# HYPERSONIC FLOW MODELS IN ASTROPHYSICS AND APPLIED PHYSICS

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## ABSTRACT

The evolution of the models during the last 100 years emphasized that their structure depends significantly on the nature on the media through which they propagate, but still more on their velocity which is a sensitive parameter for the elementary processes at work inside them. Starting from a simple “discontinuity” in a flow, models have become more and more complex insofar as numerical computations allowed to describe phenomena with increasing accuracy at decreasing and mainly various time and space scales (3). The shockwaves appear successively hydrodynamical, supersonic, hyperenthalpic and hypersonic depending on the energy sources and fluxes crossing them as their propagation velocity increases, so that one can no longer deal with physical quantities balances through dimensionless surfaces. Hereafter we shall ignore magnetic fields and collisionless media which generate a different problem., but we show that similar questions are relevant in astrophysics and reentry shocks of vehicles allowing cross fertilization of researches.

## INTRODUCTION

A shock wave is some kind of quick changing rate in a gas (or liquid) flow. Now the nature of the physical quantity quickly changing allows some classification between shock waves with more or less cutting edges. For instance a laminar flow becomes shocked when the fluid velocity “crosses” the local sound velocity, but though this is usually spectacular, one could imagine a smooth transition: the thickness of the discontinuity, usually represented by a two dimensional surface is in fact directly related to the mean free path of the fluid atoms.

Now a shock wave propagating through a multi-species particle becomes an hyperenthalpic shock when the heat flow can no longer be ignored and become a non negligible term in the energy equation. However, as for purely hydrodynamic shocks the problem remains local, and local balance equations can still describe the fluid. Of course, this is still a problem of orders of magnitude.

Now for still stronger shocks the collisions produce a separation between the electrons and the other heavy particles which behave at least as a two fluid medium sensitive to different phenomena, in particular concerning collisions (but non exclusively). Recombinations occur after a region where the two fluids, heavy particles (neutral, excited an ionized atoms) on one the hand, electrons on the other hand follow their own laws and then produce a radiative flux coming from all directions which completely change the nature of the problem. Due to the velocity of the energetic photons produced, which exceeds any other velocity throughout the structure, photons cross the “front” of the shock (we call front the thinnest zone, that in a first approximation may be considered like a surface) and are absorbed, depending to their wavelength, either in a “radiative precursor” or “at infinity”, which means that light is emitted in front of the wave. By contrast the medium past the recombination point is quickly optically thick. This is quite different from the thermal precursor which may be produced by the pre-heating of the medium before the front shock because it involves the whole medium around the shock and *a priori* requires a 3D treatment over large distances for the radiative transfer. Consequently, at any point in space, the balance equations for each species depends on what occurred at any other point in space a short (various) time before because of the large light velocity.

In the sequel, we shall describe the collisionnal media as multi-species media: each atom in its ground levef, as well as in any excited or ionized level, is the unit particle of a defined species. There is also a gas of electrons and “gases of photons”. Equations of balance will be written for each species (this means that reactions are “instantaneous”). We ignore the other cases.

We shall investigate three cases in which the difficulties are not the same, from which useful solving techniques can be interchanged. Table 1 displays the main different characteristics of the media concerned by sections I and II in order to show that, in spite of the differences in the specific values of the parameters, the undimensioned equations are similar, so that cross fertilization is possible. . Finally scaling laws can be found for other systems or devices, as in experimental nozzles with various geometrical designs.

| Circumstellar Media | Atmospheric Motion |
|---|---|
| $H_2$ , H | $N_2$ , $O_2$ |
| $1000\ K \leq T \leq 3000\ K$ | $T \approx 250\ K\ (61\ km)$ |
| $60\ Km/s \leq T \leq 70\ Km/s$ | $V \cong 10\ Km/s$ |

**Different Physical Conditions but similar Physical Phenomena**

→ hyperenthalpic flows and non local problem
→ non– equilibrium thermochemistry
→ aerodynamics and radiative transfer coupled

Table 1

## I CIRCUMSTELLAR SHOCK WAVES AROUND EVOLVED STARS: BASIC CONDITIONS AND ASSUMPTIONS

Let us consider late type stars with intermediate mass (say one to three solar masses), when they leave their long stage on the main sequence and evolve in a much lower time delay in unstable stages in which their luminosity varies periodically, with periods of the order of a few years). During one period, spectroscopic features evolve in such a way that this evolution can be understood in spherical symmetry in terms of the propagation of one (or two) thin layers (compared to the star radius) of strongly heated emitting gases travelling from the photosphere up to a tenth of stellar radii, then weakening and dissipating.
Of course spherical symmetry is a crude approximation in so unstable circumstellar media as shown by interferometric imaging. However the spectroscopic features do not seem to be highly sensitive to the real shape of the layer, as results from the computations based on this approximation compared to observations. This will be partially explained in section III. In any case, the thickness of the layer (of the order of a few 10000 km) in terms of its radius (at this stage of the order of several hundred millions kms) is very small, so that one dimensional models in plane symmetry can be used as a good first step to model a piece of the sphere: this is very important since it allows to ignore geometrical effects at least for hydrodynamics (see later). Usually, due to the strong instability of the star, it is considered that the thin hot shell can be produced after the front of a shock wave, and this the reason why we finally try to model the propagation of a one dimentional shock wave under the conditions of the circumstellar atmospheres.
In fact if we wanted really to build models of radiative shocks, we should introduce somewhere a source of energy. Shock waves are emitting energy in an irreversible way so that, in the case of a self-consistent steady state system the energy supply of the hot zone behind the front must be fueled by a permanent source: this is the theoretical unrealistic consequence of the assumption of steady state). Indeed, like in several domains in physics, the problem could find a more realistic solution by replacing the infinity of energy by relaxing the independence from time variations. A real shock wave is generated by some physical mechanism, it grows, it decays an disappears. For instance close to stars, this occurs in something like 10 stellar radii. However, at the present time we ignore too much details at both ends of this sequence (in particular what happens within and above the star photosphere and still more in the region where shocks interact with dust formation (at which height and how) to imagine realistic scenarii of this process. Similarly shocks produced in shock tubes in the laboratory to check the theory are still designed to be compared in that part of their trajectory where they can be considered as planar and in steady state (for sake of simplicity of the measurements of the observable parameters.
Thus sequences of models in steady state propagating in homogeneous environments evolving slowly during the propagation of the wave remain the most acceptable way of investigating the physical processes at work in such structures. Observations are in progress at a faster rate and may be they will bring new constraints or information to improve the steady state models. Thus we now consider only steady state shocks propagating through a given “unpertturbed” medium at equilibrium. Nevertheless such an assumption produces a new difficulty (relaxed in reentry

