CORONAL JET TURBULENT ACTIVITY TO EXPLAIN DISTORTED EMISSION LINE

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ABSTRACT

The turbulence is a fundamental input in stellar atmospheres and as it is, one should take account of it in all diagnostic of spectral lines. This turbulence occurs at a finite scale and is frequently observed in the chromosphere and lower corona, particularly at the base of the so-called Impulsive Events (I.E.). In this work, a model of Non-LTE transfer using both partial and complete redistribution is considered to take full account of the structure of the velocity field, including a finite spatial correlation between the velocities. In the opposite of classical works which calculate mean profiles, this model is rather concentrating on the computation of the deviation to the averaged value. The results seem to invalidate simple studies based on the consideration of lines formed in an averaged medium.

In this contribution, the problem is generalized to account for both partial and complete frequency redistribution of photons in the reference frame of atoms, with a systematic comparison between the two results. This is made important due to the progress in spatial resolution of modern observations (SoHO, HST, FUSE,…) that may help to discriminate between compelling line broadening processes which renews the great interest of considering fluctuating quantities against the averaged ones. Obvious applications include the analysis of the so-called turbulent events and of the wave signatures.

2. POSITION OF PROBLEM

2.1. Description

The model in its basic component is well described in Magnan, 1976, and in a more qualitative and specific way to the problem in question, by Loucif and Magnan, 1981. We will point out here some points essential to the comprehension of the problem arising, and enumerate some approximations of a practical nature. One considers an atmospheric medium in presence of a completely non-thermic random velocity field. At the different points of the medium, these velocities are not completely independent: It exists a certain spatial correlation between these velocities. We take account of it in the following way: The medium is divided into “rigid” volumes (or cells) of different sizes, in each point of a same volume velocity is constant, but it can take a completely different value on another volume of gas to remain constant there along this one, and so on. Velocities of various volumes are statistically independent and obey a supposed Gaussian law, of parameter b indicating the most probable velocity representing the velocity of turbulence:

\[
P(v)dv = \frac{1}{(b\sqrt{\pi})^2}\exp\left(-\frac{(v_x^2 + v_y^2 + v_z^2)}{b^2}\right)dv (1)
\]

In the medium thus made up of turbulent cells, we should examine the problem of transfer of radiation.
in a spectral line. Which is then the radiation which can be emitted by a particular cell having a particular velocity \( v \). The incident radiation \( I_1 \) on a given cell depends on the velocity of all the other cells which contribute to this radiation (including the velocity of the considered particular cell - fig.1.):

\[
I = I(v_1, v_2, ..., v_n)
\]

(2)

In the continuous exchange between the radiation and the matter, velocity \( v \) enters in the absorption coefficient which becomes thus a stochastic variable, and the intensity of the radiation which depends on it is then a fluctuating quantity. In front of this random aspect of the problem, one often concentrated on the determination of the mean emergent intensity \(< I_e >\), a quantity generally observed in the stellar spectra (Frish, 1975; Magnan, 1976). In this work we rather interested in the deviation from this average: we calculate in given points (cells) of the medium individual profiles corresponding to a certain realization of the velocity field. This realization consists of the consideration of an ensemble of \( n \) cells assigned of \( n \) particular velocities \( v_1, v_2, ..., v_n \) where we determine the emergent intensity of a given cell. In other words, a "particular realization" is equivalent to a particular choice of a given set of velocities \( v_1, v_2, ..., v_n \). This calculation of \( I \) by taking account of all velocities of cells is realizable in itself, but in addition to its arbitrary character, requires enormous calculations and presents a secondary interest. To solve the problem we will easily show that by using the approximation of the "effective" cells (mean cells) described by Magnan (1976), the emergent radiation of a cell depends only on velocity of this one, the other cells being replaced by effective cells. All would go then as if the last cell, assigned a particular velocity \( v \), were illuminated by an average radiation (fig.2).

2.2. Physical processes

We consider a typical simplified Non-LTE case, where photons are created uniformly within the medium at the expense of thermal energy. In the layer of optical thickness \( \tau \) a number of \( eB_\tau \) photons are emitted for the first time in each direction (the medium being considered as one-dimensional). Afterwards the photons are allowed to diffuse in the medium but at each scattering event there is a probability \( \epsilon \) for the photons to be destroyed, its energy returning to the thermal pool. The probability of absorption within the medium is characterized by the shape factor \( \phi_\tau = \int_{-\infty}^{\infty} F(x, x')dx' \) at the frequency \( x \), the integration being done on the full emission frequencies. In the case of complete frequency redistribution, we have \( \phi_\tau = \phi_0 \phi_\tau \) (where \( \phi_0 \) is taken the same as \( \phi_0 \) and \( \phi_0 \) is taken as the Voigt function \( U(\delta, \epsilon) \). After an absorption the frequency distribution of the reemitted photon is taken as the same function \( U \) in the frame of reference of the matter at the point where the scattering occurs. In the other considered case of partial frequency redistribution, \( F_{x, x'} = \frac{\partial R(a, x, x')}{\partial x} \) (See Mihalas in "Stellar Atmospheres", 2nd Ed., p.422). The frequencies are conveniently expressed in units of Doppler width as:

\[
x = v/\sigma = (c/\alpha)/(\Delta \nu/\nu_0), \text{ where } \alpha \text{ is the thermal velocity of the considered atom. The quantities } \epsilon \text{ and } \delta \text{ are both chosen as } 10^{-3} \text{ in the results that follow.}
\]

