SOLAR ORIGIN OF NEAR-RELATIVISTIC IMPULSIVE ELECTRON EVENTS

M. Pick[1], D. Maia[2], S. J. Wang[3], A . Lecacheux[1] and S. E. Hawkins III[4]

[1] *LESIA, UMR 8100 CNRS, Observatoire de Paris-Meudon,Meudon, 92195, France*
[2] *CICGE, Observatório Astronómico Prof. Manuel de Barros, Faculdade de Ciências da Universidade do Porto, 4430-146 Vila Nova de Gaia, Portugal*
[3] *National Astronomical Observatories, Chinese Academy of Sciences, Beijing, 1000, P. R. China*
[4] *The Johns Hopkins University, Applied Physics Lab, Laurel, Md 20723, USA*

ABSTRACT

There is increasing evidence suggesting that coronal acceleration supplies at least part of the particles observed during solar energetic particle events, yet coronal processes tend to be mostly disregarded in these studies. This is often due to the fact that the coronal restructuring in the early development of the associated flare and/or coronal mass ejection event is extremely fast (on the order of a few minutes) and can encompass most of the solar disk, thus requiring a full disk solar imager with very high time-cadence, and wide spectral coverage. An important subset of the energetic particle events are the near-relativistic impulsive electron events detected near Earth: their onsets can be traced back to a release time in the low corona with accuracies on the order of a couple of minutes. We investigate a series of impulsive electron events from 1998 to 2001 using energetic electron data measured in situ by the Electron, Proton, and Alpha Monitor (EPAM) experiment on the Advanced Composition Explorer (ACE) spacecraft, and radio coronal observations from the Nançay Radioheliograph, the Decametric Array from Nançay and the WAVES experiment on the WIND spacecraft. EPAM measures electrons in the energy range from 40 to 300 keV over a wide range of look directions and with better than 1 minute time resolution, while the Nançay radioheliograph provides images of the solar corona at 5 different frequencies with time cadence of 8 images per second and per frequency. This study focuses on the events which correspond to a delay, between the inferred injection times of the electrons at the Sun, and the electromagnetic emissions from flares, of at least 5 minutes. Radio signatures are found near the estimated time of the electron release for each of the events. The timing and spectral characteristics of the radio emissions, when compared with the properties of the particles seen at EPAM, strongly support an acceleration process in the corona but at highly variable heights from one event to the other.

INTRODUCTION

Interplanetary electron beams can be detected in situ by experiments on board spacecraft, but also remotely by the type III radio emissions that trace their progression along open magnetic field lines. Assuming that the electrons detected in situ, and the electrons at the origin of type III emission, are part of the same population, then one would expect that the time between the electromagnetic signature at a few MHz, and the onset of the impulsive electron event, measured at a near-Earth spacecraft, should correspond to the travel time for a distance of about 1.2 AU. In fact, the onsets of in situ impulsive electron events were found to be associated with radio type III bursts (Lin, 1985). Recent work, however, has revealed that this association is more complex than previously thought. At energies above 25 keV, many of the impulsive events show delays from a few minutes up to half an hour between the inferred injection time at the Sun, and the type III burst or flare signatures (Krucker et al., 1999; Haggerty and Roelof, 2002). These results were used as evidence for the existence of two different electron populations associated with impulsive electron events: one related to flares at the origin of the type III emission, and another produced later at higher energies. The open question is obviously the accelerating mechanism for this second class of electrons.

Krucker et al. (1999) found that EIT coronal waves were observed for roughly 3/4 of the delayed electron events. They suggested that these events are more likely related to the propagating coronal wave than to the flare phenomenon itself. They left open the question whether or not the moving wave front is responsible for directly accelerating the particles, or alternatively for triggering other phenomena, far from the flare site, that would lead to the particle release. Haggerty and Roelof (2002) suggested that the electrons that produce type III radio bursts below 14 MHz, have energies of only a few keV, and that escaping near relativistic electrons are accelerated by an out-going shock, launched near the time of the radio emission, and are released at a radial distance around 2-3 solar radii. By finding a correlation between the delays and the velocity of coronal mass ejections (CMEs) associated with these events, Simnett et al. (2002) proposed that CME-driven shocks are responsible for the acceleration of impulsive solar electrons at energies above 25 keV.

