THEMIS as particle detector: Spectropolarimetry of solar flares(*)

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Summary. — The progressive phases of three solar flares have been observed with THEMIS in July 2000, using the multiline spectropolarimetric MTR mode. A preliminary analysis of the characteristics of the polarization of the Hα and Hβ lines observed at the beginning of the progressive phase of one of these flares is presented.

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1. – Introduction

The relative contribution of ions and electrons to the flare energy budget is not well known yet. On the basis of the large hard–X-ray flux observed during the impulsive phase of solar flares, it has long been assumed that electrons carry practically the whole of the energy released. For some time, only high-energy protons above 1 MeV were detected, and only rather recently, has proton acceleration been assumed to contribute significantly to the global flare energetics [1-3].

The energy needed for protons to play a role in the solar-flare energy balance must be carried by low-energy protons ($E < 1$ MeV). These protons cannot be detected by γ-ray observations and other diagnostics are needed. The shape of chromospheric line profiles and impact polarization measurements are possible diagnostics tools [4, 5].

Impact polarization observations, together with hard–X-ray observations, can provide information on the nature and density flux of the beam particles [6, 7]. Most impact line

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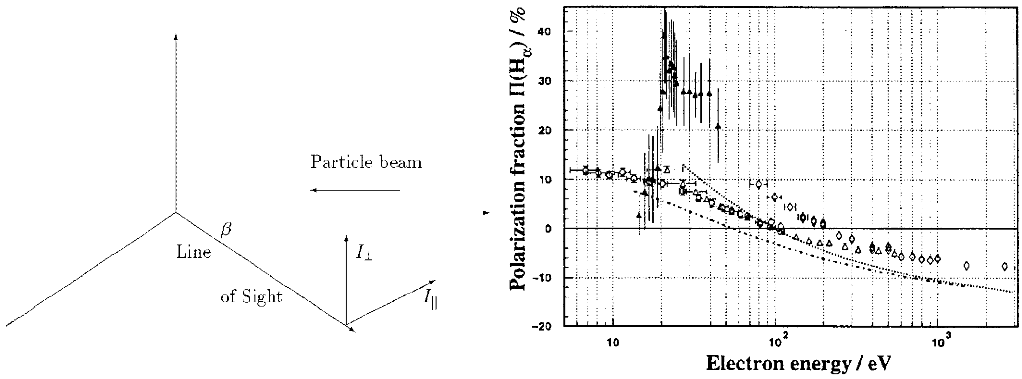

Fig. 1. – On the left: definition of impact line polarization. On the right: $P(90°, E)$ for the Hα line and for electron, proton or ion beams as a function of the electron equivalent energy in eV, taken from [10]. Experiments: electrons: dark triangles and diamonds; protons: empty triangles; He^+: circles. Theory: electrons: dashed line; protons: dot-dashed line.

polarization observations in solar flares have been limited to the Hα line [8]. The MTR mode on THEMIS offers the opportunity of multiline flare observations and we report here some preliminary results.

2. – Impact polarization

2˙1. *Beam of monokinetic particles.* – The monochromatic radiation emitted by an atom collisionally excited by a beam of monokinetic particles of energy E may be linearly polarized [9]. 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 β the angle between these two directions (fig. 1), the degree of linear polarization $P(\beta, E)$ is defined by

$$P(\beta, E) = (I_\parallel - I_\perp)/(I_\parallel + I_\perp)\,,$$

$P(\beta, E)$ is related to the maximum of polarization observable at 90° from the beam propagation direction, $P(90°, E)$, by

$$P(\beta, E) = P(90°, E)\frac{\sin^2\beta}{1 - P(90°,\, E)\cos^2\beta}.$$

As shown in fig. 1, $P(90°, E)$ is a function of the nature of the particle, electron, proton or ion and of the particle energy. $P(90°,\, E)$ changes sign for a turnover energy E_0. For the Hα line, E_0 is of about 200 eV for electrons and 200 keV for protons.

