be so elusive that we had to wait over three decades for the peering eye of Hubble to monitor Europa for signs of venting activity. A newly discovered plume seen towering more than about 100 kilometers above the surface in 2016 is at precisely the same location as a similar plume seen on this moon two years earlier by Hubble (Fig. 13). These observations bolster evidence that the plumes are a real phenomenon, flaring up intermittently in the same region on Europa. The location of the plumes corresponds to the position of an unusually warm spot on Europa's icy crust, as measured in the late 1990s by NASA's Galileo spacecraft. It is speculated that this might be circumstantial evidence for material venting from the moon's subsurface. The water in the plumes is believed to come from a subsurface ocean on Europa and could be associated with the global ocean that is believed to be present beneath the frozen crust. The plumes offer an opportunity to sample what might be in the ocean, in the search for life on that distant moon.

Figure 14 is the first ever image of a 400 km-long river in an alien world, cap-

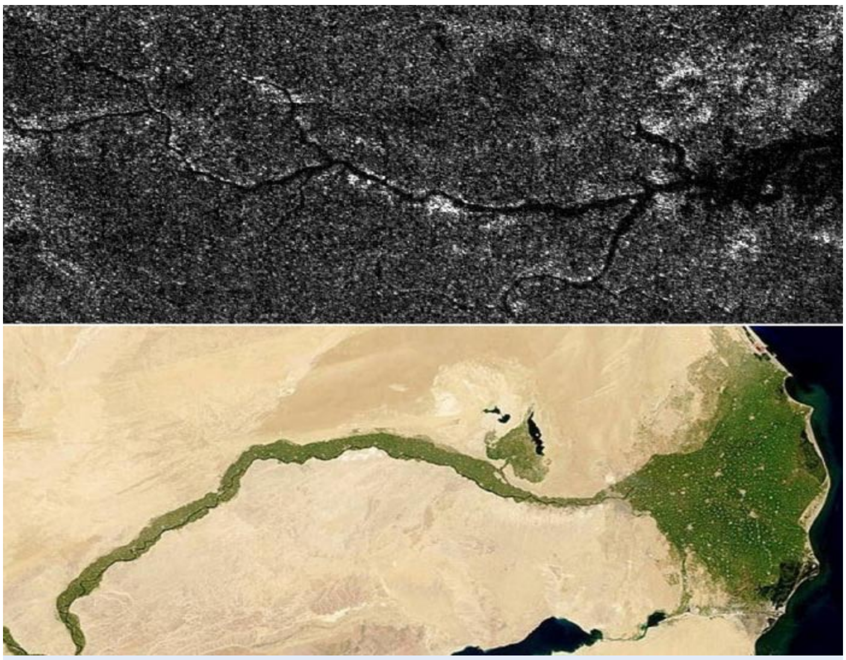


Figure 14: *(top): Vid Flumina, a river of liquid methane and ethane on Saturn's moon Titan. Image credit: NASA/JPL-Caltech/ASI. (bottom). The Nile river. Image credit: NASA.*

tured by NASA's Cassini spacecraft. **Vid Flumina** is a river of liquid methane and ethane on **Saturn's moon Titan.** The river has been compared to the Nile. It is more than 400 km long and flows into Titan's second largest hydrocarbon sea, Ligeia Mare. Radar studies show that Vid Flumina and its tributaries flow through canyons about one km wide and 0.57 km deep, with slopes of about 40°. Flowing methane was detected in the channels. The elevation of the main channel was found to be within 1 m of that of Ligeia Mare, while tributary channels have higher elevations. The canyons are thought to have formed by erosion stimulated either by uplift of the area or a decline in the level of Ligeia Mare.

A historic crossing of the **Heliopause** by Voyager 1 took place in 2012 at 122 AU (Fig. 15). Voyager 1 is already now travelling in the ISM, heading towards the nearest star (Fig. 16). A prominent role in the exploration of the planetary system has been played by prof. S. Krimigis, former Head of the Space Department (1991-2004), Johns Hopkins University, Applied Physics Laboratory and his instruments.

Turning next to major discoveries in **Astrophysics**, we should first mention the role of the **Hubble Space telescope** (HST), which in its almost 30 years life till now (1990-2019) has recorded some of the most detailed visible astronomical images ever, allowing a deep view into space and time. Many of the HST observations have led to breakthroughs in astrophysics, such as accurately determining the rate of expansion of the Universe. HST has produced an amazing outcome till now: about 15.000 publications with 700.000 citations, more than 2 papers per day and 20% of astronomy papers give a reference to HST while more than 600 PhD thesis are based on its findings. The NASA chart at the left depicts the evolution of detecting the early Universe, from ground-based space telescopes to HST and the future JWST.

Located 1.500 light-years away from Earth, **the Orion nebula** is our closest massive star-formation factory, containing several thousand young stars with disks surrounding them. A composite image from NASA's Hubble and Spitzer Space Telescopes shows the Orion nebula in an explosion of infrared, ultraviolet and visible-light colors (Fig. 18). This

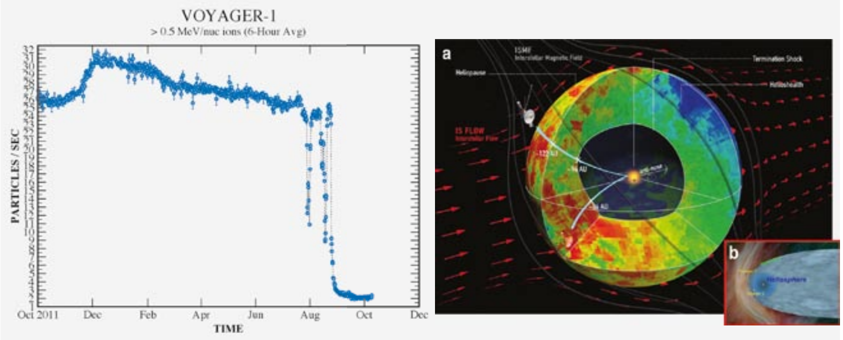


Figure 15. *(left): Readings from the instrument LA1 on Voyager 1 consisting of collisions of greater than 0.5 MeV/nuc nuclei, principally protons, sensitive to low-energy phenomena in interplanetary space. Credit: NASA. (right): The new bubble-like symmetric shape of the heliosphere with label (a) observed by Voyager and Cassini, proposed in the article of K. Dialynas, S.M. Krimigis, D.G. Mitchell, R.B. Decker and E.C. Roelof,* Nature Astronomy, *Vol. 1, 2017. The inset with label (b) refers to the old magnetosphere-like heliotail model used till now.*

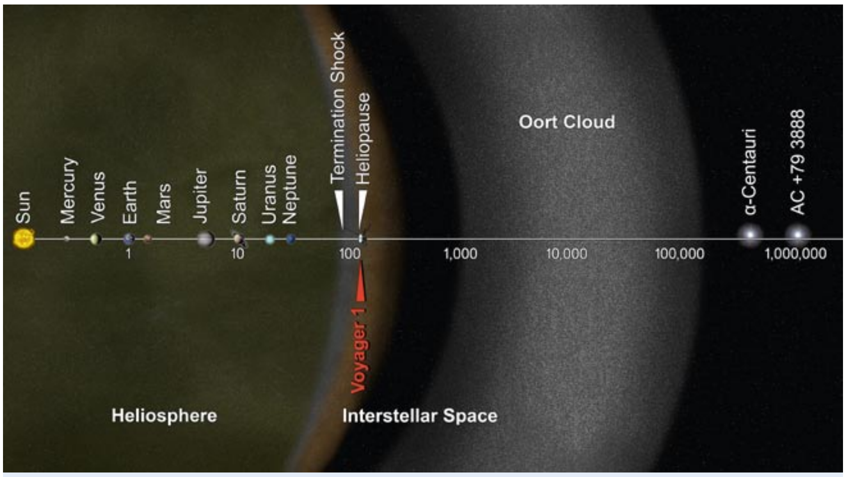


***Figure 16:** According to the data of Fig. 15 (above-left), Voyager 1 crossed the Heliopause in August 2012. Logarithmic scale of the Solar System with Voyager 1's position. Gliese 445 on the far right, by way of contrast, is approximately at a distance 10,000 times further from the Sun than Voyager is now.*

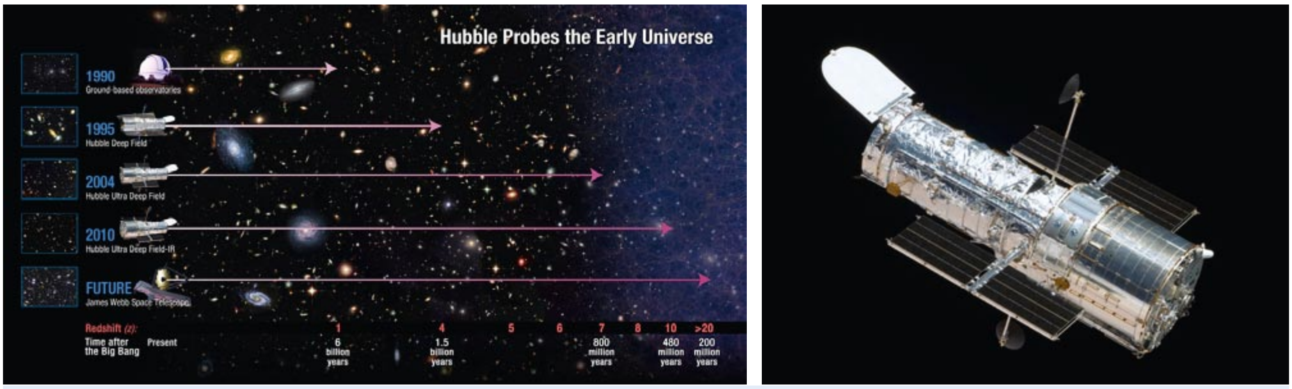


***Figure 17:** Illustration of ground based observatories, the Hubble Space telescope and the upcoming James Webb Space telescope, in probing the early Universe. Illustration Credit: NASA, ESA, and A. Feild (STScI).*

image was *painted* by hundreds of baby stars on a *canvas* of gas and dust, with intense ultraviolet light and strong stellar winds as *brushes*. At the heart of this *artwork* is the set of the four monstrously massive stars, the Trapezium. These behemoths are approximately 100,000 times brighter than our sun. Their community can be identified as the yellow smudge near the center of the composite. The swirls of green are ultraviolet emission by hydrogen and sulfur gases heated by intense ultraviolet radiation from the Trapezium's stars. Wisps of red, also detected by Spitzer, indicate infrared light from illuminated clouds containing carbon-rich molecules of polycyclic aromatic hydrocarbons. [On Earth, polycyclic aromatic hydrocarbons are found on burnt toast and in automobile exhaust]. Additional stars in Orion are sprinkled throughout the image in a rainbow of colors. Spitzer exposed infant stars deeply embedded in a cocoon of dust and gas (orange-yellow dots). HST found less embedded stars (specks of green) and stars in the foreground (blue). Stellar winds from clusters of newborn stars scattered throughout the cloud etched all of the well-defined ridges and cavities.

HST views of three gaseous jets in Figure 19 from three newly forming stars have shown a level of detail in the star formation process, which has helped to solve decade-old questions about the secrets of star birth. (Upper left): View of the protostellar object HH-30 revealing an edge-on disk of dust encircling a newly forming star. Light from the forming star illuminates the top and bottom surfaces of the disk, making them visible, while the star itself is hidden behind the densest parts of the disk. (Upper right): View of the more distant jet in the object HH-34 shows a remarkable beaded structure. This structure is produced by a machine-gun-like blast of 'bullets' of dense gas ejected from the star at speeds of 800 thousand kilometres per hour. The scale in both images is 1.000 AU. (Bottom image): This view of HH-47 reveals a very complicated jet pattern that indicates the star (hidden inside a dust cloud near the left edge of the image) might be wobbling, possibly caused by the gravitational pull of a companion star. Although the outflow is bipolar, only one jet is visible. The counterjet is invisible as it is moving away from Earth into the dark cloud that hosts the star inside it. At infrared wavelengths, however, it is clearly visible. The object is at a distance of about 1470 light years in the constellation Vela and the length of the visible jet is about one light year, while the overall actual size of the complex is about 10 light years.

HL Tauri is a very young T Tauri star in the constellation Taurus, approximately 450 light-years from Earth in the Taurus Molecular Cloud. The luminosity and effective temperature of HL Tauri imply that its age is less than 100.000 years. It is surrounded by a protoplanetary disk (Fig. 20) with size about 300 AU, greater than our solar system, marked by dark bands visible in submillimeter radiation that may indicate a number of planets in the process of formation. All stars are believed to form within clouds of gas and dust that collapse under gravity. Over time, the surrounding dust particles stick together, growing into sand, pebbles, and larger-size rocks, which eventually settle into a thin protoplanetary disk where asteroids, comets, and planets form. Once these planetary bodies acquire enough mass, they dramatically reshape the structure of their natal disk, fashioning rings and gaps as the planets sweep their orbits clear of debris and shepherd dust

Figure 18: *The Orion nebula, photographed by the Hubble and the Spitzer Space telescope. Credit: NASA.*

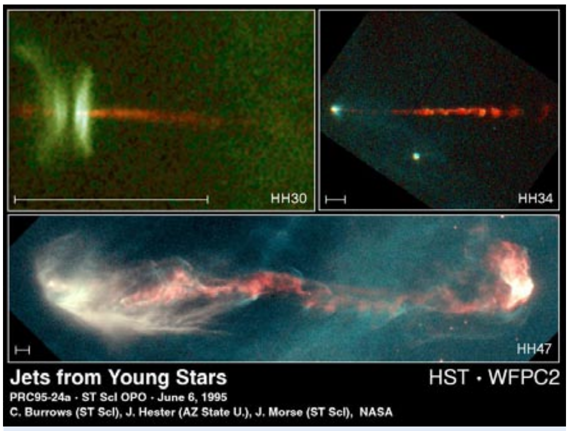


Figure 19: *Three Herbig-Haro objects, clockwise from top: HH30, HH34 and HH47, photographed by the HST. Credit: C. Burrows (STScI & ESA), J. Hester (Arizona State University), J. Morse/STScI and NASA.*

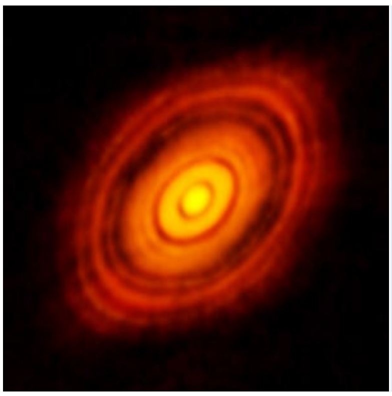


Figure 20: *The HL Tau protoplanetary disk, with a size of about 300 AU. Credit: ALMA (NRAO/ESO/NAOJ); C. Brogan, B. Saxton (NRAO/AUI/NSF)*

and gas into tighter and more confined zones. This HL Tau disk is also accompanied by the Herbig–Haro object HH 151, wherein a jet of gas emitted along the rotational axis of the disk is colliding with nearby interstellar dust and gas.

51 Pegasi b, is an extrasolar planet approximately 50 light-years away in the constellation of Pegasus. It is the first exoplanet to be discovered orbiting a main-sequence star, the Sun-like star 51 Pegasi. It marked a breakthrough in astronomical research and it is the prototype for a class of planets called hot Jupiters. In 2017, traces of water were discovered in the planet's atmosphere.

