Chin. J. Astron. Astrophys. Vol. 3 (2003), No. 4, 381–390
(http://www.chjaa.org or http://chjaa.bao.ac.cn)

Chinese Journal of Astronomy and Astrophysics

Solar Partial N-burst*

Zong-Jun Ning[1], Yu-Ying Liu[1], Qi-Jun Fu[1] and Fu-Ying Xu[2]

[1] National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012
[2] Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008

Received 2003 January 10; accepted 2003 April 2

Abstract We present a new sub-class of type III solar radio burst at the high frequencies around 6.0 GHz. In addition to a descending and an ascending branch on the dynamic spectrum, it has an inverted morphology different from the simple type U-burst. We call it "partial N-burst" because it is interpreted as the known N-burst minus its first branch. The partial N-burst presented here was detected among a reverse slope type III (RS-III) burst group prior to the type V solar radio continuum and was simultaneously recorded by two spectrometers at the National Astronomical Observatories, Chinese Academy of Sciences (NAOC, 5.20–7.60 GHz) and at Purple Mountain Observatory (PMO, 4.50–7.50 GHz) on 1999 August 25. After the N-burst and M-burst, the partial N-burst is a third piece of evidence for a magnetic mirror effect in solar radio observation, when the same electron is reflected at a pinched foot of a flare loop.

Key words: Sun: radio radiation — Sun: magnetic fields

1 INTRODUCTION

Solar radio type III bursts are interpreted as being produced by electron beams moving out of the corona along open field lines at a speed of about c/3 (Wild 1950). They appear as an emission that rapidly drifts toward lower frequencies on the dynamic spectrum. This kind of bursts is generally called ordinary (or normal) type III bursts, and their negative frequency drifting rate is called ordinary or normal drift. In contrast, reverse slope type III bursts (RS-III), with positively drifting dynamic spectra, are attributed to electron beams propagating downward along magnetic lines to the higher density corona (Sawant et al. 1994; Aschwanden et al. 1995; Bastain et al. 1998), and the positive rate is called reverse slope (or abnormal) drift. At frequencies above 1000 MHz, the reverse slope type is more usual than the ordinary type (Melendez et al. 1999).

In some cases, the burst starts as an ordinary type burst, then the drift rate gradually changes from negative through zero to positive. This type of burst is so-called inverted-U burst (or simply U-burst) after its appearance on the dynamic spectrum. Type U burst is a sub-class

* Supported by the National Natural Science Foundation of China.

of type III bursts, since it is interpreted as an emission produced by an electron beam travelling along a closed magnetic arch from the first foot point to the second foot point. If the magnetic tube is pinched at the second foot point, then electrons with not too small pitch angles are reflected and may then generate a normal type III burst on their way up. We then have an N-burst (Caroubalos et al. 1987; Hillaris et al. 1988; Karlicky et al. 1996). Sometimes, if the electrons are mirrored backward to the first foot from the second one, a second U-burst after the first one comes into being on the dynamic spectrum. The combination of these two consecutive U-bursts together is known as an M-burst (Ning et al. 2000) If the tube is pinched also at the first foot, then the beam electrons might be captured for a period between the two mirrors and we have a type V solar radio burst (Weiss et al. 1965).

We present a new burst type that was simultaneously detected on 1999 August 25 by two spectrometers located more than 1000 km apart, one at the National Astronomical Observatories, Chinese Academy of Sciences (NAOC), the other at Purple Mountain Observatory (PMO). In contrast to a U-type emission, the present burst starts with a RS-III burst. Then its drift rate makes a sharp turn, changing quickly from positive through zero to negative. We call this burst a "partial N-burst" because it could be interpreted as consisting of the second and third branches of an N-burst. In fact, this type of burst is not rare. Wang et al. (2001) reported centimetric type N and type M bursts. Xu et al. (2001) reported similar spectral phenomena at waveband 4.5–7.5 GHz. For finding such phenomena microwave spectrometers with a high temporal and spectral resolution and high sensitivity are necessary.

In Sect. 2, we describe the observations, and we analyze the data and burst properties in Sect. 3. In Sect. 4, we discuss a possible model and provide observational lines of evidence for the partial N burst. Our conclusion is stated in Sect. 5.

