Optical View of Particle Acceleration and Complementarity with HESSI

Jean-Claude Hénoux

Observatoire de Paris, DASOP/LPSH(UMR8645), 5 Place Jules Janssen, F-92195 Meudon Cedex, France

Abstract. When they reach the low temperature solar atmosphere, source of optical radiation, energetic particles significantly contribute to particles excitation and ionization, leading to enhanced line and continuum emission. The profiles of the lines emitted by local atoms collisionally excited by non-thermal protons or electrons are ultimately related to the non thermal particles energy deposition rate depth dependence. This can be used to discriminate between these particles. Also a typical line profile is expected from lines emitted by accelerated protons, once they have captured, by local charge exchange, an electron, offering a tool for detecting protons and ions bombardment.

The anisotropy of the angular velocity distribution function of particle beams makes possible for the lines emitted to be linearly polarized. Impact polarization observations in solar flares, together with hard X-ray and γ-ray observations, allow to extend to low energies (≤ 1 MeV) the estimation of the energy distribution of the proton energy flux. This makes possible to determine the amount of energy carried by protons. This energy flux seems to be equal to, or even higher than, the amount of energy carried by electrons, putting constraints on the particle acceleration mechanism in solar flares.

1. Introduction

Flares are unique in the astrophysical realm for the great diversity of diagnostic data they provide to understand particle acceleration (Miller et al., 1997). Energetic particles, electrons and ions, accelerated in solar flares interact with the solar atmosphere. The resulting emission of visible, UV, X-ray and γ-ray photons provides informations on the energy spectrum of the non thermal particles - electrons or ions number flux.

Non thermal particle energy spectra can usually be represented by power laws. Hard X-ray and γ-ray observations alone lead to a significant uncertainty on the amount of energy carried by energetic particles and on the relative contribution of electrons and ions to the flare energy budget. Hopefully, the modification of the physical state of the bombarded cold atmosphere provides additional information on the nature, energy, number flux and even velocity angular distribution of the incoming particles. This information lies in the intensity, shape and polarization of the resulting line and continuum emission spectrum.
2. Lines intensity profiles as a diagnostic for particle bombardment

2.1. Profiles of lines emitted by the chromospheric target

The excitation by energetic particles of the atomic species present in the chromospheric target leads to possible diagnostics for particle bombardment. Hudson (1972), Lin and Hudson (1976), first pointed out the significance of non-thermal ionization and excitation by electron beams. Non-thermal electrons and non-thermal protons contribute both, not only to the ionization state of the solar low temperature atmosphere, but also to the non-thermal excitation of the cold target atoms and not fully ionized ions. The line intensity profiles of the Hα hydrogen line and of the Ca II K line resulting from non-thermal excitation (Fang et al., 1993; Hénoux et al. 1993) provide possible diagnostics of energetic particles bombardment.

**Non-thermal excitation rates of hydrogen** In a weakly ionized atmosphere, most of the energy deposited by a beam of particles is lost in the collisional excitation and ionization of its main constituent, hydrogen. At a given column density $N$, the rate $\frac{dE^H}{dt}(N)$ of energy deposited per unit volume in inelastic collisions with hydrogen, for an electron or a proton beam, with a number flux proportional to $E^{-\delta}$, carrying a total energy flux $F^1$ above a low energy cutoff $E_1$, can be derived (Emslie, 1978; Hénoux & Chambe, 1979). The energy deposited goes mainly into excitation and ionization of hydrogen. The rate of energy deposit once computed at any depth can be related to the hydrogen collisional non-thermal excitation and ionization rates $C_{1j}^B(N)$ and $C_{1c}^B(N)$ since:

$$\frac{dE^H}{dt}(N) \approx n_H(\sum_j \kappa_{1j} C_{1j}^B(N) + \kappa_{1c} C_{1c}^B(N)),$$

where $\kappa_{1j}$ and $\kappa_{1c}$ are respectively the excitation energies to levels $j$ and the ionization energy. In a steady state situation, assuming that the ratios of the excitation and ionization cross sections do not vary significantly with energy, and therefore that $C_{1j}^B/C_{1i}^B = \sigma_{1j}/\sigma_{1i}$, the various non-thermal rates can be derived and introduced in the statistical equilibrium equations that relate the population of the continuum and bound levels of a four levels hydrogen atom. In this approach, the secondary electrons, produced through non thermal ionization of the atmosphere, are supposed to be included, as hot thermal electrons, in the empirical flare thermal model used.

