SPECIAL SESSION
DEDICATED TO PHILIPPE DELACHE

THE SCIENTIFIC ACHIEVEMENTS OF P. DELACHE

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Abstract. An overview of the multiple facets of Philippe Delache's scientific achievements is presented, from his early involvement in experimental work and space research, through his re-orientation towards radiative transfer, astrophysics, and then the study of the global Sun and its internal structure, and the study of the interior of Jupiter. The constant concern of P. Delache for a proper and correct mathematical analysis of the problems and for modelling, are outlined in this brief overview. The generous character, the profound and complex personality, as well as the human qualities of this very talented scientist, among which modesty is very prominent, are presented in this description of a remarkable career which ended much too early.

1. Introduction

Describing Philippe Delache's scientific achievements in a few pages is a real challenge. It is both simple and very difficult. It is simple because he is the author or co-author of an abundant scientific literature and has written several excellent reports which describe how he himself perceived his own work. On the other hand, it is difficult because of the diversity of the topics he addressed in his too short scientific life, always merging a rigorous mathematical analysis with a precise and clear physical judgement. As a mark for a long-lasting friendship over the years and of my deep appreciation for his work and that of his students, I have accepted to take up this challenge.

Delache was born on 8 October 1937 at Semur-en-Auxois in Burgundy, some two- and-a-half months before me. After his secondary studies at the Lycée Carnot in Dijon, he joined the Ecole Normale Supérieure in Paris where he stayed from 1956 until 1960. A very important aspect of his stay

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at the Ecole Normale Supérieure was his strong inclination towards mathematics, a discipline which he enjoyed more than any other at that time. This explains his constant inclination for the analytical approach, for modelling, and his rigour in the understanding of physical phenomena.

At the same time, like many of that generation, including P. Léna and myself, he was influenced by the enormous possibilities offered by space research, following the successful launch of Sputnik-1, the first artificial satellite of the Earth, by the Soviets in October 1957. This is how he became involved in experimental work and rejoined the newly created Service d'Aéronomie of J.E. Blamont, still hosted at that time at the Ecole Normale Supérieure.

I have known Delache since 1961 when I joined the Service d'Aéronomie myself. He was then preparing his thesis based on an experimental type of work. During the four years that we cohabited at the Service d'Aéronomie and until he rejoined the Observatory of Nice, then directed by J-C. Pecker, we had frequent and friendly contacts. After his departure to Nice, these contacts became less frequent, due to the distance, but remained excellent and always profound and very productive. We worked again closely in 1980-1983, when he joined the study team of the DISCO mission, the ancestor of SOHO. We also interacted frequently during the time he was a member of the Comité de Direction of my own laboratory, LPSP, at Verrières-le-Buisson.

I can identify four main phases in the scientific career of Delache: the experimenter phase, the return to theory and the thesis work, the radiative transfer phase, and the study of the global Sun. This enumeration defines a broad frame which I will now detail, trying to project an illumination on the extremely rich life and on the achievements of this bright brain. I will not address however, any of the long periods in Delache's career devoted to administration and teaching, as well as to the directorship of the Observatory at Nice (he was Director in 1969-1972, in 1975, and in 1989-1994), neither his frequent involvement in committees as an advisor or as an expert in the many areas where he was able to contribute wise and needed advice, in particular in solar physics and space research. These duties certainly absorbed a substantial portion of his time, which makes a posteriori his very productive scientific career even more impressive.

2. The Experimenter Phase

Any student at the Ecole Normale Supérieure willing to become a Professor had to prepare a Diplôme d'Etudes Supérieures, a sort of small thesis representing about one year of scientific work. Delache prepared it under the directorship of Blamont in the group of A. Kastler and P. Brossel, where an important effort was devoted to the study of the optical resonance of hydrogen and of alkaline vapours, in view of studying the Earth's atmosphere and various astrophysical objects.

The topic of his work was the study of an infrared transition of oxygen involving a level excited by the absorption of Lyman beta photons from hydrogen at 102.5nm, a phenomenon which had been invoked to explain an anomaly in the intensity of this line in various planetary nebulae. His work, of an experimental nature, consisted in simulating the process experimentally, using laboratory hydrogen and oxygen cells. The experimental set-up was not simple but Delache could confirm the reality of the process. After his Diplôme (Delache,1960), he was offered the possibility to continue his experimental work, studying the solar Lyman alpha radiation of hydrogen at 121.6 nm and its absorption by the Earth's upper atmosphere by means of rockets or artificial satellites.