On the other hand, Maia et al. (2001b), demonstrated for one flare/CME event, July 14, 2000, that electrons can be accelerated and released far away from the flare region. They proposed that this acceleration is due to large scale magnetic restructuring (probably triggered by the interaction of coronal waves) of magnetic structures during the CME development and its lateral expansion.

In this study, we have investigated the coronal and interplanetary radio emission associated with impulsive near-relativistic electron events. The events are taken from the list in Haggerty and Roelof (2002). The present analysis differs from the previous one on two points: i- Radio spectral observations cover a large frequency range, from dm to km wavelengths, and consequently a large range of altitudes; ii- the locations of the radio sources are provided at decimeter-meter wavelengths.

THE OBSERVATIONS

The energetic electron events were observed by the EPAM instrument aboard the ACE spacecraft which measures the 38-315 keV energy range (Gold et al., 1998). The WIND/WAVES experiment provided solar radio emission in the frequency range from 14 MHz to 20 kHz (Bougeret et al., 1995). Observations at decameter wavelengths were obtained by the Nanȩy Decameter Array, DAM, operating in the frequency range 20-70 MHz (Lecacheux, 2000). The Multifrequency Nançay Radioheliograph, NRH, provided images of the radio bursts at five frequencies (432 MHz-150 MHz; Kerdraon et Delouis, 1996). Observations of the coronal features associated with the radio events were obtained with the SOHO Large Angle Solar Coronagraph (LASCO; Brueckner et al., 1995).

DATA ANALYSIS

Data analysis was performed for 11 events for which complete spectral coverage and NRH imaging observations were available. Five electron events were associated with a radio emission exhibiting a complex spatial, spectral and temporal evolution. They corresponded to "delays" of at least 5 minutes (3 of them with delays longer than 10 min). The other six events corresponded to delays shorter than 5 minutes and were associated with type III burst groups. This study summarizes preliminary results on the set of events with delays of at least 5 minutes. The comparison of the radio emission observed by the NRH, the DAM and WAVES spectrographs was systematically performed for each event. This comparison is illustrated for three of the events showing delays over 5 minutes (18 February 2000, 31 May 1999, and 1 May 2000).

The procedure for selecting the events and for identifying the electron onsets are carefully explained in Haggerty and Roelof (2002). To simultaneously follow the changes in intensity, and position, of the sources seen in the NRH images, we will use one-dimensional dynamical plots. These are obtained by integrating the NRH solar images in the north-south or the east-west directions, and displaying the corresponding one-dimensional scans in sequence, as a function of time. This is shown in Figures 2, 3 and 6. Note that a source which will be located for example at the equator and at the west or east limb will correspond to $\pm$ 1 in the east-west NRH plots, whereas, a source located at the north or south pole will correspond to $\pm$ 1 in the south-north NRH plots.

31 May 1999

The event on 31 May 1999, presents a delay, between the onset of type III emission and inferred electron release time, exceeding 10 minutes. As shown in the LASCO/NRH composite in Figure 1 the event is associated with radio