2 OBSERVATIONS

In order to study in detail solar radio bursts at the high frequencies of decimetric and microwave bands, a broad band radio spectrometer was developed by the solar radio astronomical community of China (Fu et al. 1995). It consists of five separate components covering the frequency ranges of 0.70–1.40 GHz, 1.00–2.00 GHz, 2.60–3.80 GHz, 4.50–7.50 GHz and 5.20–7.60 GHz. Since July 1999, the 5.20–7.60 GHz spectrometer has been put into operation at the NAOC. It has a frequency resolution of 20 MHz and a time resolution of 5 ms, while allowing high sensitivity and high accuracy measurement of circular polarization. At the same time, another spectrometer covering 4.50–7.50 GHz, (the coverage having been expanded from an original coverage), was working at PMO. This spectrometer has a time resolution of 5 ms as well and a frequency resolution of 10 MHz. It detects total intensity but not polarizations.

On 1999 August 25, these two spectrometers simultaneously recorded a cluster of RS-III bursts followed by a microwave type V continuum. An overview of this radio event recorded by the NAOC spectrometer is given in Fig. 1. This event spilled over the whole frequency range of 5.20–7.60 GHz of the NAOC spectrometer, and lasted from 0133 UT to 0142 UT. Meanwhile, according to the Solar-Geophysical Data reports, there was a M3.6/1N flare detected by GOES in the NOAA Region 8674 located at S28E21. The M3.6 flare in SXR lasted from 0132 UT to 0140 UT and reached maximum at 0136 UT. This flare was also detected in H_α by LEAR at the same location from 0135 UT to 0156 UT, and also with a maximum at 0136 UT. In addition, metric type V solar radio bursts were detected by LEAR and PALE over the range 30–80 MHz (or 25–75 MHz) from 0133 UT to 0144 UT. Meanwhile, type III bursts were recorded by CULG and HIRA in the frequency range 18–430 MHz (or 25–420 MHz) from 0133 UT to 0140 UT and type 4(S/F) radio bursts were observed by LEAR and PALE at the fixed frequency 2695 MHz from 0134 UT to 0135 UT. At another working frequency, 8800 MHz, a short type 8(S) burst was recorded by LEAR and PALE around 0135 UT. Furthermore, according to the NAOC observations, the radio event stayed unpolarized over the whole frequency range all the time.