His main thesis work consisted in developing the hydrogen cells, a delicate experimental work based on the development of sophisticated technologies, first to create atomic hydrogen from the dissociation of the molecule, then to seal the cells so that the optical thickness could be precisely controlled (Blamont, Delache and Stober,1964). The tightness of the metal-to-glass sealing was particularly challenging and Delache spent long days working in semi-darkness in the noisy ambiance created by an army of oil vapour pumps.

We often met in the laboratory where I was also preparing an experimental thesis on the ultraviolet imagery and spectroscopy of the Sun using rocket- borne spectrographs and telescopes of my own making. These encounters offered opportunities for scientific discussions and for semi-sour comments on the difficulties of space research where results are only achieved once in space, after many months or years of hard laboratory work with, unfortunately, little to publish, and the slogan "publish or perish", even though he and I could invoke being involved in pioneering work, applied already. That scarcity of scientific production, although not of his responsibility, concerned Delache deeply. It is also fair to say that he was more inclined toward the theoretical implications of his work than by its experimental character, as pioneering as it might be, and for which substantial fractions of his days, and of his nights, were absorbed.

In the course of our discussions I advised him to talk to Pecker, then my thesis advisor for the astrophysical implications of my work. Delache was particularly appreciative of the type of balance through which, between Blamont and Pecker, I could control the progress of my research, in spite of some spectacular failures of the Véronique rocket which carried my instruments. Torn apart as he was between staying at the Service d'Aéronomie and joining Pecker at Nice, he decided on the latter, however not without sorrow and regrets. His relations with his former director certainly cooled down substantially after that departure, but they always remained courteous. Delache, as the manifestation perhaps of a hidden regret, never did break the umbilical chord which tied him to his former research career, and he always felt inclined to return, while distancing himself nevertheless from too deep an involvement.

A posteriori, there was a lot for him to be proud of, which his experimental work led to in the study of the Sun and of the geocorona. Using hydrogen absorption cells and sounding rockets, his student, J. Quessette, measured the vertical distribution of hydrogen in the Earth's upper atmosphere. Using similar devices, Blamont's student, A. Vidal-Madjar, obtained the best, at the time, solar Lyman alpha profile from the American OSO-5 satellite. Similarly, the distribution of atmospheric hydrogen and its temperature were measured extensively on board the French D2-A satellite as well as on NASA's OSO-5. Finally, the distribution of hydrogen around comets was determined for the first time by J-L. Bertaux, another student of Blamont, using the same technique. In fact, hydrogen cells are still used today by Bertaux on SOHO to measure the penetration of interstellar hydrogen in the heliosphere (SWAN experiment). All these experiments are essentially the legacy of Delache's early experimental work at the Service d'Aéronomie.

3. The Return to Theory and the Thesis Work

At Meudon, under Pecker's guidance, Delache started purely theoretical work, far away from his early experimental involvement. His work was to study and interpret the apparent over-abundances of heavy ions such as nickel and iron, as compared with their photospheric values. The problem is non-stationary and must be treated as such. Delache applied irreversible thermodynamic processes, taking into account thermal diffusion between the cold photosphere and the hot corona, as well as gravitational sorting in the expanding solar wind. He resolved simultaneously the equations of diffusion and of ionisation for all states of ionisation and for different velocities of coronal expansion (Figure 1 and 2).

He presented his thesis in 1967 (Delache, 1967), some two years after he started this work totally new for him, a time record! Later, it was shown that the introduction of new and more precise oscillator strengths considerably reduces the amplitude of the abundance anomalies. However, Delache's basic treatment of the problem, in particular the effect of gravitational sorting, is correct. Today, his work has a direct application in the understanding of the abundance variations measured between the photosphere and the corona for elements with low first ionisation potential (10eV), as measured in particular by Ulysses and SOHO (Geiss *et al.*, 1995).

