3-D DESCRIPTION OF VERTICAL CURRENT SHEETS WITH APPLICATION TO SOLAR FLARES

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ABSTRACT. Following a brief review of the processes which have been suggested for explaining the occurrence of solar flares we suggest a new scenario which builds on the achievements of previous scenarios, but includes an important addition. This addition is the suggestion that the current sheets, which develop naturally in 3-D cases with gravity from impacting independent magnetic structures (i.e. approaching current systems), do not consist of horizontal currents but are instead predominantly vertical current systems. This suggestion is based on the fact that as the subphotospheric sources of the magnetic field displace or emerge the upper photosphere and lower chromosphere regions, where plasma beta is near unity, will experience predominantly horizontal mass motions which will lead to a distorted 3-D configurations of the magnetic field having stored free energy. In our scenario, a vertically flowing current sheet separates the plasma regions associated with either of the subphotospheric sources. This reflects the balanced tension of the two stressed fields which twist around each other. This leads naturally to a metastable or unstable situation as the twisted field emerges into a low beta region where vertical motions are not inhibited by gravity.

In our flare scenario the impulsive energy release occurs, initially, not by reconnection but mainly by the rapid change of the magnetic field which has become unstable. During the impulsive phase the field lines contort in such way as to realign the electric current sheet into a minimum energy horizontal flow. This contortion produces very large electric fields which will accelerate particles. As the current evolves to a horizontal configuration the magnetic field expands vertically, which can be accompanied by eruptions of material. The instability of a horizontal current is well known and causes the magnetic field to undergo a rapid outward expansion. In our scenario, fast reconnection is not necessary to trigger the flare, however, slow reconnection would occur continuously in the current layer at the locations of potential flaring. During the initial rearrangement of the field strong plasma turbulence develops. Following the impulsive phase, the final current sheet will experience faster reconnection which we believe responsible for the gradual phase of the flare. This reconnection will dissipate part of the current and will produce sustained and extended heating in the flare region and in the postflare loops.

Introduction

It is known that an initially potential or force-free magnetic field configuration containing X-type neutral points, embedded in a highly conducting low-beta plasma, develops magnetic neutral sheets in place of neutral points when strains are externally imposed (see Parker 1983a). This can be understood as the result of the development of electric currents in highly conductive plasma layers arising from externally induced changes of the magnetic field. Because of its diamagnetic character the plasma reacts to these changes by forming rising electric currents which further distort the field and produce forces on the original drivers of the field changes. These forces are such that they oppose the external changes, and are capable of driving substantial motions in a moderate or low beta plasma. The plasma motions are such that the currents collapse into narrow current sheets due to the Lorentz forces. An effect of the formation of the current sheets is to convert the mechanical energy, which went into the driving of the external sources, into the free (and therefore available for dissipation) magnetic energy of the current sheets. The dissipation of the current sheets, through slow magnetic field reconnection, releases this energy and converts it to thermal plasma energy.

The dissipation of numerous small and narrow current sheets produced in the tenuous corona by the shuffling of the magnetic fields by convective motions has been suggested as the source of stellar coronal heating (Parker 1983b). More extended current sheets have been suggested for explaining full fledged solar flares (e.g. Heyvaerts, Priest and Rust, 1977, and Low 1987). These current sheets result from the evolution of large-scale active region magnetic fields. The evolution has been considered a result of emergence of new bipolar field (Heyvaerts, Priest and Rust, 1977), sideways bumping and cancellation of magnetic bipoles (Machado and Moore 1986), or magnetic footpoint displacements (Low 1987). However the problem still remains of how these large current sheets can be built up without in the process experiencing major dissipation of their energy, and why they release their energy impulsively. This requires that the magnetic configuration evolves to a metastable state where it can remain for a substantial time as it builds up its free energy under the action of the slow photospheric mass flows, and that the transition from the metastable state to one of lower energy occurs explosively releasing energy and producing a substantial flux of accelerated particles.

We note that both, the Heyvaerts, Priest and Rust, and the Low scenarios, as well as other flare models (e.g. Kupperus and Raadu 1974, Kopp and Pneuman 1976, and Martens and Kuin 1989), consider the current sheets only in two-dimensions, where the electric currents flow essentially in the horizontal direction while the field expands vertically from a boundary surface at which conditions are imposed. They only consider low-beta plasmas and assume that the footpoints of the field are displaced arbitrarily.