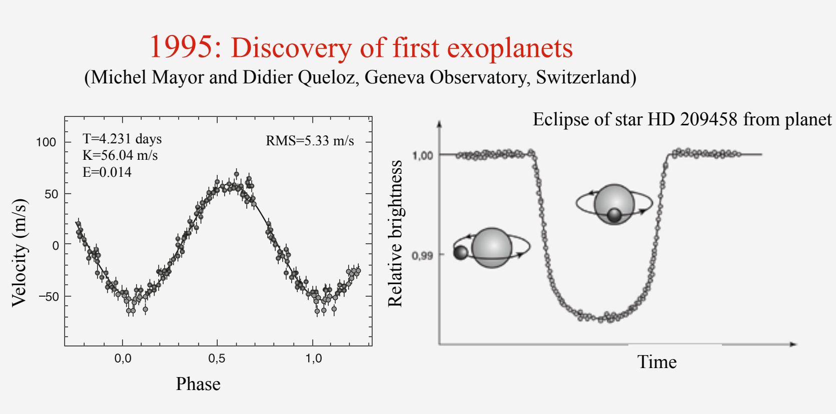
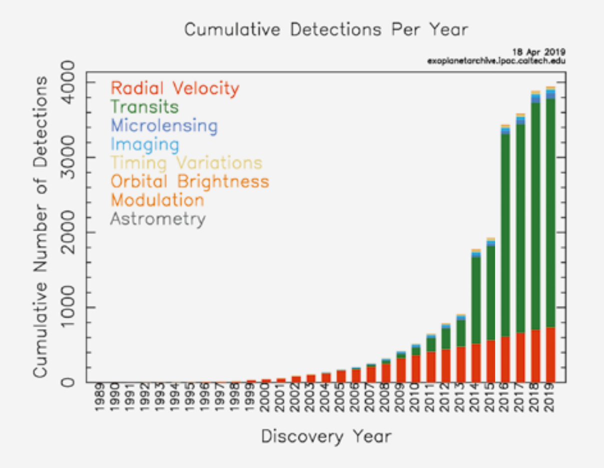


Figure 21: *(left). The light curve of 51 Pegasi b, giving its radial velocity as a function of the phase of the orbital motion around the center of mass of the binary system. Credit: G. Marcy P. Butler, San Francisco State University. (right). Light curve of the slight dimming of the star HD 209458 due to a planet passing directly in front of it, HST/STIS, April-May 2000. Credit: NASA, T. M. Brown, D. Charbonneau, R. L. Gilliland, R. W. Noyes, & A. Burrows.*

Figure 22: *Cumulative detection of exoplanets grouped by discovery method. Credit: NASA Exoplanet archive https://exoplanetarchive.ipac.caltech.edu.*



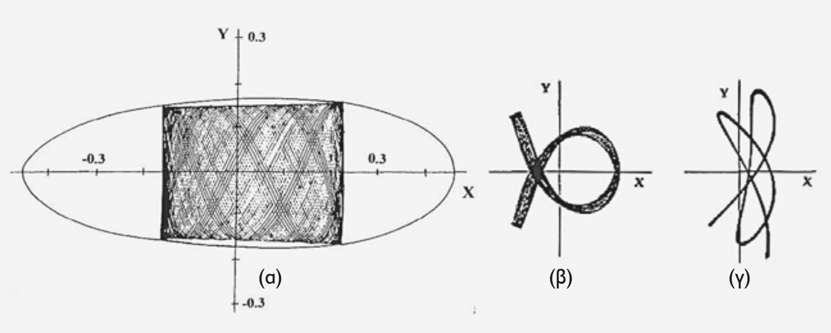


Figure 23: *Stellar orbits at the meridional plane of axisymmetric galaxies. (a) Far away from resonances (β) near the resonance 2/3 (γ) near the resonance 5/4.*

The radial reflex motion of a star in response to an orbiting planet can be measured through precise Doppler measurement, revealing the period, distance and shape of the orbit and providing information about the orbiting planet's mass. The detection of planetary transits is among the oldest planet detection methods. Other less efficient methods are direct imaging, gravitational microlensing, astrometry, timing variations and orbital brightness modulation.

In the area of **Galactic Dynamics**, some of the most important discoveries have been made by prof. George Contopoulos and his group:

- The "third integral" (1960), which explains the shapes of stellar orbits in a galaxy.
- He developed (1966) numerical programs for calculating higher order terms of the third integral and gave for it a series expansion, which does not converge near stable periodic orbits but it does converge near unstable periodic orbits, wherein there is chaotic behavior and hence it is useful to study chaotic orbits. Another related contribution is the proof that resonance overlap creates chaos.
- He has shown (1971) that galactic spirals are trailing and not leading.
- He developed the nonlinear theory of galactic spirals, as density waves (1979).
- In 1980 he has shown that galactic bars end at corotation, while the most prominent galactic spirals in nonbar galaxies end near the resonance 4/1 (1985). Also, he has shown that galactic spirals (outside corotation) consist of chaotic orbits and provided an analytical expression of these stellar orbits.
- Chaotic behavior was found around two black holes, actually the first discovery of chaos in General Relativity (1990).
- In 1994 it was found that the spectra of various dynamical systems are covariant and in the areas of chaotic orbits there exist small regions of organized orbits.
- In 2006 they studied order and chaos in quantum mechanics (de Broglie – Bohm theory) and found new cases of integrable systems. The conditions under which a density distribution tends to the limiting distribution $|\Psi|^2$ of quantum mechanics (where Ψ

is the wave function) were calculated and also several cases where chaotic behavior does not cover all space.

The **P-Pdot diagram** is very useful for following the lives of **pulsars**, playing a role similar to the Hertzsprung-Russell diagram for ordinary stars. It encodes a tremendous amount of information about the pulsar population and its properties, as determined and estimated from two of the primary observables, P and Pdot (Fig. 24). Using those parameters, one can estimate the pulsar age, magnetic field strength B, and spin-down power E. In the horizontal axis is the period ranging from about 1 msec for the fastest-spinning pulsar known, at present, which rotates once every 1.4 milliseconds, that's 716 times per second. Until now, the slowest-spinning pulsar is located in the constellation Cassiopeia some 5,200 light-years away from Earth, and spins at the much slower rate of once every 23.5 seconds. Almost all short-period pulsars below the spin-up line are in binary systems, as evidenced by periodic (i.e. orbital) variations in their observed pulse periods.

Figure 25 is a diagram showing the evidence that the **Binary Pulsar** B1913+16 (the Hulse-Taylor pulsar) emits gravitational radiation. As gravitational radiation carries energy away from the binary system, the orbit loses energy, the stars spiral in toward each other, and the pulsar runs "early" in its orbit. The dots are measurements of how early the pulsar is in its orbit, while the curve represents the expected behavior if gravitational waves are carrying energy away from the system at the rate predicated by Einstein's Theory of General Relativity. The excellent agreement between observation and theory represents the strongest current evidence for the existence of gravitational radiation.

The first direct detection of **gravitational waves** and the first observation of the collision and merger of a pair of black holes took place at the 14th of Sept 2015 (GW150914). Two black holes with masses of about 36 times and 29 times the mass of the Sun, merged while the post-merger merger spinning black hole had a mass of about 62 times the Sun's mass. The GW150914 occurred at a distance of more than one billion light years. Figure 26 shows the reconstructed gravitational-wave strain (as seen by LIGO at Hanford) with the predictions of the best-matching waveform computed from general relativity, over the three stages of the event: *inspiral*, *merger* and *ringdown*. Also shown are the separation and velocity of the black holes, and how they change as the merger event unfolds. The gravitational-wave power radiated by GW150914 was more than ten times greater than the combined luminosity (i.e. the light power) of every star and galaxy in the observable Universe.

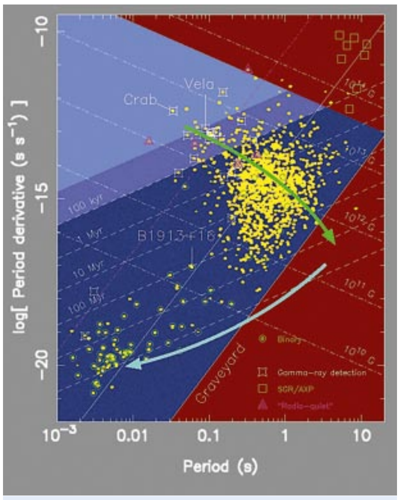


Figure 24: *The P-Pdot diagram for pulsars. Credit: The Un. of Manchester, Jodrell Bank Observatory.*

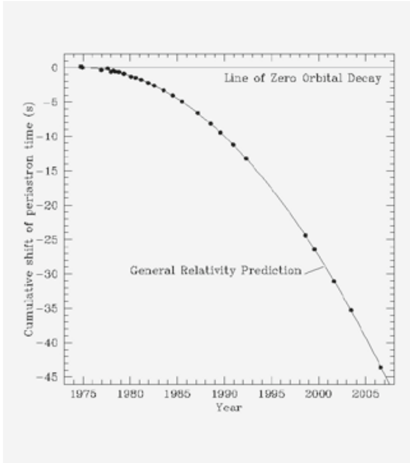


Figure 25: *Credit: Timing Measurements of the Relativistic Binary Pulsar PSR B1913+16J. M. Weisberg, D.J. Nice, and J.H. Taylor,* Astrophysical Journal*, 722, 1030–1034, 2010.*

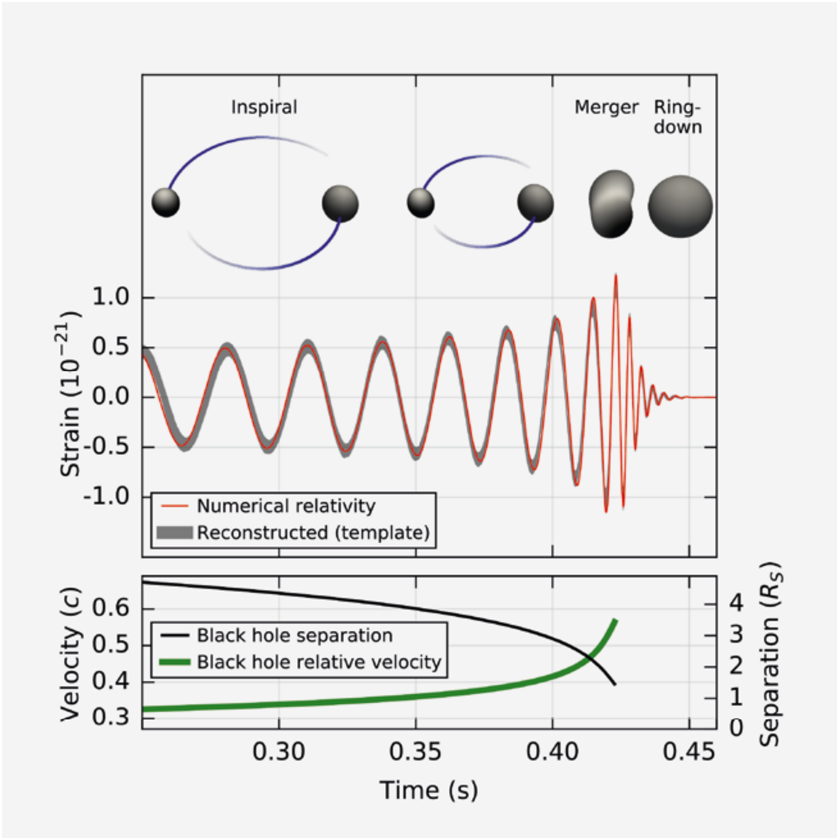


Figure 26: *Some key results of the analysis of GW150914, compa-ring the reconstructed gravitational-wave strain (as seen by H1 at Hanford) with the predictions of the best-matching waveform computed from general relativity, over the three stages of the event: inspiral, merger and ringdown. Also shown are the separation and velocity of the black holes, and how they change as the merger event unfolds. Credit: LIGO Virgo Collaboration (https://www.ligo.org/science/Publication-GW150914/).*

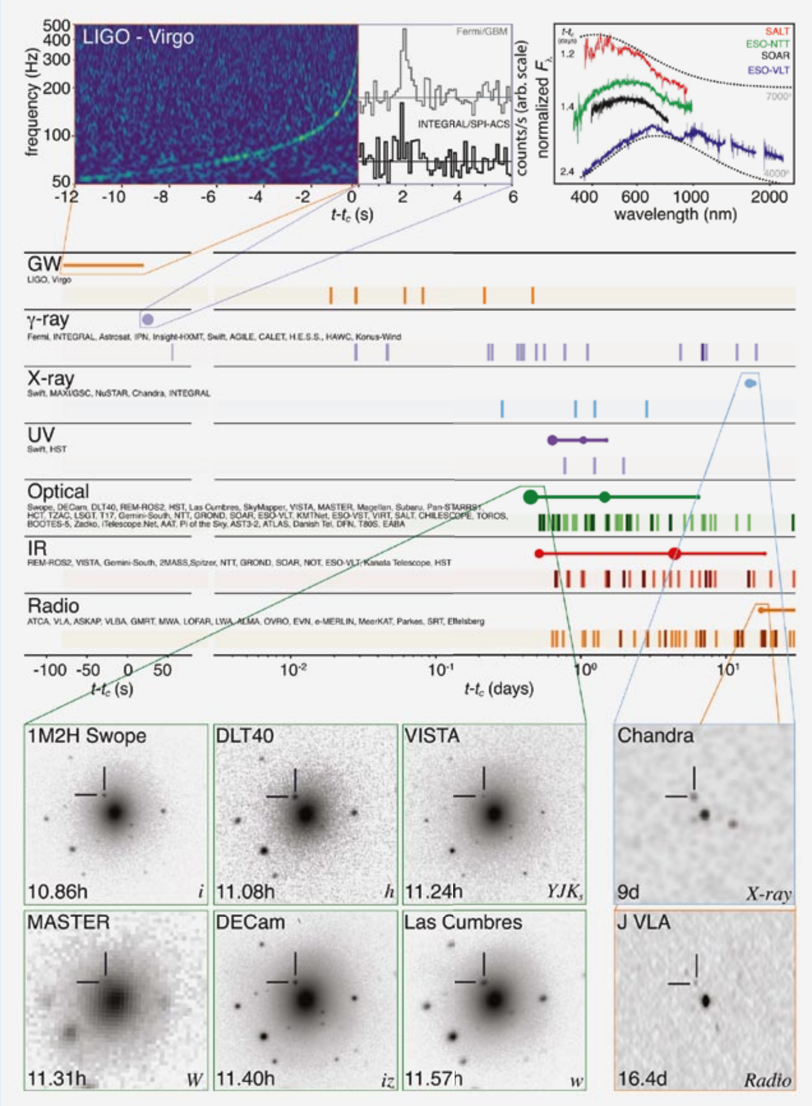


Figure 27:

Timeline of the discovery of GW170817 and the follow-up observations are shown by messenger and wavelength relative to the time t_c of the gravitational-wave event. Two types of information are shown for each band/messenger. First, the shaded dashes represent the times when information was reported in a Gamma-ray Coordinates Network (GCN) Circular. The names of the relevant instruments, facilities, or observing teams are collected at the beginning of the row. Second, representative observations in each band are shown as solid circles with their areas approximately scaled by brightness; the solid lines indicate when the source was detectable by at least one telescope. Magnification insets give a picture of the first detections in the gravitational-wave, gamma-ray, optical, X-ray, and radio bands. They are respectively illustrated by the combined spectrogram of the signals received by LIGO-Hanford and LIGO-Livingston, the Fermi-GBM and INTEGRAL/SPI-ACS light curves matched in time resolution and phase, 15×15 postage stamps extracted from the initial six observations of the source and four early spectra taken with the SALT (at t_c + 1.2 days), ESO-NTT (at t_c + 1.4 days), the SOAR 4 m telescope (at t_c + 1.4 days) and ESO-VLT-XShooter (at t_c + 2.4 days), and the first X-ray and radio detections of the same source by Chandra and JVLA. In order to show representative spectral energy distributions, each spectrum is normalized to its maximum and shifted arbitrarily along the linear y-axis.

Credit: Multi-messenger Observations of a Binary Neutron Star Merger, ApJL, *Vol. 848, p. 59, 2017.*

Apparent **Superluminal Motion in the Quasar 3C 279** (Fig. 28): during the interval of 6 years (1998-1992), blob B ejected from the Quasar has moved at a projected distance of about 25 light years. Thus, its apparent speed was about 4c. However, this can be understood as if B is moving with a speed very close to c, at an angle of 2 degrees with respect to the line from the observer to the center A of the quasar.

Observations of astrophysical jets in the radio, visible, X-rays, etc, as in Fig. 29, show that these **jets retain a self-similar structure** as we "zoom in", from the largest scale of Mpc (e.g., in Cygnus A, M87, NGC 6251, Hercules A, etc) to the smallest observed scale yet observed (a few pc).

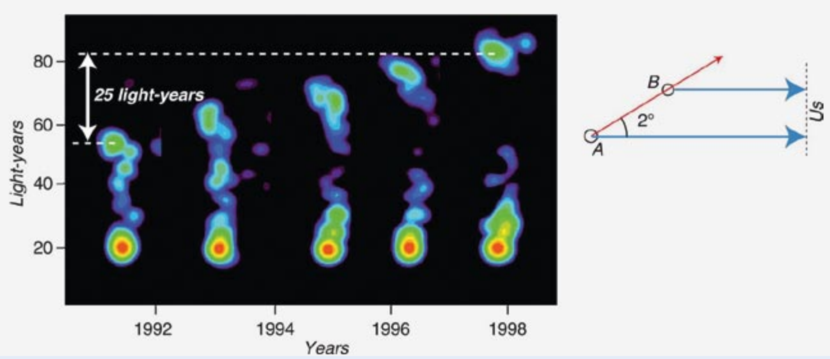


***Figure 28:** Apparent Superluminal Motion in the Quasar 3C 279.Credit: NRAO.*

This fact has sparked an analytical description of astrophysical jets by the author and his collaborators, by using self-similar solutions of the full set of the magnetohydrodynamic (MHD) equations (examples are shown in Fig. 30). It has been shown that there exist three cases of selfsimilar MHD solutions, those characterized by *meridional, radial* and *planar selfsimilarity*. This classification includes as special cases all known models for MHD astrophysical outflows, such as the classical Parker description of a stellar wind, or, the Blandford & Payne model of a magnetorotational disc-wind. Additionally, a new integral is derived for the transition of an outflow from an efficient magnetic rotator with a collimated jet to an inefficient magnetic rotator with a radial wind [Sauty, C., & Tsinganos, K., *A&A*, Vol. 287, p. 893 (1994)].