3. METHOD OF SOLUTION AND PRACTICAL SIMPLIFICATIONS

The problem of radiative transfer is examined in only one direction and the variation of non-thermic velocities only considered according to this direction of propagation of the light (we then calculate a radiation propagating through a "column" cells randomly moving according to a certain line of sight). The dimension \( \lambda \) of a cell is constant and we take in a given realization all the cells identical. We use the method of addition of layers described by Sobolev (1963) in its simplest version: the doubling. An essential parameter is the number \( n \) of these cells, which can vary from \( n=1 \) (macro turbulence) to \( n \to \infty \) (micro turbulence). In a given realization, this number is such as: \( n\lambda = T \), where \( T \) is the total optical depth over which the radiation is integrated to surface. The parameter \( n \) thus makes it possible to explore all the realizations between the limits of micro- and macro-turbulence (fig.2). In this method of adding which is particularly adapted to the considered problem, we consider the emergent intensity \( I_1 \) from a given cell as a functional of the intensity \( I_1 \) incident onto that cell. In a synthetic way that can be applied to very general cases we write for each cell a set of equations of the form:

\[
I(v) = E(v) + \{ M\{v\}\}.I_1
\]

(3)

Where \( v \) is the velocity of the considered cell taken separately, \( E \) a constant term characterizing the emission of the cell when it is isolated and \( M \) a matrix operator which designs relaxation and transmission matrices at the same time and so, connecting the outward intensity to the inward one. Now, when the particular cell is moving in the turbulent medium (with the particular velocity \( v \)), the previous equation becomes:

\[
I(v; v_1, ..., v_n) = E(v) + \{ M\{v\}\}.I_1(v; v_1, ..., v_n)
\]

(4)

Now the difficulty of the non-LTE problem lies in the correlation between the intensity \( I_1 \) incident onto a cell and the operator \( M \) characterizing the same cell. There exists a correlation because the intensity leaving the cell is likely to return onto the same cell it has left after scattering in the medium and then keeps a memory of the cell it has left, especially in what concerns the velocity of the cell. The effective cell approximation introduced by Magnan, 1976 consists precisely in neglecting the stated correlation. The essence of this approximation consists in supposing that in case a given photon happens to come back in a cell it has crossed previously then it sees a velocity which is statistically independent of the velocity the cell had before. Conversely when a photon encounters a given velocity it behaves as if it had never seen it before. By the approximation the photon history is clearly reduced to a Markov process with no back correlation. So in particular the intensity incident onto a cell is independent of the cell velocity (See also Loucif, 1981 for more details). Using the approximation, the previous equation finally becomes:
Figure 1. Schematic representation of turbulent cells moving with particular velocities \(v_1, \ldots, v_n\). Each cell receives energy from all the others, and the intensity \(I_e\) emerging from a given cell depends on the all cells' velocities in the medium.

\[
\langle I_e(v; v_1, \ldots, v_n) \rangle = E(v) + \{M(v)\}
\]

\[
\langle I_s(v; v_1, \ldots, v_n) \rangle > (5)
\]

As a consequence of the foregoing the solution of the problem is obtained in the following way. The cell at the surface of which we want to determine the emerging intensity is assigned a particular velocity \(v\). On the contrary the other cells, over which we take an average, are replaced by effective cells with mean coefficients computed in accordance with the formulae in Loucif (1981) generalized to both partial and complete frequency redistribution. An example of obtained results is shown in figure 4.

4. DISCUSSION AND CONCLUSION

The resulting profiles are essentially sensitive to two factors, the optical depth of the cell (the correlation length of turbulence) and its velocity. Both partial and complete redistribution give comparable evolution, while partial redistribution produces much less broadening. Our approach is likely to be connected with certain observed profiles in order to discriminate between the two functions. Without doubt the most noticeable features of the theoretical profiles are first the broadening and second the multiple reversals or accidents in the line shape. They are interpreted in terms of a combination of velocity effects and scattering effects or more exactly as a manifestation of non-LTE scattering effects in the presence of a velocity field. Indeed, as for the optically thick case, a static medium usually leads to an emission line with a double peak that results from multi-scattering and thermal motion effects. The introduction of turbulence not only shifted the center of the line (as should do any bulk motion) but also introduced particular features that are relevant to the fluctuations of the last layer in front of the observer. The results show that the velocity field is indeed crucial for determining the line shape. At sight of the present computed profiles it is difficult not to think of a large amount of lines observed by actual modern observations (SOHO, HST, etc... - See fig.3). The other major remark concerns the very large deviations from the mean value observed here, the deviations are larger the correlation length is larger. The result seems to show that the very notion of a kind of "mean" atmosphere is meaningless. Really, the very good spatial resolution of modern observations renews the great interest of considering individual profiles against the averaged ones, and urges the astrophysicists to envisage new diagnostic techniques (e.g. Gouttebroze et al., 1989).

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REFERENCES

Figure 4. Example of emerging profiles from a turbulent medium for \( v = 2 \) (the velocity of the last emitting layer) and different values of \( \tau \). Calculations were made for both partial (dashed lines) and complete frequency distribution (solid lines). Note that for \( \tau < 1 \), both distributions yield the same profile.