2˙2. *Monoenergetic particles with an axially symmetrical velocity distribution function* $f(v, \alpha)$. – Presumably the angular velocity distribution function of energetic particles will not be a delta-function. However, assuming an axially symmetrical velocity distribution function per unit solid angle $f(v, \alpha)$, where α is the angle between the particle velocity vector and the symmetry axis, it was found [11] that the preceding equation for $P(\beta, E)$

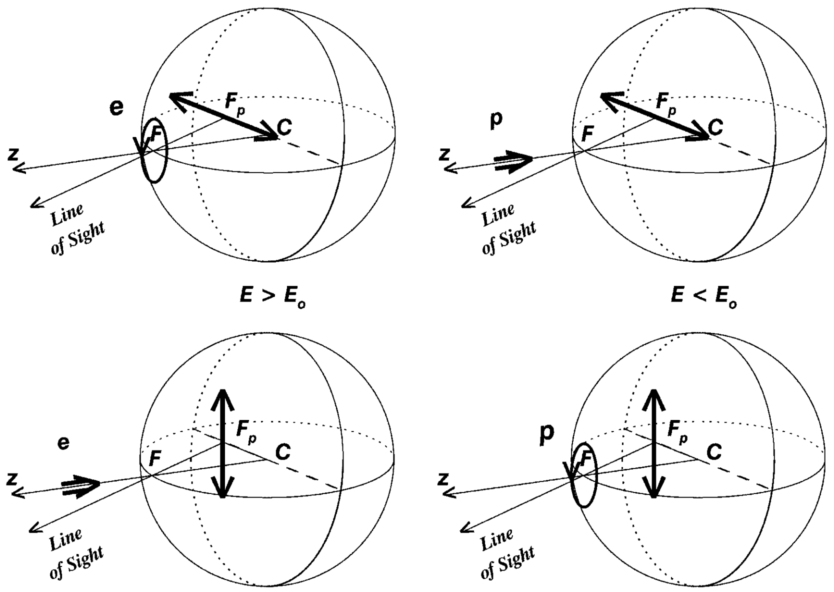

Fig. 2. – Possible origin of radial and tangential linear polarization: on the left electrons of energy $E > E_0$ and on the right protons of energy $E < E_0$. The double arrow and the small ellipse near the flare location F on the solar surface represent particle beams or particles moving horizontally. F_p is the projection of F on the solar disk.

is unchanged provided that β now represents the line of sight to symmetry axis angle and that $P(90°, E)$ is replaced by

$$\frac{P(90°,E)\,(3J_2 - J_0)}{2J_0 + P(90°,\,E)(J_2 - J_0)} \;\simeq\; P(90°,\,E)\left(\frac{3J_2}{2J_0} - \frac{1}{2}\right),$$

where

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

The correction factor $3J_2/2J_0 - 1/2$ is positive (negative) for propagation mainly parallel (perpendicular) to the symmetry axis.

2˙3. *Deriving the nature of the particles from the direction of polarization.* – Atmospheric bombardment by energetic particles with non-isotropic velocity distribution functions (v.d.f.) is expected to lead to the emission of polarized light with two possible directions of polarization differing by 90°. For a vertical axis of symmetry of the v.d.f., these privileged directions are respectively the radial flare to disk center direction and the direction tangential to the solar limb for a flare on the limb.

Conversely, *a priori*, depending on particle energy, two main particle travelling directions can explain a given observed direction of linear polarization, and that for both electrons and protons. Fortunately, beam electrons reaching the chromosphere with an energy below E_0 (≈ 200 eV) will have lost their directivity and would not generate polarized radiation, and protons with energy below 200 keV at chromospheric level will