problems): it throws out all boundary conditions at infinity. As we shall see hereafter this is a huge problem, since all "infinities" are not the same place in practice, depending on the wavelengths.
Fortunately, atoms and molecules of such circumstellar media are at more than 75% those of hydrogen (+ 20% helium + some other components), so that we assume that the medium is made of pure hydrogen ignoring the minor C, N, O, and heavier elements all named "metals" with very small abundances. However, there is a subsequent heavy drawback due to the behavior of the first excited level of the hydrogen atom which is populated and depopulated at a much higher rate than any other level and requires a specific treatment in spite of the strong coupling of its population to other parameters. In Due to the magnitudes of the energies of the excited and ionized atoms of hydrogen, the shock wave is organized in a hierarchical structure looking like "russian dolls" corresponding to the scale lengths of the regions in which the series of radiations (Lyman a, Lyman continuum, Balmer Continuum, …) are optically thin. Thus one can approach the problem by increasing progressively the number of excitation levels taken into account, without to much perturbing the thermo and hydro dynamics of the core structures essentially governed by the population of the lower levels.
In addition, there is a series of distances (strictly speaking a continuum if one would not discretize the spectrum in some way), each one corresponding to some range of wavelengths at which boundary conditions apply and describe the way in which the radiations become optically thick. Mathematically speaking, this means that all the boundary conditions apply at both infinities, before and beyond the shock front. In fact we observe that the substructures of the shock wave, even concerning the hydrodynamics, are governed by absorption and emission properties of the gases, in turn governed by the optical properties of the gases. Each boundary condition meaning that some medium becomes optically thick for some radiation corresponds to the asymptotic stiffness of the equations describing the radiative fluxes, so that we have a continuum set of stiff equations with boundary conditions over a continuum range of distances from the shock front.

*The "mean photon"*

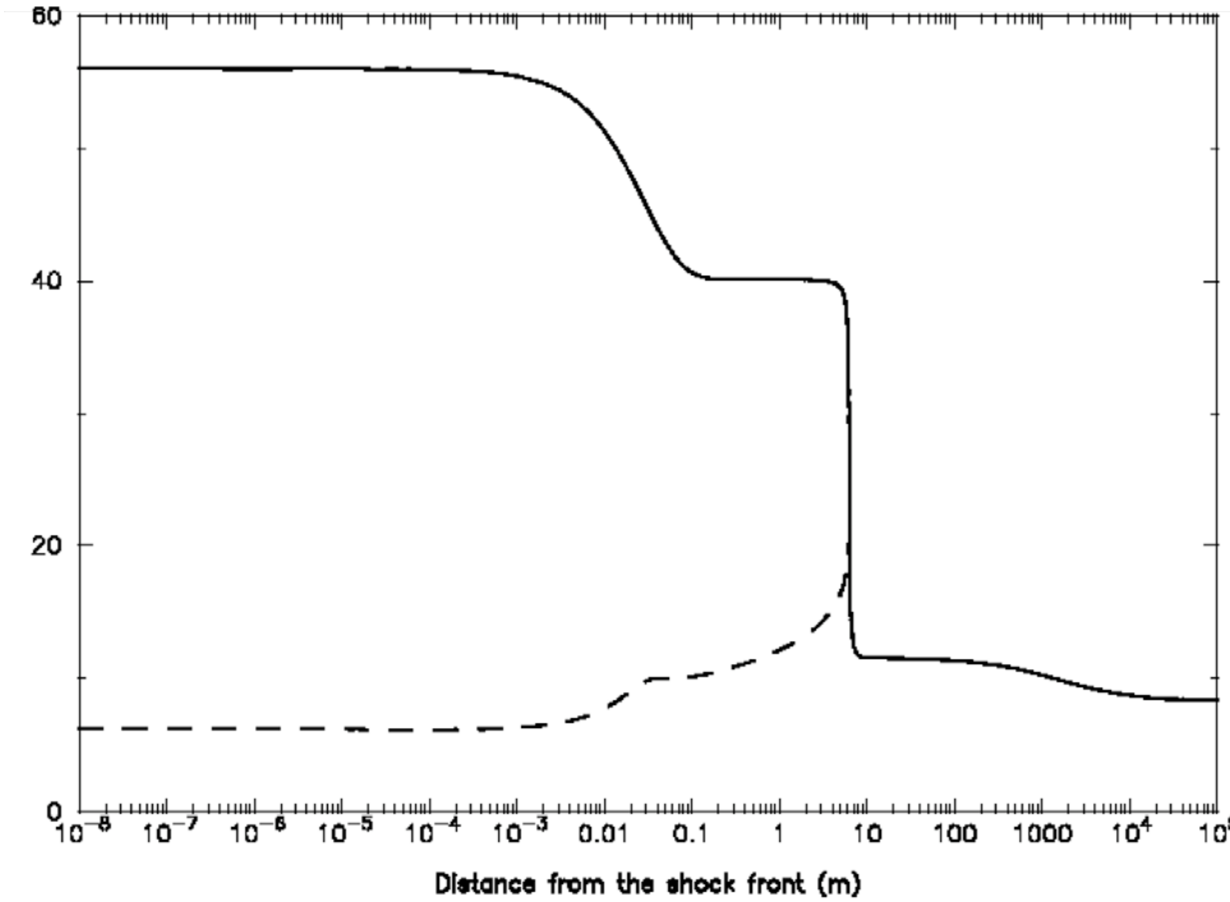
To remove this drawback, we discretize the spectrum and introduce the concept of « *mean photon* » with a given energy. The energy of the mean photon of a radiation corresponding to some transition is determined in such a way that both the total energy and the number of photons are conserved. Since the gases cross rapidly the structures of the shock, the equilibrium is never recovered: then the statistics of the mean photons, just as the populations of the various excitation level are determined by balance equations, which are indeed rate equations, one per population of each energy level. Thus it is assumed that the transitions between two excitation (or ionization) states can be compared to chemical reactions occuring much faster than the characteristic thermodynamic and dynamic time scales, which is certainly the case … except, may be, in the dynamic and thermodynamic short transition layer, which is taken as an infinitely thin discontinuity. Of course it is not strictly necessary to discretize the spectrum so drastically and each spectrum band, instead of beeing reduced to one photon could be discretized into several photons, each one corresponding to some range in the thermodynamic temperature, instead of reducing the the temperature profile to one "effective temperature" located within the range of thermodynamic temperatures. However, first the low sensitivity of the results to variations of the "effective temperatures" suggests that this should not improve the results at a level greater than the uncertainties due to the other approximations, and then the stiff problems would be replaced by boundary value problems with variable boundaries in a large range of distances. Thus, the solution would not be very much easier for a small and uncertain advantage.

