THE ASTROPHYSICAL JOURNAL, 547:1159–1166, 2001 February 1

A SOURCE OF ENERGETIC PARTICLES ASSOCIATED WITH SOLAR FLARES

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Received 2000 March 10; accepted 2000 August 28

ABSTRACT

Energetic particles produced at a solar flare event are an issue of great theoretical interest. A scenario involving magnetic field reconnection and newborn ions produced by ionization of neutral atoms in the lower corona is proposed by Wu. A series of two-dimensional hybrid simulations has been carried out to investigate this scenario further, and the results are presented in this paper. It is shown that under certain conditions the proposed process can produce protons with energies in the range of 10–100 MeV with a timescale of 10^{-4} to 10^{-3} s in a reconnection layer via the so-called ion pickup process. The acceleration process is sensitive to the ambient magnetic field. The maximum energy attainable is also discussed in terms of altitudes above the photosphere on the basis of a certain magnetic field model.

Subject headings: acceleration of particles — Sun: flares — Sun: magnetic fields

1. INTRODUCTION

One of the most fascinating issues in solar physics is concerned with the physical origin of the energetic particles generated at times of chromospheric flares. Discussions of observational results are extensively reported in the literature. Understanding the physics of the energization process poses a highly challenging theoretical task. Although research in this area has a long history, many issues are either still unsettled or are not understood at all. The fact of the matter is that this subject is an immensely complex topic.

The literature devoted to the theoretical discussion of relevant acceleration processes may be grouped into several major categories, which include (1) acceleration by a DC electric field (Holman 1985; Holman & Benka 1992; Tsuneta 1995; Litvinenko 1996), (2) stochastic acceleration (Smith & Brice 1964; Miller 1991, 1997; Steinacker & Miller 1992; Miller & Vinas 1993; Miller & Roberts 1995; Miller, Larosa, & Moore 1996; Roth & Temerin 1998; Kocharov et al. 1999), and (3) shock-related acceleration processes (Ellison & Ramaty 1985; Decker 1988; Krauss-Varban, Burgess, & Wu 1989; Zank & Gaisser 1992; Somov & Kosugi 1997; Tsuneta & Naito 1998; Berezhko & Donald 1999). The references cited here are mainly used as examples and are by no means complete. A comprehensive discussion of these acceleration processes and more detailed lists of references may be found in recent review articles by Miller et al. (1997) and Aschwanden (1999b). However, we point out that most of the theoretical discussions mainly deal with the electrons. *Few theories dedicated to very rapid acceleration of ions have been proposed. Observational results seem to imply that in a large impulsive flare event ions can be energized to a level of several hundred MeV on a very short timescale.*

Before proceeding further, we remark that the discussion in the present paper is concerned only with the acceleration of ions, rather than heating, in the lower corona. To be more specific, we are particularly interested in the production of flare-associated energetic protons with energies in the range of several tens to several hundred MeV.

To address the generation of these energetic particles, theoretical models have been suggested. Of course, any proposed scenario is subject to physical constraints. For example, it must satisfy a required timescale. Since an acceleration process is usually localized, the timescale is determined by the spatial size of the region where the acceleration takes place.

Admittedly, the spatial scales are often overestimated because of a variety of reasons. The essential point is that the relevant spatial scale must be consistent with the peculiar acceleration process. For example, a flare site may normally cover a spatial dimension of the order of 1000–10,000 km. If we suggest that energetic particles are attributed to shock acceleration, then the relevant scale length should be comparable to the thickness of the shock wave rather than the size of the flare site. Since the thickness of a collisionless shock is typically several ion inertial lengths, c/ω_{pi} (Tidman & Krall 1971), it is considerably smaller than the size of the flare site. In the lower corona where the plasma density may be assumed to be 10^9 cc^{-1} (Newkirk 1967; Zheleznyakov 1970; Aschwanden & Benz 1997), the spatial scale (several ion inertial lengths) is less than 1 km. In this case, to produce 100 MeV protons by shock acceleration would require a timescale of 10^{-5} s. This example is given only for the sake of discussion.

The purpose of the present paper is to discuss a new scenario that can lead to very efficient ion acceleration. The scenario encompasses two basic elements, namely, magnetic field reconnection and newly created ions produced by the ionization of neutral atoms. The basic physical notion will be discussed in § 2. Here, we remark on several points. First, it is not the purpose of the present paper to discuss the general physics of solar flares, although our discussion adopts the idea that magnetic field reconnection plays a key role in solar flares (e.g., Sturrock 1966, 1980; Heyvaerts, Priest, & Rust 1977). Second, the present discussion is a continuation and elaboration of the study initiated by Wu (1996) and Wu et al. (1998). The preceding papers placed emphasis on the physical concept, whereas the objective of the present discussion is to demonstrate by numerical simulation that the conjectured process is viable. Although in Wu et al. (1998) one-dimensional hybrid simulation has

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already been used to provide a qualitative and approximate discussion, it is desirable to study the problem with a simulation code that can describe a more realistic situation.

The structure of the paper is as follows: First, in order to make the discussion self-contained, we discuss some of the basic points and ideas in § 2. In § 3 we discuss the numerical study and simulation results. Subsequently, § 4 presents discussion and conclusions

2. BASIC CONSIDERATIONS

In this section we review some basic considerations. Since the notion is very different from the acceleration processes discussed in the literature, the following subsections are presented for the purpose of clarification so that the readers can obtain a better physical picture.