Spectacular **jets** powered by the gravitational energy of a supermassive black hole in the core of the elliptical galaxy **Hercules A** (Fig. 31) illustrate the

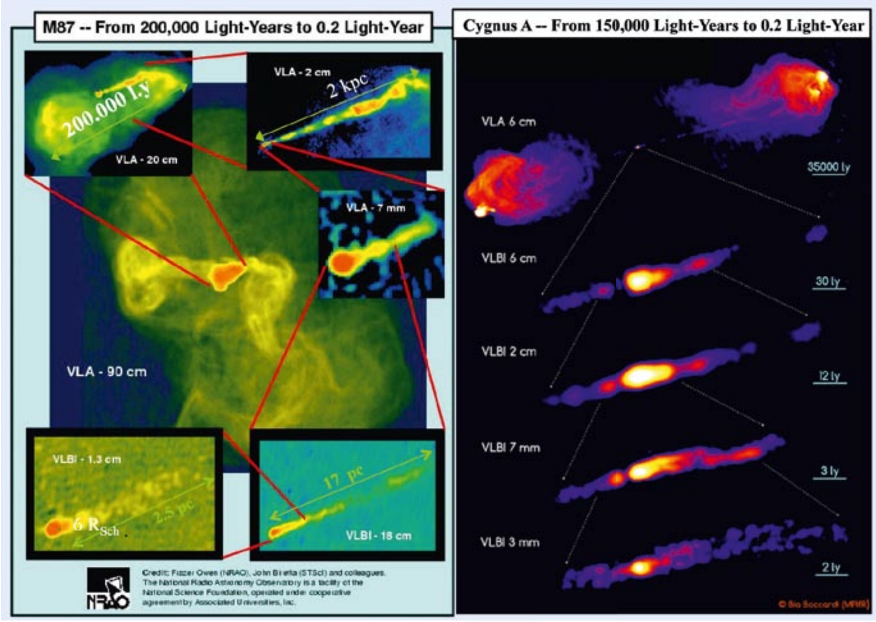


Figure 29:
Radio observations of two AGN jets, M87 (left) and Cygnus A (right) on scales from hundreds of thousands of light-years imaged with the Very Large Array to the sub-light-years scale probed with mm-VLBI. Self similarity of the jet structures in scales 1: 10^6 is evident.
Credit:
Boccardi, B., Krichbaum, T.P., Ros, E. et al. Astron. Astrophys. Rev. *(2017) 25: 4.*
https://doi.org/10.1007/s00159-017-0105-6.

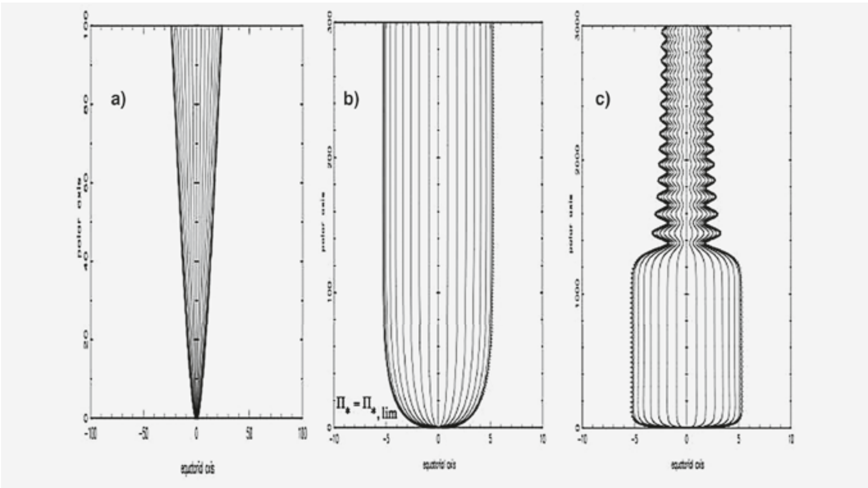


Figure 30:
Poloidal streamlines of three meridionally self-similar MHD solutions with: radial asymptotics in a), cylindrical asymptotics without oscillations in b), collimation with oscillations in c).
[From Sauty, Tsinganos & Trussoni, A&A 389, 1068–1085 (2002)].

Figure 31:
Spectacular jets powered by the gravitational energy of a supermassive black hole in the core of the elliptical galaxy Hercules A.
The elliptical galaxy harbors a 2.5-billion-solar-mass central black hole, that is 1,000 times more massive than the black hole in the Milky Way.
The VLA radio data reveal enormous, optically invisible jets that, at 1.5 million light-years wide, dwarf the visible galaxy from which they emerge.
Credit: Hubble Space Telescope's Wide Field Camera 3, and the Karl G. Jansky Very Large Array (VLA) radio telescope in New Mexico.

combined imaging power of two of astronomy's cutting-edge tools, the Hubble Space Telescope's Wide Field Camera 3, and the recently upgraded Karl G. Jansky Very Large Array (VLA) radio telescope in New Mexico.

Some two billion light-years away, the yellowish elliptical galaxy in the center of the image appears quite ordinary as seen by Hubble in visible wavelengths of light. The elliptical galaxy is roughly 1,000 times more massive than the bulge of our Milky Way and harbors a 2.5-billion-solar-mass central black hole that is 1,000 times more massive than the black hole in the Milky Way.

But the innocuous-looking galaxy, also known as 3C 348, has long been known as the brightest radio-emitting object in the constellation Hercules. Emitting nearly a billion times more power in radio wavelengths than our Sun, the galaxy is one of the brightest extragalactic radio sources in the entire sky.

The VLA radio data reveal enormous, optically invisible jets that, at 1.5 million light-years wide, dwarf the visible galaxy from which they emerge. The jets are very-high-energy plasma beams and magnetic fields shot at nearly the speed of light from the vicinity of the black hole. The outer portions of both jets show unusual ring-like structures suggesting a history of multiple outbursts from the supermassive black hole at the center of the galaxy.

The innermost parts of the jets are not visible because of the extreme velocity of the material; relativistic effects confine all of the light to a narrow cone aligned with the jets, and so that light is not seen by us. Far from the galaxy, the jets become unstable and break up into the rings and wisps. The entire radio source is surrounded by a very hot, X-ray-emitting cloud of gas, not seen in this optical-radio composite.

Cosmic gamma ray bursts (GRBs) were discovered by accident in the late 1960's by satellites designed to detect gamma rays produced by atomic bomb tests on Earth. The GRBs appear first as a brilliant flash of gamma rays, that rises and falls in a matter of minutes. These bursts are often followed by afterglows at X-ray, optical and radio wavelengths. A major leap forward in understanding the source of cosmic GRBs was made when the Burst and Transient Source Experiment (BATSE) was launched aboard the Compton Gamma Ray Observatory in 1991 (Fig. 32). BATSE had an all-sky monitor that was capable of detecting a GRB virtually anywhere in the sky. Over a period of 9 years BATSE recorded thousands of GRBs, about 1 per day. Among other things, these results showed that the bursts occurred at random all over the sky If the bursts were associated with objects in our Milky Way Galaxy, they would not show such a universal distribution. Rather, they would be concentrated along the plane of our galaxy like most of the matter in the Milky Way. The BATSE data was so good that it allowed astronomers to also rule out the possibility that the GRBs might be originating in the halo of our galaxy.

A simple way to achieve a high efficiency and a nonthermal spectrum in the GRBs, which is currently the most widely invoked explanation, is by recon

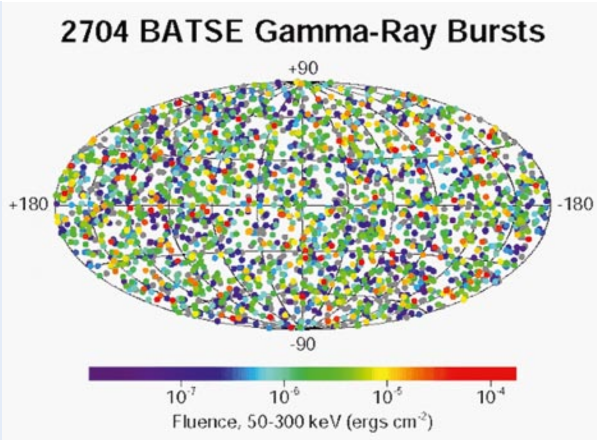


Figure 32: *CGRO/BATSE Gamma ray Bursts, the most powerful explosions in the Universe after the Big Bang. These BATSE data allowed astronomers to rule out the possibility that the GRBs might be originating in the halo of our galaxy. Credit: NASA/GSFC.*

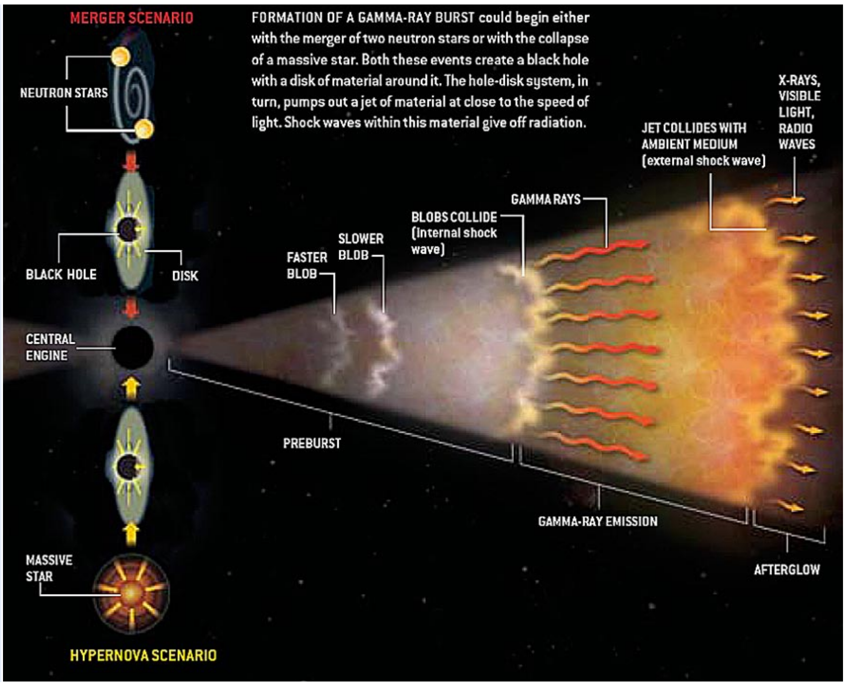


Figure 33: *Visualisation of the fireball model for GRBs, from Gehrels, N., Piro, L., & Leonard, P. J. T.,* Scientific American, *287 (2002). Credit: Juan Velasco.*

verting the kinetic energy of the flow into random energy via shocks, after the flow has become optically thin. According to this **"fireball" model**, we can distinguish several stages explaining the appearance of a GRB (Fig. 33):

1) The progenitor produces jets of material consisting essentially of packets of electrons, ejected sporadically in a particular direction. These packets are expelled at different ultra-relativistic speeds.
2) Very violent shocks take place when these packets of electrons come into contact with each other in internal shocks. The layers of material expelled at different speeds end up colliding, the fastest layers catching up with the slowest. These shock fronts will abruptly generate gamma rays (prompt emission).
3) There are also external shocks where these same layers of matter interact later with the surrounding environment of the progenitor. This gives rise to less intense, less energetic radiation, which is spread out over time and composed of X-rays, visible light and radio waves (*the afterglow emission*).

GRBs are the most powerful explosions in the Universe after the Big. Bang. As their distances are billions of light years, in order that they are visible from such large distances, they need to have huge energies: in a few seconds their output equals the energy the Sun emits throughout all its life of billions of years. At the same time GRBs are occuring only once in a million of years in a galaxy. It is only because there exist billions of galaxies that we observe them. However, *if a GRB happens in our Galaxy with its beam hitting the Earth, then, all life on Earth would be extinguished!*

At **the center of our Milky Way Galaxy lies a supermassive black hole.** Once a controversial claim, this conclusion is now solidly based on 16 years of observations that map the orbits of 28 stars very near the galactic center. Using European Southern Observatory telescopes and sophisticated near infrared cameras, we have patiently measured the positions of the stars over time, following one star, designated S2, through a complete orbit as it came within about 1 light-day of the center of the Milky Way (Fig. 34). The results convincingly show that S2 is moving under the influence of the enormous gravity of a compact, unseen object – a black hole with 4 million times the mass of the Sun. The ability to track stars so close to the galactic center accurately measures the black hole's mass and also determines the distance to the center to be 27,000 light-years. This deep, near-infrared image shows the crowded inner 3 light-years of the central Milky Way.

M87 hosts a supermassive black hole, lying at the center of this supergiant elliptical galaxy. This black hole has swallowed up a mass equivalent to 6.5 billion times the mass of our Sun. The image in Fig. 35 shows a bright ring formed as light bends in the intense gravity around this supermassive black hole. M87 has a radius of about 500.000 light years, but the radius of the black hole is only 130 light years. Around the galaxy there is a disk extending up to 25.000 AU, while its inner edges reach a few Schwarzschild radii R_{Sch}. The resolution needed to observe the shadow of the black hole (with a radius of 2.6 R_{Sch}) is 20 μarcseconds, at the distance of 55 million light years of M87, at the wavelength of 1.3 mm of the Event Horizon Telescope (EHT) operating via VLBI. This long-sought image provides the strongest evidence to date for the existence of supermassive black holes and opens a new window onto the study of black holes, their event horizons and gravity.

A jet of electrons and other subatomic particles traveling at nearly the speed of light streams out from M87 and it was observed more than a century ago by Curtis (1917).

The **Coma Cluster** at a mean distance of about 320 million light years

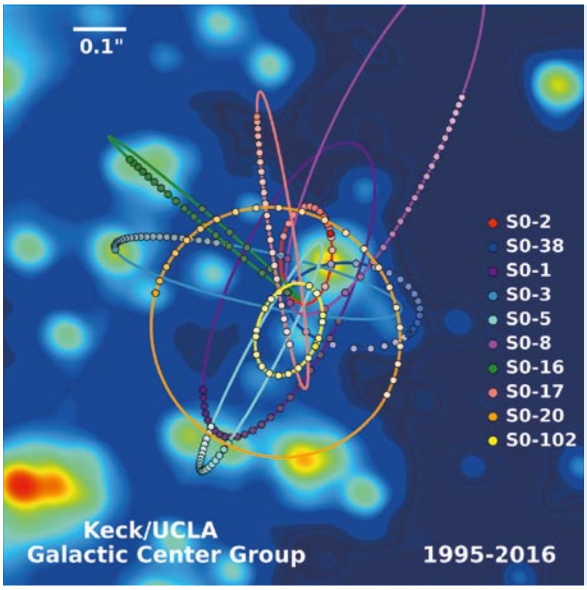


Figure 34: *Orbits of stars within the central 1.0 × 1.0 arcseconds of our Galaxy. In the background, is the central portion of a diffraction-limited image taken in 2016. While every star in this image has been seen to move over the past 17 years, estimates of orbital parameters are best constrained for stars that have been observed through at least one turning point of their orbit. The annual average positions for these stars are plotted as colored dots, which have increasing color saturation with time. Also plotted are the best fitting simultaneous orbital solutions. Credit: Keck/UCLA Galactic Center group.*

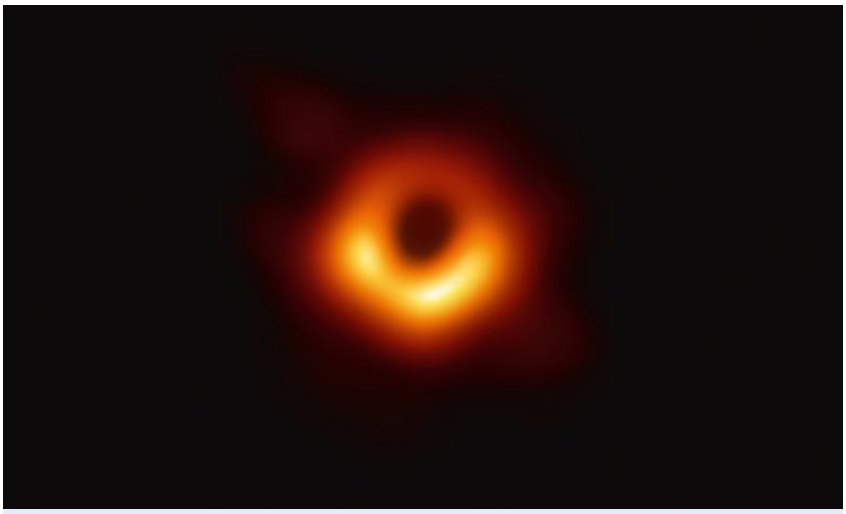


Figure 35: *First image in false colour of the shadow of a black hole, using the Event Horizon Telescope's observations of the center of the galaxy M87. Credit: Event Horizon Telescope Collaboration.*