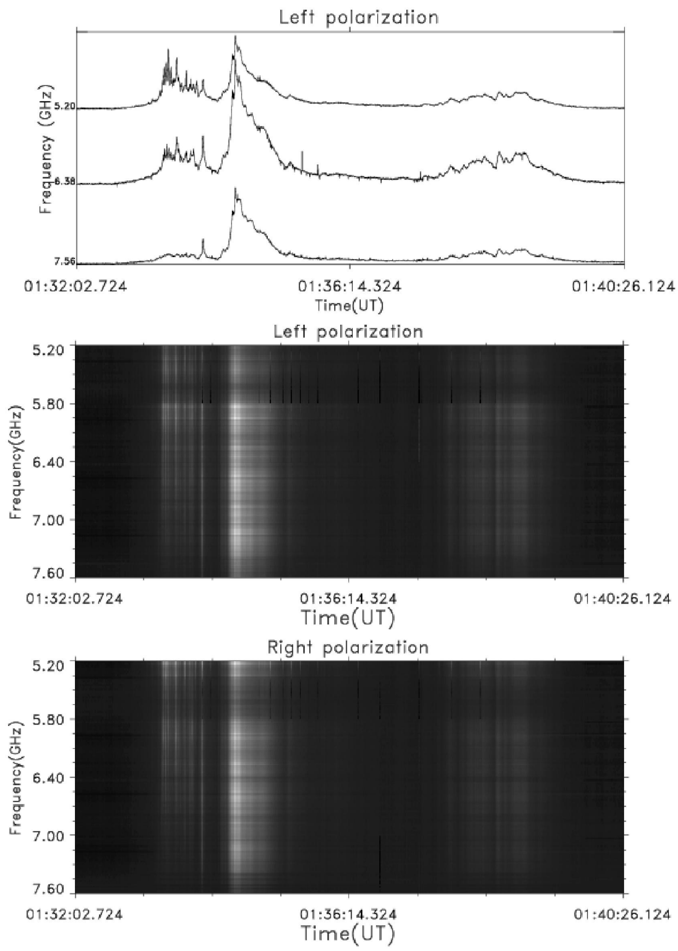

Fig. 1 Time profile and dynamic spectrum of the solar radio event recorded by the NAOC spectrometer (5.20–7.60 GHz) on 1999 August 25. A cluster of type III-RS is detected from 0133 UT to 0135 UT, and is followed by a microwave type V continuum for about 7 minutes.

3 DATA ANALYSIS

3.1 Microwave Type V Bursts

Observational properties of metric type V bursts are usually thought to be a diffuse continuum with a moderate duration following or associated with a type III burst group (Wild 1959). We call this event shown on Fig. 1 a "microwave type V burst" because of the same morphological characteristics as metric type V event: a broad diffuse continuum following an RS-III group and associated with a solar flare. The RS-III group (more than 10 individual bursts) lasting from 0133 UT to 0135 UT prior to the microwave type V continuum, had reverse slope drifting rates ranging from 1.54 GHz s^{-1} to 7.70 GHz s^{-1}, which is one to two orders higher than typical drifting rate of ordinary metric type III bursts. As shown in Fig. 1, the RS-III intensity decreased with increasing frequency, and some of the bursts faded away on certain frequencies around 7.60 GHz. The following microwave type V continuum occurred on a broad band and with a moderate duration of about 7 minutes. According to the observations of LEAR and PALE, this microwave event was very weak at the frequency of 8800 MHz with a short duration around 0135 UT .

3.2 Partial N-burst

High resolution dynamic spectra reveal two types of fine structures with special morphology—microwave type U-burst and partial N-burst occurring in succession among the RS-III group preceding the microwave type V continuum. Figure 2 shows the dynamic spectrum of the present partial N-burst. Like a type U-burst, it consists of a descending and an ascending branch, but it presents an inverted morphology to the simple U-burst on the dynamic spectrum. The present partial N-burst has a narrow bandwidth from 5.21–6.20 GHz, and a total duration (separation between the descending and ascending branches) of less than 1 second. The turnover point ranges from 6.04–6.10 GHz. The time intervals covered by the descending and ascending branches of the partial N-burst are 01:34:44.463–01:34:44.704 UT and 01:34:44.704–01:34:44.816 UT, respectively. According to the NAOC observations, the sense and degree of polarization are the same for the two branches of the partial N-burst, which was almost unpolarized all the time.

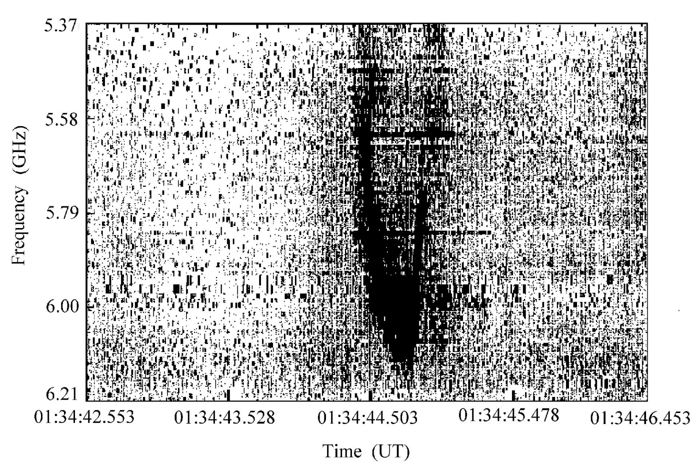

Fig. 2 Dynamic spectra of the partial N-burst recorded by the PMO spectrometer at 4.50–7.50 GHz on 1999 August 25.

4 DISCUSSION

According to the observations shown in Fig. 2, it is very likely that the presented burst is a mirrored burst. As mentioned above, we call this burst a partial N burst: for it consists only of the second and third branches of an N-burst.