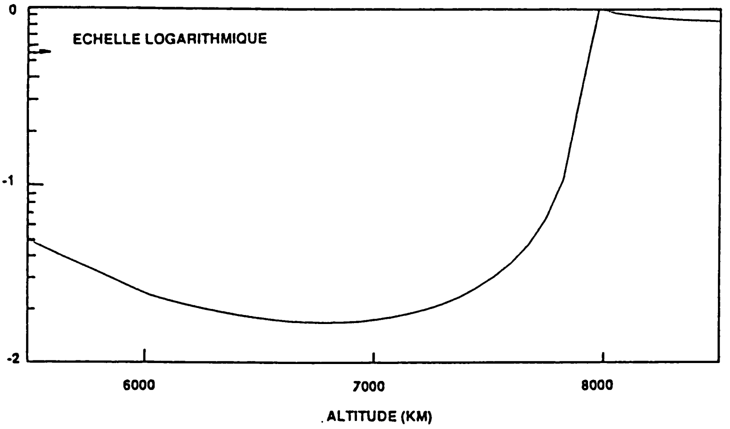

Figure 1. Variation of the total abundance of nickel for a given model of the corona and an initial wind velocity of 5 km/s (from Delache, 1967).

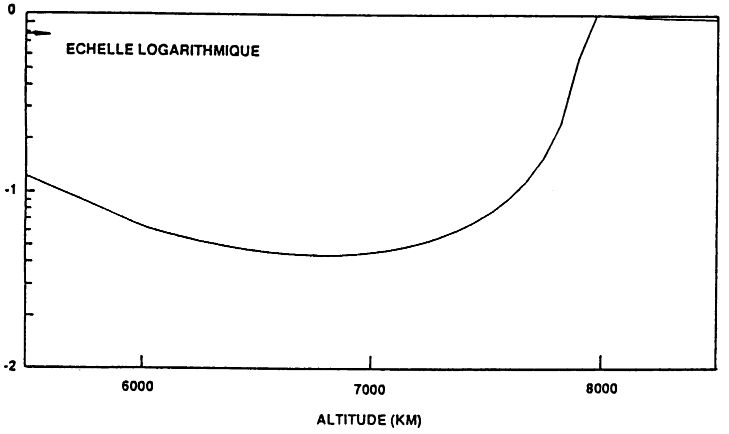

Figure 2. Same as Fig. 1 but with an initial wind velocity of 10 km/s (from Delache, 1967).

Although we were no longer in the same laboratory, we continued to interact closely, and it is worth mentioning at this stage his contribution to the inversion of the Laplace Transform, an essential problem for me in attempting to derive a source function from my solar limb-darkening data. Unfortunately, he never published a paper on that issue. He could have done so, in particular on the occasion of the Bilderberg conference which he and I attended in April 1967, which aimed at establishing a new model of the solar atmosphere (de Jager and Gingerich, 1968), and where his participation and contribution to this conference was very active.

Like me, he was puzzled by the presence of a prominent discontinuity in the solar continuum at 208.0 nm. Although its wavelength coincides with the photo ionisation limit of neutral aluminium, it is too strong to be due to this element alone. The 2S1/2 - 1S1/2 transition of hydrogen can involve a two-photon process which peaks in the ultraviolet at about 208.0 nm. He has shown that the converse process, i.e. the excitation of the upper level through absorption of ultraviolet photons, contributes to the continuous absorption coefficient in equal proportion to the absorption of other elements, including AlI, and at about the right wavelength.

4. The Radiative Transfer Era

Once at Nice, which he rejoined in 1967, Delache became more and more involved in radiative transfer problems in stellar atmospheres, interstellar matter, and kept a keen interest for solar physics, in particular the problem of coronal heating. Amazingly, he also became interested in the understanding in the excitation mechanisms of OH masers, invoking possible plasma instabilities (Delache, 1969). Together with his co-worker G. Reinisch, he has shown that this process is unlikely to contribute to maser emission. However his idea of the coupling between a coherent wave and a plasma can explain the existence of secondary peaks in the radio spectrum of these sources.

Certainly, his most important contribution during this period was the resolution of time dependent radiative transfer problems which formed the main part of the thesis work of her student Ch. Froeschlé (Delache, 1968, and Delache *et al.* 1972). He applied his methodology to radiative cooling of dense interstellar clouds in their pre-stellar phase and also to the equilibrium and evolution of chromospheric structures, for which a quasi static hypothesis clearly does not apply (Delache 1973).

The fundamental aspect of his work, which Delache was particularly proud of, was the demonstration that an approximate analytical method, as opposed to lengthy and heavy numerical simulations using the big - and then expensive - computers, could represent fairly accurately the source functions of lines emitted in non LTE conditions: through a rigorous and simple physical reasoning, he follows the time evolution of a photon and evaluates its probability of escape from an optically thick and scattering medium at various frequencies in the line profile. Figure 3 reproduces his results which have been published in the Astrophysical Journal (Delache 1974).