*The "photon soup" at the fluid velocity*

As above mentioned, close after the shock front, the rate equation for the Lyman $\alpha$ transition degenerates into a non differential equation (the differential term can be neglected compared to all other terms): de-excitationsoccurs almost locally though the medium remains optically thin: the Lyman$\alpha$ photons become trapped in the gas, there is a "photon soup" travelling at the fluid velocity and no longer at the light velocity,

*At the other infinity: the far wake*

Now, in that part of the wake where all radiations become optically thick, microscopic processes become optically thick, microscopic processes that have never beenstudied under so exotic conditions become significantly efficient. This is the case for the three-body recombinations. A full treatment of this important process is a huge work. In particular, it requires a




Exemple of temperature of heavy particles (continuous curve) and electron temperature (dashed curve) in 1000K versus the distance from the shock front behind it for a shock wave (details of the model in ref {1}. H,H*,H+ and H2 are the considered species.

very fine multi-level description of the atom leading to too much complicated calculations. It was decided to use an approximated model expected to give at least the correct order of magnitude of the three-body recombination rate in the range of temperature and density of the wake was used, and also to perform computations for over and under estimations of the calculated rate. This is sufficient to give a rather good approximation of the effects on the overall shock structure and to emphasize the role played by the three-body recombinations, which cannot be ignored.

In any case, any accurate modelling of the zone beyond the radiative relaxaxion zone, the far wake where the hydrodynamic relaxation occurs, is still forbidden as long as finer descriptions of the concerned microscopic processes cannot be included in the models.

The figure corresponds to a model propagating at at a velocity of 41 km/s. The main features observed are :

1/ A high compression rate far in the wake (close to 24), much larger than that allowed by pure thermodynamics.

2/ The compression occuring in two steps, the first one about 12, the second one 24.

3/ After the shock front, electrons and the other « heavy particles » (molecules, atoms, ions) behave as two independant fluids and the first compression step appears when the two fluids mix into one fluid and the medium becomes optically thick for the Lyman continuum flux, after a peak of electron recombinations with ions. This compression is associated with a strong breaking of the fluid. The gas is still optically thin for the Balmer continuum (which can escape before the shock front, in the « unperturbed medium ».

4/ The second step (less steep though so high) appears when the gas is optically thick for the Balmer continuum.

5/ The radiative loss due to the emission of the Balmer continuum represents up to 75% of the kinetic energy of the gas entering the shock.