2.1. *Ion Pickup via Alfvén Waves*

In view of the fact that the plasma in the corona as well as in interplanetary space is basically collisionless, one would think that a moving plasma such as the solar wind could not pick up newly created ions that are nearly motionless in the same frame of reference. This issue was resolved in the mid 1980s in a series of theoretical studies (Winske et al. 1984, 1985) that were motivated by several experimental programs such as the AMPTE and *International Cometary Explorer* (*ICE*) missions, which were carried out to investigate newly ionized particles near the Earth and comets. The primary finding is that a fast-moving plasma can indeed pick up motionless newborn ions via pitch-angle scattering by enhanced Alfvén waves. A review of the early theories concerning this process is given in Yoon & Wu (1991). This result has an important implication. That is, ions with initially low energies can be accelerated to high energies, provided that the background plasma is moving with a velocity much higher than its Alfvén speed. Moreover, this process enables the pickup ions to attain maximum velocities about twice the background plasma velocity. This result is relevant in the scenario to be discussed later.

Here we reiterate that enhanced Alfvén waves are necessary in the ion pickup process. These waves can be either self-consistently excited by the newborn ions or are intrinsic to the ambient plasma. Theoretical discussions of the self-consistent excitation of Alfvén waves were given in Wu & Davidson (1972), Winske et al. (1985), Gary et al. (1986), and many other subsequent authors (see review articles by Yoon & Wu 1991 and Brinca 1991). The prediction was verified by in situ observations with *ICE* and other spacecraft (Tsurutani & Smith 1985a, 1985b; Neubauer et al. 1986; Saito et al. 1986; Smith et al. 1986; Yumoto, Saito, & Nakagawa 1986). On the other hand, enhanced Alfvén waves intrinsic to the solar wind are well known (Belcher & Davis 1971; Denskat, Beinroth, & Neubauer 1983). Finally, the Alfvén waves specifically associated with a reconnection layer are observed in MHD simulations. This finding is discussed in Ma, Lee, & Otto (1985).

Here we want to point out that the implication of acceleration via the ion pickup process was not fully appreciated beyond the cometary application. Most of the attention during the 1980s was paid mainly to the issue of whether the solar wind can indeed pick up newborn cometary ions. As a matter of fact, the pickup process itself was not thoroughly comprehended until quite recently. For example, Li et al. (1997) discussed the case of a relative velocity between the background plasma and newborn ions much greater than the Alfvén speed and also examined the case in which high levels of intrinsic Alfvénic turbulence were present, making the usual gyroresonance unnecessary. Such a physical parameter regime has not been discussed in the usual ion pickup theories.

In general, the pickup process may be attributed to both pitch-angle diffusion and pitch-angle scattering. The former is a collective process mainly due to resonant wave-particle interactions while the wave fields are weak and the latter, which is often dominant, is dictated by direct interaction between the wave fields and the particles. One may also interpret the pitch-angle scattering process as a result of induced electric fields associated with the waves, as viewed from the wave frame.

2.2. *Magnetic Reconnection*

We propose three reasons why magnetic field reconnection is conjectured to be important in the proposed model:

1. Most solar flare models involve magnetic field reconnections. If observed energetic particles are associated with solar flares, it is natural to consider that reconnection is responsible for the production of these particles.
2. Observed electromagnetic emissions indicate that a source region often simultaneously produces ascending and descending energetic particles. The temporal correlation of the X-ray emitted from the chromosphere and the type III radio bursts emitted in the corona in a typical a flare event presents clear evidence (Kane 1972, 1981; Aschwanden 1999a). Since only acceleration taking place in a magnetic field reconnection layer can produce simultaneously these ascending and descending energetic particles, it is compelling to suggest that reconnection is essential. However, the notion to be discussed in our theory differs from the models suggested in the literature (Acton et al. 1992; Svestka & Cliver 1992; Tsuneta & Lemen 1993; Uchida 1993; Hudson 1994; Shibata 1994; Tsuneta 1996).
3. The so-called outflow velocity in a reconnection layer is nearly equal to Alfvén speed outside the layer (Sonnerup 1979; Lee 1994). This implies that, if reconnection occurs in a region where the local magnetic field is strong, the outflow speed can be very high. Thus, if the pickup process mentioned earlier should be operative in this region, low-energy ions can be accelerated to attain very high energies.

The common belief is that particle acceleration occurs in the diffusion region, where many controversial physical issues are still not understood, at least from microscopic theoretical point of view (Lottermoser, Scholer, & Matthews 1998; Nakamura, Fujimoto, & Maezawa 1998; Shay et al. 1998, 1999; Krauss-Varban, Karimabadi, & Omidi 1999). The physical picture in the present case is very different from the usual approach. The acceleration process of interest actually takes place far away from the diffusion region and depends mainly on the outflow as well as enhanced hydromagnetic waves spontaneously produced in the reconnection layer. Thus, what precisely happens in the diffusion region is not our concern.

It is well known that the gas in the chromosphere is partially ionized because of relatively low temperature there. At higher altitudes, say above the transition layer, there is a large temperature gradient. Consequently, the degree of ionization is expected to increase progressively because of the increasing temperature. Diminishing hydrogen line emission at higher altitudes in the corona is a clear indication (Jastrow & Thompson 1972). In the corona not only protons but also helium ions are freshly created because of the ionization of neutral atoms. We assume that these newborn ions exist pervasively in the active regions, meaning they also occur inside the reconnection layer. The central issue of interest is how the reconnection process affects these newborn ions. The primary objective of § 3 is to address this issue.