4.1 Solar Radio N-burst

Previous observations have given some examples where a simple U-burst is immediately followed by a third ascending branch (negative frequency drifting), suggesting the capital letter N on the dynamic spectrum. This burst type is called N-burst. A detailed analysis of the time profiles showed that the duration of the beam emission steadily increases in time along the three successive branches of an N-burst, suggesting that the event was produced by the same electron beam and that the burst actually traces reflections on magnetic mirrors near coronal loop foot points (Caroubalos et al. 1987). Subsequently, the same conclusion on the much broader branch that follows the N-burst was drawn from numerical simulations (Hillaris et al. 1988; Karlicky et al. 1996). For example, the branch 3 (upward, decreasing frequency) is broader than branch 2 (downward, increasing frequency), which, in turn, is broader than branch 1 (upward decreasing frequency) on the given frequency. This viewpoint was thought to be the observational feature that distinguishes an N-burst from a U-burst being simply followed by another, unrelated normal type III burst (Caroubalos et al. 1987).

According to the above understanding of N-burst, the ascending branch of the present burst is expected to be much broader than the descending branch. However, this is in conflict with the observations shown in Fig. 2. Figure 3 shows the evolution of the duration (measured from the time profiles of each frequency channel) of the two branches of the partial N-burst: the ascending branch is *narrower* than the descending branch. This fact led to the slope of linear regression from the descending to the ascending branch being negative ($\mathrm{d}D(t)/\mathrm{d}t < 0$), which contradicts the earlier conclusion of (Caroubalos et al.1987) that the duration regularly increases along the successive branches of an N-burst. Clearly, this is because the ascending branch decreases its duration with the peak time ($\mathrm{d}D_a(t)/\mathrm{d}t < 0$), but the slope of the linear regression of the descending branch is positive ($\mathrm{d}D_d(t)/\mathrm{d}t > 0$).

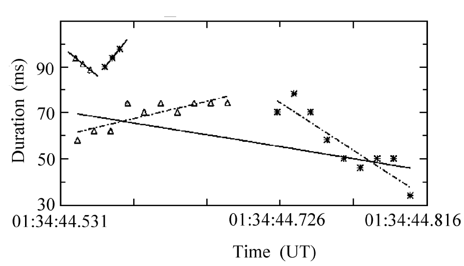

Fig. 3 Different durations D(t) of the two branches of the partial N-burst, (triangles for the descending branch, asterisks, the ascending branch).

4.2 Evidence of Partial N-burst

The contradiction above is due to collisions on the mirrored beam. As noted earlier, the partial N-burst appears among the RS-III bursts, the mirrored beam would be strongly colliding with, and intercepted by the downward beams traced by the other RS-III bursts, which is different from the single N-burst previously reported (Caroubalos et al. 1987). This collision is predominant during the whole mirror progress. On the other hand, the electrons which had been mirrored along the original path would collide with others which were mirrored lately in the same beam. Because there could be many electrons in the beam, the magnitude is much higher than in the numerical simulations (e.g., 20 test particles by Karlicky et al. 1996). So, the distribution of the mirrored beam may be changed by such collisions, which results in a shortening of the beam extension in time. Consequently the ascending branch decreases its duration with the peak time, and has a negative slope of in the linear regression in Fig. 3. Observationally, the ascending branch of the present partial N-burst is shorter than the descending one. On the other hand, the ascending branch gradually dies away just because of these collisions.

One piece of evidence for the mirror process is the continuity of the duration from the ending frequencies of the descending branch to the beginning of the ascending one. As shown in Fig. 3, the duration is continuous through the turnover point. This is because the beam extension keeps the same before and after the mirror reflection. Another observational, indirect piece of evidence is that the high resolution dynamic spectra revealed no other beam bursts around the descending branch.