**Resulting hydrogen Balmer Hα line intensity profiles** The statistical equilibrium equations and the transfer equations, coupled with the particle conservation and hydrostatic equilibrium equations, can be solved, for various values of the parameters $F^1$, $E_1$ and $\delta$ describing the electron and proton beams, for various empirical flare models, like $F_1$ and $F_2$ (Machado & al., 1980). The resulting shape of the hydrogen Balmer Hα profile as shown in Fig.1 depends on the depths of penetration of the particle beams.

The Hα line profiles of a chromosphere bombarded by an electron beam can show in the line core an emission peak, either pure or with central absorption. For beams carrying an energy flux higher than $10^{11}$ erg cm$^{-2}$ s$^{-1}$, energy is deposited deep in the chromosphere at optical depths higher than unity and
Figure 1.  $H\alpha$ line profiles, with non-thermal hydrogen collisional excitation and ionization included, for respectively an electron (left two columns), and a proton beam (right two columns) for models $F_1$ (first and third column) and $F_2$ (second and fourth column); dotted lines profiles ignore non thermal excitation. $J_1$ takes the values: - for electrons: $5 \times 10^{10}$ (three dots per dash), $1 \times 10^{11}$ (dash-dotted line), $5 \times 10^{11}$ (dashed line) and $1 \times 10^{12}$ (full line) ergs cm$^{-2}$ s$^{-1}$ - for protons: $1 \times 10^9$ (three dots per dash), $5 \times 10^9$ (dash-dotted line), $1 \times 10^{10}$ (dashed line), $5 \times 10^{11}$ (full line) ergs cm$^{-2}$ s$^{-1}$. The low energy cut-off $E_1$ is respectively 20 keV for electrons and 150 keV for protons.

some of the photons created by hydrogen non-thermal excitation are absorbed, leading to a line central reversal. For electron beams carrying a low energy flux or with a steep power spectrum, the beam energy is deposited mainly in the upper chromosphere, and an emission peak is generated in the line center, as for protons. Since the amplitude of the absorption decreases for high chromospheric temperatures, profiles computed for the hot empirical flare model $F_2$ show less central absorption in the emission peak and are closer to the profiles created by proton bombardment. Contrary to electrons, protons deposit their energy in the highest chromospheric layers. Therefore, the photons generated are not absorbed by the atmosphere above and an emission peak is created in the line center, (Hénoux et al.,1993). This result holds whatever the chromospheric flare temperature. However, a very high pressure in the corona can produce the same effect, that makes this diagnostic method ambiguous.

The $H\alpha$ line profiles are not good diagnostic tools for proton beams, since electron beams, or even a high pressure corona, could generate similar line profiles. Their use as diagnostic for electron beams is also not straightforward. Only electron beams with rather high energy flux produce characteristic profiles with an absorption core in the central emission peak, as long as the chromospheric temperature remains moderate. The shape of the $H\alpha$ line profile depends on the chromospheric temperature, density and motion, and shall therefore vary in time, not only as a function of the hard X-ray emission intensity but also as
function of the time integral of this hard X-ray emission and of the associated soft X-ray flux.

The time evolution of the hydrogen lines formation process has not been considered here. A detailed study of the time dependence of the Hα line profile, that ignores non-thermal effects but takes into account the dynamic response of the chromosphere, has been done by Canfield and Gayley (1987). The profile depends both on the characteristics of the energy deposit mode and on the chromosphere hydrodynamic response. Then, taking into account non thermal process, Heinzel (1999) pointed out that at the beginning of the particle bombardment the dominance of the collisional excitation over the photorecombination process could lead temporarily to a decrease of the Hα line intensity.

2.2. Lines resulting from charge exchange

A specific diagnostic for proton bombardment results from the property of protons to capture electrons from the neutral chromospheric hydrogen target. They become excited neutral hydrogen atoms and consequently emit Doppler shifted lines (Orral and Zirker, 1976; Canfield and Chang, 1985). Computations of the resulting enhancement of emission in Hα, Lyα and Lyβ lines (Fang et al., 1995; Zhao et al., 1997) showed that the non-thermal emission of the Hα line is not detectable, while the Lyβ line could be used to diagnose the proton beam bombardment.