3. TWO-DIMENSIONAL SIMULATIONS

In an attempt to demonstrate the hypothesis put forth by Wu (1996), Wu et al. (1998) have carried out numerical simulations based on a one-dimensional hybrid code under the postulate that the acceleration process can be accomplished very quickly, making the one-dimensional approximation justifiable. Indeed, one-dimensional simulations have been very successful in the study of cometary newborn ions. For example, it was by means of a one-dimensional hybrid simulation that the pickup of newborn cometary ions was shown to be accomplished within one or two ion gyroperiods (Wu, Winske, & Gaffey 1986; Price & Wu 1987; Terasawa 1989), a result comparable to *ICE* observations.

However, there is a conspicuous difference between the cometary case and the reconnection case. In the latter case, the magnetic field gradient and curvature can have important effects on the pickup process. They may even prevent the pickup process from happening. This concern is based on the following considerations: First, near the neutral sheet the magnetic field is very weak, meaning the gyroradii of the newborn ions can be comparable to the scale length of the local magnetic field gradient. Moreover, if the outflow speed is high, the effect of the magnetic field gradient and curvature on the pickup process could be very important, which means the one-dimensional model is vitiated. With these points in mind, we feel that a study based on two-dimensional simulation is definitely desirable. We report our findings and present the results below.

3.1. *Physical Model*

To facilitate our discussion, we consider the situation in which the inflow as well as the magnetic field configuration are symmetric on both sides of the neutral sheet. The plasma beta associated with the inflow is assumed to be very low, a situation that is supposed to be true in active regions. In our simulations we choose the plasma beta to be $(1.0–2.5) \times 10^{-3}$. The initial magnetic field lines are considered to be parallel to the x-axis, but the field strength varies in the z-direction so that (Harris 1962)

$$\boldsymbol{B} = B(z)\hat{\boldsymbol{x}} = B_0 \tanh(z/\delta)\hat{\boldsymbol{x}} , \tag{1}$$

where $\hat{\boldsymbol{x}}$ is a unit vector parallel to the x-axis, δ is the half width of the initial current sheet, and B_0 is the magnetic field intensity outside the reconnection layer. On the other hand, the corresponding plasma density model is taken to be

$$n(z) = n_0 + n_1 \operatorname{sech}^2(z/\delta) , \tag{2}$$

where n_0 denotes the density outside the reconnection layer and n_1 is the density inside the plasma sheet. The inflow speed that drives the reconnection is modeled initially by

$$\boldsymbol{V}(x) = V_0 \cosh(x/\Delta)\hat{\boldsymbol{x}} , \tag{3}$$

where V_0 is the highest driven speed at the center, $x = 0$ of inflow boundary, and Δ is the spatial width of the inhomogeneous distribution of driven speed profile. Let us denote the density of newborn ions by $n_{\rm nb}$ and define the rate of creation of the newborn ions associated with the continuous ionization process that take place over the entire region of interest by

$$\varepsilon = \frac{1}{n_0}\frac{dn_{\rm nb}}{dt} . \tag{4}$$

We use a two-dimensional hybrid code similar to that used by Lin & Swift (1995) and Lin & Xie (1997) in which electrons are treated as massless fluid and ions are treated as particles that satisfy the following equation of motion:

$$\frac{dV_i}{dt} = \boldsymbol{E} + V_i \times \boldsymbol{B} - \eta(u_i - u_e) , \tag{5}$$

where u_i and u_e are average drift velocities associated with the ions and electrons, respectively, and η denotes an effective collision frequency that is assumed to decay spatially in the following manner:

$$\eta = \eta_0 \exp[-(x^2 + z^2)/\lambda_0^2] . \tag{6}$$

We postulate that $\eta_0 = 1.5\Omega_0$ and $\lambda_0 = c/\omega_{p0}$. ($\Omega_0$ and ω_{p0} are the ion gyrofrequency and ion plasma frequency outside the reconnection layer, respectively.)

In the simulation we use $V_{\rm A0}$ (the Alfvén speed outside the reconnection layer), λ_0, and Ω_0 for normalized velocity, spatial scale, and time. Henceforth, all physical quantities are normalized by $\boldsymbol{r} \to \boldsymbol{r}/\lambda_0$, $\boldsymbol{v} \to \boldsymbol{v}/V_{\rm A0}$, and $t \to \Omega_0 t$. We choose $V_0 = 0.1$, $\delta = 1.5$, $\Delta = 50$, $\varepsilon = 10^{-9}$ to 10^{-7}, and $n_1/n_0 = 4$. The dimensions of the simulation system are $L_x = 200$ and $L_z = 100$. The simulation boundaries are taken to be $z = \pm 0.5L_z$ and $x = \pm 0.5L_x$. It is found that the newborn ions do not significantly affect the reconnection process because their population is rather small, but their dynamical characteristics are greatly influenced by the outflow and reconnecting field lines.

3.2. *Simulation Results*

We have considered driven magnetic reconnections under the following initial conditions: $V_0/V_{\rm A0} = 0.1$ and $V_{\rm th0}/V_{\rm A0} = 0.05$. In this case reconnection begins to take place at about $t = 100$, and by $t = 200$ the process appears to reach a steady state. At that time continuous injection of newborn ions is initiated. The newborn ions are injected randomly in space with no flow velocity but with small thermal speeds. We have designated $\Delta t = 0$ to be the moment at which the injection of newborn ions starts, which is, in fact, equivalent to $t = 200$. In the following discussion we present the essential results.