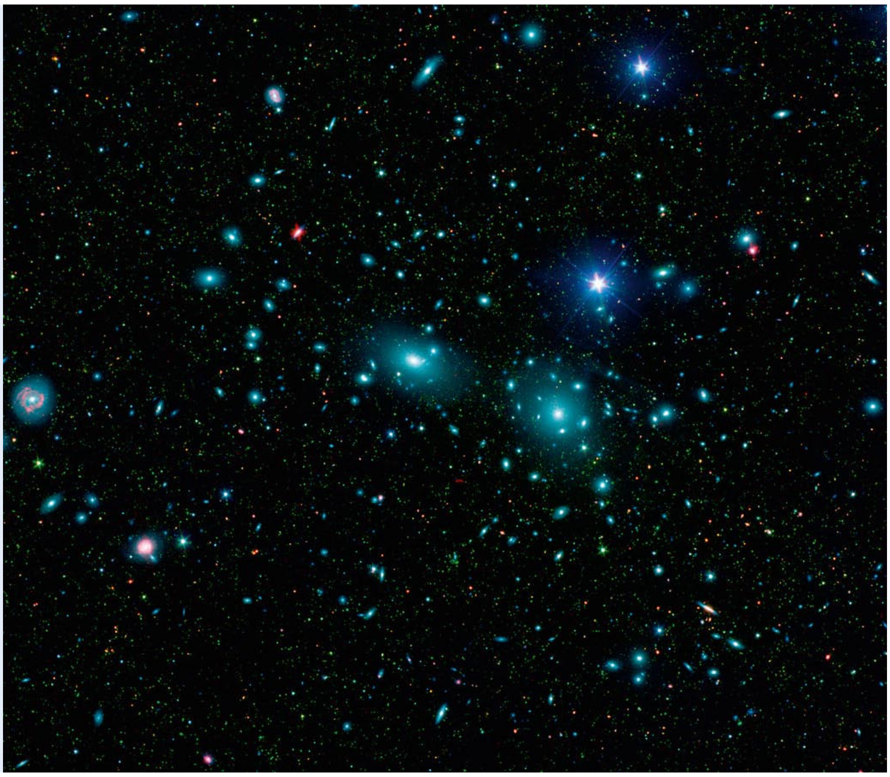


Figure 36: *A Sloan Digital Sky Survey/Spitzer Space Telescope mosaic of the Coma Cluster in long-wavelength infrared (red), short-wavelength infrared (green), and visible light. The central region is dominated by two supergiant elliptical galaxies: NGC 4874 and NGC 4889. The many faint green smudges are dwarf galaxies in the cluster. The Coma Cluster consists of approximately 1,000 galaxies spread over about two degrees on the sky — roughly the size of our thumb held at arm's length, and four times the size of the Sun and the Moon seen from Earth. A straightforward application of classical mechanics, the virial theorem relates the velocity of orbiting objects to the amount of gravitational force acting on them. Careful measurements of the light and the galactic velocities in this cluster were performed by Fritz Zwicky (1933). He was thus able to calculate the total mass of the Coma Cluster from his measured galactic velocities. This led him to suggest the existence of* dark matter. *Credit: NASA/JPL-Caltech/GSFC/SDSS.*

from Earth is a large cluster of galaxies that contains over 1,000 identified galaxies, overwhelmingly elliptical and S0 galaxies, with only a few spirals of younger age (Fig. 36). It is located in and takes its name from the constellation Coma Berenices. The cluster is within a few degrees of the north galactic pole on the sky. In 1933 Fritz Zwicky showed that the galaxies of the Coma Cluster were moving too fast for the cluster to be bound together by the visible matter of its galaxies. Hence, about 90% of the mass of the Coma cluster is believed to be in the form of dark matter. Although the idea of dark matter would not be accepted for another fifty years, Zwicky wrote that the galaxies must be held together by some *dunkle Materie*.

In **Cosmology**, one of the observational foundations for the Big Bang model is the observed **expansion of the Universe.** Measurement of the expansion rate is a critical part of cosmology and it has been found that the expansion rate is very nearly "flat". That is, **the universe is very close to the critical density,** above which it would slow down and collapse inward toward a future "big crunch". One of the great challenges of astronomy and astrophysics is distance measurement over the vast distances of the Universe. Since the 1990s it has become apparent that type Ia supernovae offer a unique opportunity for the consistent measurement of distance out to perhaps 1000 Mpc. Measurement at these great distances provided the first data to suggest that the expansion rate of the universe is actually accelerating. That acceleration implies an energy density that acts in opposition to gravity which would cause the expansion to accelerate. This is an energy density which we have not directly detected observationally and it has been named "*dark energy*". The data summarized in Fig. 37 involve the measurement of the redshifts of the distant supernovae. The observed magnitudes are plotted against the redshift parameter z. Note that there are a number of Type 1a supernovae around z=0.6, which with a Hubble constant of 71 km/s/Mpc are at a distance of about 5 billion light years.

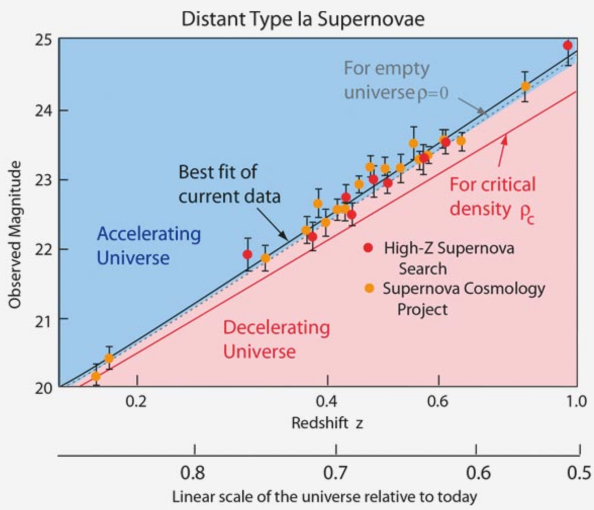


Figure 37: *Measurement of the redshifts of the distant type Ia supernovae. Credit: Perlmutter, S., Supernovae, dark energy and the accelerating Universe, Physics Today 56, No. 4, 53, 2003.*

Microwave observations of the CMB provide a snapshot of the universe when it was roughly 380,000 years old, corresponding to a redshift z~1100. All-sky microwave maps from the DMR (Differential Microwave Radiometer) instrument aboard the COBE satellite showed

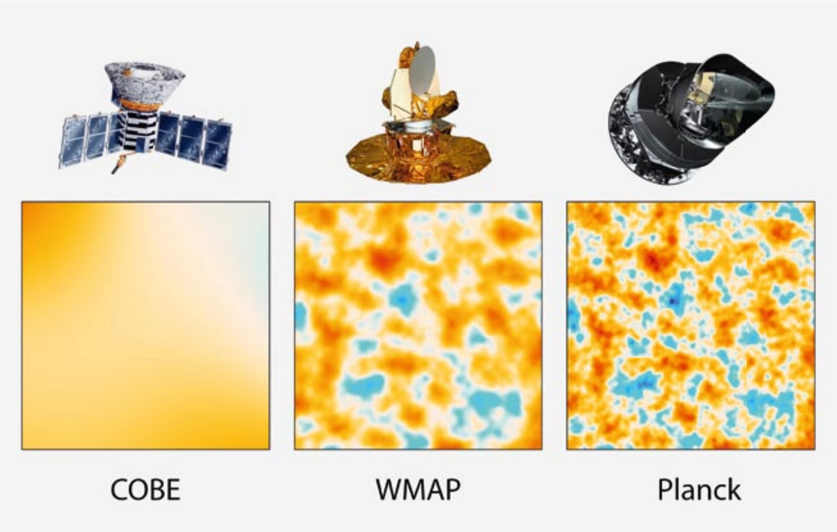


Figure 38: *Graphic illustrating the evolution of satellites designed to measure the anisotropies of the cosmic microwave background in 10-square-degree patches of all-sky maps. Image credit: NASA/JPL-Caltech/ESA*

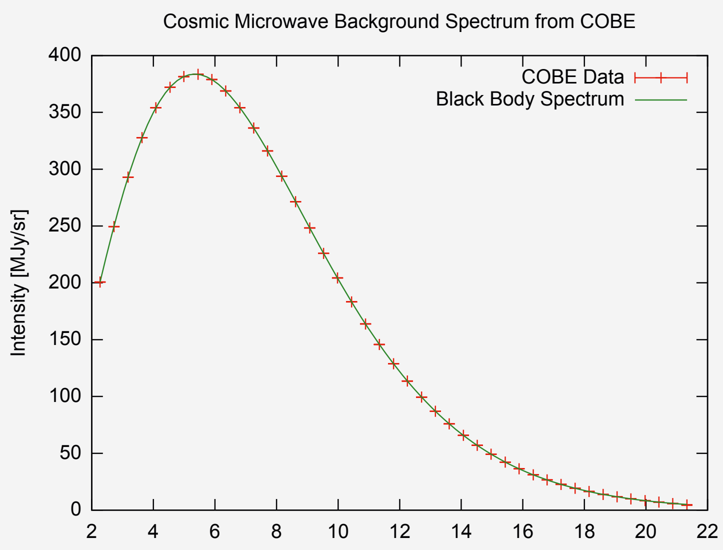


Figure 39: *Data from COBE showed a perfect fit between the black body curve predicted by big bang theory and that observed in the microwave background. Credit: Measurement of the Cosmic Microwave Background Spectrum by the COBE FIRAS Instrument, Mather et al.* Astrophysical Journal, *420, 439 (1994).*

definitively that small amplitude intrinsic temperature variations (anisotropies) existed in the CMB, at a level of about 1 in 100.000. Subsequent satellite missions with improved frequency coverage, polarization sensitivity, higher spatial resolution and signal-to- noise include WMAP (Wilkinson Microwave Anisotropy Probe) and Planck. The three panels in Fig. 38 illustrate how the increased spatial resolution achieved with each new generation of instruments has added to our knowledge of the CMB. Each panel shows the same 10 square degree patch of sky, but depicts how the same CMB anisotropies would appear at the resolution of COBE/DMR (1989-1993), WMAP (2001-2010) and Planck (2009-2013) satellite missions.

COBE measurements showed a perfect fit between the black body curve predicted by Big Bang theory and that observed in the microwave background (Fig. 39). The vertical axis "MJy/sr" corresponds to 10^6 Jansky per steradian, where a Jansky is 10^{-26} Watts per square-meter per Hertz. The horizontal axis ("1/cm") corresponds to the reciprocal of the microwave wavelength (in cm), which is proportional to the microwave frequency. The error bars are too small to be displayed by a computer screen, but vastly exaggerated error bars were included to show the measured data points. In fact, NASA's comment on this famous original picture is as follows: "The plot gives the Cosmic Microwave Background (CMB) spectrum plotted in waves per centimeter vs. intensity. The solid curve shows the expected intensity from a single temperature blackbody spectrum, as predicted by the hot Big Bang theory. A blackbody is a hypothetical body that absorbs all electromagnetic radiation falling on it and reflects none whatsoever. The FIRAS data were taken at 34 positions equally spaced along this curve. The FIRAS data match the curve so exactly, with error uncertainties less than the width of the blackbody curve, that it is impossible to distinguish the data from the theoretical curve. These precise CMB measurements show that 99.97% of the radiant energy of the Universe was released within the first year after the Big Bang itself. All theories that attempt to explain the origin of large scale structure seen in the Universe today must now conform to the constraints imposed by these measurements. The results show that the radiation matches the predictions of the hot Big Bang theory to an extraordinary degree. See Mather et al. 1994, Astrophysical Journal, 420, 439, 'Measurement of the Cosmic Microwave Background Spectrum by the COBE FIRAS Instrument,' Wright et al. 1994, Astrophysical Journal, 420, 450, 'Interpretation of the COBE FIRAS CMBR Spectrum,' and Fixsen et al. 1996, Astrophysical Journal, 473, 576, 'The Cosmic Microwave Background Spectrum from the Full COBE FIRAS Data Sets' for details."

Fig. 40 (next page) shows **the CMB angular power spectrum measured by WMAP** and several balloon-borne and ground-based experiments. This angular power spectrum gives the anisotropy of the CMB and contains information about the formation of the Universe and its current contents. The angular power spectrum is a plot of how much the temperature varies from point to point on the sky (the y-axis variable) vs. the angular frequency ell (the x-axis variable). For example, ell=200 means that there are 200 cycles around the sky. These data are perfectly consistent with a flat Universe that is dominated by a vacuum energy density of cosmological constant which provides 73 percent of the total density of the Universe. Another 23 percent of the density is dark matter. Only 4 percent of the density is ordinary matter made of protons and neutrons. With 7 years of WMAP data, and improved ground-based and balloon-borne experiments, the consistency with ΛCDM remains excellent.

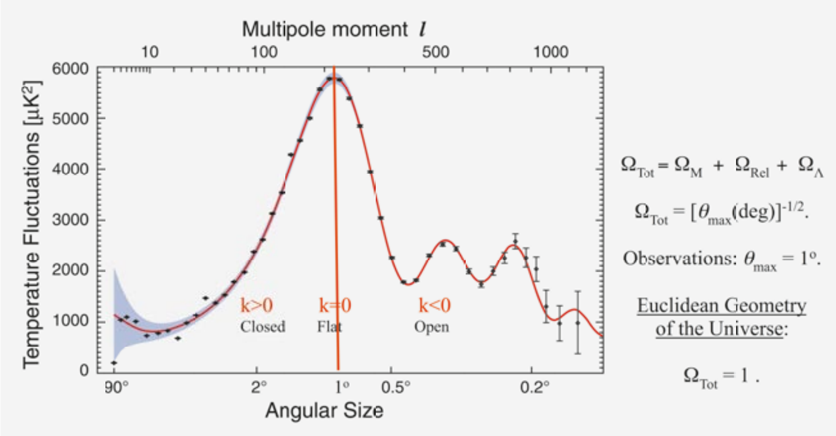


Figure 40: *The angular spectrum of the fluctuations in the WMAP full-sky map. This shows the relative brightness of the spots in the map vs. the size of the spots. The shape of this curve contains a wealth of information about the history the universe. Based on the 7 year data release. Credit: NASA / WMAP Science Team.*

If we go all the way back in the Universe history, we arrive at a singularity, where all matter and energy in the entire Universe was condensed into a single point, a singular event in spacetime. However, if that were the way things worked, there would be a number of puzzles based on the observations we have.

1) Why would the Universe have the same temperature everywhere? The different regions of space from different directions wouldn't have had time to exchange information and thermalize, so there's no reason for them to be at the same temperature. Yet the Universe, everywhere we looked, had the same background 2.73 K temperature.
2) Why would the Universe be perfectly spatially flat? The expansion rate and the energy density are two completely independent quantities, yet they must be equal to one part in 10^{24} in order to produce the flat Universe we have today.

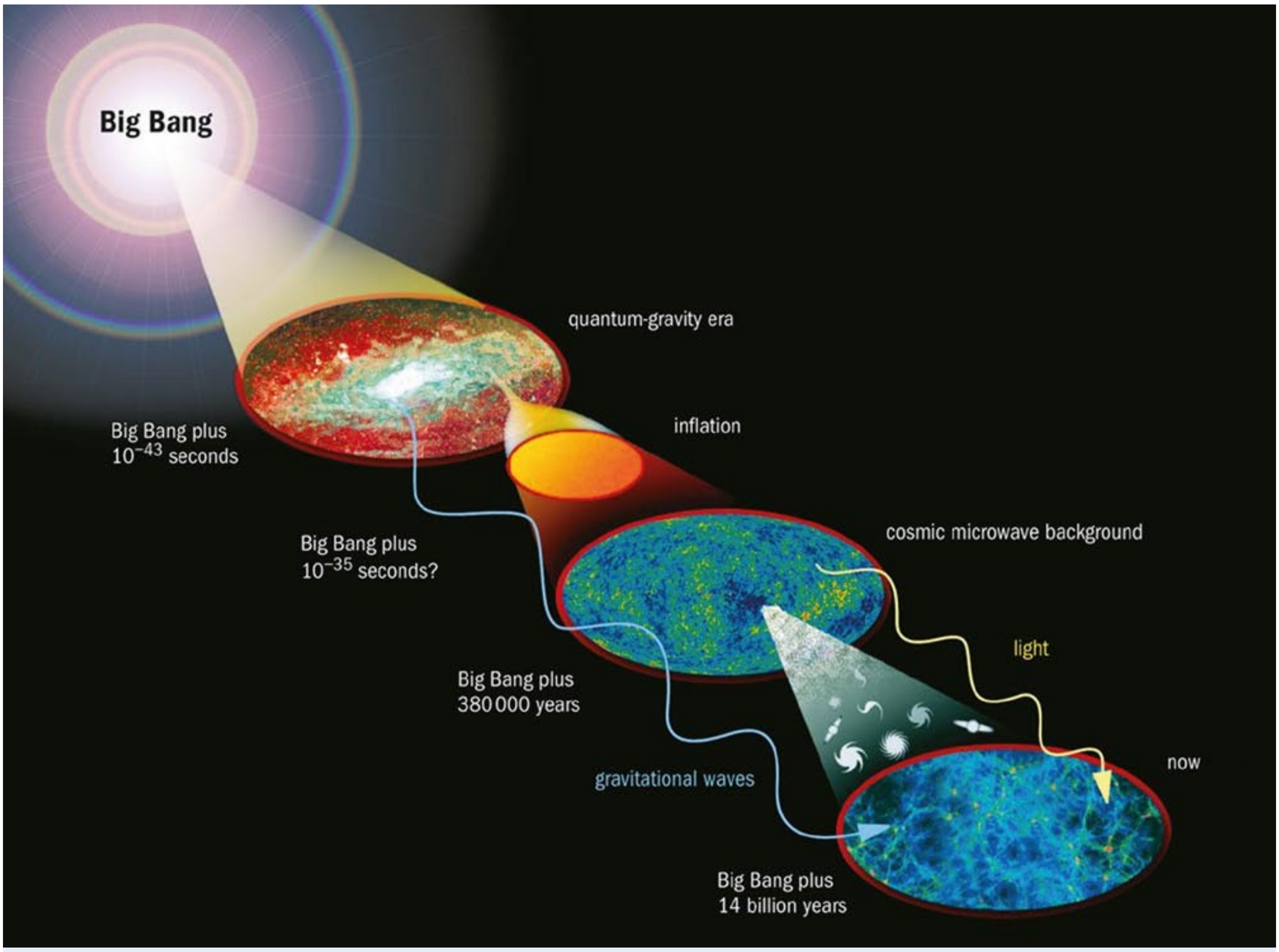


Figure 41: *The first light of the universe – the afterglow of the Big Bang – emerged 375,000 years after the Big Bang. Patterns imprinted on this light encode the events that happened only a tiny fraction of a second after the Big Bang. In turn, these patterns are the seeds of the development of the structures of galaxies we now see billions of years after the Big Bang. Credit: NASA / WMAP Science Team.*

3) Why are there no leftover high-energy relics, as practically every high-energy theory predicts? There are no magnetic monopoles, no heavy, right-handed neutrinos, no relics from the era of grand unification, etc.