His ideas have been exploited and refined by several scientists, in particular R.G Athay and A. Skumanich in Boulder, and by his colleagues at Nice , Uriel and Hélène Frisch. They are often quoted and considered as a reference in the domain. Generalising the escape probability method, he

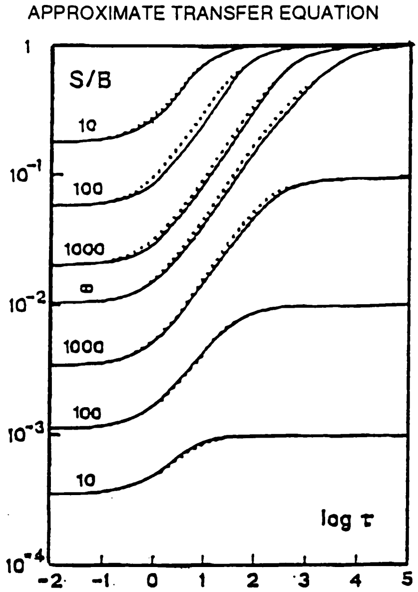

Figure 3. ***full lines***, ordinary iteration, ***dotted lines***, solution of the approximate transfer equation. Curves are labeled with the number of iterations, corresponding also to the nondimensional time T. Below the limiting solution ($T = \infty$), they correspond to the initial condition $S = 0$; above, to S = B. (From Delache, 1974).

applied them to the interpretation of quasar spectra and, together with S. Collin-Souffrin, S. Dumont and H. Frisch (Collin-Souffrin *et al.*, 1981) he then proposed observing programmes for the Hubble Space Telescope, in a sense: a return to space research!

Space research in fact was always present just beneath the surface of his interests. I could test it directly on the occasion of the preparation of the IAU symposium which the two of us organised at Nice in the summer of 1976 which was devoted to the Energy Balance and Hydrodynamics of the Solar Chromosphere and Transition Region and was essentially based on the availability of new space data from 0SO-8 and Saliut-6 (Bonnet and Delache 1977).

His involvement in radiative transfer problems gradually faded out in the late seventies. He was still interested, however, in solar physics and in such fundamental issues as coronal heating where he recognised the limits imposed by the insufficient quality of the data. The then fashionable assumption that the dissipation of acoustic waves in the upper solar atmosphere might cause the temperature to rise in the chromosphere and the corona, led him to look more closely at solar oscillations. He had always been interested in these oscillations, as far back as 1964 when F. Roddier

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at the Service d'Aéronomie observed them with an atomic strontium jet spectrometer which provided an unequalled spectral resolution. He then looked more carefully at the work of Roddier's group at the University of Nice where G. Grec and E. Fossat used sodium cells - the same which M.-L. Chanin developed earlier at the Service d'Aéronomie - to observe the global oscillations of the Sun. That, to me, marks the start of the most intense and of the richest phase of his scientific activity, unfortunately the last.

5. The Study of the Global Sun

In the winter of 1979-1980, Grec and Fossat came back from Antarctica where they had observed the global oscillations of the Sun for more than four consecutive days without interruption at this period of the year. Due to the long time span, their results were then the cleanest and certainly the most accurate for the detection of the pressure modes. Delache was enthusiastic.

At the same time, together with a group of solar phycisists, among whom was C. Fröhlich, I was involved in an ESA assessment study for a small satellite to measure the solar constant and its variation with the solar cycle, as well as the spectral irradiance of the Sun in the visible and the ultraviolet. The "Dual Irradiance and Solar Constant Observatory", DISCO, was to be placed in orbit around Lagrangian point L1 located between the Sun and the Earth. Already, C. Fröhlich using radiometric data obtained with ACRIM on the Solar Maximum Mission, had provided evidence of p-modes, and DISCO, with its L1 orbit, would clearly lead to an improvement. Delache proposed that we should also consider the possibility of observing the solar velocity oscillations, using sodium cells. His main interest was to observe the gravity modes which probe the solar interior down to the very core, in view of addressing such fundamental questions as the solar neutrinos deficit. He was invited to join the DISCO study team.