The velocity distributions of newborn ions at $t = 260$ in various regions are displayed in Figure 1. Region A is close to the neutral sheet, as indicated in the uppermost panel. The average angle between the magnetic field lines and the x-axis in the sample boxes is about 20°. In the lower panels the newborn ions are plotted in phase spaces $V_\parallel$-$V_\perp$ and $V_y/V_{\rm A0}$-$V_z/V_{\rm A0}$. In region A the velocity distribution in $V_\parallel$-$V_\perp$ space has the shape of a spherical shell, similar to that obtained and observed for pickup ions in the solar wind. It is seen that in this region the ions possess a bulk speed $|u_{0x}| = 0.71$, as indicated in the figure, which is approximately the center of the shell distribution of the newborn

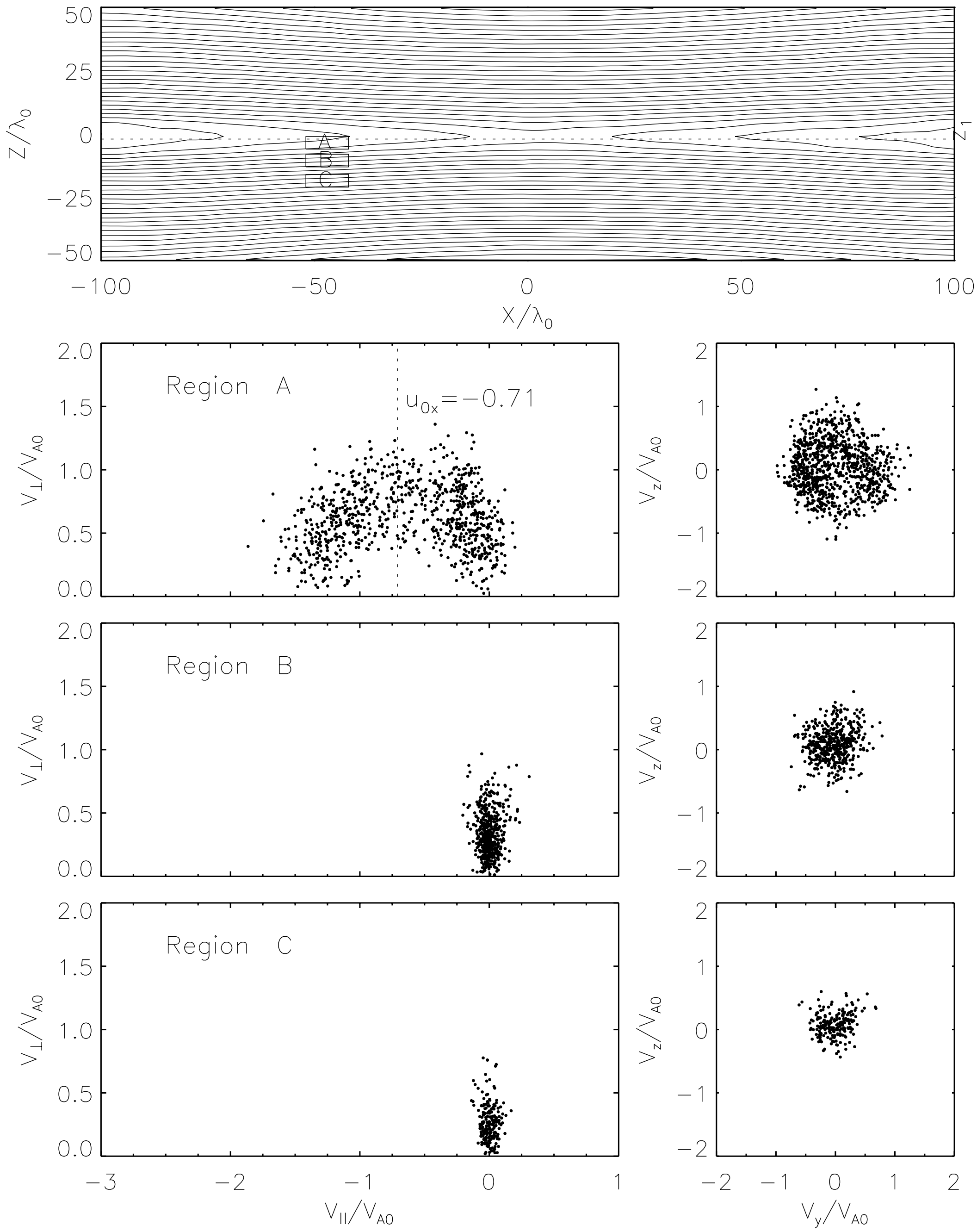

FIG. 1.—*Top panel*: contours of reconnection magnetic field at the steady state. *Bottom six panels*: Newborn ion phase-space plots in three sample boxes labeled A, B, and C. Only in region A, close to the neutral sheet, do the ions undergo appreciable pitch-angle scattering by Alfvén waves and get picked up by the outflowing plasma.

ions. The formation of the shell distribution is evidently due to pitch-angle scattering by enhanced ultra–low-frequency (ULF) waves.

In regions B and C the newborn ions do not possess shell distribution since they are sampled sufficiently away from the reconnection layer. However, obviously the newborn ions attain a certain level of acceleration in $V_\perp$ because of the induced electric field E_y associated with the inflow. Such an effect diminishes in regions far away from the reconnection layer.

It is desirable to understand the nature of the enhanced hydromagnetic waves in the reconnection layer. In Figure 2 we plot B_y (associated with the waves) and V_y (of the newborn ions) versus x at $z = z_1$ (which is indicated in Fig. 1). It is seen that in regions where $x > 0$, V_y and B_y have basically similar phases, whereas in regions where $x < 0$ they have largely opposite phases. These results seem to imply that the enhanced waves are mainly Alfvén waves. However, near $x = 0$ (the diffusion region) the Alfvén wavelike characteristics are not clearly discernible.