In 1979, the idea was proposed that an early phase of exponential expansion could solve all of these problems, and would make additional predictions about the Universe that we could go and look for. This was the novel idea of **cosmic inflation.** Figure 41 depicts the earliest stages of the Universe, which set up the initial conditions that everything we see today has evolved from.

The early Universe was radiation-dominated, until the temperature dropped enough for matter density to dominate. The energy density of dark energy is assumed to be constant, for some given equation of state parameter. Because the matter energy density drops as the scale factor increased, dark energy began to dominate in the recent past (Fig. 42). At the present time wherein the scale factor $a(t) = 1$, we live in a Universe dominated by dark energy. If the Lambda CDM model is correct, the Universe will be completely dominated by dark energy in future epochs. The matter density will keep decreasing as the Universe expands. Our Milky Way will merge with the Andromeda Galaxy and eventually, the entire Local Group will coalesce into one galaxy. The luminosities of galaxies will begin to decrease as the stars run out of fuel and the supply of gas for star formation is exhausted. In the very far future, this galaxy will be the only one in our Hubble patch, as all the other galaxies will pass behind the cosmological horizon. The night sky, except the stars in the Local Group, will be very dark. Stellar remnants will either escape galaxies or fall into the central supermassive black hole. Eventually, baryonic matter may disappear altogether as all nucleons including protons decay, or all matter may decay into iron. In either scenario, the Universe will end up being dominated by black holes, which will evaporate by Hawking radiation. The end result is a Dark Era with an almost empty universe, and the entire universe in an extremely low energy state, with a possible heat death as entropy production ceases (see, e.g., Adams, Relativity: an introduction to space-time physics, 1997). What happens after that is rather speculative.

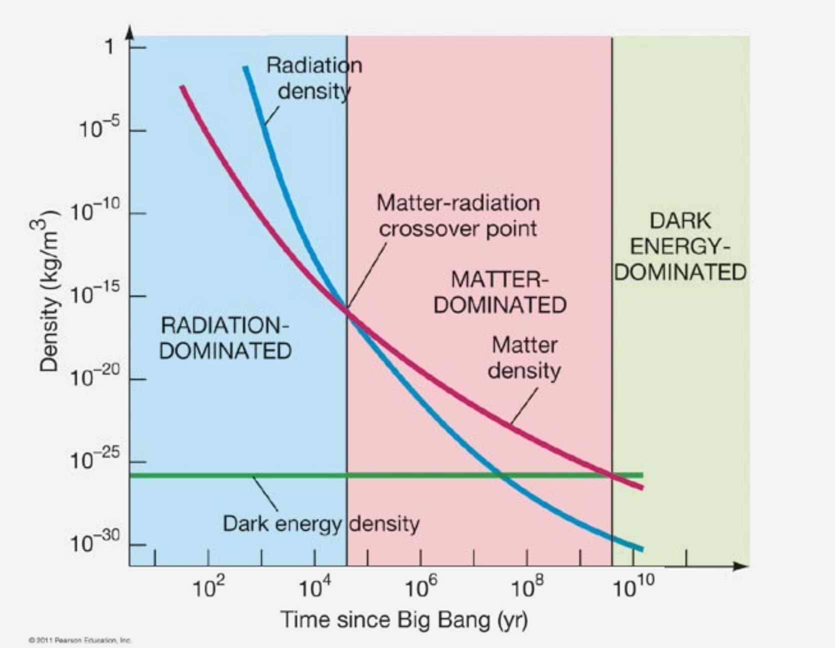


Figure 42: *The density evolution of the main components of the Universe. Credit: Pearson Education Inc. (2011).*

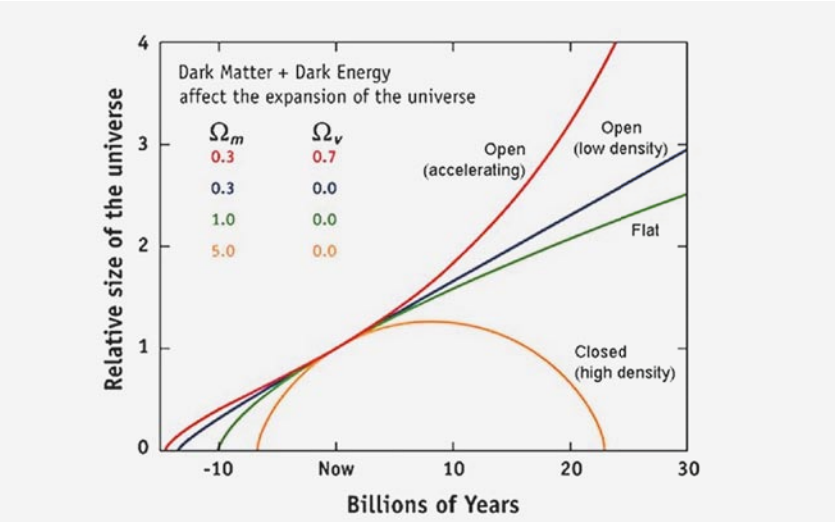


Figure 43: *Possible scenarios for the expansion (and possibly contraction) of the universe are shown. Credit: NASA/GSFC.*

Possible **scenarios for the expansion** (and possibly contraction) **of the Universe** are shown in Fig. 43. The bottom orange curve represents a closed, high density Universe which expands for several billion years, then ultimately turns around and collapses under its own weight. The green curve represents a flat, critical density Universe in which the expansion rate continually slows down (the curves becomes ever more horizontal). The blue curve shows an open, low density Universe whose expansion is also slowing down, but not as much as the previous two because the pull of gravity is not as strong. The top (red) curve shows a Universe in which a large fraction of the matter is in a form dubbed *dark energy* which is causing the expansion of the Universe to accelerate. There is growing evidence that our Universe is following the red curve.

Acknowledgements

The author is indebted to prof. S. Krimizis and Drs A. Vourlidas and T. Economou for discussions related to important discoveries in their own field of expertise.

The upper solar atmosphere. A brief history and recent results

by **Constantinos Gontikakis**

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

Abstract:

The upper solar atmosphere presents many complex dynamic phenomena that are far from fully understood. Due to the high temperatures in the solar atmosphere, especially in the solar corona and transition region and also in the chromosphere, an important fraction of the plasma emission takes place in the Ultraviolet part of the spectrum. The study of the upper solar atmosphere began in the late 19th century, when it was found beyond doubt that the structures visible during solar eclipses emanate from the Sun. Today, many space missions observe the solar atmosphere. This paper presents EUV spectra and images emitted from a solar active region observed with two space observatories, the Interface Region Imaging Spectrograph (IRIS) instrument and the Atmospheric Imaging Assembly (AIA) telescope, showing the morphologies of the solar structures that appear in the chromosphere, the transition region and the corona.

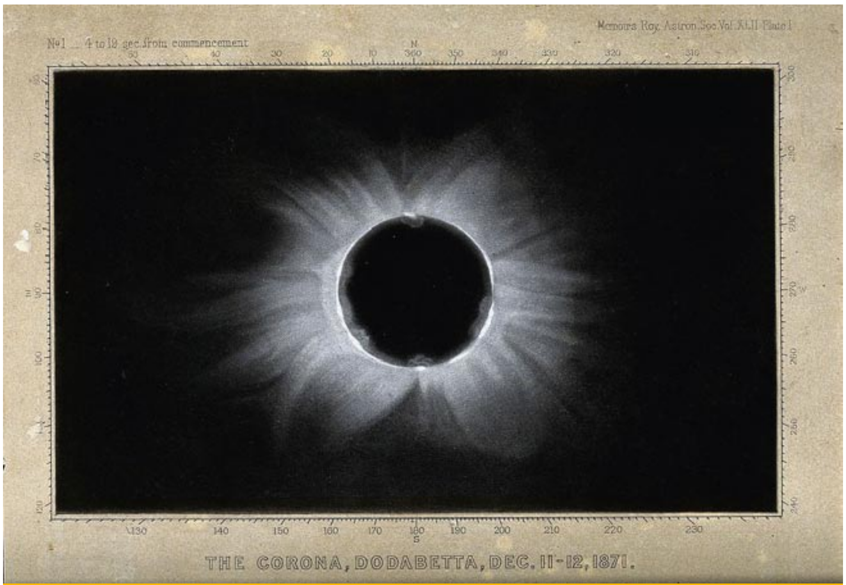


***Figure 1:** The total eclipse of December 1871 recorded at Doddabetta, India. Source: Wikipedia*

1. Introduction: brief history of solar corona research

The study of the upper solar atmosphere, composed of the chromosphere and corona, was compromised during the previous centuries due to the rare occasions of total solar eclipses. Up to the end of the 18th century, the structures seen during solar eclipses were often attributed to the presence of an atmosphere around the Moon (Dollfus 1956). This confusion started being clarified with the first photographs of solar eclipses. Real progress was achieved with the use of spectroscopy during eclipses and the understanding of the significance of spectra thanks to the work of Gustav Kirchhoff in the 19th century (Foukal 2012). During the eclipse of 1868, astronomers J. Janssen and J. Norman Lockyer, working independently, realized that the prominences, observed with spectroscopes were part of the solar atmosphere and that there were bright enough to be observed outside of solar eclipses. Moreover, they observed for the first time a spectral line of Helium at 5874.8Å, emitted by the chromosphere, when this element was still unknown. During the eclipse of 1871, J. Janssen realized that the photospheric Fraunhofer lines are also visible in the coronal spectrum, which was a decisive element for the understanding of the fact that the corona is part of the solar atmosphere (Foukal 2012). The Fraunhofer lines observed above the limb where due to the reflection of photospheric light on dust particles concentrated at the level of the ecliptic plane. This reflected light is called the F-corona (Golub and Pasachoff 1997).

Charles Young reported the observation of an emission green line emitted from the corona during the solar eclipse of 1869 (Young, 1872, 1899). The exact wavelength of the green line, 5303 Å, was determined in 1899 and did not correspond to the emission of a known element. Other coronal emissions in the visible band of the spectrum, fainter than the green line – such as a red (6374Å) and a yellow (5694Å) line – could not be identified with the emissions of known elements either.

This remained a mystery until 1941, when studies by Edlén and Grotian identified the green line with a metastable transition of Fe XIV (Haddia et al 2014), and the red and yellow lines with transitions of Fe X and Ca XV respectively. Scientists hence realized that these ions are formed by a gas of one million Kelvin and, from then on, began to search for a mechanism that could heat the corona.

The ultraviolet spectrum for wavelengths lower than 2000Å cannot penetrate the Earth's atmosphere to reach the surface of the Earth. The study of the UV coincided with the beginning of space exploration, when rockets reached altitudes above the atmospheric ozone layer. Spectra were obtained with rocket flights and with the first satellites in the 1960s (Tousey 1963).

An important finding in these early spectra was the double line of Mg II

2795.5Å, 2802.69Å. These lines were named Mg II k and h, because of their correspondence to the Fraunhofer lines designated by the letters H and K, which are emitted by the Ca II ion at 3933.6Å and 3968.5Å in the violet part of the visible spectrum. The Mg II lines have a complex spectral structure and are formed at the interface between the photosphere and chromosphere, in the region of the lower temperature of the solar atmosphere (Tousey 1963). Efforts for the theoretical interpretation of the Ca II and Mg II lines were made with numerical simulations of radiative transfer. These simulations began in the 1960s (Dumont 1967) with major advances in the 1980s (Lemaire & Gouttebroze 1983) and are still performed today with increasing levels of complexity (Carlsson et al 2015).

Skylab was the first space station set in orbit by NASA that included a set of solar telescopes operated by the astronauts. The observations made on Skylab helped to clarify important structures of the solar corona, such as the coronal holes and active regions, and also resulted in new information on the physics of the transition region (Del Zanna, Mason 2018).

Over the last twenty years, the spectrographs used in solar observation are found aboard the SOHO spacecraft and include the Coronal Diagnostic Spectrometer (CDS) and the Solar Ultraviolet Measurement of Emitted Radiation (SUMER).

This paper presents observations of the chromosphere, and the transition region that were recorded with the Interface Region Imaging Spectrograph (IRIS), as well as coronal images recorded with the Atmospheric Imaging Assembly (AIA) telescope on board the Solar Dynamic Observatory (SDO).

The IRIS instrument records three spectral wave bands 1332-1358 Å, 1389-1407 Å, and 2783-2834 Å. Each of these wave bands includes couples of bright spectral lines: the Mg II k, h chromospheric lines, the C II 1334 Å, 1335 Å, and the Si IV 1393 Å, 1402 Å transition region lines. IRIS has a very good spatial resolution of 0.33arc-seconds and a good spectral resolution of 0.05Å. IRIS can perform rasters with a 0.33×175 arc-seconds^2 slit and can simultaneously record movies with a field of view of 175×175 arc-seconds^2 with the slit positioned at the center of the field of view. This gives the opportunity to inspect the morphology of the solar structures around the slit image during the raster (De Pontieu et al 2014).

2. Structure of the transition region

The study of the ultraviolet solar spectrum has shown that there is a region of plasma having an intermediate temperature between the chromosphere and the corona. These temperatures are 20000 K and 10^6 K. This region produces many spectral lines in emission and is called the transition region. Some models show that the temperature of the transition region may rise abruptly from roughly 2×10^4 K to 10^6 K over a few hundred km, acting as a thin interface between the chromosphere and the corona.

The transition region presents some phenomena that are still not totally clarified. On average, the spectral lines formed at transition region temperatures present Doppler shifts towards the red. This would correspond to plasma motions towards the solar surface with speeds of 5 to 10 km/s (Doschek et al 1976, Peter & Judge, 1999). This phenomenon is dependent on the line formation temperatures.

For temperatures of 10^5 K, we have the maximum of this phenomenon with downward velocities of 10 km/s approximately. For lower temperatures, the velocity decreases to 2 km/s. For temperatures higher than 500000 K, the Doppler shift changes sign, indicating motions away from the solar surface of the order of 2-5 km/s (Peter & Judge 1999).

Example of the morphology of the transition region with IRIS

This section presents a typical non-flaring active region that was observed with the IRIS spectrograph. The active region has the code name NOAA 12529 and was observed on 18 April 2016. During this observation, the active region was close to the West solar limb. The active region includes a large sunspot. Figure 2 shows the location of NOAA 12529 on the solar disk in the 171Å and in the 1700Å filtergrams of the AIA telescope on board the SDO satellite.

IRIS performed a scanning over a field of view indicated on the 1700Å image as a white box. The scan recorded spectra in the Si IV 1394Å, 1402Å, in Mg II k and h lines, and in C II 1334.53Å and 1335.71Å. This report comments on the Mg II and Si IV lines. The raster was performed from 01:14:09UT to 02:16:05UT.

A detailed analysis of the Si IV lines can be found in Gontikakis and Vial (2018), while the present work provides a short presentation of the Si IV 1393Å data and a preliminary comparison of the Si IV 1393Å with the Mg II k images. Figure 2 shows the intensity map and the dopplergram of the Si IV 1394Å line. These two images were computed by performing a Gaussian fit on the Si IV 1394Å line. The morphology of the intensity presents bright plage areas sur-

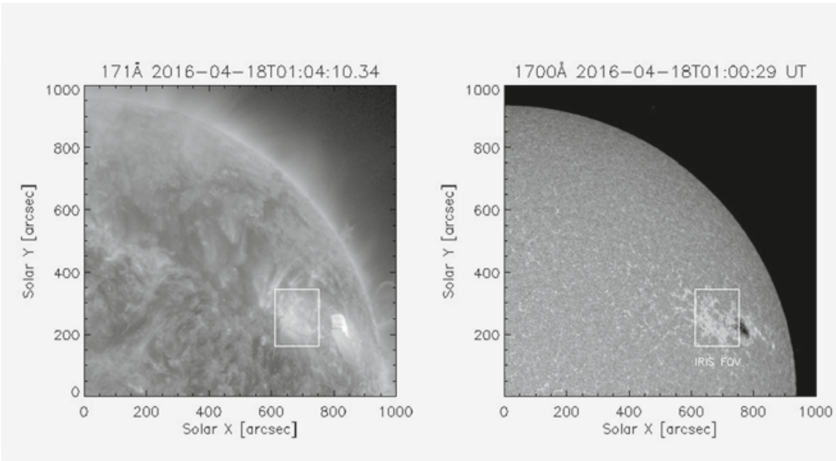


Figure 2: *The northwest part of the solar disk in the coronal 171Å emission (left panel) and in the continuum of 1700Å, both observed with the SDO/AIA telescope. Active region 12529 is seen near the west limb along with its large sunspot. The field of view of the IRIS raster is seen as a white box. The 1700Å image is formed at the chromospheric minimum temperature.*

rounded by dark quiet sun regions. Many loop-like structures are present in the image. They are concentrated at the boundaries between plage and quiet sun areas. Elongated structures, that must be low-lying loops, oriented roughly along the East West direction can be found in the right part of the image, as for example in the area with X from 700 to 740 arc-seconds and Y from 250 to 280 arc-seconds measured from the disk center. The dopplergram mostly shows motions toward the solar surface, visible in red color on the dopplergram. This phenomenon seems to be the redshift effect observed in the transition region (Doschek et al 1976). A few blueshifted areas are present along some low-lying loops.