For more than two years we worked very closely on the definition of DISCO, the ancestor of SOHO. One of the most promising experiments was indeed the sodium cell, similar in its working principle to that of Grec and Fossat, but which had to be miniaturised from a size of a fraction of a cubic metre to a few tens of cubic centimetres. That required a complete re-definition of the instrumentation together with its space qualification. That was the first opportunity for Delache to become again intensively involved, at least for the duration of the DISCO study, in an experimental type of work.

DISCO was not selected by ESA, having lost in March 1983 a fierce competition with ISO, the Infrared Space Observatory. Our study work was therefore put on hold, but SOHO was born (Huber *et al.* 1996) and, naturally, Delache became involved in the SOHO study. His interests switched back more to theory and in particular to the possibility of detecting the global and gravity modes, an effort which required a thorough mathematical and physical treatment of the noise problem, which Delache was very motivated to address.

Most intriguing in the 1980's was the presence in the power spectrum of solar oscillations of a 160 mn mode, detected both at Stanford University and at Crimea Observatory. Delache was keen to understand the nature of this prominent feature which might be either a gravity mode or simply an atmospheric artefact. He invested considerable time and energy in its interpretation (Delache, 1981), and started a close collaboration with P. Scherrer at Stanford. As P. Scherrer describes in his contribution to this special session (Scherrer, this issue), Delache became a real "gravity mode hunter". Both co-signed a paper in Nature on the detection of gravity modes (Delache and Scherrer, 1983). The SOHO data have shown how difficult their detection is, and how optimistic it was then to think that they could be detected from the ground. However, that work was very useful in assessing the limits and the difficulties of their detection. A close collaboration also started with C. Fröhlich, whom he knew from his earlier involvement in the DISCO team, on the detection of solar luminosity pressure and gravity modes (Fröhlich and Delache, 1984).

During our DISCO study, the possibility that long-term luminosity variations might result in similar variations in the solar diameter was often raised. Assuming that thermal energy is converted into potential energy and vice versa, if the solar constant varies with solar activity, as proven by SMM and other space data, the diameter should also vary. Quietly, and with his usual curiosity, Delache looked in more depth into the astrometric measurements of the solar diameter made with the astrolabe at CERGA, near Nice, by F. Laclare. The two of them showed the existence of an apparent anticorrelation between the length of the solar diameter and the level of solar activity (Delache, Laclare and Sadsaoud 1985). Not content with this observation alone, he discussed in more depth and for the first time the validity of the astrolabe measurements, taking into account the effect of active regions at the limb.

In the last period of his activity, he never abandoned his permanent inclination for analytical and mathematical problems. With A. Vigouroux he started a thorough and critical analysis of the Fourier transform as applied to long term solar variations. They showed that the wavelet transform, which makes no implicit assumptions as to the standing character of the waves, offered a better representation of the long-term variations of the solar diameter and of its irradiance (Vigouroux and Delache, 1993). Having in mind to reach the physical phenomena at play in the solar core, he

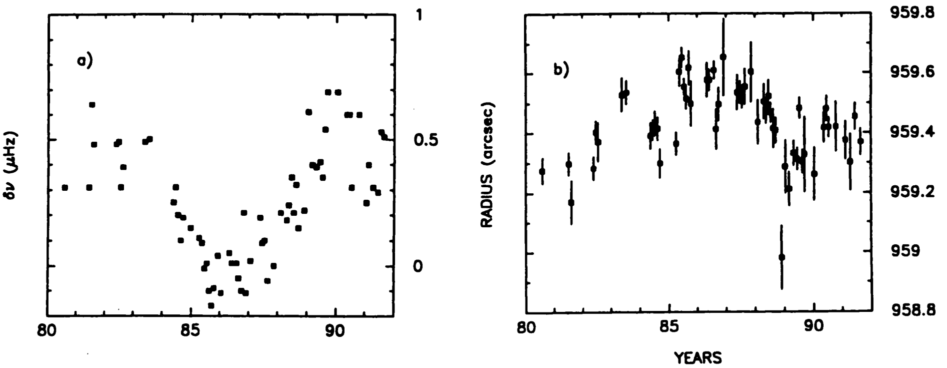

Figure 4. (a) Frequency shifts of low-degree solar p-modes vs . time. The reference is taken as the value at solar activity minimum (see text). (b) Radius measurements averaged over identical time intervals vs . time. (From Delache *et al.*, 1993).