In Figure 3 we present the value of a quantity $\int_x B_y^2(x, z, t)dx$ (averaged over x), which is proportional to the wave energy and is a function of z. It is shown in Figure 3*a* that $\int_x B_y^2(x, z, t)dx$ peaks mainly near $z = 0$ in a sheet that has a thickness of about $\pm 10\lambda_0$. Clearly the wave energy varies in time. In the early stage ($\Delta t = 4$–40) wave

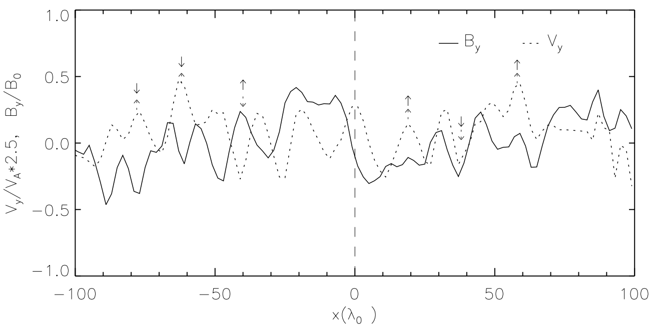

FIG. 2.—Plot of y component magnetic field B_y and averaged ion velocity v_y. Note that wavelike quasi-periodic structure are noticeable sufficiently away from the diffusion region, $x \sim 0$.

energy seems to grow, but later on the waves appear to settle down to a saturation level. In Figure 3b $\int\int_{x,\ z} B_y^2(x, z, t)dxdz$ is plotted as a function of time. Two cases are shown, one without the injection and other with

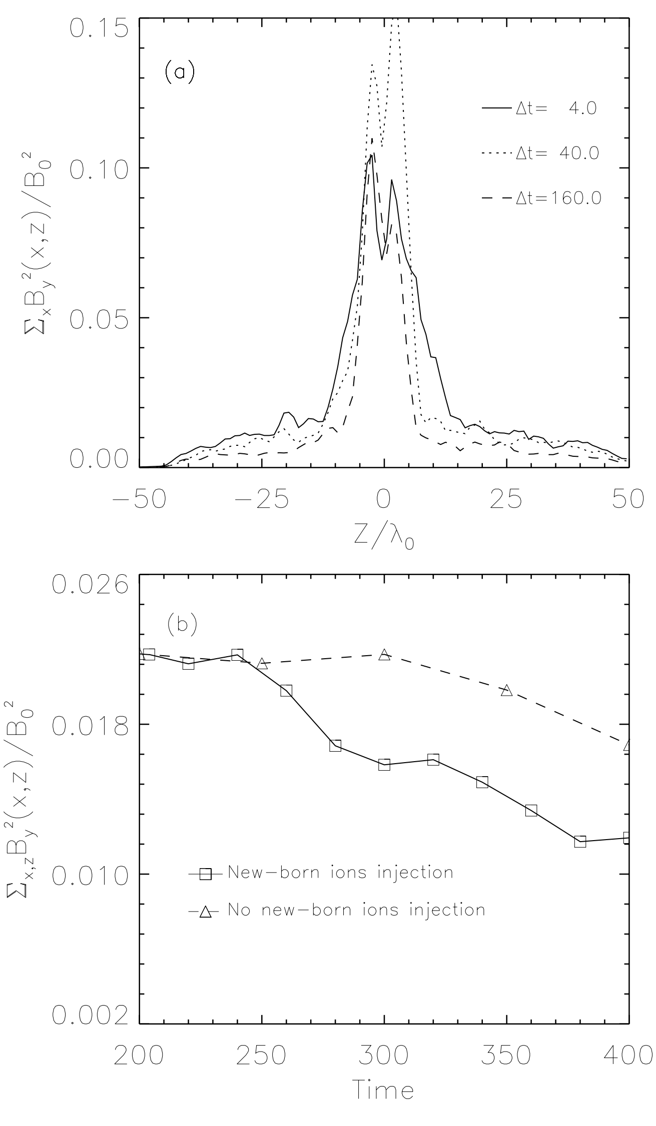

FIG. 3.—(a) x-averaged magnetic field energy density vs. z. Note that intense wave activity is concentrated near the current sheet. (b) Average magnetic wave energy density vs. time. Two cases are shown, one without and the other with the injection of newborn ions. With the newborn ions, part of the wave energy goes into the acceleration of newborn ions.

the continuous injection of newborn ions. An interesting point is that the newborn ions tend to reduce the wave energy. Physically this result may be attributed to the fact that waves consume energy to accelerate the newborn ions.

As discussed in § 3.1, enhanced ULF waves peak mainly in the current sheet with a thickness roughly $\pm 10\lambda_0$. Thus, it is desirable to examine the velocity distributions of the newborn ions in various regions along the sheet. In Figure 4 we study three locations D, E, and F (where region E corresponds to A in Fig. 1). It is seen that at locations such as D and E, sufficiently far from the diffusion region, the newborn ions possess spherical shell distributions due to pickup, whereas at F, which corresponds to the diffusion region where few ULF waves are present, newborn ions basically are not affected. Furthermore, at D and E the distributions of newborn ions are nearly axisymmetric in V_y-V_z space, but at F obviously the magnitude of V_y is less than V_z on the average. The latter again is due to the effect of inductive electric field, E_y.

Figure 5 displays the velocity distribution function of newborn ions in region E at several different times. It is shown that at $\Delta t = 4$ the distribution forms a partial shell due to pitch-angle scattering. Moreover, at this time the distribution in V_y-V_z space is clearly anisotropic. By $\Delta t = 20$ a spherical shell is basically formed. As the pickup process continues further, the formation of the shell distribution is asymptotically completed at around $\Delta t = 40$.