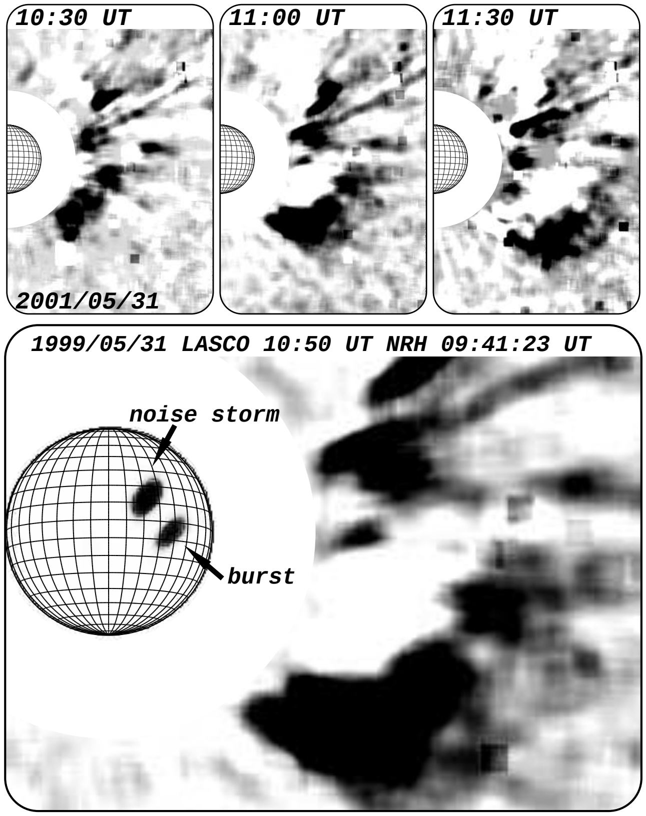

Fig. 1. 31 May 1999. A faint CME (as expected for an event near Sun center) is seen moving outward in the LASCO C2 running difference images on the top. On the bottom, a composite image shows the position of the radio sources at 0941:23 UT superposed on a LASCO C2 image of the CME at 1050 UT.

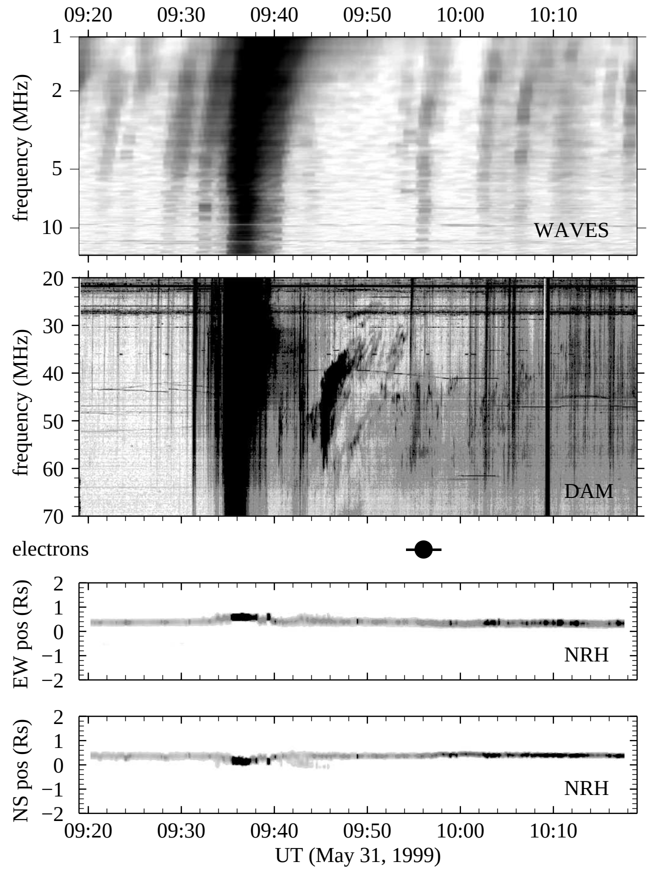

Fig. 2. Comparison of the radio emission observed by the NRH radioheliograph (bottom), the DAM (middle) and WIND (top) radiospectrographs. The dot with the horizontal bar (estimate of the error) indicates the electron injection time at the Sun, inferred from the onset time at the Sun for electrons with energies above 100 keV.

sources relatively close to the Sun center. The associated CME is rather faint and hard to follow in LASCO images. The event presents some remarkable spectral features in the metric/decametric wavelength range. Figure 2 displays the comparison between the east-west scan at 164 MHz, integrated to 10 sec., the DAM and the WAVES spectra. This figure shows that the metric type III burst group observed by the NRH (also at higher frequency up to at least 327 MHz) coincides in time with the type III bursts seen in the DAM and WAVES spectra. This is followed by a second phase of activity, characterized by a noise storm enhancement at dm-m wavelengths which corresponds at decametric/kilometric wavelengths to a type III storm. These observations firmly show that the electrons propagated from the corona to the interplanetary medium along open magnetic lines. The NRH images, show that the source of metric emission is located at a position close but distinct from the position of the outburst. The onset of the electron event coincides with the onset of this second phase.

Similar radio events were observed during the SMM mission (Kerdraon et al., 1983). The onset or enhancement of of noise storms was found to be systematically associated with a region of coronal magnetic reconfiguration revealed by distinct white light changes coinciding with the location of the radio source.