3. Impact linear line polarization as diagnostic for non thermal particles

Collisional excitation by particles with anisotropic velocity distribution functions generally leads to the emission of linearly polarized lines, the polarization of which provides additional information on the non thermal particles.

3.1. Main Properties of Impact Polarization

Polarization generated by a monenergetic beam of particles The monochromatic radiation emitted by an atom collisionally excited by a beam of monoenergetic particles of energy \( E \) may be linearly polarized (Percival et al., 1959; Kleinpoppen, 1969; Heddle, 1979; Kazantsev et al., 1994; Kazantsev and Hénoux, 1995). Calling respectively \( I_\parallel \) and \( I_\perp \) the intensities of the vibrations parallel and perpendicular to the plane defined by the beam and the line of sight, and \( \beta \) the angle between the beam and the direction of observation, the polarization \( P(\beta, E) \) is defined, as illustrated in Fig.2, by:

\[
P(\beta, E) = \frac{(I_\parallel - I_\perp)}{(I_\parallel + I_\perp)}.
\]

(2)

\( P(\beta, E) \) is related to \( P(90^\circ, E) \), maximum of polarization observable at \( 90^\circ \) from the beam direction by:

\[
P(\beta, E) = P(90^\circ, E) \frac{\sin^2 \beta}{1 - P(90^\circ, E) \cos^2 \beta}.
\]

(3)

As shown on the right part of Fig.2 (Werner et al., 1996), \( P(90^\circ, E) \) is function of the nature of the particle - electron, proton, ion - and of the particle...
Figure 2. On the left: Definition of the polarization degree produced in impact excitation. On the right: Energy dependence of $P(90^\circ, E)$, for the hydrogen H$\alpha$ line, as a function of the equivalent electron energy in eV. of the incoming particle. Experiments: dark triangles and lozanges (electrons); empty triangles (protons); circles (He$^+$). Theory: dashed line (electrons); dotted dashed line (protons).

energy. $P(90^\circ, E)$ changes of sign for a turn over energy $E_0$ that is of about 200 eV for electrons and 200 keV for protons.

*Impact polarization generated by monoenergetic particles with a given velocity distribution $f(v, \alpha)$*  
Assuming axial symmetry around the beam direction of propagation, and defining the moments $J_n$ of the velocity distribution function $f(v, \alpha)$ as

$$J_n = \int_0^\pi f(v, \alpha) \cos^n \alpha \sin \alpha \, d\alpha,$$

where $\alpha$ is the angle between the particle velocity vector and the beam axis of symmetry, the polarization can be related to the first even moments $J_0$ and $J_2$ of the particle velocity distribution function. The polarization $P(\theta, E)$, where $\theta$ is the angle between the line of sight and the symmetry axis, is then obtained by replacing in equation (3) $\beta$ by $\theta$ and $P(90^\circ, E)$ by $P(90^\circ, E)$ with

$$P(90^\circ, E) = \frac{P(90^\circ, E)(3J_2 - J_0)}{2J_0 + P(90^\circ, E)(J_2 - J_0)} \approx P(90^\circ, E)\left(\frac{3J_2}{2J_0} - 1\right)$$

(4)

For no monoenergetic particles, integration must be made over the particle energy.

3.2. Use of line impact linear polarization to discriminate between proton and electron beams

The degree and orientation of linear impact polarization is related to the nature and energies of the particles, the orientation of the symmetry axis of the particle velocity distribution function relative to the line of sight, and the energy distribution of the moments $J_0$ and $J_2$ of the particles velocity distribution functions.
Figure 3. Hα line profiles formed in an atmosphere represented by empirical models C (left) and F₁ (right), either without (full line) or with X-ray irradiation, for 1-300 energy fluxes of 8 \times 10^7 (dashed line) and 8 \times 10^8 (dashed-dotted line) ergs cm\(^{-2}\) s\(^{-1}\).

Therefore, for a definite diagnostic, impact polarization measurements still require complementary observations in radio, soft, hard X-rays and γ-rays.

Various modes of energy transport present in solar flares, i.e. heat conduction, soft X-ray irradiation, protons and electrons bombardment generate non-thermal particles with anisotropic velocity distribution functions and could lead to impact line polarization.

Heat conduction may also lead to impact polarization of UV and EUV lines formed in the transition region, where the heat flux is maximum, but it is expected to have negligible effects on chromospheric lines.