Figure 3 shows the mean spectrum over a large part of the FOV of the Mg II k and h lines (left panel) and of the Si IV 1393Å and 1402Å lines (right panel). The Si IV lines are formed at a temperature of 80000K in the transition region. This is the temperature where the Si IV ions have their maximum concentration that takes place when the ionization process is in equilibrium and is caused by electron collisions.

Most of the time, the Si IV lines are optically thin and are excited though electronic collisions. They form a doublet, and the 1393Å line has a peak intensity that is twice the intensity of the 1402Å line for the case of an optically thin plasma dominated by electron collisions. Sometimes, Si IV can be excited by photons through resonance scattering. In this case, the line ratio 1393/1402 is higher than 2. This phenomenon provides increased understanding of the conditions in the solar plasma, as presented in Gontikakis and Vial (2018).

Between the two Si IV lines, there are two O IV lines at 1399.7Å and 1401.1Å. These two weak lines are sensitive to the electron density, so their intensity ratio can provide electron density measurements (Gontikakis and Vial 2018). However, the counts in the O IV lines are low and measuring these spectra is very difficult.

The Mg II k and h lines spectrum looks very different from the Si IV lines spectrum. The central parts of the Mg II lines, which extend at ±0.5Å from their rest wavelengths, are in emission. On the other hand, their spectral wings, which extend at ±5Å from their rest wavelength, are in absorption. Between the two lines, their wings overlap. This combination of an emission central part with wings in absorption results because the wings are formed in the upper photosphere and they absorb the photospheric continuum while the central peaks are formed in the lower chromosphere. Two weaker Mg II lines are seen in absorption at 2791.6Å and 2798.8Å. The Mn I 2799.094Å line is used to correct the instrumental alteration of the wavelength axis in order to compute Doppler shifts for the Mg I k line (Pereira et al 2019)

Figure 5 shows an intensity and dopplergram of the Mg II k line at 2756.352Å along with the coronal image at 171Å observed with AIA. These images are co-aligned with the ones in Figure 3. On the large scale, the structures in Mg II k intensity look like the ones of Si IV. As the Mg II k line is brighter (see Fig. 4) than the Si IV 1393Å line by a factor of roughly 90, the dark areas have enough signal in the Mg II k line where we can see many structures. The small loops between plage and quiet areas, as well as the elongated areas, are also present.

The Mg II k dopplergram seems roughly similar to the dopplegram for Si IV (Figure 2) on the large scale as the plage area is also redshifted and the areas of the low-lying loops present an important blueshift. However, a scatter plot between the two dopplergrams shows poor correlation. On the other

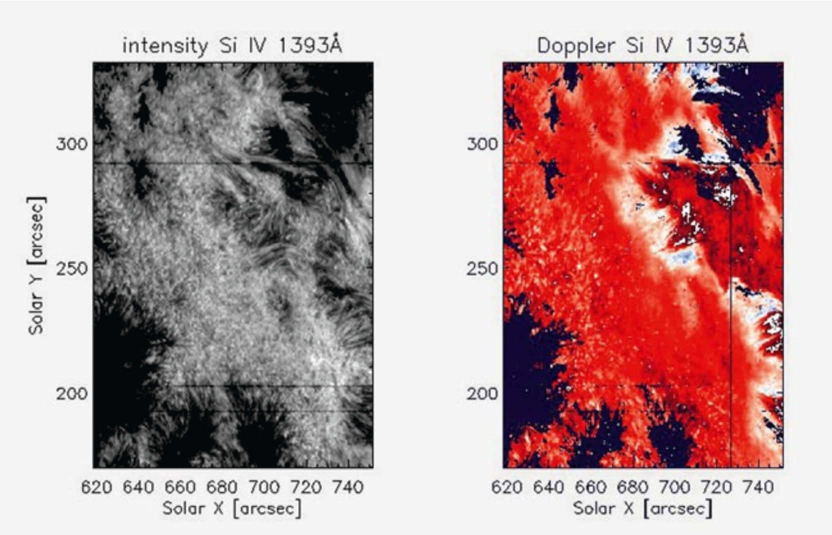


Figure 3: *Intensity map (left panel) and the dopplergram (right panel) of the Si IV 1393Å line. The X and Y axes show the distance from the solar disk in arc-seconds. The Doppler map red/blue colors indicate motions away/towards the observer, along the line of sight. Horizontal lines are reference lines of the instrument for co-alignment purposes.*

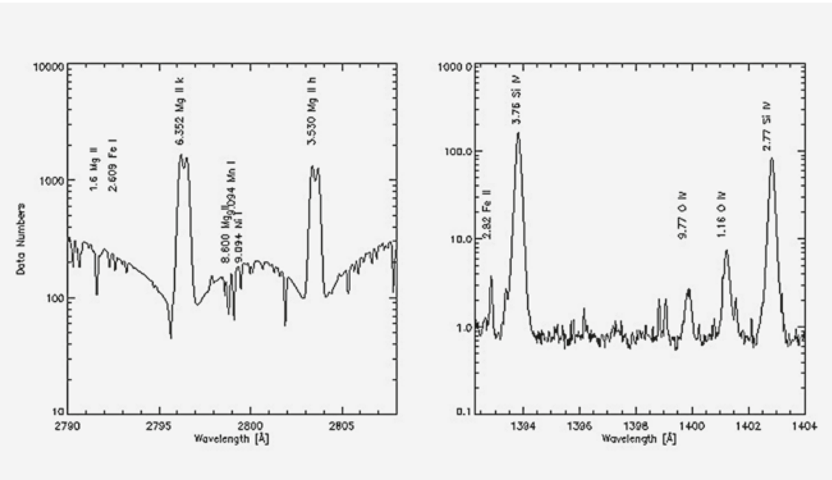


Figure 4 *Average spectra of Mg II lines (left panel) and Si IV lines (right panel) over a section of the IRIS raster. Notice that the Mg II lines intensities are higher than the Si IV intensities by a factor higher than 10.*

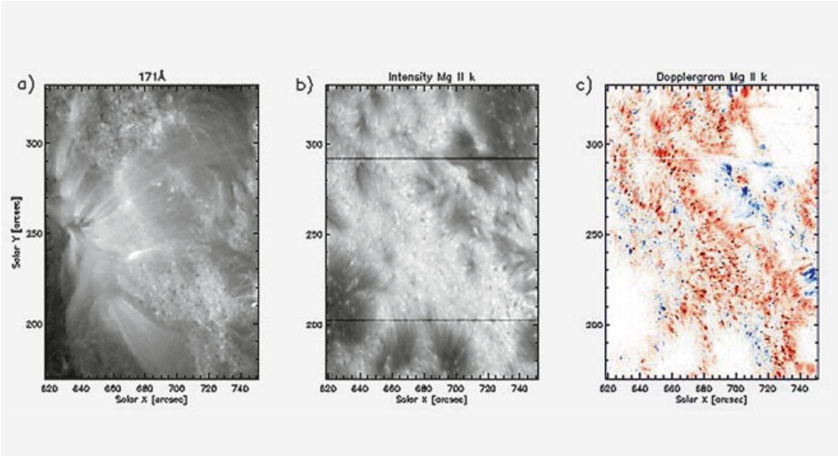


Figure 5 *A coronal image in the 171Å (panel a). The Mg II k intensity map (panel b) and the dopplergram (panel c) computed from the Mg II k line. The image in panel b was computed by simply summing the counts in the Mg II k line. For the dopplergram, the method described in Pereira et al 2019 was applied. The 171Å image was observed at 01:25UT, during the IRIS raster.*

hand, in some areas along loops, blueshifts in Mg II k are correlated with redshifts in the Si IV. This finding is interesting and needs further investigation. The co-alignement with the 171Å line is not totally correct because the IRIS raster is recorded over a period of one hour during which the image is perturbed due to solar rotation, while the 171Å image has a 2 s exposure time.

A pattern of small structures, called the moss, is present in the 171Å and is also recognizable in the Mg II image, as for example in the region from 630 arcseconds to 680 arc-seconds along the X axis and from 290 arc-seconds over to 330 arc-seconds along the Y axis. The moss pattern is believed to be at the base of very hot loops. Large scale loops are present in the 171Å, as the ones that have their east foot anchored around (x,y)=(640arcsec,255arcsec) while they extend towards the west part of the image. These largescale structures are coronal and are absent from the Mg II k and Si IV 1393Å images.

Discussion

The study of the upper solar atmosphere, from the chromosphere to the corona, greatly advanced during the 20th century thanks, mostly, to space exploration. One of the important aims of present-day solar research is to find the connections between the Chromosphere Transition Region and Corona in different structures (Kontogiannis et al 2018, Lites et al 2008). This is crucial, as the process of energy transfer between the different atmospheric levels is not fully understood. This task can be accomplished using detailed spectral observations with high spectral spatial and temporal resolutions, as the solar structures are small and very dynamic.

This paper presented the morphology of an active region in the chromospheric Mg II k and the transition region's Si IV 1393Å, along with the coronal image in 171Å. Even in this reduced and preliminary analysis, we can see the similarities between the fine structures in these images. The spatial resolution of IRIS can resolve the file elongated structures of the transition region much better than previous instruments. Studies of the relationship between the chromosphere and the transition region are interesting. The analysis of current data needs more work in order to lead to solid conclusions.

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Modeling Jets and Winds: a long greek collaboration

by **Christophe Sauty**

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1. Introduction

In 1988, I arrived in Crete for my Master internship under the supervision of Joseph Ventura and Nick Kylafis on radiative transfer in Neutron stars. This was already a very nice and fruitful starting collaboration with Greece. In fact, loving ancient Greece since the age of seven and modern Greece since I first came in 1981 (since then I need to come once a year at least), I had ask for the possibility to do my internship there. Yet, the real deep link I manage to build with the greek astrophysical community, was when I started my PhD under the supervision of Kanaris Tsinganos, when so many greeks are longing to do their studies abroad. I had the supply funding from France and my official supervisor was Jean Heyvaerts. Though, he was always very supportive, he was more like a competitor and a colleague to us. His best compliment was however that "we were achieving very complicated stuff." Thanks to the collaboration with Kanaris on outflows, winds and jets, I have developed several collaborations inside Greece (G. Surlantzis, I. Contopoulos, N. Vlahakis) as well as outside especially with Italy (E. Trussoni, Turin) and Portugal (J. Lima, Porto). As usual the hellenistic culture is spreading and invading the whole Roman Empire.

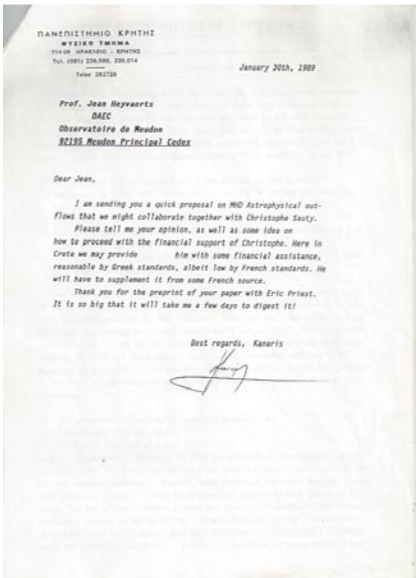
In the following I recall a few results obtained during all those years of collaboration with Greece, which lead me to be a member of the Astronomical Hellenic Society long before being a member of the French one, to speak the truth. This started with the study of the Solar Wind until 2007, since then we left a bit this field (Sec. 2.1). Then we concentrated on outflows from young forming low mass stars from class III, II (Sec. 2.2), I (Sec. 2.3) to class 0 (Sec. 2.4) as a matter of fact. Then, we broadened our spectrum going to relativistic MHD (Sec. 3.1) and building new analytical methods to study the spine jet from black holes, both the outflow (Sec. 3.2) and the inflow (Sec. 3.3) that connects the outer jet to the black hole itself. This was the occasion to dig some very important theoretical results on critical points and collimation criteria (Sec. 4.1). On that point our analytical work leads us to start considering numerical simulation from a new perspective (Sec. 4.2).

2. Solar wind and Young Stars

2.1. Starting with Solar Physics

All started in 1989, when Kanaris Tsinganos proposed me a subject for my PhD. At that time it was a proposal from my mandatory civil service (see Fig. 1). This was the beginning of a long study of this meridional self similar class of solutions that Kanaris Tsinganos had started in previous publications with B.C. Low, E. Trussoni and G. Vlastou, [86.1, 88.1, 89.1, 90.1, 91.1]. This class had a free geometry and the possibility to add magnetic field and rotation. The separation of variables is obtained as an expansion in the magnetic flux keeping only the dipolar term in its variation with colatitude. Then all forces are expanded on a basis of zeroth and first order terms in magnetic flux. However in this Newtonian metric, solutions are exact solutions. The model in its full extension was presented in [94.2], hereafter ST94, and explored in details in many following publications [99.2, 04.2]

In 1992, the two first papers [92.2, 92.1] on the subject came out with already an emphasis on the Solar Wind, especially modelling Munro & Jackson 1977 Solar Coronal Hole [77.1] and the jet of SS433. During this time, I was also involved in a collaboration on flows in solar arcades with G. Surlantzis as he was finishing his PhD with K. Tsinganos [94.1]. Concerning the Solar Wind, this model is able to take into account the latitudinal variation from the fast wind to the slow wind but with a smoother dipolar variation than the very sharp transition seen by ULYSSES space mission [05.1]. In fact we pursued to study solar


ΠΑΝΕΠΙΣΤΗΜΙΟ ΚΡΗΤΗΣ
ΦΥΣΙΚΟ ΤΜΗΜΑ

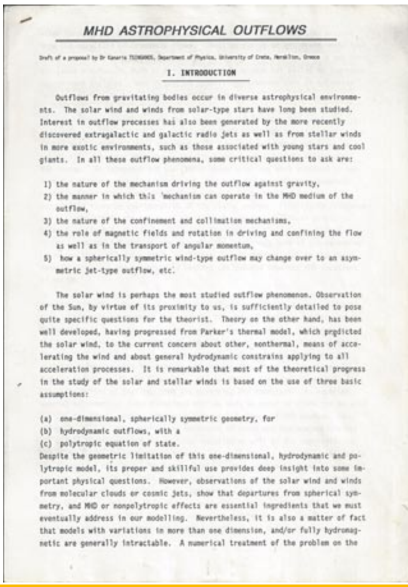
January 30th, 1989

Prof. Jean Heyvaerts
DAEC
Observatoire de Meudon
92195 Meudon Principal Cedex

Dear Jean,

I am sending you a quick proposal on MHD Astrophysical outflows that we might collaborate together with Christophe Sauty.
Please tell me your opinion, as well as some idea on how to proceed with the financial support of Christophe. Here in Crete we may provide him with some financial assistance, reasonable by Greek standards, albeit low by French standards. He will have to supplement it from some French source.
Thank you for the preprint of your paper with Eric Priest. It is so big that it will take me a few days to digest it!

Best regards, Kanaris


MHD ASTROPHYSICAL OUTFLOWS

I. INTRODUCTION

Outflows from gravitating bodies occur in diverse astrophysical environments. The solar wind and winds from solar-type stars have long been studied. Interest in outflow processes has also been generated by the more recently discovered extragalactic and galactic radio jets as well as from stellar winds in more exotic environments, such as those associated with young stars and cool giants. In all these outflow phenomena, some critical questions to ask are:

1) the nature of the mechanism driving the outflow against gravity,
2) the manner in which this mechanism can operate in the MHD medium of the outflow,
3) the nature of the confinement and collimation mechanisms,
4) the role of magnetic fields and rotation in driving and confining the flow as well as in the transport of angular momentum,
5) how a spherically symmetric wind-type outflow may change over to an asymmetric jet-type outflow, etc.