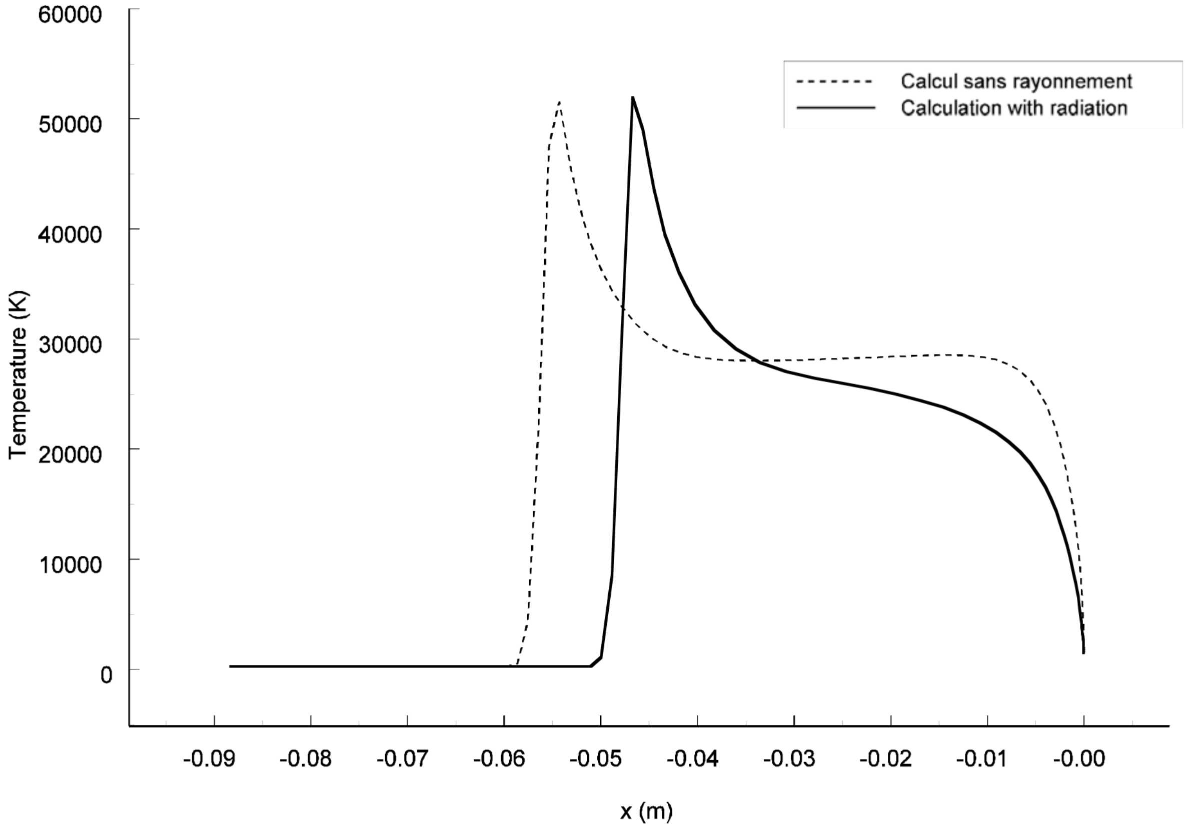
6/ In this model two energy levels have been taken into account for the molecules (H2 molecules or separated atoms). Note that molecules still coexist with atoms (during a short time delay), just behind the discontinuity at 56000 K. Three energy levels where taken into account for the H atom (ground level, 1st level and ionization level). Improved new models should include a higher number of energy levels of the atoms, at least to describe accurately the far wake (hydrodynamic relaxation) and for this describe more accurately three body recombinations. Finally the problem of boundaries remain the dominant problem (where to locate them ?), in particular to obtain more than 1D models and to improve the treatment of the radiative transfer, which in fact is actually a 3D problem.

## I REENTRY OF BODIES IN PLANETARY ATMOSPHERES

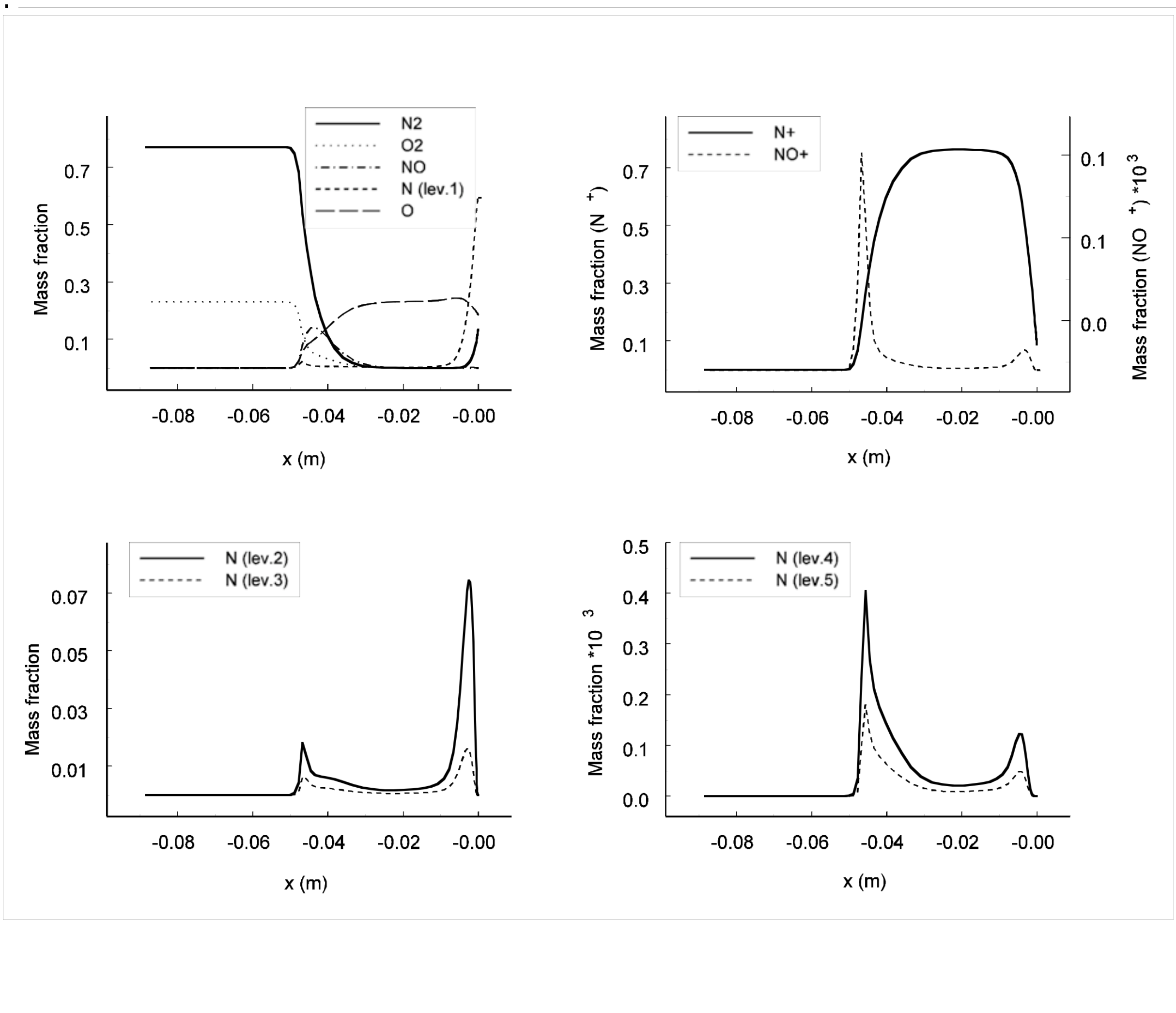
Now we consider some body flying in space (a spatial vehicle or a meteor) in the conditions given in table 1. A peculiar class of shock waves is generated preceding the body, for which collisions, heat transfer and sometimes radiation are governing phenomena. For low velocities, the dominant processes are collisions between particles other than electrons leading to few ionization and excitations. By contrast, for higher velocities, the presence of electrons leads to additional physico-chemical processes: electronic collisions are very efficient for electronic excitation and ionization of atoms; de-excitations occur either by collisional or radiative (spontaneous or induced emission) processes. Radiative recombination leads to the emission of the strong continuum radiation. The flow structure is strongly altered throughout the shock (and also the physics), since the zone where the efficient processes are coupled is extended by the radiations up to much larger distances. In particular, again in this case, the perturbation of the medium reaches upstream layers, farther than thermal effects can do. New numerical methods must be developed in order to take into account the strong coupling between aerodynamics and radiation in a general way, without the use of equilibrium approximations.