In the case of the Heyvaerts, Priest and Rust scenario the current sheet is nearly horizontal and prevents the emerging field from expanding upwards into the preexisting field (see their Figure 3). These authors suggest that the sheet becomes unstable to reconnection as a result of a thermal instability. In the case of the Low scenario the current sheet is vertical and allows for an upwards expansion of the overlying field (see his Figure 6) as a result of the pulling apart of the magnetic footpoints at the boundary. Both configurations imply the presence of significant forces over the sources which produce the interacting field.

The Stressed Equilibrium

The main difference between our scenario and all others involving current sheets is in the direction of the current flow through the current sheet. All previous models assume that the current in this layer flows horizontally, but our assumption is that it flows vertically. In either case, the currents must close and currents flow in both the horizontal and vertical directions. However, the closing currents are outside of the neutral current sheet, they flow along the magnetic field (i.e. they are force-free) and therefore do not correspond to a strong stress in the field.

Our idea is based on the consideration that, in the solar atmosphere, the low-beta approximation is only good for the coronal layers (beta ~0.0025 for B=100 G). At the photosphere the low-beta approximation does not hold (beta~2.5 for B=1000 G at z=0). In the intermediate layers where the magnetic fields are usually measured (100 <z<600 km) neither the low nor high-beta approximation applies. It is therefore likely that any configuration of the magnetic field which produces Lorentz forces at these levels would result in large scale mass flows such that the magnetic configuration will relax toward net zero force. Of course, these motions will have relatively low velocities, of the order of the subphotospheric flows which are responsible for the stressing. The motions are predominantly horizontal because of the effects of gravity.

Recent measurements of vector magnetic fields have indicated that regions experiencing large flares usually display large magnetic "shear" (Hagyard 1988). This "shear" consists of the departure from a potential configuration of the horizontal component of the magnetic field, and has been interpreted as showing the existence of vertical electric currents (Hagyard 1988, Fan, Canfield and McClymont 1990). These vertical currents are interpreted in a regular force-free magnetic configuration without singular neutral points. However it is not clear whether they bear any relationship to the occurrence of flares. If any of these vertical currents are really current sheets and correspond to neutral sheets (i.e. surfaces of null magnetic field), they would represent strains of the field which are potential sources of dynamic phenomena and flares. The theory shows that field aligned currents of sufficient magnitude to produce helical magnetic fields would be susceptible to the kink instability before even a few turns are reached. This suggests that helical configurations cannot easily accumulate substantial free energy. However, the electric currents in a neutral sheet can reach high values and are limited only by plasma effects. These current layers correspond to locations in which the magnetic pressure is uniform and the tension forces of two curved magnetic fields balance each other.

In Figures 1 and 2 we sketch the magnetic configuration of our scenario. The figures represent only one of a large number of possibilities depending on the nature of the magnetic fields and possible subphotospheric motions. The figures are simplified schemes intended only for illustrative purposes and must not be interpreted as a detailed model of a particular case. Because of the basic complexity of the three-dimensional representation we give here the details of its construction and present several views. The Figure 1 is generated by plotting the magnetic field lines which result from a system of two parallel line currents (1 and 2) flowing in the y direction. These currents are located in the plane $z=0$ at $x=D$ and $x=-D$, and extend from $y=-D$ to $y=D$ with equal intensities I. In Figure 2 we add to the previous currents two antiparallel vertical line currents (3 and 4) which, for practical purposes, represent two vertically flowing current layers. These currents are in the plane $x=0$ at $y=-D/2$ and $y=D/2$, and extend from $z=-D/2$ to $z=D/2$ with equal intensities $I/5$. The sense of the current is opposed in both semi-planes of positive and negative y. In these conditions the field lines emerge from the subphotosphere (plane $z=0$) and, as they approach the plane $x=0$, the lines diverge toward large positive and negative values of y in such way as to avoid approaching the vertical currents (3 and 4). Some field lines close without crossing the $x=0$ plane, others close on opposite sides of this plane by avoiding the vertical currents, while other field lines run above the vertical currents and are not affected by them. Of course, the actual configuration must be more complicated because of the finite size of the current systems and the closing of the currents, for both the line and sheet currents. This closing may occur along the field lines which lie at the boundaries of the sheet and then the configuration would contain both current sheets and related field aligned currents. The configuration shown in the figure can be obtained by setting up an initial potential state with the two line currents and without the current sheet. This state will have a neutral line and it will develop a current sheet as both currents are pulled together. The current sheet will be of the form shown in Figure 2 if the fluid is allowed to diverge horizontally under the action of a central compression and its vertical flow is inhibited by gravity. This structure, as are many of the most interesting cases, will be overlooked in a purely two-dimensional analysis. Considering the magnetic energy of our configuration of Figure 1, we can compute its energy from the theory of inductance (which saves complicated integral of the magnetic field). If one assumes that the configuration extends to infinity in the y direction one finds that the energy per unit length (along y) diverges logarithmically. However, this is just an artifact of the incompleteness of the model and is due to the lack of consideration of the closing currents (i.e. the whole circuit). In order to deal with this deficiency of the model, and for simplicity, we assume that the currents are limited along the y axis. Under these conditions, the total energy is the sum of the individual self-energies of the two currents plus the mutual interaction energy,