18 February 2000

Figure 3 displays the comparison between the east-west scan at 164 MHz, the DAM and the WAVES spectra. The WAVES type III burst coincides in time with a meter outburst and a complex DAM event. This event includes a type II burst which appears at 09:24 UT at 70 MHz, reaches around 09:28 UT an altitude corresponding to the plasma level at 40 MHz (or the harmonic, unlikely for this event) and then stops abruptly. In this case, the NRH profiles at 164 MHz, don't show the overlying 40 MHz feature. This burst is followed by a secondary type II like

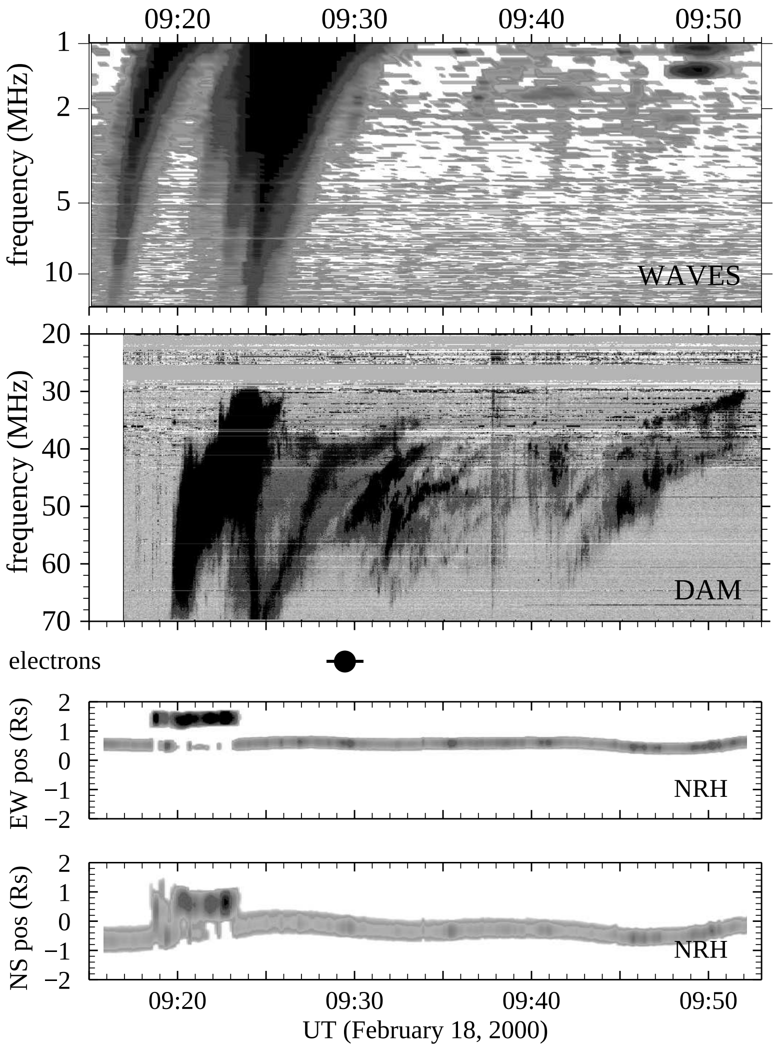

Fig. 3. Comparison of the radio emission observed by the NRH radioheliograph (bottom), the DAM (middle) and WIND (top) radiospectrographs. The 20-30 MHz frequency interval in the DAM spectrum was cut on this day by a filter as a protection against high interferency levels. The dot with the horizontal bar (estimate of the error) indicates the electron injection time at the Sun, inferred from the onset time at the Sun for electrons with energies above 100 keV.