Relative to the reconnection layer and diffusion region, the newborn ions are initially motionless. However, because of the outflow and ULF waves, the newborn ions are accelerated via the pickup process. As a result, they gain energy. In Figure 6 we show the power spectrum of those newborn ions that can escape from the reconnection layer, where $f(E)$ represents the energy distribution function of particles that corresponds to the differential energy spectrum. The distribution function $f(E)$ is normalized in such a way that $\int f(E)dE = 1$. For the sake of reference, we have designated the characteristic energy $E = 1$ in Figure 6, which indicates the theoretical kinetic energy associated with the outflow plasma. Characteristic energy $E = 4$ denotes the theoretically predicted maximum kinetic energy of the newborn ions (Wu 1996). The power spectrum of the accelerated newborn ions is calculated from the simulation results at three different times. The solid line depicts the spectrum at $\Delta t = 4$. It is seen that although it is still early, the newborn ions have already gained a significant amount of energy. The dotted line describes the spectrum at $\Delta t = 40$, and the dashed line depicts the spectrum at $\Delta t = 100$. Evidently the evolution of the power spectrum from $\Delta t = 40$ to $\Delta t = 100$ is rather insignificant. The final result can be modeled by a power-law expression with two different spectral indices. If we write $f(E) = E^{-\alpha}$, it is estimated that the two indices are $\alpha = 1.56$ and 9.8.

4. DISCUSSION AND CONCLUSIONS

In view of the fact that many acceleration processes have been suggested, there may exist numerous sources of solar energetic particles. In this paper we discuss a new scenario that may be operative in active regions associated with solar flares. In the present study we are especially interested in the production of energetic protons with energies in the range of 10–100 MeV within a small source region. In other words, we are looking for an exceedingly fast acceleration process.

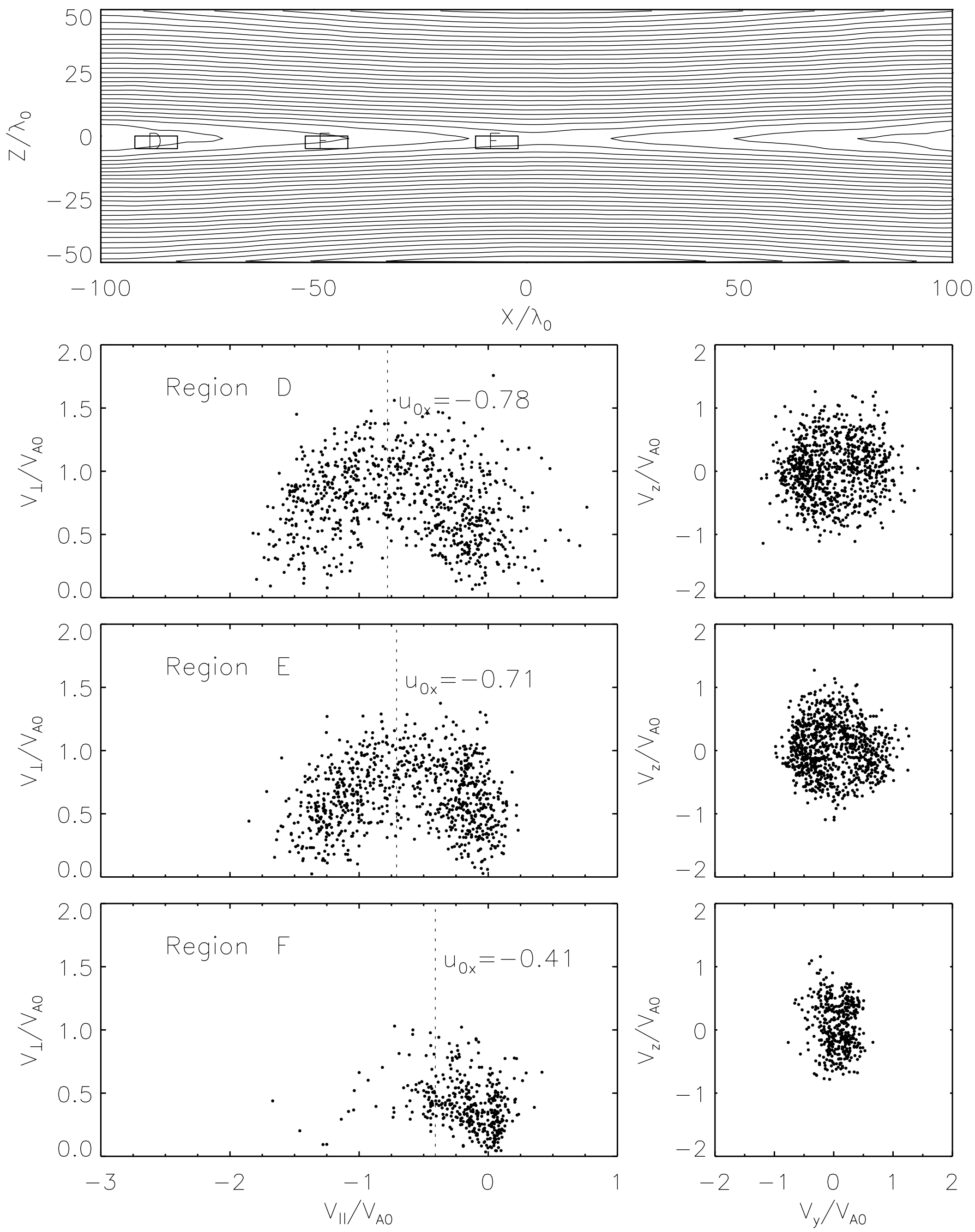

FIG. 4.—Same format as in Fig. 1, except that the sample boxes are taken along the current sheet at different locations away from the diffusion region. Note that very little acceleration is experienced by the ions near the diffusion region F, but the ions gain acceleration as they flow out from the diffusion region (D and E).