The solar wind is perhaps the most studied outflow phenomenon. Observation of the Sun, by virtue of its proximity to us, is sufficiently detailed to pose quite specific questions for the theorist. Theory on the other hand, has been well developed, having progressed from Parker's thermal model, which predicted the solar wind, to the current concern about other, nonthermal, means of accelerating the wind and about general hydrodynamic constrains applying to all acceleration processes. It is remarkable that most of the theoretical progress in the study of the solar and stellar winds is based on the use of three basic assumptions:

(a) one-dimensional, spherically symmetric geometry, for
(b) hydrodynamic outflows, with a
(c) polytropic equation of state.
Despite the geometric limitation of this one-dimensional, hydrodynamic and polytropic model, its proper and skillful use provides deep insight into some important physical questions. However, observations of the solar wind and winds from molecular clouds or cosmic jets, show that departures from spherical symmetry, and MHD or nonpolytropic effects are essential ingredients that we must eventually address in our modelling. Nevertheless, it is also a matter of fact that models with variations in more than one dimension, and/or fully hydromagnetic are generally intractable. A numerical treatment of the problem on the

Figure 1: *The two first pages of the draft of a PhD proposal sent by Kanaris Tsinganos to Jean Heyvaerts in 1989.*

outflows in several other papers and in collaboration with J. Lima who had developed in collaboration with K. Tsinganos another self-similar model for helicoidal flows [01.1], hereafter LPT, i.e. conical flows with rotation, but including higher multipoles in the colatitudinal expansion. This allows for a better description of the sharp transition between the slow and the fast wind. In 2007, we achieved a nice modelling of the global Solar wind by combining the two models [07. 1]. The ST94 model was used to describe the dipolar geometry of the Solar Wind in the first radii close to the Sun where the wind is accelerated in the coronal hole and the streamers, around the equatorial magnetic dead zone. This solution is matched on large distances to the LPT model to fit ULYSSES data between 1 and 5 AU. The model can fit the expected geometry and dynamics of the Solar wind. As a by product, it gives a cartography of the expected necessary heating to sustain such dynamics. A first guess was that turbulence and magnetic heating could explain it, but of course we have to pursue on that direction.

2.2. Young stars

The model because of its flexibility was also a unique tool to describe jets from young stars and especially the stellar component of the inner jet. This was already underlying the application of our model to jets in the ST94 paper. At that time the stellar component of the jet was not in fashion. In 2000 for his master thesis, Z. Meliani found a solution that could very well fit the observational data of the RY Tau micro jet, see [07.2], which was finally published in 2011 [11.1]. However, the disk locking mechanism came out to be inefficient in extracting angular momentum from the star [04.3]. Matt & Pudritz in a series papers (e.g. [05.3, 05.2]) showed that the braking of the central star could be a natural consequence of the stellar wind.

This was confirmed in our modelling of the micro jet of RY Tau ([11.1], see Fig. 2). The parameters of the model where fixed from the observational data given in [07.2] mainly the mass and the radius of the star and the mass loss rate, 3 $10^{-9} M_\odot/yr$ from the micro jet. However we can rescale these values, as more recent data suggest a slightly larger radius and mass. This does change the result quantitatively not qualitatively. As an output of the model we got a reasonable dipolar magnetic field of the star, a bit less than 1 G, and a rather low stellar rotation rate. At the time of the study, this low rotation was in the lowest range of observed values. As the jet is mainly driven by magnetic and pressure turbulence (Alfvén waves), the magneto-centrifugal driving is not very efficient and the rotation of the star does not affect the dynamics. Most of all, the solution predicted the electron density, which turned out to fit the measurements at different distances from the star of the UV data.

In fact, this spine jet self similar model is very efficient to describe low mass accreting stars where the central jet is mainly coming from the star. Evolved Classical and Weak line T Tauri are of course the best target to study with this model.

2.3. From star to disk

However, it it obvious that for early classical T Tauri stars like DG Tau or class I YSO jets, most of the mass loss comes from the disk itself. In a collaboration with N. Vlahakis, we studied the possibility for radial self-similar solutions "à la" Blandford and Payne [82.1] to cross all critical points. At that time, N. Vlahakis had already produced several papers during his PhD with K. Tsinganos on searching for new classes of self-similar solutions, developing a unique systematic theorem to dig such classes [97.1, 99.1]. Indeed, we found the first disk wind solution crossing all critical points [00.1], namely the slow and fast magnetosonic points besides the Alfvén. No one had cross the fast magnetosonic surface so far, though it is essential as this is this surface that causally disconnects the far distance jet from it source. This condition must be fulfilled because of the strong terminal shocks we see in all jets, no matter the scale. We started integrating from the Alfvén surface to get the radial self similar solution as we did for meridional self similar solutions. This new break was improved later on by F. Casse and J. Ferreira who finally produced a complete disk wind solution crossing all critical points and connecting to the accretion flow in the disk [04.5].

2.4. From Class II to Class 0

On his way back to Greece, from the USA, I met I. Contopoulos through his collaboration with K. Tsinganos. I. Con-

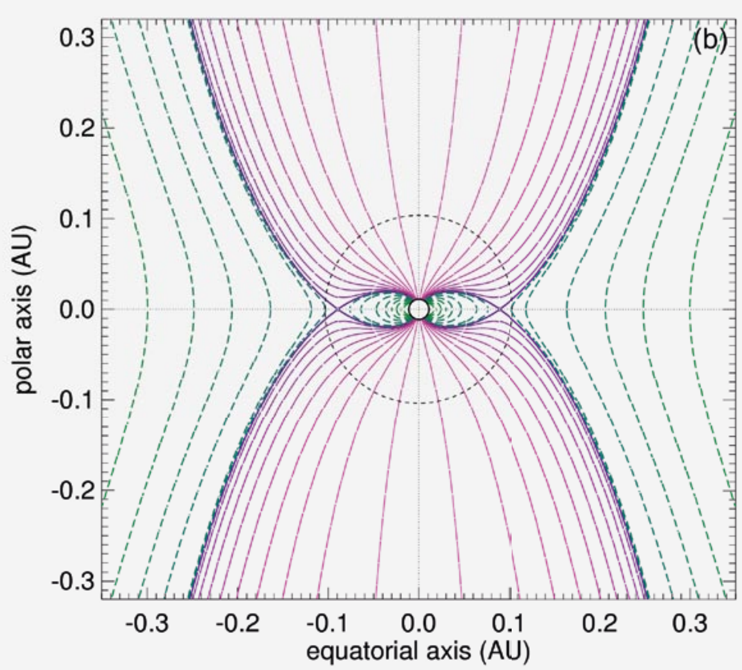


Figure 2: *Analytical solution for RY Tau from [?]. The stellar wind, which collimates into a cylindrical jet at large distances, is the set of pink poloidal field/stream lines. The green dashed lines are the magnetospheric dead/accretion zone and the disk wind, two regions we do not intend to model here consistently.*

topoulos spent some time in Paris and he brought to my attention a very interesting subject on an even earlier class of YSO jets, namely the Class 0 objects discovered in 1994 by André and collaborators [94.5]. His idea (see [01.2]) was simple but brilliant. As the cloud collapse and form an accretion disk, in the free fall region that connects to the Keplerian disk, the advected magnetic field is bent even if the magnetic Prandtl number in the disk is unity. This last reasonable assumption means that in the disk, where accretion is not yet efficient, the magnetic field is vertical such that no wind is driven. However at the border with the free falling region, it is sufficiently bent by the external geometry to magneto-centrifugally drive a wind. We solved the geometry of the magnetic field assuming it is force free. Then the Bernoulli equation gives the acceleration of the flow along the lines. This very simple model suggests that up to 40% of the accreted mass can be put into the wind, thus providing a very powerfull source for the outflow. This can be done at a very early phase of the formation of the star, even before the proto star has turned into a star typical of Class 0 objects.

3. Relativistic flows

3.1. Slow rotating jets from Black Holes and relativistic thermodynamics

We were rapidly tempted to extend our model to the relativistic domain in order to explore the possibility of jet models for AGN. N. Vlahakis had done a very extensive study of the generalisation of disk wind models to the relativistic regime both for AGN and GRB jets [03.2, 03.1, 04.6, 04.4]. We focalized in the inner part of the jet, the spine jet, that may originate from the black hole.

We first explored the thermodynamics in a simpler relativistic Parker wind model [04.1], using Taub's approximation of Synge's equation of state [48.1, 58.1]. This allowed us to explore how relativistic winds can be thermally accelerated when they are heated to ultrarelativistic temperatures. Taub's equation of state is a simple way to handle both a ultrarelativistic plasma with an adiabatic index of 4/3 close to the source and non relativistic temperatures on large distances where the adiabatic index is only 5/3. Using 4/3 on all distances assumes that the temperature remains everywhere very large, which is not physical. It artificially gives an index less than Parker's value of 3/2, which allows to have a wind solution. This study also showed that from isothermal to adiabatic, the relativistic temperatures always enhance the thermal acceleration of the flow, increasing the terminal velocity.

As it was not possible to obtain exact meridional self similar solutions in the relativistic case, partly because of the Lorentz factor and partly because the metric itself does not split into variables, we chose to pursue the idea of expanding with the magnetic flux [06.1]. This time, all quantities, forces, Lorentz factor and metrics are expanded. This does not simply reduce on a choice of variable separation of the integral quantities, though this part is unchanged. The solutions obtained through this expansion are valid only close to the rotational axis. It is adapted to model spine jets accelerated above the black hole. This model would give qualitatively sufficiently high Lorentz factors to be applied to explain the dichotomy between FRI and FRII [10.1].

However, our first two attempts for Schwarzschild black holes [06.1] and Kerr black holes [14.2] could not model outflows that would cross the light cylinder. Though in this case, which is not force free, the light cylinder is no longer a critical surface. Its effect is mixed with the Alfvén surface such that there is only one singular surface, which is a generalized Alfvén surface. However, we thought it was necessary to neglect the light cylinder effect in the forces and in the critical surface. This was adding an extra approximation as the lines were approaching the light cylinder location. Thus these two attempts to model a spine jet could have only jets with cylindrical asymptotics, confined within the light cylinder.

3.2. GRMHD: a complete set

In collaboration with N. Vlahakis and K. Tsinganos, V. Cayatte and myself supervised the PhD of L. Chantry. L. Chantry was able to make a complete expansion of the meridional self similar model to GRMHD (MHD in general relativity) for Schwarzschild and Kerr black holes, i.e. non rotating and rotating black holes. This time, effects of the light cylinder in the equations of motion were all taken into account. Basically, the Alfvén surfaces, which were chosen to be spherical so far, have a more complex shape but the real critical surfaces (generalized Alfvén, slow and fast magnetosonic surfaces) remain spherical. This implies also that the energy distribution depends now on the colatitude.

This model is capable of producing solutions with very high Lorentz factors with reasonable temperature profiles, because crossing the Light cylinder – though it is no longer a critical surface– allows to have more magnetic acceleration similarly to what was shown by N. Vlahakis (e.g. [03.2, 03.1] for disk winds. Besides cylindrically collimated jets fitted for describing spine jets from AGN, we also obtained conical (helicoidal) solutions. Such solutions are interesting for winds, or loosely collimated outflows, but also for some GRBs as we are not sure that the small opening angles observed are not due to fragmentation of a larger wind.

From the magnetic flux of typical solutions, using Zamaninasab's equation [14.6], it was possible to link the magnetic flux to the expected accretion rate, though we do not solve for the accretion flow. This gives us a value for the jet power to accretion power ratio. Our solutions have a power of a few to almost 50% comparable to numerical simulations by Tchekovskoy & McKinney (e.g. [11.2, 12.3].

3.3. Inflows and Outflows

Another, big advantage of such solutions is to produce inflows besides the outflow solutions. In other words, the jet forms on a surface called the stagnation surface, but in order to connect it to the central black hole, an inflow is also created from the same stagnation surface down to the black hole. In order to use the same model, we choose here to model the stagnation zone as a surface like in the first paper of Globus and Levinson [13.1]. The stagnation zone could also be a thick layer as in Globus and Levinson second paper [14.1]. This would require to build a completely new model. Something we may do in the future. So using a single model, we were able to produce inflow/outflow solutions from the central black hole to large distances in the spine jet as seen in Figs. 3 (see also 4). The inflow and the outflow start from the red circle. Both flows are crossing the modified slow (green circle) and Alfvén/fast (blue circle) critical surfaces. In red, we have also represented the location of the inner and outer light cylinders though they are not critical.

This model can produce solutions, see Fig. 4, of spine jets that efficiently extract angular momentum and energy from the central black hole, in a free geometry. Conversely to Globus and Levison [13.1, 14.1] we did not need to fix the geometry. We neither had to assume the flow to be in a force free equilibrium as in other models, e.g. works by Nathanail and Contopoulos [14.4, 15.1, 16.1], Mc Kinney and collaborators [11.2, 12.3]. Theses solutions are complementary to those magnetic flux dominated solutions showing that angular momentum and energy can be extracted even in a turbulent pressure driven flow. The mechanism at work is neither a pure Blandford-Znajek one or a Penrose one but rather a combination of the two as it is impossible to disentangle, in the process, magnetic fields from inertia.

4. From analytics to numerics

4.1. On critical points and magnetic collimation

The study of self similar solutions was a unique occasion to go deeply into the problem of critical points. Dealing with meridional and radial self-similarity, we discovered that the usual standard approach of critical points as the surfaces where the poloidal velocity of the flow coincides with the three MHD wave velocity was not correct, see Tsinganos et al 1996 [96.1]. In fact the critical surface must satisfy the self-similarity symmetry. Thus, in radial self-similar solutions, the critical surfaces are cones and the latitudinal component of the velocity is equal to the MHD wave velocity on each critical cone. Conversely, in meridional self-similar solutions, critical surfaces are spherical. Note that because the fast and the Aflvén surfaces must coincide on the polar axis, the three critical surfaces reduce to two spherical ones, the slow and the Alfvén. On those surfaces, this is the radial component of the velocity, which is equal to the MHD wave velocities. As shown by Bogovalov in 1994 [94.6], the standard approach of solving the Bernoulli equation for a given geometry and the standard definition of the critical points is in fact the definition of the MHD ergosphere, i.e. the zones where the MHD equations, under steady and axisymmetric assumptions, change of nature from elliptic to hyperbolic and vice versa. The real critical surfaces are in between, they are limiting characteristic surfaces or so called separatrices.

Self-similar solutions revealed that there was a strong analogy between MHD flows and metrics in general relativity. In the case of a non rotating black hole, i.e. Schwarzschild metric, the ergosphere and the event horizon coincides. This is also the case in Parker's wind and in Bondi's spherical accretion. This is also the case, as soon as the the geometry of the flow is fixed. For rotating black holes with a Kerr metric, the ergosphere and the event horizon do not coincide. However, there is still enough symmetry (axisymmetry) such that the event horizon can be given by a local definition. Its shape is known a priori. This is also the case in self similar solutions where the self-similar symmetry imposes the shape of the critical surfaces, which is known a priori. In the general case, with no symmetry or in the time dependent case, the ergosphere and the vent horizon do not coincide. The event horizon is only known globally, once the metric is solved. This is the same in MHD, the flow pattern must be solved to know the location of the limiting characteristic surface. In numerics, solving for the collapse of two merging black holes, it is thus essential to have inner boundary conditions well within the event horizons such that they do not affect the outer metric during the simulation of the collapse. This is also the case in modelling time dependent jets. One must take care that the outer boundary is far beyond the modified fast magnetosonic surface to be sure that shocks or outer boundary conditions will not affect the outflow upstream. Even though MHD event horizons do not appear any more as critical surfaces (the time dependent equations are always of hyperbolic type), they still play a role in limiting the inner number of boundaries that are free in order to asymptotically reach a steady state.

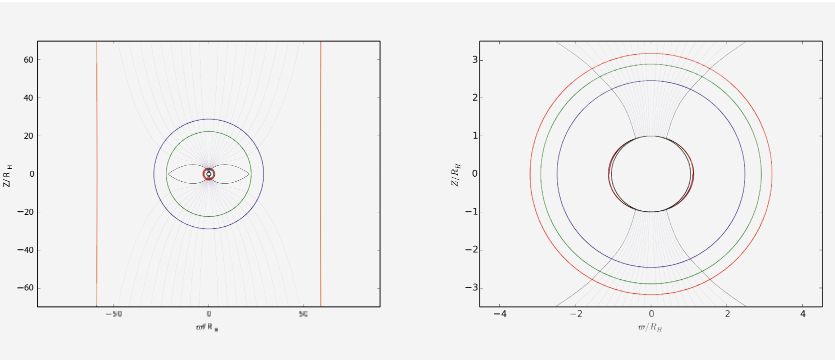


Figure 3: *A representative outflow/inflow solution. On the left, the poloidal field/stream lines on large scale with an inner zoom on the right. Fieldlines are represented only in the open fieldline region. The equatorial zone cannot be modeled with our approach and corresponds to the accretion domain. It is left empty.*

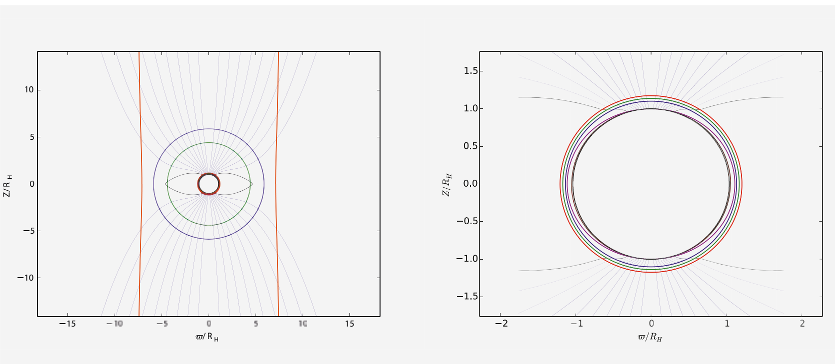


Figure 4: *A typical outflow/inflow solution which extract both angular momentum and energy from the black hole. The inflow zone is much more squeezed and the stagnation surface very close to the horizon, in order for the solution to be efficient.*

Our meridional self-similar solutions were also the occasion to develop the concept of magnetic collimation efficiency. It turns out that in order to understand collimation, one must combine the Bernoulli equation along the flow (Energy conservation) together with the transverse force balance. Collimation is achieved when the remaining energy on a non polar streamline, once the energy necessary to accelerate the flow is taken out, is larger than the same remaining energy along the polar axis. Of course, part of this energy comes from the pressure of the gas. However, we expect in most jets this part of the collimation to be negligible or even having a negative effect because at least on large distances, the jet may be over-pressured, the pressure being higher along the axis than out. Then, the magnetic energy in the magnetic rotator may supply the lack of pressure confinement. However, to be exact this magnetic criterion as to take into account that out of the polar axis of the jet, part of the magnetic rotational energy is used to supply the lack of gas pressure to accelerate the flow (the temperature drops). This is the magnetocentrifugal acceleration, which is eventually dominant far from the polar axis. So if you substract from the total magnetic energy the part that leads to magnetocentrifugal driving, you obtain the energy reservoir left to collimate the flow, if it is positive. If it is negative the flow geometry will adjust itself into a conical wind. This calculation is rather complex because in order to calculate the remaining magnetic energy that collimates, you have to calculate the variations of thermal and magnetic driving against gravitation between a non polar and a polar streamline. This magnetic criterion for collimation exists both for Newtonian and fully relativistic flows in the frame of this self-similarity. In the case of meridional self similar models, due to the extra symmetry, this criterion was given by a single parameter, called ε. However, it would not be surprinsing that this criterion could be extended to more general flows.