4.3 Effect of Beam Velocity on the Frequency Drift

A third, but indirect piece of evidence for the mirror process is the different frequency drifting rates of the two branches. We measured an average rate of 3.6 GHz s^{-1} for the descending branch and one of 4.5 GHz s^{-1} for the ascending one. As shown on Fig. 2, the ascending branch is drifting more rapidly than the descending one. This is because of the different directions of propagation of the incident and mirrored beams. The angle between the beam and the observer is different in the two beams. Neglecting the reflection and scattering caused by density inhomogeneities, the apparent frequency drift is

$$\frac{\mathrm{d}f}{\mathrm{d}t} = \left(\frac{1}{v} - \frac{\cos\theta}{c}\right)^{-1} \frac{\mathrm{d}f}{\mathrm{d}s} \tag{1}$$

(Wild et al. 1959) (θ, angle between the beam and the observer; s, coordinate along the trajectory). As noted before, $\mathrm{d}f/\mathrm{d}s$ is the same in the incident and mirrored beams because they are moving along the same path in the loop. Although we are not able to measure it exactly, θ should change from an obtuse angle when the incident beam is travelling downward into the denser plasma layer (corresponding to a higher local plasma frequency) to an acute angle when the mirrored beam propagates backward along the same magnetic lines. Thus the factor $\cos\theta/c$ in Eq. (1) changes from a negative value for the descending branch to a positive value for the ascending branch and the drift rate of the ascending branch becomes larger than that of the descending branch. The incident beam velocity (v) might be of the same order as that of the mirrored beam.

Although the descending branch has an average rate of 3.6 GHz s^{-1}, Fig. 2 shows its drift rate is decreasing with increasing frequencies as well, especially at the frequency range 6.00–6.10 GHz. This is because the beam velocity v in Eq. (1) which is parallel to the magnetic lines, is gradually decreasing during the mirror process, and the velocity will be zero ($v = 0$)

at the reflected point (this we shall prove later). Thus, the descending branch is drifting more and more slowly. Finally, the drifting rate becomes zero at the turnover point where the beam electrons are being mirrored.

Therefore, the magnitude and direction of the beam velocity directly affect the drifting rates of the branches of the partial N-burst. This is proper to the beam mirror process.

4.4 Magnetic Mirror

Figure 4 shows the field configuration of a magnetic mirror where the field lines are converging. The field strength is increasing forward. When an electron moving into the mirror, if the magnetic field is stationary or approximately so, there will be two adiabatic invariants: the kinetic energy K of the electron and the magnetic moment μ of the current produced by the electron spiraling along the field lines,

$$K = K_{\|} + K_{\perp} = \text{const}, \tag{2}$$

$$\mu = K_{\perp}/B = \text{const}, \tag{3}$$

where $K_{\|}$ and $K_{\perp}$ are the parallel and perpendicular (to the magnetic field line) components of the electron kinetic energy K. From the formulas above, an electron will be reflected at the mirror if the field is strong enough. Because $K_{\perp}$ increases with increasing field B, when $K_{\perp}(= \mu B) = K$, we have $K_{\|} = 0$ or $v_{\|}$=0 (the component of electron velocity parallel with the field line, which is just the beam velocity), the electron will be reflected back. This is the mirroring process. From the dynamic aspect, the mirroring process basically results from the effects of the parallel component of the Lorentz force $\boldsymbol{f}$ acting on the electron.

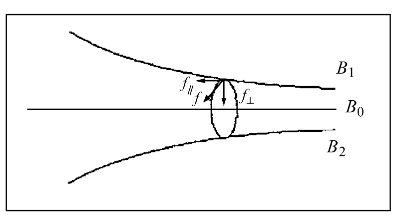

Fig. 4 Configuration of a magnetic mirror. The Larmor loop is in the instantaneously spiralling plane of the electron, $f_{\perp}$ and $f_{\|}$ are the components of the Lorentz force $\boldsymbol{f}$ perpendicular and parallel to the field line.

4.5 Electron beam life and magnetic field strength around the mirror point

We have identified the burst in Fig. 2 to be a partial N-burst, so plasma radiation mechanism is expected. For the present burst, in contrast to type U burst, the electron beam must propagate through a relatively dense medium (corresponding to the turnover point). In fact, as noted above, the beam can be quickly isotropized by Coulomb collisions in this high density medium unless certain different conditions are met. As a matter of fact, these collisions result in the RS-III burst group dying away with increasing frequencies. The collision time is given by

$$\tau_D = 3.1 \times 10^{-20} \left(\frac{v^3}{n_e} \right) \text{(s)}$$

(Benz et al. 1992), where $n_e(\text{cm}^{-3})$ is the electron density and $v(\text{cm s}^{-1})$ is the electron beam speed. The plasma frequency corresponds closely to the observed frequency for plasma radiation mechanism: from which we deduce the electron density around the source, $n_e \simeq 4.46 \times 10^{11} \text{cm}^{-3}$ at the local plasma frequency of 6.00 GHz. To achieve a lifetime $\tau_D \geq 0.070\,\text{s}$ (which is an average duration at the fixed frequencies of the descending and ascending branches) as required by the present observation on the partial N-burst, we estimate $v \simeq 10^{10}$ cm s$^{-1} \simeq \frac{c}{3}$.