Photoionization by soft X-ray (Hénoux and Nakagawa, 1977; Hénoux and Rust, 1980), generates photoelectrons that move originally in the horizontal direction. Depending of their initial energy, photoelectrons keep some anisotropy (Hénoux and Karlický, 1999) and, by impact, they lead to the emission of photons linearly polarized in the radial direction. The net resulting polarization degree depends on the relative importance of this line excitation process compared to the other collisional and radiative process. As shown in Fig.3, the contribution of photoelectrons to Hα line formation, and to the degree of radial linear polarization in a 7.5 nm band centered on the hydrogen Hα line center, significant in a quiet sun atmosphere is negligible (Hénoux and Karlický, 1999) when the atmosphere has been heated to the temperatures of empirical flares models like F₁ (Machado et al., 1980). Only for the quiet sun C model, does the maximum degree of polarization produced by photoelectrons reach 2.5% for a X-ray energy flux close to 10^9 ergs cm\(^{-2}\) s\(^{-1}\) in the 0.1-30 nm wavelength band. For model F₁ the maximum degree of polarization does not exceed 1 %. Since during flares chromospheric temperature and densities are expected to rise significantly, electron and proton beams remain the best candidates for being at the origin of the observed impact polarization.

Electrons High energy electrons above 10 to 20 keV are often seen as carrying most of the flare energy and as being able to deposit up to 10\(^{32}\) ergs in the solar atmosphere, explaining the formation of a hot, soft X-ray emitting, coronal plasma by bombardment of the upper layers of the solar chromosphere. In order to reach the chromosphere with a significant directivity, the electrons must have an energy well above the 200 eV turn-over energy \(E_0\). In flares outside the solar
disk center, these high energy electrons would lead, if precipitating along the vertical direction, to a tangential direction of polarization, parallel to the solar limb (However, this conclusion depends on the particles pitch angle distribution since high energy electrons spiralling around the solar vertical with a pitch angle close to 90° would generate a radial direction of polarization). As presented below, tangential Hα linear polarization was observed during the impulsive phase of a solar flare (see Fig.5).

*Protons* Due to their heavier mass, protons, contrary to electrons, keep their directivity in Coulomb collisions with the solar chromosphere neutral hydrogen target (Hénoux et al.,1990; Firstova et al.,1997; Vogt et al., 1998). Therefore, impact polarization is a way, and presumably the only one, to detect, from the ground, protons of energy below 1 MeV.

From γ-ray nuclear lines observations, it is well established that protons and ions are accelerated above 1 MeV during solar flares. The extension towards lower energies of the energy spectrum of MeV protons is uncertain. Previously, the energy spectrum of protons and ions was represented by Bessel functions with a flat maximum at a few MeV and a power law decrease at high energies. With such spectrum, the observed ratio of the nuclear Ne 1.634 MeV and O 6.1 MeV lines requires the Ne/O abundance ratio to be enhanced in solar flares. However, by using a power law down to the low energy part of the proton energy spectrum, there is no more need of having a peculiar Ne/O abundance ratio in solar flares, since low energy particles \(E < 3\) MeV) would contribute significantly to the excitation of the 1.634 Ne nuclear line (Share et al.,1995) and less to the one of the 6.1 MeV O line. Consequently, increasing the relative proton number flux at low energy enhances the Ne/O line ratio in agreement with observations without implying abundances anomalies (Ramaty et al.,1995). Since there is no known reason to cut the proton energy spectrum at 1 MeV, protons with a power law energy spectrum down to a few hundreds of keV would then play the most important role in the energetic of solar flares, carrying an energy flux orders of magnitude higher than the one carried by electrons.

Protons of energy below 1 MeV do not emit γ-ray lines. Hopefully they are not significantly deviated in Coulomb collisions (Hénoux et al.,1990; Firstova et al.,1997; Vogt et al., 1998) and can then generate impact polarized line radiation. The turn over energy \(E_0\) for protons is about 200 keV. Therefore, in flares outside the solar disk center, protons of energy below 200 keV would lead, if precipitating around the vertical direction, to a radial direction of polarization, in the flare to disk center direction. Indeed, this conclusion depends on the particles pitch angle distribution; protons below 200 keV, spiralling around the solar vertical with a pitch angle close to 90°, would generate a tangential direction of polarization.