The gas is assumed to be composed of independent fluids flowing at the same velocity (collisions are strong enough to avoid any dynamical drift), one for each chemical species: $N_2$, $O_2$, NO, $NO^+$, $N^+$, N (with five electronic levels), O and electrons. Three body reaction data are better known than in the previous case. Still now, there are so many fluids as atoms in ground state and excited or ionized states (ions) and the population of each energy level is governed by a balance equation (the transitions are considered as “zero time chemical reactions”). However the nature of the gases (oxygen, nitrogen,, …) and subsequently their optical properties are different. Moreover there is now a solid boundary at a finite distance from the shock wave, downstream the surface of the body. The first difference removes the problems generated by the very particular behavior of the first excited level of the hydrogen atom, but implies new (more easily) solvable problems. The second one is more important: while it removes the problem of stiffness of the equations: it introduces another non negligible constraint: the description of the behavior of the surface of the body when reacting to the contact of both the ionized gas and the emitted photons, since the gas reaching the surface is not optically thick:. Indeed, at least in the case considered hereafter of a body moving in the terrestrial atmosphere at 14 Km/s under the conditions of a reentry at 63 km of altitude of the Rosetta probe (P = 15.49 Pa, T = 240.1 K), the vibrationnally excited molecules are not fully relaxed when the gas reaches the surface, so that equilibrium is far from being recovered. Thus we have to describe the effects of radiations and plasma flow when striking the surface: refexion, sputtering or desorption of particles, surface chemistry … and the overall structure of the flow in front of the body surface (or the shield if any) is rather different upon different assumptions. Nevertheles, it is precisely because we can now investigate the behaviour of gases governed by similar equations, under different boundary conditions, previously investigated using methods developed separately by two different scientific communities, that cross fertilization can be fruitful

Of course, the geometry is an important problem because we have a body with finite dimensions (with a nose radius of 0.5 m) at a temperature of 1500 K. Nevertheless, since the tridimentional radiative transfer cannot yet be solved with fluid motion and radiation so far from equilibrium, it can be observed that the thickness of the perturbed zone is minimum along the stagnation line, in the vicinity of which the conditions of cylindrical symmetry are the best, so that the problem can be approached again using a model in plane symmetry, with the parameters of this region, expecting thus to find a not so bad idea of the effects to be checked Thus, we use the acquired expertise to introduce radiations in a self consistent way in an existing 2D hydrodynamical code reduced to 1D close to the stagnation line. In particular, the “mean photon” approximation defined above with a set allowed to make the system of equations tractable with the ion $N^+$. In the model, corresponding to the following figures the surface of the wall is “non catalytic” and fully reflecting for the radiations (zero net radiative flux on the body surface). The gas is assumed to be composed of independent fluids flowing at the same velocity (collisions are strong enough to avoid any dynamical drift. Fig. 1, taken from {ref.2} shows the translational temperature profiles common to all the species of heavy particles (not electrons) in the two cases where the strong continuum radiation emitted by recombinations is ignored (dotted curve) or taken into account (full curve).



Calcul sans rayonnement
Calculation with radiation
Temperature (K)
x (m)

N2
O2
NO
N (lev.1)
O
Mass fraction
x (m)
N+
NO+
Mass fraction (N +)
Mass fraction (NO +) *10 3
N (lev.2)
N (lev.3)
N (lev.4)
N (lev.5)
Mass fraction *10 3

The results of fig.1 are obviously different: The peak of temperature corresponding to the hydrodynamic discontinuity moves closer to the body surface by approximately 18% of the thickness of the shocked plasma layer. This evidences of the role played by the radiations. Then the incident radiative flux on the wall is of the order of 22 MW/m2 to be compared to the 4 MW/m2 of the non radiative heat flux. In all cases of reentry at high velocities the heat fluxes on the wall of the space vehicle (or its shield, if any) are dominated by the radiative component.
The second figure (same case as fig.1) ) indicates the variations of the the mass fraction profiles along the stagnation line. The origin is on the right hand side: it is the surface of the body (logarithmic scale). Populations of the various levels are highly perturbed behind the shock.