$$E_1 = L_1 I_1^2 + L_2 I_2^2 + M_{12} I_1 I_2$$

where L and M are the self- and mutual-inductances. The total magnetic energy in the configuration of the Figure 2, can be calculated by adding the self and mutual energies due to the vertical currents,

$$E_2 = E_1 + \Delta E$$

with

$$\Delta E = L_3 I_3^2 + M_{31} I_3 I_1 + M_{32} I_3 I_2 + L_4 I_4^2 + M_{41} I_4 I_1 + M_{42} I_4 I_2 + M_{34} I_3 I_4$$

The interaction terms between the vertical and horizontal currents vanish because

$$M_{31} = M_{32} = M_{41} = M_{42} = 0$$

and the mutual term between the vertical currents is negative

$$M_{34} < 0.$$

The energy of this configuration is intermediate between the energies which would result from rotating the two vertical currents into the directions aligned or antialigned with respect to the line currents. The excess energy (ΔE) over the potential case with only the two current lines (E_1) corresponds to stress in the magnetic field and free energy. It is readily seen that dissipating the self-energies of the vertical currents requires the Joule effect and therefore implies reconnection. Alternatively the excess energy can be reduced by a realignment of the currents without Joule dissipation.

We suggest that the current sheet separating two independent magnetic structures must also be vertical in the case where one of the systems emerges slowly within the other (i.e. a current system emerges slowly into the field of another current system). Horizontal current layers cannot initially develop because in the photospheric layers the plasma beta is lower than unity and the action of gravity makes vertical expansion of the fields very difficult. Instead, vertical current layers can easily develop as the magnetic structures find a stressed, twisted, equilibrium configuration through horizontal motions. In our scenario, these horizontal motions are generated by the field emergence and they are not driven by external horizontal forces. This contrasts with models in which horizontal motions are arbitrarily imposed as a mean to stress the field. During the growth phase of the stressed equilibrium, horizontal motions will occur at the upper photospheric layers. When equilibrium is reached the motions would cease, or at least decrease, while the field remains in a quasi-equilibrium. Slow reconnection will occur at the boundaries of the sheet as the system slowly merges. We consider this stressed equilibrium as an inevitable consequence of the slow merging of the magnetic structures through the upper photospheric layers under the action of gravity. If this merging proceeds faster than the establishment of the stressed equilibrium through the horizontal motions, then, the current sheets may become horizontal and the field will expand upwards as it emerges. This case would not lead to a metastable situation, but only a small stress in the field which is immediately released and would not lead to a solar flare. The situation can be visualized as that of two springs forced against each other while they are prevented from expanding outward by a plane surface. In the stressed equilibrium the lateral tensions balance, but this balance will become precarious as the system emerges slowly into a regime which permits vertical expansion.

We have shown how the slow merging of two current systems through the photosphere drives toward a stressed equilibrium with vertically flowing current layers. Some slow reconnection may be occurring in this stressed state, which will correspond to a heating, or preheating of the area.