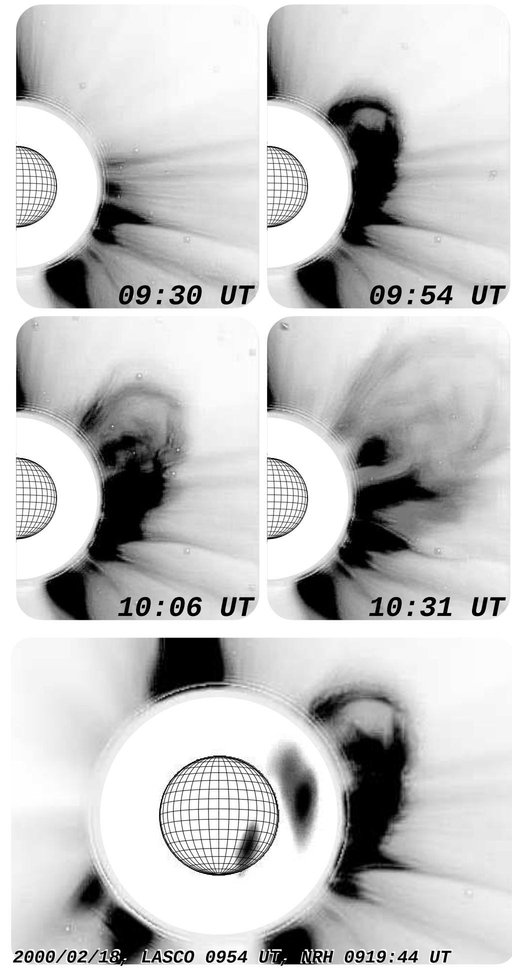

Fig. 4. 18 February 2000. CME development as seen by the LASCO C2 coronagraphs, with an image at the bottom which is a composite of a coronagraph image superimposed on one image of the NRH at 09:19 UT

burst, exhibiting three spectral lanes and a slower drifting rate. Another conspicuous feature in the same frequency range is the presence of at least one horizontal feature preceding the type II burst. This feature is rather similar to features described by Reiner et al. (1999). They attributed these emissions to electrons moving in an highly disturbed medium. The inferred release time of the electron event coincides with the sudden change in the DAM spectrum and the appearance of the secondary type II burst. Subsequent activity, around 09:40 UT exhibits a similar decametric spectral pattern. A likely interpretation is that the electron acceleration is due to the interaction of a shock wave with a coronal region leading to magnetic flux interaction and production of a secondary shock as previously reported (e.g. Pick et al., 1998, Pohjolainen et al., 2001). If we assume that the first type II burst was emitted at the plasma frequency, the height of the interaction region near 40 MHz can be roughly estimated to be 1.8 Rs from the Sun center (using two times the Newkirk model).

A CME was also associated with this event. Figure 4 displays a composite image obtained by the NRH at 164 MHz and later on by LASCO. (Note the presence of a noise storm in the southern hemisphere). The meter radio source is complex. Both the radio source seen at 0.5 Rs at 09:19 UT and the CME have a similar projected lateral

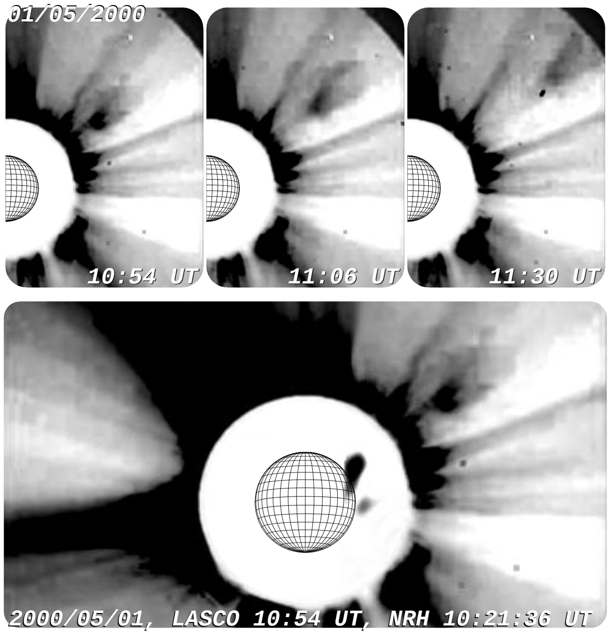

Fig. 5. The 1 May 2000 event is related to a very narrow feature, seen in these LASCO C2 images moving outward with a velocity about 1330 km/s. On the bottom, the sources of radio emission at 10:19 UT are superimposed on a LASCO C2 image at 10:54 UT. The northern radio source moves outward with a velocity about 1500 km/s.