The plasma parameter β, which expresses the ratio of the thermal to magnetic pressure, is given by $\beta = 3.47 \times 10^{-15} n_e T / B^2$. In order for the coronal plasma to be magnetically confined in the active region, $\beta < 1$. In the present case, we find that the magnetic field has to exceed 130 G when we postulate the source temperature to be $T = 10^7$ K. We can deduce $\frac{\sin^2 \alpha_0}{B_0} = \frac{\sin^2 \alpha}{B}$ from Eq. (2) (here, B_0 and B: magnetic field, α_0 and α: pitch angle of the electron), B and α are the local values at any point of the trajectory, but B_0 and α_0 are the values at the injection point of the electron (which is usually believed to be near the top of the arch). At the mirror point $\alpha = \frac{\pi}{2}$. In this case, the field strength is

$$B_{\text{mirror}} = \frac{B_0}{\sin^2 \alpha_0}\,.$$

If we assume $B_0 = 130$ G (the field strength around the top of arch) and the injected pitch angle $\alpha_0 = 80^\circ$, we can roughly estimate the field strength around the mirror point,

$$B_{\text{mirror}} \sim 135\text{G}.$$

Furthermore, we can deduce the electron gyroradius R_α at any point of the electron trajectory,

$$R_\alpha = 5.69 \times 10^{-8} v_\perp / B \leq R_{\text{mirror,max}} \simeq 4.2 \text{ cm}\,.$$

Here $R_{\text{mirror,max}}$ is the maximum gyroradius of the electron at the mirror point where the component $v_\perp$ of the velocity perpendicular to the field line reaches its maximum, equaling the beam velocity

$$v_\perp = v \simeq \frac{\text{c}}{3}\,.$$

The radiation close to the plasma frequency is strongly absorbed by inverse bremsstrahlung (free-free absorption). The optical depth τ of free-free absorption, which reduces the emitted intensity by a factor of $e^{-\tau}$ per unit path length, is given by (Dulk 1985)

$$\tau = 1.5 \times 10^{-17} T^{-3/2} \nu^2 \lambda_\perp\,,$$

where T [K] is the coronal temperature, ν [Hz] is the observed frequency. An exponential density decreasing along the path has been assumed with a transverse scale length $\lambda_\perp$ [cm]. This equation shows that the collision absorption depends strongly on the emission frequency, and plasma emission is more attenuated at high than low frequencies. For the present burst, the optical depth $\tau \simeq 1$ is expected for the radio emission propagating out from the source to the observer and we obtain

$$\lambda_\perp \leq 60\,\text{km}\,,$$

when $T = 10^7$ K again.

5 CONCLUSION

We have identified an example of a new sub-class of solar type III radio burst from simultaneous recordings by two spectrometers at NAOC and PMO on 1999 August 25. It consists of a descending and an ascending branch on the dynamic spectrum. We call it a "partial N-burst", meaning an N-burst without the first branch. We interpret it as consisting of the second and third branches of an N-burst of previously known type, i.e., it is an emission produced by the same electron beam before and after being mirrored around a pinched foot of the closed arch. Thus, the partial N-burst is the third piece of evidence, based on radio bursts, for a magnetic mirror effect on electron beams in the solar corona, after the known N-burst and M-burst (Caroubalos et al. 1987; Hillaris et al. 1988; Karlicky et al. 1996; Ning et al. 2000).