The essence of our model is that freshly created ions inside a reconnection layer can be accelerated via a "pickup" process (Yoon & Wu 1991). This process can be very effective and rapid if the background plasma is moving with a high velocity. Our point is that in solar active regions the outflow in a reconnection layer can have a very high velocity when the local magnetic field outside the layer is sufficiently high. Thus, the suggested acceleration process can be significant. The purpose of the present study is to demonstrate this point by means of two-dimensional hybrid simulations. In this section we summarize and discuss the important results.

If we denote the ion inertial length by λ, it is found that the spatial scale of the reconnection region is about 200λ. For purposes of illustration, let us consider that the plasma density is 10^9 cm^{-3}. As a result, we find that $\lambda \sim 0.05$ km. This implies that the spatial dimension of the reconnection region is about 10 km. This spatial scale is far smaller than that of the flare site, say (5×10^3)–(5×10^4) km (Aschwanden & Benz 1997). In other words, when we estimate the required timescale of the acceleration process, we should not use the scale of the flare site. Rather, we should use the actual dimension of the acceleration region. Now let us consider the case that ions are able to attain an average

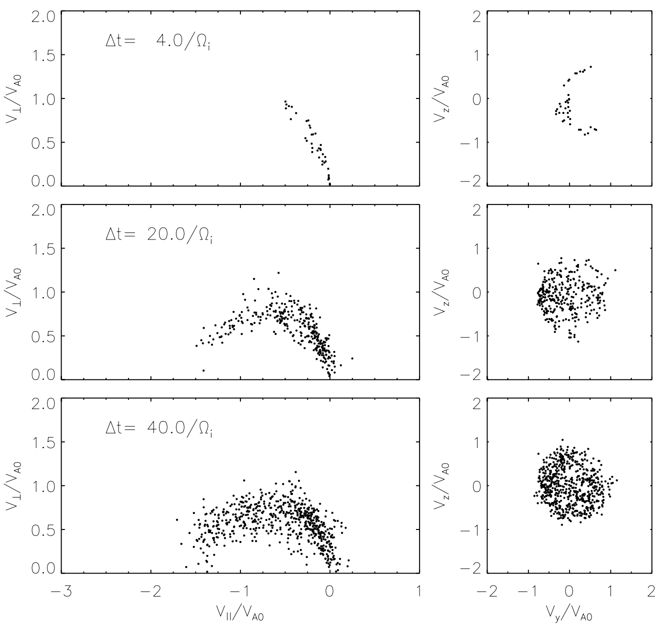

FIG. 5.—Velocity phase-space plot in the same format as in lower panels of Figs. 1 and 4 for region E at different times. This shows that the pickup process is indeed very rapid.

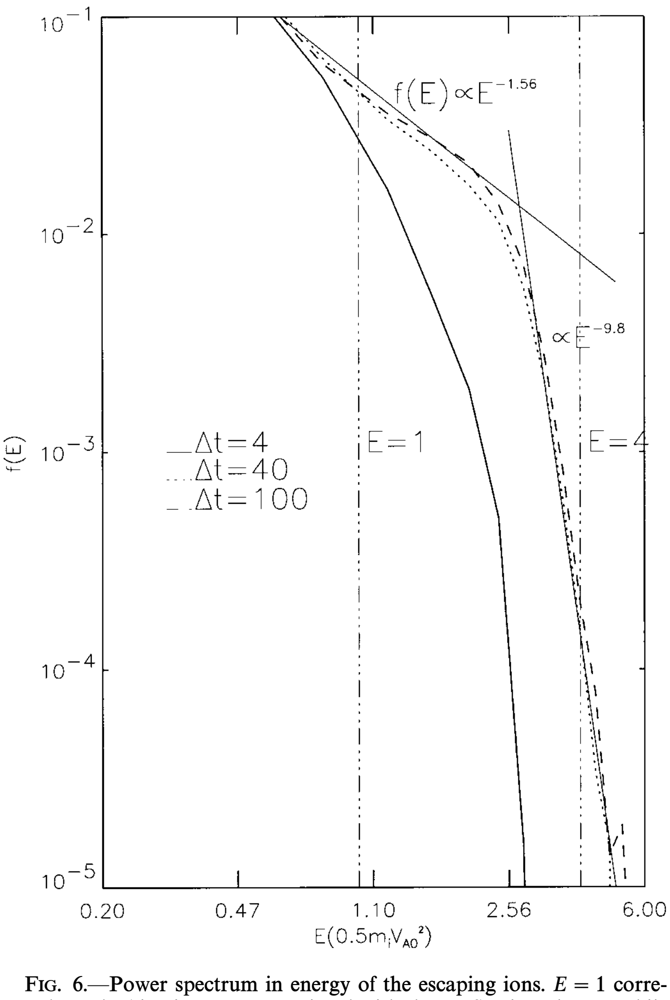

FIG. 6.—Power spectrum in energy of the escaping ions. $E = 1$ corresponds to the kinetic energy associated with the outflowing plasma, while $E = 4$ indicates the predicted kinetic energy associated with the accelerated newborn ions.