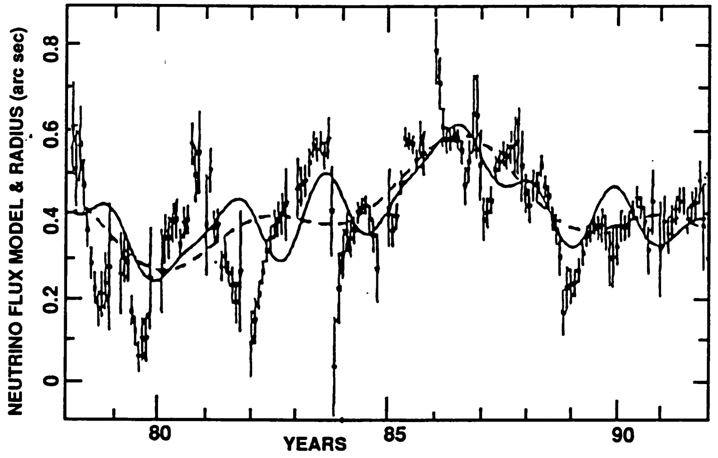

Figure 5. Combinations "a" (dashed line) and "d" (solid line) of significant harmonics in neutrino spectrum compared with radius ($R_\odot - 959,0$ arcsec) (points with error bars). (From Gavryusev *et al.*, 1994).

analysed possible correlations between the flux of neutrinos, as measured by Davis in the US, and the solar diameter. Together with an international group of collaborators, he discussed possible time correlations between the long term variations of the frequencies of p-modes, the solar radius and the neutrino flux (Delache *et al.* 1993), paying due and careful attention to the problem of extracting a meaningful signal from a high level of noise (Delache *et al.* 1992), Figure 4 and 5.

Having tested the usefulness and power of this new mathematical instrument, he then exploited fully the wavelet analysis, applying it with A. Vigouroux to all possible manifestations of solar long term variability, having permanently in mind to properly understand the solar machinery and more particularly the solar dynamo, and possibly to predict the intensity of solar activity, based on a correct understanding of the past. That was the subject of the last publication he wrote (Vigouroux and Delache, 1994). This work also led to a series of posthumous articles with A. Vigouroux and J.M. Pap (Pap, Vigouroux and Delache, 1995; Vigouroux, Pap and Delache, 1996).

This description of Delache's achievements would be incomplete if I were not to mention his work on Jupiter. This apparently curious derivation from his previous work is a natural consequence of what he did for the study of the solar interior. Knowing the discontinuities which exist in the internal structure of the giant planet, he proposed to B. Mosser to compute the spectrum of its possible oscillations (Mosser, Delache and Gautier, 1988-a and 1988-b). This led him, together with Schmider and Fossat, to propose an observation of the planet at the Observatoire de Haute Provence and then to use the infrared Fourier spectrometer of the large Canadian French and Hawaïan telescope, a work which has been conducted by J. Gay, J.P Maillard and D. Mekarnia (Mosser *et al.*, 1991; and 1993); Figure 6.

He deeply regretted that his too intense involvement in administrative tasks prevented him from being more directly involved in this research. He gave up the Directorship of the Observatoire de la Côte d'Azur in Spring 1994, just a few months before he disappeared and, unfortunately, he could never fully enjoy the exploitation of his remarkable ideas. He was without any doubt the discreet conductor of an activity which had its centre of gravity at Nice and which, for more than 10 years, using new theoretical and observatory methods, led to remarkable and determining progress in our understanding of the solar, stellar, and planetary interiors. Naturally, he became a co-investigator on all the seismology experiments of SOHO: GOLF, VIRGO, and MDI. Knowing the extraordinary quality of the data that these instruments provide, I cannot but deeply regret that he is not here to see them and to work on them. His diagnostic capability would certainly have created an explosion of new ideas. In fact it is the whole set of SOHO data which would have enthused him, from seismology to coronal observations, with the newest and the most accurate abundance determinations of the solar wind. SOHO's success would have offered him the crowning of his constant involvement and interest in solar physics.