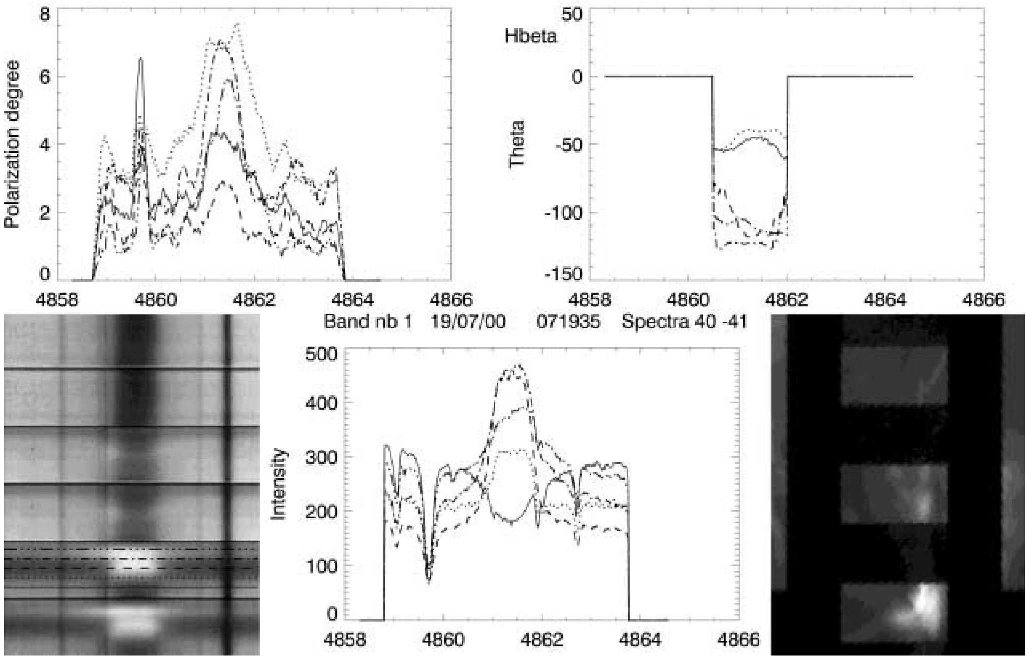

Fig. 3. – Spectral profiles of the intensity, degree of polarization and θ, the angle between the direction of linear polarization and the flare to disk center direction, for the Hα line. These profiles are spatially integrated over 2 arc second along the spectrograph slit in five regions. The same representation is used for all profiles and for the positioning of the spatial cuts on the spectrogram at bottom left. A Hα picture of the field of view is at the bottom right.

presumably dominate over the high-energy part of the proton energy distribution spectrum. Then, as illustrated in fig. 2, only two possibilities are left to explain a given observed direction of polarization:

– a radial direction of polarization could be due either to low-energy protons moving predominantly in the vertical direction or to high-energy electrons moving horizontally.

– A tangential direction of polarization could be due either to low-energy protons moving horizontally or to high-energy electrons moving predominantly in the vertical direction.

Other complementary data, especially hard–X-ray observations, which detect high-energy electrons, would help to discriminate between these possibilities.

3. – THEMIS observations

THEMIS, as a polarization-free telescope, is well suited to linear polarization measurements. Moreover, the MTR mode allows multiline spectroscopy. Four lines were simultaneously observed, the Hα, Hβ, Na D_1 and Na D_2 lines. A grid at the polarimeter's entrance in F1 allows easy separation, without additional optics, of the extraordinary and ordinary beams that carry the $I + S$ and $I - S$ signals, where S is a given Stokes parameter (U, Q or V) [12]. The field of view is divided into three bands of 16 second of arc separated by 16 second of arc. The progressive phases of three solar flares were