Last but not least, working on self similar models lead us to develop the idea that counter rotation in jets could be a very natural result of the magnetization of the jets (see[12.1, 14.3]). We showed both analytically and numerically that having parts in the jet constantly or episodically counter rotating was no surprise. In particular, using only the first integrals of steady axisymmetric flows, either non relativistic or fully relativistic (in GRMHD), we showed that there was a very simple criterion to have counter rotation, i.e. a jet that rotates in the opposite direction of its source, either a star or a disk. This result is independent of any further assumptions and is not restricted to self-similar models. First integrals are simply mass flux and magnetic flux conservations, isorotation law and angular momentum conservation. In the relativistic case, one needs to add energy conservation. In non relativistic flows, the criterion is very simple. If by chance the flow decelerates after crossing the Alfvén surface to a velocity below some threshold value, which is more or less the velocity of the flow at the Alfvénic transition times some geometrical factor close to unity, then the jet counter rotates. In the case of ultra-relativistic flows, where the bulk velocity is very close to *c*, the condition is rather that the enthalpy decreases below some threshold value close to its value at the Alfvén transition. So if by some means, cooling or shocks, the flow looses enough enthalpy or velocity, it will naturally counter rotate conserving angular momentum. The jet is basically capable of counterrotating because it is magnetized. Thus counterrotation appears because there is a transfer of angular momentum from the fluid reservoir to the magnetic one. The biggest surprise may not be that counter rotation is a natural phenomenon, but rather that it is, if observed, a clear signature of the magnetization of the flow.

4.2. Dead zones and accretion flows

Self similar solutions can also be used as initial and boundary conditions for numerical simulations. In a collaboration with the Portuguese team in CAUP (J. Lima, F. Gameiro, R. Albuquerque), K. Tsinganos, V. Cayatte, N. Vlahakis and myself are involved in making new numerical simulations of T Tauri stellar jets. We used our RY Tau solution as initial conditions for the jet and the magnetospheric accretion zone. In the accretion zone, we simply invert the direction of the flow in the region of closed field lines of the analytical solution, as well as the toroidal magnetic field component. This way we keep comparable values and sign for the total angular momentum flux and for the isorotation law. We also increase the density and the velocity by multiplying the initial analytical values by the same factor in the whole zone. As the magnetic field dominates the equilibrium in the whole region (small plasma beta), changing the inertia does not affect strongly the initial equilibrium. The accretion disk is treated as a boundary condition on the equatorial plane. Its structure is given by the equilibrium of the analytical solution itself with an increased density as for the magnetospheric accretion flow. As the accretion disk stops before reaching the star, the accretion flow stops at the inner disk radius, below which there is a static dead zone. The static dead zone is simply the analytical solution with or without enhanced density. There, the poloidal velocity is put to zero as well as the toroidal magnetic field component, while the magnetosphere is in solid rotation as it is static.

We have performed simulations with low and high accretion rates and observed a dichotomic behaviour [17.1]. If the accretion rate is high enough we have a sporadic magnetospheric ejection as in previous simulations (e.g. [09.2, 13.2, 15.2] and references therein). If the accretion rate is low, the outflow adapt itself and there is a low density, almost static zone with negligible mass flux between the stellar jet and the disk wind. In a few rotations of the star (less than 5 instead of a few tens), the whole structure is completely steady and the simulation can run for ever. Starting closer to equilibrium strongly reduces the computing time to reach the final steady state.

We have increased the mass in the static zone. For high density the overall structure still reaches a steady or quasi steady state but the high density in the dead zone helps the formation of sporadic mass ejection.

Of course we did not treat completely the accretion disk, which remains a mere boundary condition. Besides, as we take the initial analytical solution on the equatorial plane with a strong magnetic field, the disk is not in Keplerian rotation. This could be the case for strongly magnetized disks [89.2]. Yet, if it were Keplerian, this would not affect strongly the inner flow dynamics, because the

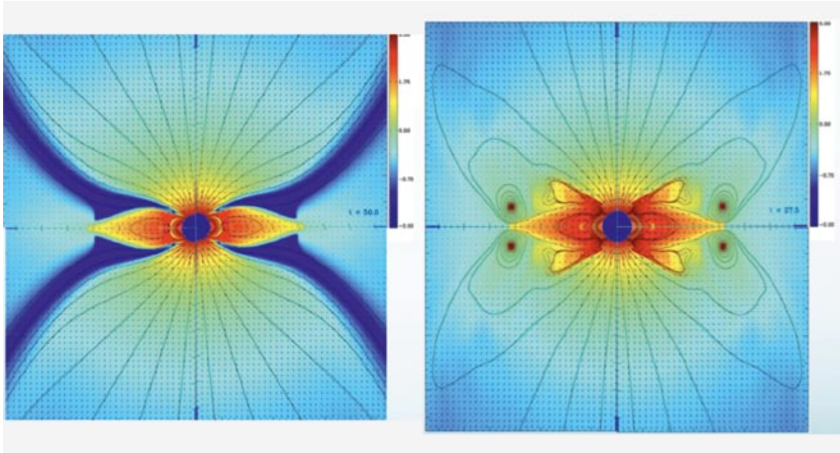


Figure 5: *Two simulations of RY Tau stellar jet with magnetospheric accretion and low density dead zone. On the left, the initial accretion rate in the magnetosphere is below 15 times the ejection rate and above 20 times on the right. The plots show isocontours of the expected luminosity*

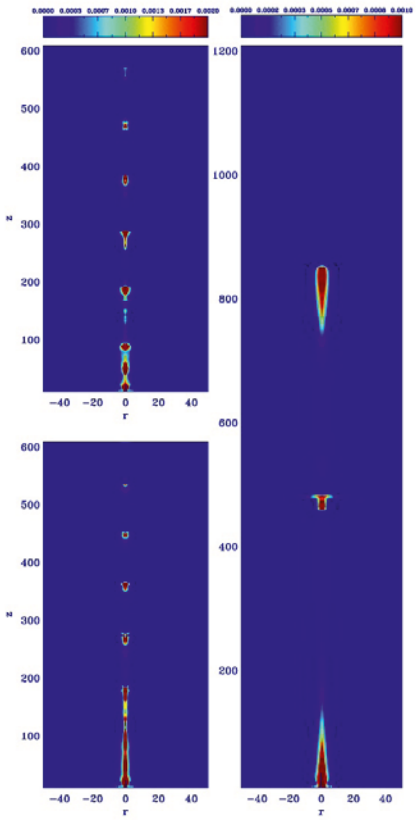


Figure 6: *Two solutions of large scale jets from [09.1]. On the left the mass flux of the stellar jet in the two simulations varies on a time scale of 10 years, which creates regular knots every 100 AU, typical of what we see in HH34. On the right the variation timescale is 100 years, which gives knots every 1000 AU, typical of HH30.*

weak disk wind we have is mainly pressure driven. In such disks, the magneto centrifugal launching is not essential.

4.3 Disk winds and stellar jets

Next step is to combine the inner meridional self similar stellar/magnetospheric solution to the external radial self-similar disk wind. This is yet to be done to analyse the launching region of the jet including the heating of the stellar and the disk coronae. T. Matsakos [08.1, 09.1, 12.2] already studied multicomponent stellar and disk jets on large distances using as initial solutions a combination of self-similar solutions but for adiabatic flows. In particular, it turned out that even though the stellar jet is insignificant but variable on timescales of the stellar activity, typically 10 to 100 years, regular knots will form as expected. Those knots are typical spaced by 100 AU as in HH34 to 1000 AU as in HH30 (Fig. 6).

5. Conclusions

In this publication I have tried to make a overview of my past and current greek collaborations on modelling jets and winds. From the Solar wind to extragalactic jets and Gamma Ray Bursts, including all classes of Young Stellar Jets (O, I, II, III), I hope I have shown there is a very strong and vivid dynamic on these subjects in Greece, especially thanks to the impulse of Kanaris Tsinganos. This expertise covers all the aspects from theory to numerics and now we see that we can reach a level of modelling that can be directly compared to observations of specific objects. Now Iannis Contopoulos and Nektarios Vlahakis are senior researchers too and I do not mention other colleagues in the field of jets with whom I have not collaborate directly, like Apostolos Mastichiadis etc., but there is a new generation coming like Kostas Gourgouliatos in Patra and hopefully some other in the next future. I think Europe is a unique construction for exchanges and my hope is that we can strengthen it via research. So for all these reasons I am very happy and proud to be a member of ELASET for a few decades now and very thank full to have the opportunity to write this brief summary of this nice collection of results.

Acknowledgements

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Astronomical Conferences & Schools in Greece during 2018

In this issue we have the brief presentations of three conferences and schools, which took place in Greece during 2018, for which the organizers sent us a summary of their main results.
These are:

- The Olympian Symposium 2018 "Gas and stars from milli- to mega- parsecs", 28 May - 1 June, Paralia Katerini
- "Touching the Planets, Evaluating Excellence", 2-3 July 2018, Athens
- The 3rd Summer School of HEL.A.S. "Neutron Stars and Gravitational Waves", Thessaloniki in 8-12 October

1 The Olympian Symposium 2018 Gas and stars from milli- to mega- parsecs

28 May - 1 June, 2018. Paralia Katerini. Greece

The Olympian Symposium 2018 took place the week of 28 May - 1 June 2018 in Paralia Katerini, Pieria prefecture. It was organized by the non-profit organization Olympian Centre for Astrophysics (OCfA). This Symposium was the third, overall, Olympian Symposium, a successful series that started in 2014 focusing on various topics in Astrophysics and Cosmology. The Olympian Symposium 2018 was officially organized under the auspices of the Hellenic National Commission for UNESCO and the Section of Astronomy, Astrophysics and Mechanics of the Aristotle University of Thessaloniki. It was financially sponsored by the ISM-SPP Priority Program 1573 of the German Foundation of Research (Deutsche Forschungsgemeinschaft), the Chalmers Initiative on Cosmic Origins (CICO) international research team, and the Municipality of Katerini.

The conference was attended by 160 participants from more than 60 institutions and 30 different countries. A total of about sixty-eight presentations focused on topics of the dynamical and chemical evolution of the local and distant interstellar medium (ISM), the (extra-)galactic star-formation process and the role of feedback, turbulence and magnetic fields, and how computational ISM chemistry bridges real and modelled observations (synthetic imaging). About 100 posters were also shown. Their authors had the opportunity to deliver a short presentation concerning the presented results. Moreover, a poster presentation competition took place with the first three winners receiving a certificate and "Pythagora's cup" as a gift.

Sixteen distinguished scientists of the field were invited by the organizers: Crystal Brogan (NRAO), Timea Csengeri (MPIfR), James Dale (Hertfordshire), Neal Evans (UT Austin, KASI), Rachel Friesen (NRAO), Alvaro Hacar (Leiden), Nick Indriolo (STScI), Desika Narayanan (Florida), Christine Koepferl (LMU), Stella Offner (UT Austin), Eve Ostriker (Princeton),

Padelis Papadopoulos (AUTh), Daniel Seifried (Cologne), Serena Viti (UCL), Derek Ward-Thompson (UCLan), and Naoki Watanabe (Hokkaido). The invited speakers presented review talks and results of significant importance for the field of ISM.

As outreach activities are a key element of OCfA's activities, Padelis Papadopoulos (AUTh) gave a public outreach talk in the city of Katerini on Sunday 27 May 2018, before the start of the conference, that was attended by approximately 200 locals. Furthermore, a free excursion to Vergina and Pella was offered to all participants enabling them to get acquainted with the treasures and culture of Ancient Macedonia. An additional hiking activity on Mt. Olympus with the enormous help of the Rescue Team of Pieria took place on Saturday 2 June, after the end of the conference. Finally, a small lithograph (oldprint) was offered as a remembrance gift to the participants of this successful conference.

The website of the conference is:

www.olympiansymposium.org

Conference photo:

http://www.olympiansymposium.org/data/ConferencePhoto.jpg

2

"Touching the Planets, Evaluating Excellence" Report on Europlanet Outreach Workshop

July 2-3, 2018, Athens

Measuring the impact of outreach activities can help you improve the effectiveness of your activities and help convince your supervisors or funders that your time and resources have been well spent. However, collecting this information can be a challenge.

Overcoming this challenge was the aim of the workshop "Touching the Planets, Evaluating Excellence", attended by 18 amateur astronomers, teachers, early career researchers and outreach providers gathered in Athens to share their experiences of running outreach activities and improve their evaluation skills.

The Workshop was organized by the National and Kapodistrian University of Athens and the Europlanet 2020 RI project.

Europlanet has been developing a set of easy-to-use evaluation tools to support outreach providers and educators in measuring and appraising the impact of their activities. The Europlanet Evaluation toolkit is intended to provide advice and resources that can be simply and easily integrated into normal outreach and education activities. The kit includes 14 tools, as well as a number of variations, that are suitable for a variety of audiences and activity formats. The Athens workshop included an introduction to the toolkit by one of its creators, Dr Jen DeWitt from UCL (University College London), plus an opportunity for participants to try out four of the tools during interactive sessions. Feedback from the participants was incorporated into the final version of the toolkit.

The workshop was part of a series of conference sessions and stand-alone workshops provided through the Europlanet 2020 RI project for outreach providers and science communicators working both professionally and voluntarily to engage the public with planetary science. The workshops aim to build networks, share resources and best practice, brainstorm to develop new ideas for effective communication, and to keep in touch with the latest scientific achievements through contact with the broader scientific community.

"Touching the Planets, Evaluating Excellence" was held in the historic "Kostis Palamas" Building of the National and Kapodistrian University of Athens. At the end of the first day, the workshop participants were treated to an evening at the National Observatory of Athens's Thissio visitor centre on the Hill of the Nymphs.

Local Organising Committee: Nantia Moutsouroufi, MSc, Dr. Eleni Chatzichristou, and Prof. Ioannis A. Daglis. Image credit: Stratos Koufos. Tour of the National Observatory of Athens: Panagiotis Evangelopoulos.

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3rd Summer School of H.E.L.A.S. : "Neutron Stars and Gravitational Waves"

October 8-12, 2018, Thessaloniki,

The 3rd Summer School of H.E.L.A.S. was organized at the Aristotle University of Thessaloniki in 8-12 October 2018. The school was supported by the Aristotle University of Thessaloniki, by the Department of Physics and by the Section of Astrophysics, Astronomy and Mechanics. The school was also supported by a DAAD grant for the academic collaboration between the relativity groups of the Aristotle University of Thessaloniki and the University of Tuebingen.

The theme of the school was "Neutron Stars and Gravitational Waves". The school attracted a large attendance, with a total of 74 participants (postdoc's, PhD/MSc students and advanced BSc students), of which 20 came from outside Greece. Greek students were from the universities of Thessaloniki, Athens, Ioannina and the Aegean.

The program consisted of several 90΄ minutes lectures on each morning, with additional lectures (many discussing exercises via python notebooks) in the afternoons.

The lectures focused on:

1) Theory of gravitational waves
2) Compact object oscillations and GW asteroseismology
3) Constraints on the neutron star equation of state
4) Compact objects in alternative theories of gravity
5) GW detectors: LIGO/VIRGO and planned 3rd generation detectors
6) LISA mission and science

The lecturers of the school were: Pau Amaro-Seoane (Barcelona), Theocharis Apostolatos (Athens), Andreas Bauswein (HITS-Heidelberg / Darmstadt), Katerina Chatziioannou (CITA Toronto), Michael Gabler (MPA-Garching), Theodoros Gaitanos (Thessaloniki), Kostas Kokkotas (Tuebingen), Georgios Lalazisis (Thessaloniki), Charalampos Moustakidis (Thessaloniki) and Nikolaos Stergioulas (Thessaloniki).

All lectures were recorded and the videos along with the teaching material can be found at:

https://www.astro.auth.gr/summer2018/

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