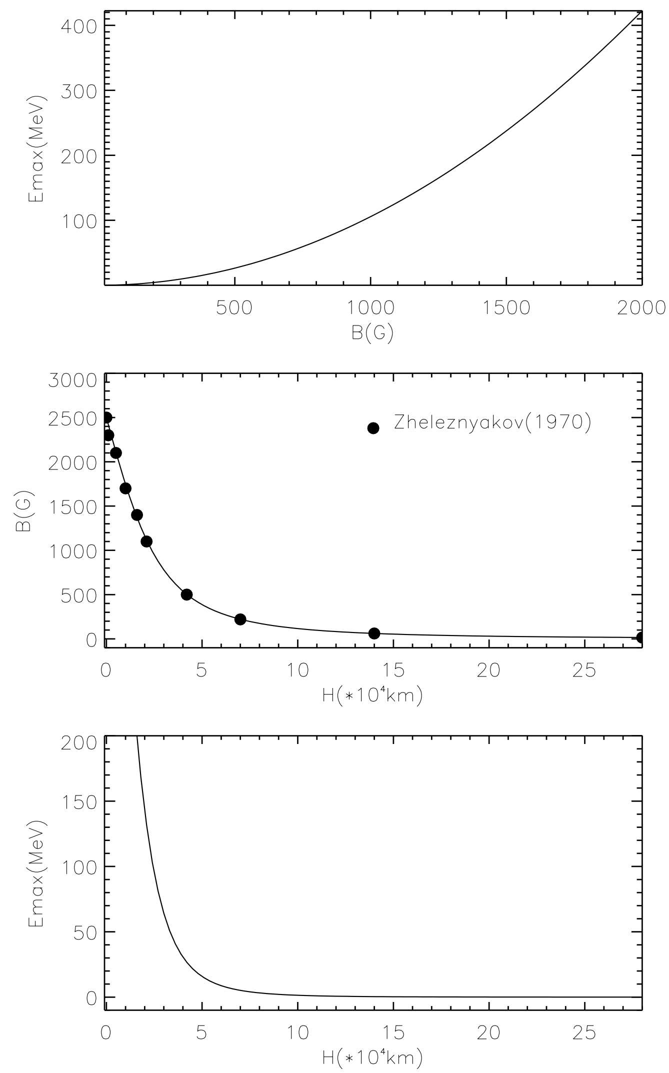

FIG. 7.—Theoretical estimate of the maximum allowable energy gain vs. the magnetic field strength (*top panel*), where the magnetic field modeled in the middle panel vs. the altitude. The bottom panel plots the same maximum energy gain as a function of the altitude.

velocity of 10^5 km s^{-1} corresponding to 100 MeV for the protons. In terms of the dimension of the reconnection region, the acceleration time is 5×10^{-4} s.

On the other hand, according to the present theory, the bulk velocity of 10^5 km s^{-1} implies that the Alfvén speed outside the reconnection layer is 5×10^4 km s^{-1}. This result also corresponds to an ambient magnetic field of about 500 G, or equivalently, the proton gyrofrequency $\Omega_i \sim 7 \times 10^5$ s^{-1}. The simulation gives a pickup time $\sim 200\Omega_i^{-1}$ or 3×10^{-4} s, which is consistent with that discussed in the preceding paragraph. From these results one can conclude that the acceleration via Alfvén wave pickup is extremely fast and efficient. To the best of our knowledge, no other process can energize ions so rapidly and effectively.

We have also computed the power spectrum of those energized particles escaping from the reconnection layer, as discussed in § 3.2. An important point is that the maximum energy attainable by the newborn protons obtained in the simulations is consistent to that estimated in Wu (1996). Moreover, we conclude that the present two-dimensional result supports the intuitive estimate as well as the earlier one-dimensional result discussed in Wu et al. (1998).

It is true that final energy attained by this process depends on the ambient magnetic field outside the reconnection layer because the outflow velocity is roughly equal to the Alfvén speed there. In Figure 7 (*top panel*) we plot the attainable maximum energy versus the ambient magnetic field. This plot is based on the assumption that the plasma density is 10^9 cm^{-3} and that the ions are protons. Furthermore, for the purpose of illustration, we have also plotted the maximum energy attainable versus altitude (*bottom panel*). To discuss this point we have used a magnetic field model suggested in Zheleznyakov (1970) for a region close to a sunspot (*middle panel*). Of course, we understand that the magnetic field model is an idealized and simplified one. Thus we only use it for low altitudes close to the photosphere. The high values of the attainable proton energy (i.e., the energy above 100 MeV) at low altitudes can be understood from the fact that Alfvén speeds there are very high. Note that the Alfvén speed determines the outflow velocity in a reconnection layer, which in turn determines the attainable energy of the newborn protons. From Figure 7 we see that the proposed acceleration process is significant mainly below 7×10^4 km.

Finally, we remark that after the energized particles have left the reconnection region, they may experience other acceleration processes such as those due to wave-particle interactions or effects of shock waves in the higher corona and interplanetary space. In short, the production of high-energy particles can be a rather complicated and lengthy process. What we have discussed in this paper is merely a part in the complete process.

The present research at the National Central University at Chungli, Taiwan, was supported by the National Science Council in Taiwan under grants NCS 89-2816-M-08-0001-6 and NCS 89-2111-M-008-019, while the efforts at the University of Maryland were supported by the National Science Foundation grant ATM 99-05508. C. S. W. is grateful to the Foundation for Development of Outstanding Scholarship for an award granted to him for his visit to the National Central University. S. W. and X. Y. W. also want to thank the National Science Council for support during their recent visit to Taiwan.

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