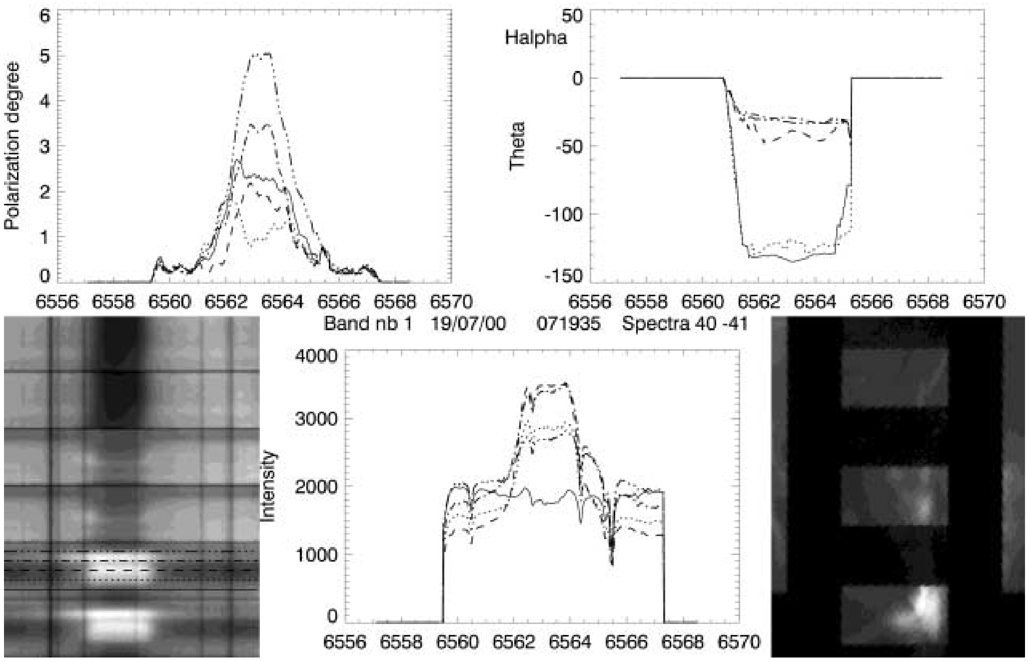

Fig. 4. – Same as fig. 3 for Hβ.

observed in July 2000. We report here some characteristics of the Hα and Hβ lines in a bright flare kernel at 07:19:35 UT, near the maximum of soft–X-ray emission, of the July 19th 3N flare in AR9087 (S21E12).

As shown in figs. 3 and 4, the lines observed are linearly polarized with a polarization degree that reaches 5 to 7 per cent. The orientation of the polarization at five positions along the slit is not distributed randomly but shows clearly two preferred directions. For Hα these directions are at 35° (±7°) and 125° (±7°) from the flare to disk-center direction. These angles differ by 90°. For Hβ the polarization directions are at 45° and 120° from the flare to disk-center direction, differing by 75°. The about 30° to 40° deviation from the radial and tangential directions can both be interpreted as due to the inclination along the local vertical of the lines of forces followed by the particles.

For three positions, the polarization is close to radial for Hα and to tangential for Hβ, that is formed deeper, and *vice versa* for the two others. Consequently, there is a nearly 90° change in the direction of polarization. It is worth noticing that the directions of polarization of the Na D2 line, formed still deeper, *i.e.* into the high photosphere below, are found to be close to the Hβ polarization directions.

Unfortunately no hard–X-ray observation is available for the flare under study. So we cannot be certain of the presence or absence of accelerated electrons. A model where beams penetrate into the atmosphere and where the inclination on the solar vertical of particle velocities is expected to increase with depth due to mirroring is the most natural one in order to explain the observed changes in polarization direction. With such model, proton beams would be required for the three cases where the Hα polarization is almost radial and electron beams for the two other cases.

Another possibility is that mirroring takes place rather at the Hα formation level and that escaping particles penetrate mostly vertically into the Hβ formation region. This model leads to the similar conclusion that both types of particles, electrons and protons, are needed. But, this time, a radial (tangential) direction of polarization would require electrons (protons).

4. – Conclusions

Just preliminary results have been presented above, based on a very limited sample and in the absence of hard–X-ray measurements. They confirm the presence in the lower atmosphere of non-thermal particles during the flare progressive phase. Indeed the analysis of the full data set must be pursued. In future, in order to check the impact polarization signature of high-energy electrons, the impulsive phase of a few solar flares has to be catched.

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