Our last scientific discussion dates back to July 1994, just a few days after Comet Shoemaker-Levy hit Jupiter, and he did not yet know whether the impact had any signature in the power spectrum of the oscillations of the planet. This was in Austria where he gave the introductory lecture at the Alpbach Summer School which that year was devoted to the Sun. This is the last time I saw him and talked to him. His lecture was the

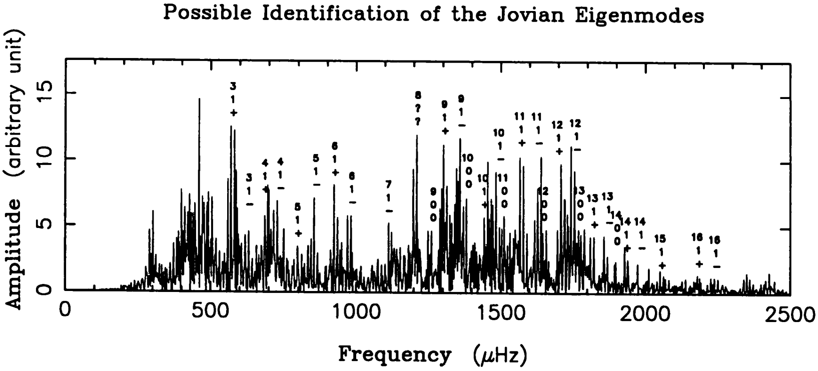

Figure 6. Identification of the $\ell = 0$ and $\ell = 1$ p modes in the observed Fourier spectrum. The values of the radial order n, the degree ℓ and the azimuthal order m ($\pm$ signifies $m = \pm 1$) are given for each identified eigenmode (from Mosser *et al.*, 1991).

most remarkable description of our present knowledge of the Sun and of its interior, a beautiful and exhaustive review of solar physics. It is a pity that the proceedings of the Summer School are no longer published, because we would certainly possess today one of the most complete and one of the clearest descriptions of the solar machinery, one which would prove once again how great an astrophysicist Philippe was.

6. Conclusion

These few pages written by someone who has followed Philippe Delache in his scientific career, sometimes closely, too often from a distance, cannot pay tribute to the achievements of such an outstanding and rich personality, who contributed so much to our understanding of the Sun and to astrophysics. To characterise and summarise such a scientific life, the best might be to use Philippe's own words, proving how modest but also how complex his personality was:

> "I am not the man of a long lasting kind of work, methodic, based on developing in depth a unique theme of research or a complex formalism. I rather like to put my fingers on those physical phenomena which come in support of, and help explaining such and such observations yet unexplained, even letting others taking care of deepening, or of extending the field on which my own ideas apply."

I think that if there is one parameter which can without any doubt be invoked to describe Philippe's attitude and ethics, it is t, time. The time he introduced in radiative transfer. The time it takes an atom to become ionised in the solar wind. The time of the oscillations of the Sun, of stars, of Jupiter. The time of correlations between p-modes frequency shifts, the neutrino flux, the solar diameter and the activity cycle. The time which is too long to conduct an experiment to completion. The time which passes too fast and forced his thirst of knowledge and his insatiable curiosity. The following paragraph is a beautiful text that he wrote about time.

I have not addressed at all here the other and numerous activities he developed in non purely scientific tasks, which absorbed a lot of his time, as Director of the Observatory at Nice, or as a professor at the University, or when he was sitting on committees, as advisor to CNRS, CNES, ESA and others. He was also an excellent communicator and he wrote several articles and gave several exemplary lectures for the general public (Delache and Amiot, 1977; Delache, 1980; Delache, 1993). He possessed a wonderful gift for explaining in simple terms the most arduous physical problems, and I can only regret that he did not spend enough time on that particular activity. He played a key role as chief editor of "Le Journal des Astronomes Français" in 1977-1980 in placing that review at the high level it has reached today.

He has been and has done all that and much more. He was the man who helped so many young, and less young, scientists, - J.P. Lafon kindly reminded me that Delache put considerable effort in 1990-1991 into the setting-up of the CNRS Research Group on circumstellar envelopes. Always with enthusiasm, always providing an invaluable moral support, never imposing his leadership by force, always letting the initiative of the young take over after his initial impulsion had been given.

He felt the permanent need to interact with others, another reason why he touched on so many issues. He felt the need to be in osmosis with his colleagues, and in nearly all fields of astrophysics, without however pretending he knew everything, having the frankness to confess his ignorance in those fields where he considered himself a novice. He felt the need to be appreciated and loved, the need to maintain his friendship, even in the case of adverse circumstances. He was a man of no rupture, and at the same time in permanent transition. He was an artist and a humorist, a magician in many senses. He was such a generous character and such a profound and sensitive personality. Above all he was a friend. The numerous seeds and trees he left will grow and blossom and give fruit for a very long time.

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