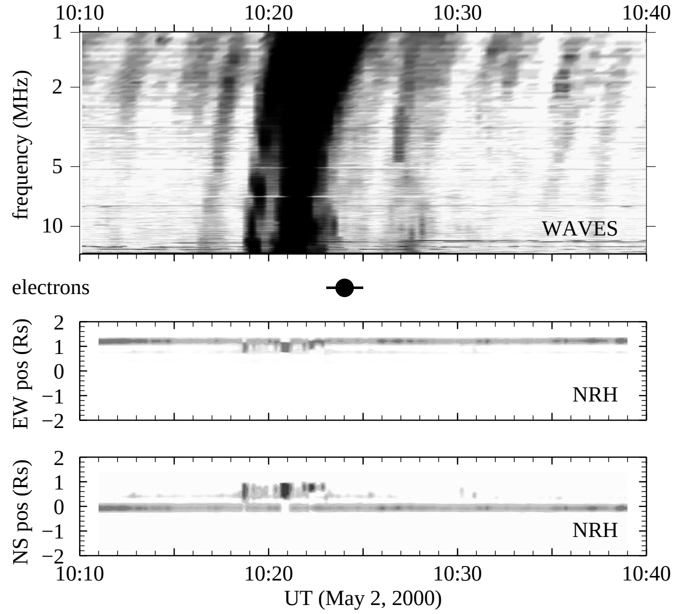

Fig. 6. Comparison of the radio emission observed by the NRH (bottom) and WAVES. The dot with the horizontal bar (estimate of the error) indicates the electron injection time at the Sun, inferred from the onset time at the Sun for electrons with energies above 100 keV.

extent. We then conclude that, around this time, the CME has already reached its full angular extent. The CME was followed in C2 and C3 field of view and moved with a constant velocity of 898 ($\pm$ 18) km/s. At 09:28 UT, it already reached an estimated height of at least 2.3 Rs from Sun center, higher than the altitude of the interaction region. These observations support the idea that the region of electron coronal acceleration lies behind the leading edge of the CME, in agreement with former results (e.g. Maia et al., 2000b).

1 May 2000

The event on 1 May 2000, is a somewhat weaker event, with no outstanding spectral features, other than an interplanetary type III burst. The delay between the type III emission (at about 10:19 UT) and inferred electron onset time at the Sun is of only about 5 minutes. This event is not accompanied by a typical CME; it is associated with a fast-moving (projected velocity of 1340 ± 70 km s^{-1}) narrow feature seen in the LASCO images in Figure 5. The event shows an interesting feature in metric wavelength radio images: a moving outward radio source, at about the same position angle as the C2 LASCO feature, and with a velocity about 1470 km s^{-1}, and extrapolating well into the height-time curve of the C2 narrow feature. The present observations are consistent with a release of energetic electrons from the corona, in the region where magnetic reconnection ejects upward the moving radio and C2 LASCO features. This event was also studied by Kahler et al. (2001) who were concerned about energetic ions rather than electrons. They drew a similar conclusion on the association between the LASCO " mini-CME", in their own language, and this impulsive SEP event.This event is also somewhat reminiscent of an event discussed in Maia at al. (2001a), who have reported on a delayed event, on November 28, 1997. From LASCO C1 images, available for the November 28, 1997 event, Maia et al. (2001a) showed that the event was related to changes occurring in a very narrow region in the low corona, and that a narrow blob-like feature was ejected from that region. EPAM detected a relatively strong impulsive electron event.

CONCLUSION

Radio signatures in the corona near the time of the electron release at the Sun were found for the 5 events. The source of quasi-relativistic electrons appears to be associated with reconfiguration of coronal magnetic field during flare/CME events. The present study suggests two kinds of restructuring: the first one could correspond to interaction between the coronal structures and the passage of some disturbance as a coronal wave or the CME bow shock; we cannot exclude an accelerating process by secondary shock following the interaction. The second one could be attributed to magnetic reconnection during newly formed streamers following the production of a CME. These observations also show that electrons can escape along open field lines toward the IP medium. The coronal altitude of the acceleration region is highly variable from one event to another one. Radio imaging and spectral information, in the meter-decameter wavelength range, gives the most direct evidence for these interactions. Detection of the associated radio signatures requires broad spectral frequency and imaging observations.

ACKNOWLEDGEMENTS

SOHO is a joint mission of international collaboration between ESA and NASA. D. Maia was partially supported by Fundação para a Ciência e Tecnologia under grant SFRH/BPD/5521/2001 and the program ESO/FNU/43776/2001. We acknowledge D. Haggerty for his help and the referees for their helpful comments.

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E-mail address of M. Pick monique.pick@obspm.fr
Manuscript received 22 November 2002, revised 28 January 2003, accepted 04 February 2003