## III SPHERICAL SYMMETRY OF THIN SHELLS

In all previous cases we finally modelled plane parallel shocks because for hyperenthalpic and still more hypersonic shocks it was admitted that both in space and in the laboratory the shock thickness is small compared to the curvature radius of the shock at least as long as we are concerned with radiation; This was the argument to find methods for reducing with not so bad accuracy the flux effects on the overall structure, and so a piece of plane tangent to the shock surface could in some way represent a local part of the shock. Otherwise 3D solving of balance equations should become necessary, even with a 1D approximation for radiation.
Though it not intuitive that large spheres can increase largely their radius without loosing their spherical shape, since instabilities due to tangential drift should probably develop, we have considered an intriguing astrophysical observable fact concerning some evolved stars. These are called "carbon stars with detached shells" because they are mainly observed among carbon stars and the spectrum of some range of wavelengths can be accurately described by assuming that a thin shell with a very large radius (several hundred stellar radii) exists beyond the radial distances within which the stellar wind is strongly accelerated. The number of stars for which this can be observed is small in spite of the fact that the phenomenon is probably common because it occurs at the end of the life of the stars with mass close to that of the sun, when the mass loss through a stellar wind becomes irregular, which happens during a short period of the life of these stars, which in turn reduces the probability of observing such objects.The empirical models accounting for their radiation is based on spherical structures with large radii but very small thickness (say $10^{-3}$ or less) fillled with clumps of denser matter). The question is now : how can such structures be generated and how van they keep their global shape under the development of purely local instabilities.
To answer this question we have built a model resulting from the interaction of spherical shockwaves due to the time variation of mass loss by the stars and followed its time evolution depending on the circumstellar media parameters. And it showed this was possible to generate local instabilities able to produce clumps like those used to build the empirical models of observables, keeping the overall symmetry unchanged

### *A new model*

The new model is based on the assumption that the observed features are the result of time variations of the mass loss of the stars, due to sharp variations of the internal structure : it is assumed that at some time t1 the mass loss increases steeply up to level which is kept constant during some time t2 and the decreases smoothly back to a lower value during t23. This produces in spherical symmetry, at time t1, a complicated structure made of two shocks F1 and G1 separated by a discontinuity surface S1 and two fans F2 and G2 also separated by a discontinuity surface S2. The complexity of the evolution of these structures depend on whether they interact or not, since G1 goes towards the star and F1 moves outwards.
The gases are still colllision dominated and hydrodynamics can be used to describe their dynamics and thermodynamics. The equations accounting for mass and momentum conservation are usual. Now, if there is also a dust component, at the distance of the shell from the star its motion is no longer coupled with that of the gas, so that the only possible interaction appears in the energy exchanges.
Thermodynamics are somewhat complicated because of the cooling due to the two main gases in the circumstellar atmospheres surrounding such stars, the molecular hydrogen H2 and the molecular carbon oxyde CO, which implies two terms in the energy equations, and in the case where dust is present two other terms describing heating and cooling due to the interaction of dust with both the gases and the ambient radiation. Thus, in order to obtain a solvable system of equations

we assume, which is reasonable, that the actual situation lies somewhere between two « extreme » cases, which we respectively denote by « frozen case » and « equilibrium case ». The « frozen case » is that in which the dust is completely uncoupled with the gases so that there is no term related to dust in the equations. The « equilibrium case » is that in which dust is included, in equilibrium with the gas. Thus the equation for energy reads :

$$\frac{\partial \varepsilon}{\partial t} + \frac{1}{R^2}\frac{\partial(\varepsilon + p)vR^2}{\partial R} = \begin{cases} 1/\text{frozen} & -q_{cool} \\ 2/\text{equilibrium} & -q_{cool} - Q_{cool} + Q_{heat} \end{cases}$$

where e, p, v, R, t denote respectively the internal energy per unit volume, the gas pressure, the gas velocity, the radial distance and the time. The terms q refer to the gas and the terms Q to the dust.

Thus, we can solve the system of equations in each case to obtain two « extreme » conditions.

To have some indication of the complexity of the problem, we can explore the time evolution of a system where interaction occurs but ignoring the right hand side terms (adiabatic conditions).

The results are given in fig.2 for the following values of the parameters

$$dM/dt = 10^{-7} \text{ solar mass/year} \quad V_1 = 15 \text{ km/s before t1}$$
$$dM/dt = 10^{-6} \text{ solar mass/year} \quad V_2 = 20 \text{ km/s during t2}$$
$$dM/dt = 10^{-8} \text{ solar mass/year} \quad V_3 = 15 \text{ km/s after t2}$$

It shows the density distribution when t23=0 (and a Mach number equal to 15), at t = 5000 years (a, before interaction)) and t = 10000 years (b, after interaction). Solid lines is concerned with the case where t2 = 500, dashed lines t2=50 years. We cannot discuss here all the informations contained in this figure, but we can note the complexity of the structure resulting from the interpenetration of the two systems of structures appearing at the starting point. Thus in the sequel we shall reduce the analyse to the outer one. In compensation we shall perform the instability analysis using 2D and even 3D models. 3D models are very much computer time consuming. Thus we shall check up to which level it is truly necessary to use such models because the results are significantly different from those of 2D models and will analyse more deeply the results of 2D models which require much less computer time to obtain accurate conclusions.