### 3.3. Hα line impact linear polarization observations

A few observations of impact line polarization in solar flares have been reported. They where made either at Paris Observatory in Meudon using PARIS, a polarimeter equipped with a monochromatic filter, or at Irkutsk putting an analyzer of polarization in front of the entrance slit of a spectrograph (Hénoux and Chambe, 1990). PARIS is an heliograph preceeded by a rotating half wave

**The June 20th 1989 flare** A solar flare was observed on June 20, 1989 at 24N and 68W. This event was accompanied by impulsive hard X-ray, γ-ray and radio emissions and by gradual soft X-ray emission. The Fig.4 shows the time variation of the impulsive hard X-ray emission, in the energy band 52 to 858 keV, together with the time variation of the γ-ray emission. Hard X-rays and γ-rays were observed respectively by the HXRBS and GRS instruments on the SMM satellite. The maximum of hard X-ray emission is reached at 14:57:30, i.e. about 3.5 minutes after the beginning of Hα and hard X-ray emission, and 4.5 minutes before the maximum of Hα emission. Below 1 MeV the γ-ray emission observed by GRS shows the same characteristics as the hard X-ray emission. Above 1 MeV, the count rates are very low.

The 0.1-0.8 nm soft X-ray radiation observed by the GOES 7 satellite, together with the Hα emission integrated over the flaring area are shown on the left of Fig. 5. Comparison of Figs. 4 and 5 shows that the peak of Hα emission at 15:02 UT follows by 4.5 minutes the maximum of hard X-ray emission; it precedes by a few minutes the soft X-ray emission flat maximum that takes place at 15:06:30. These comparison shows that the Neupert effect does not takes place: an additional source of energy deposit follows the electron bombardment. The polarization was studied from 14:54 to 15:19 UT. The time profiles of the radial and tangential components of the linear polarization vector, integrated over one minute of time and over the flaring area, are given in Fig.5. Two main polarization peaks can be seen. The lack of polarization between these two peaks is presumably due to the depolarizing effect of the local atmosphere heated by the electron bombardment (Vogt et al. 1997). The tangential component is clearly dominant at the beginning of the flare, especially from 14:55 to 14:58 UT, around the time of rise of the hard X-ray emission to its maximum, as expected from bombardment by high energy electrons. Later in the flare, the signal becomes more noisy. However, from 15:07 to 15:08 UT - at and just after the maximum of soft X-ray emission - the radial component dominates. Low energy protons are the best candidates to explain this radial linear polarization.
Figure 5. Time evolution of the soft X-ray (from GOES 7) emission (on the left) and of the radial (plain line) and tangential (dotted line) components of the polarization integrated over the flare area (on the right) for the June 20th 1989 solar flare.

*Degree of linear polarization expected from proton beam bombardment*  The transfer of population between the Zeeman excited states by the local thermal particles with isotropic velocity distributions reduces the polarization generated by a proton beam. The degree of polarization proton beams could produce has been estimated, taking into account the contribution of additional radiative and collisional processes to the Hα line formation. However, these computations gave a lower limit of the expected polarization degree since the Lyα and Lyβ radiation fields were supposed unpolarized (Vogt et al. 1997). Consequently, the Hα polarization degree was found to decrease when the density or temperature of the chromosphere was increased.

4. Conclusion

The derivation of the particles acceleration time and location, as derived from high time and spatial optical lines observations, has not been treated in this review. The comparison of Hα images of the flaring chromosphere to the magnetic topology shows that the acceleration process takes place on the magnetic separatrix at the intersection of the separators, i.e. at a location where magnetic reconnection can take place (Hénoux et al. 2000). Detailed studies of the relative timing and relative positioning - compared to the magnetic topology - of the chromospheric flare brightenings would provide informations on the magnetic energy release process.

The June 20th, 1989 observations show that a significant energy flux is carried by protons and that the energy released is higher that usually thought. That put observational constraints on the particles acceleration mechanism (Emslie et al. 2000). Used jointly with X and γ ray observations, spectropolarimetry shall not only bring informations on the nature of the accelerated particles, ions and protons versus electrons, and on their angular velocity distribution but also, by extending the range of investigation for protons down to the few hundred keV energy range, would lead to better estimates of the energy carried by protons and more generally of the amount of energy liberated in solar flares.
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