Nevertheless, the mirror process of this partial N-burst has to deal with a more complicated surrounding than in the numerical simulations previously documented (Hillaris et al. 1998; Karlicky et al. 1996). The mirrored beam has to be strongly colliding with other injected beams (downward directed) traced by an RS-III group, (this partial N-burst was found among an RS-III group). The collisions result in a shortening of the extension of the mirrored beam in time. Observationally, the ascending branch is not broader than the descending branch. Consequently, the linear slope between these two branches is negative. Because the number of test particles used in the numerical simulation is limited (e.g., Karlicky et al. 1996) and no other injected beams were assumed during the mirror process, the present observation of the partial N-burst is in conflict with the previous conclusion based on the numerical simulations of N-burst.

According to the PMO observation in Fig. 2, there are three observational, indirect pieces of evidence for the mirror process: (1) the duration continuity from the ending of the descending branch to the beginning of the ascending branch; (2) no other beam bursts around the turnover point; (3) the ascending branch drifting more rapidly than the descending branch. Although the evidence is not enough to *prove* the mirror process, the mirror process does seem capable of properly explaining the observed properties.

The injected beams tracing the RS-III group might be captured by the flare loop. In that case, all of the beams, both injected and mirrored, would collapse and mix with one another into a plasmoid. As mentioned above, the radiation from these trapped electrons (plasmoid) in the flare loop is thought to be a microwave type V burst (continuum) following the RS-III group on the dynamic spectrum. On the other band, the trapping process is critically dependent on the existence of the two mirror points and their altitudes. If they are situated below the base of the corona, the beam electrons would be damped by collision before reflection. Only when both mirror points are located at a high enough altitude, could the electrons give rise to a microwave type V burst. This condition implies that type V continuum should happen occasionally at the high frequency range. Theoretically, microwave type V burst ought to have a high frequency cutoff, corresponding to the plasma frequency of the mirror point. For example, the type V event might fade away around a frequency of 8800 MHz.

Clearly, the reflection interpretation is proper to the presented microwave type V burst, the mirror process can nicely account for the presented observations of the partial N-burst.

Acknowledgements It is a pleasure to thank Dr. De-Bang Lao and Dr. Guo Yang for supplying us with IDL software for data processing; we also thank associate scientists Hui-Rong Ji, Cong-Ling Cheng, Le-Ping Zheng, Zhi-Jun Chen, Wu-Jing Lu, Wang-Hu Su and other staff of the NAOC operating the spectrometers. This work is supported by National Natural Science Foundation of China under Nos. 49990451, 19973008 and G2000078403.

References

Aschwanden M. J., Benz A. O., 1995, ApJ, 438, 997
Baselyan L. L., Goncharov N. Yu., Zaitsev V. V., Zinichev V. A., Rapoport V. O., Tsybko Ya. G., 1974, Solar Physics, 39, 213
Bastian T. S., Benz A. O., Gary D. E., 1998, ARA&A, 36, 131
Benz A. O., Magun A., Stehling W., SU H., 1992, Solar Physics, 141, 335
Caroubalos C., Poquerusse M., Bougeret J. L., Crepel R., 1987, ApJ, 319, 503
Dulk G. H., 1985, ARA&A, 23, 169
Fu Q., Qin Z., Ji H., Pei L., 1995, Solar Physics, 160, 97
Hillaris A., Alissandrakis C. E., Vlahos L., 1988, A&A, 195, 301
Karlicky M., Mann G., Aurass H., 1996 A&A, 314, 303
Melendez J. L., Sawant J. S., Fernandes F. C. R., Benz A. O., 1999, Solar Physics, 187, 77
Ning Z., Yan Y., Fu Q., Lu Q., 2000, A&A, 364, 793
Poquerusse M., Bougeret J. L., Caroubalos C., 1984, A&A, 130, 10
Sawant H. S., Fernandes F. C. R., Neri J. A. F., 1994, ApJS, 90, 689
Wang M., Fu Q., Xie R., Duan C., 2001, A&A, 380, 318
Weiss A. A., Stewart R. T., 1965, Aust. J. Phys., 18, 143
Wild J. P., 1950, Aust. J. Sci. Res., Ser. A, 3, 541
Wild J. P., Sheridan R. V., Neylan A. A., 1959, Aust. J. Phys., 12, 369
Xu F., Yao Q., Meng X., Wu H., 2001, ChJAA, 1, 469