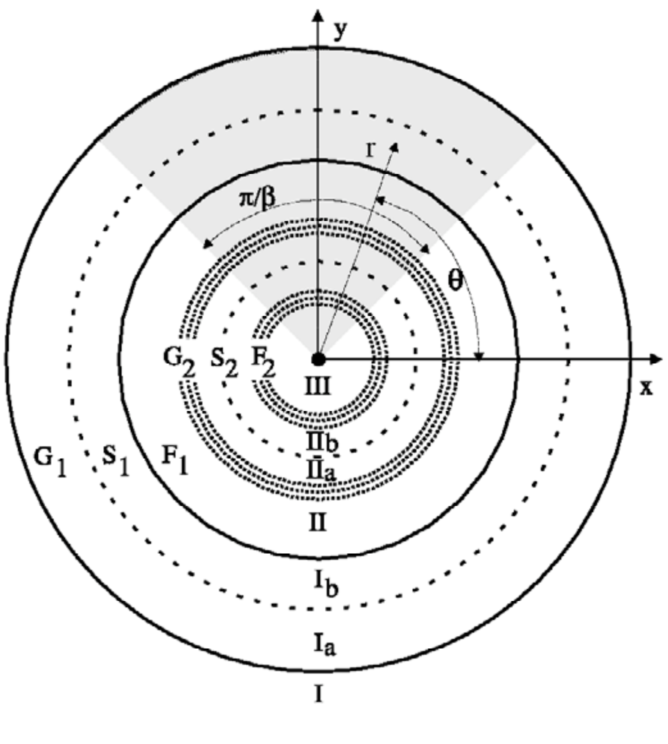



Fig.1

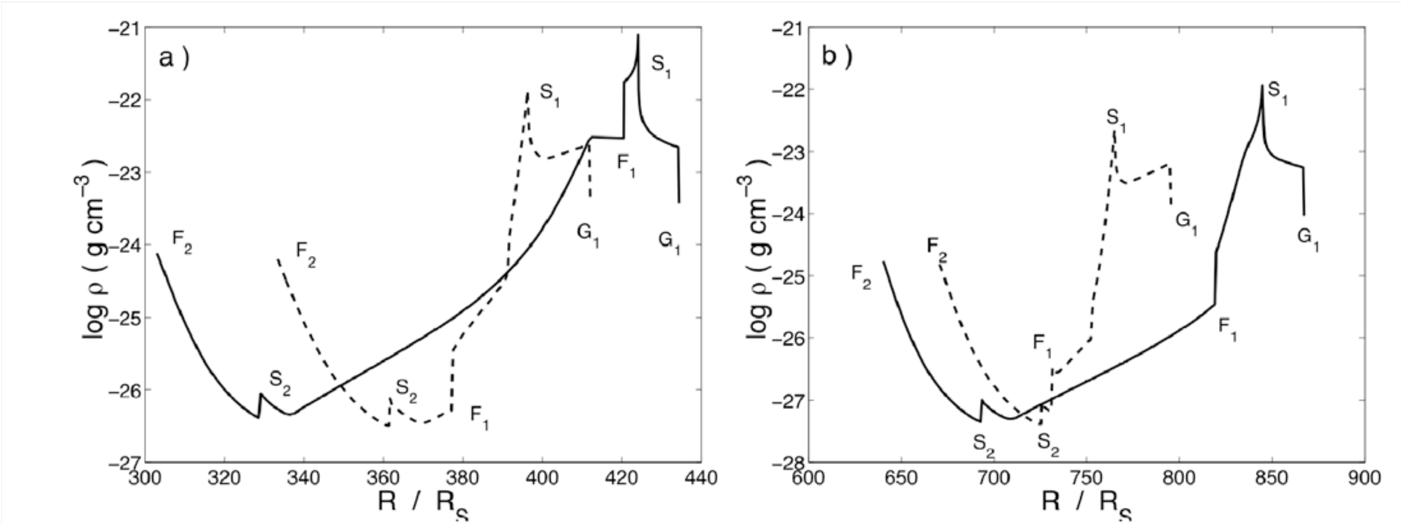



Fig.2

A second step of our investigations consists in comparing the results under similar conditions but in the « frozen » and the « equilibrium » conditions, still in 1D.
Here we only show the results of the « equilibrium » case when the mass loss due to the dust is equal to 0.5% of that due to the gas, the star effective temperature T* is equal to 2500 K (solid lines) and 1000 K (dashed lines). The star radius is equal to 1000 solar radii. Panels a and b display the density distribution at t = 10000 years for t2 infinite and t2 = 50 years respectively. Although the dust cooling dominates the gas cooling everywhere in the flow, the influence of the heating term is so strong that the temperature distribution is practically everywhere that obtained with the the radiative equilibrium function $T = 0.75\, T^*(R^*/R)^{0.4}$ . The density in the regions Ia et Ib is higher for the lowwer value of T*.

*Perturbation of the symmetry*

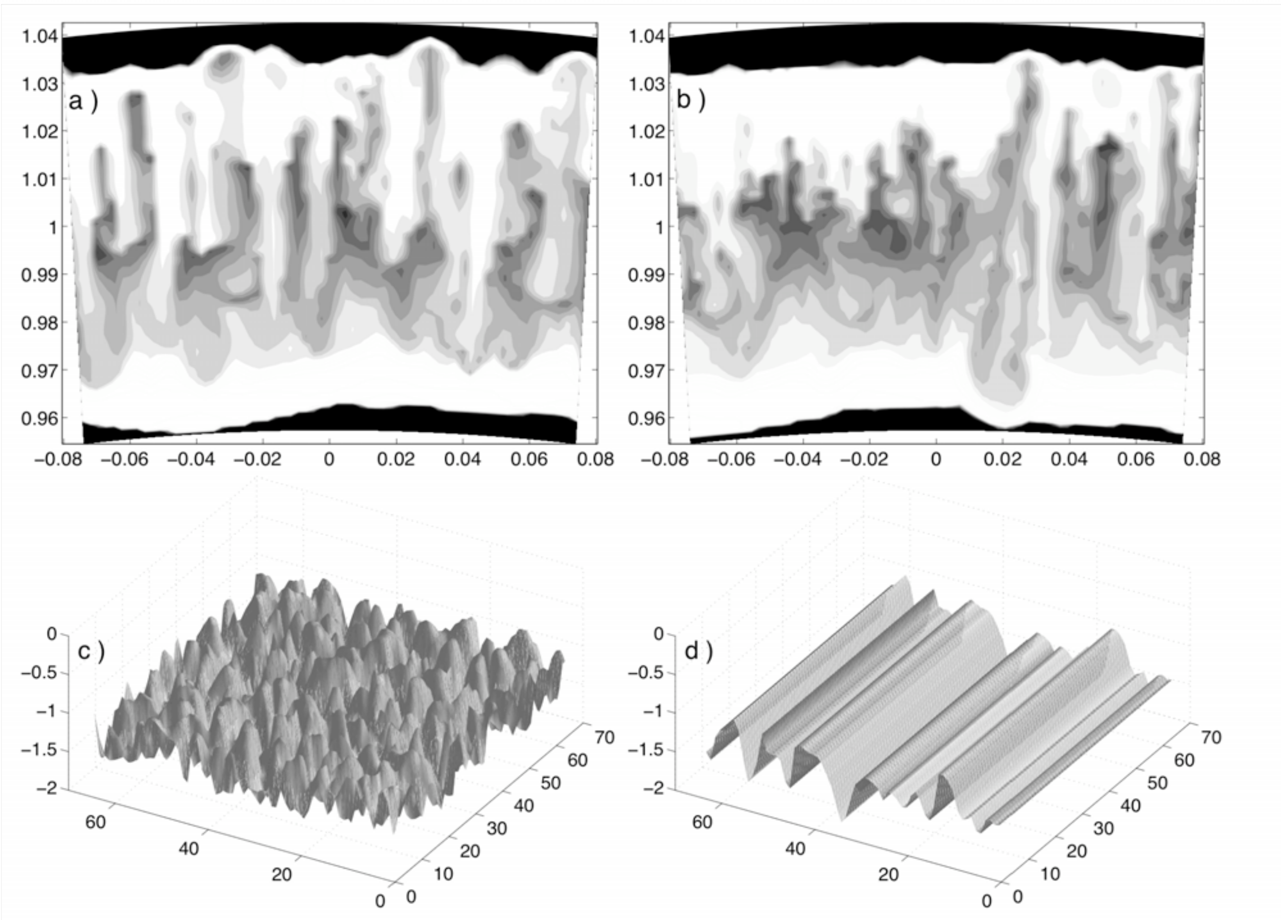
Now let us come back to the « frozen » case. The structure F1-S1-G1 of fig.1 produces a compressible fluid in decelerationg motion with a density that decreases in the direction of the flow : this can develop a Rayleigh-Taylor instability.Let random initial perturbations with amplitude e apply to the velocity of the second wind at the contact discontinuity S1. An instability develops and fingers form and penetrate towards F1. We have analysed the linear and the non linear evolutions of this instability. In order to observe the effects of the grid size in 2D models on motion in the cone with angle p/b (fig.1) to know how they are sensitive, look at the results at the final time on the (logarithmic) entropy contours of fig. 4 (b = 20, e = 0.01).
The number of grid nodes are multiplied each time by 2 in each direction. Although the results of simulations (number of fingers, depth of penetration) differ noticeably in the early stages of the flow evolution, the differences decrease for increasing time, while the amplitude and wave numbers of the strongest modes evolve towards quite similar values.
By contrast, the flow in the « equilibrium case » was found stable with respect to any acceptable perturbations, which does not suggests any mechanism for the development of an instability.

*3D Perturbation of the flow*

In general modeling 3D perturbations is very much computer time consuming because it requires very fine grids. Thus, we wondered whether the decelerating flow described above is unstable with respect to 3D perturbations and, if it is true, what can be the differences between the two cases. First we investigated the evolution of 3D flows under axially symmetric perturbations. The solutions obtained with 2D simulations under the same values of parameters are the same during all the flow evolution. This validates the 3D code.
Then we introduced a true 3D perturbation. In the last figures the resulting distribution functions for entropy are displayed for different cross sections of the regions Ia and Ib (fig.1) of the 3D flow pattern, for a frozen shell with t2 = 50, t23 = 5, at time t = 10000 years, with a Mach number of 100. Panel **a** corresponds to the plane q = p/2 , **b** to the plane f = p/2 (cf fig.1), **c** presents the 3D protrusions and **d** what is obtained in 2D with same conditions. Abscissas in **c** and **d** are in units of number of grid points. Initial perturbations have same amplitude .

The flow is obviously unstable under 3D perturbations and the penetration depth together with the extreme values of the physical quantities are quite similar to those of the 2D case. Following what was observed, we can conclude that 2D simulations with rather fine grids may be used for to obtain preliminary estimates of the parameters of detached shells around carbon stars.Now, in the « equilibrium » case, accurately taking into account the dust grain energy balance reduces significantly the factors driving the Rayleigh-Taylor instability. Thus, we found no instability in the « equilibrium » approach, in spite of the probable existence of a mechanism able to switch on a kind of instability different from the R-T instability in quasi-isothermal flows.

Finally, we claim that the results of the instability modeling in the « frozen » approach give the upper limit for instabilities, under the form of growth of local swellings in spherical shells.
Some comparisons between the computation results and observational data demonstrated good coincidence in the most important points. In particular, the simulations revealed the observed thicknesses of the shells, which remain small compared to the radial distance in all cases. They also qualitatively reproduced the observed inhomogeneities.
Of course, we performed many other computations under larger ranges of data than presented here. For a detailed discussion we refer to (4). Nevertheless the main conclusions are those given here and suggest new approaches of global and local thin shell instabilities.





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