The Flare

Now we will show, how this equilibrium unleashes into an erupting phenomena with the capability of particle acceleration. We do not provide any details on how the stressed state is temporarily maintained in the low beta solar corona. However, we suggest that the equilibrium margin is linked both to the fact that the current layers are highly inhomogeneous and composed of many filamentary structures, and to the large size of the whole stressed system. The trigger remains undefined in our scenario. It may be a fluctuation in the position of the footpoints or just a narrowing to zero of the equilibrium margin, due to slow reconnection. We emphasize that not all currents give rise to a flare, but only those which re responsible for the actual field stress, i.e. those corresponding to the vertical current sheet.

In our scenario the energy available for sudden release is not that of the magnetic pressure but only the part corresponding to the magnetic tension (usually a small fraction). Also, most of the electric currents do not undergo sudden dissipation. Instead, the currents only rearrange themselves in such way as to reduce their interaction energy (i.e. the energy due to their mutual inductance) to a minimum. Once the equilibrium from the previous stressed state is lost, a rapid evolution starts. This evolution corresponds to the releasing of the magnetic stress which was marked by the vertical current layer. As this current layer evolves from vertical to horizontal, the whole magnetic field expands and could even attain an open configuration. This would correspond to a fast eruption, and the unwinding and spreading of the magnetic field over a large volume. The untwisting of the stressed field during this stage releases the magnetic tension and produces strong electric fields. The electric fields, are in turn, responsible for accelerating particles to large energies and for the hard X-ray emission. This phase corresponds to the impulsive phase of the flare. We suggest that during this phase horizontal motions will occur in the low chromosphere reflecting the reaction on the footpoints of the untwisting fields.

Finally, a new pseudo-equilibrium is reached in which the current sheet has evolved to a nearly horizontal configuration. The energy of this configuration is lower than that of the vertical current layer, and the field extends upward to large heights in the corona. The further evolution of the horizontal currents has been suggested previously to relate to prominence eruptions. This final configuration may be either stable or unstable with respect to a fast eruption. Its stability depending on the relative magnitude of the current contained in the sheet to the subphotospheric currents and on the height of the current sheet after it becomes horizontal. If it is unstable the current sheet will collapse and probably be ejected together with a plasmoid of closed magnetic fields. Alternatively it may remain as a quasi-stable feature. In this case slow reconnection will occur and potential loops will appear gradually as the current layer is dissipated. This last process will span times far longer than those of the impulsive phase, and would correspond to the gradual rise and decay phase of flares.

Finally we note that the release of the stress in a particular section of an active region, does not imply the release of all the stress throughout the region. More likely, if the sources of the energy remain (i.e. the approaching of different current systems), the release of the stress in a particular location, will result in the beginning of the accumulation of stress in another area.

The Flux Emergence

The question of magnetic flux emergence is linked to the emergence of new electric currents into a pre-existing field. The pre-existing field, in turn, can be considered as a field produced by some large scale, remote currents. Our view is based in the simple fact that for any magnetic field to exist a current distribution must also exist. We then consider that even at times of minimum solar activity some magnetic field is present in the solar atmospheric regions. Such field is produced by electric currents which are probably buried in the Sun's convective layer, and probably at its base. If a limited size current system emerges toward the solar surface, it will interact with the pre-existing field in two ways. The pre-existing field will exert some force over the current carrying plasma attempting to align the emerging current with that of the original current in the pre-existing field. This force, however, can only affect subtly the deep layers of the Sun because of the large plasma-beta. And could only produce important changes in the motions close to the surface. In addition, there is an effect of generating current layers if the two currents are not aligned.

This is illustrated in the Figures 3 and 4. These figures are again highly schematic and should not be considered as describing an actual model. Rather they are intended to show the physical process which occurs in more complicated situations. In both cases we include a buried line current producing a magnetic field above z=0, and an emerging line current close to the surface.

In Figures 3 the emerging line current is parallel to the buried current and in Figure 4 the emerging current is antiparallel to the buried current, in both cases the emerging current is smaller. In Figure 3a the emerging current is somewhat below the surface z=0, and the net potential magnetic field does not have neutral layers. In Figure 3b, after the emerging current reaches the surface, the field modifies by expanding vertically. In this case the change in the field does not affect the topology of the lines but only their shape. The change can be achieved by slow continuous plasma motions and neither substantial electric currents nor current layers are necessary.

When the emerging current is antiparallel to the buried line current the situation is very different (Figure 4). This case is likely to occur when new active regions emerge in the midst of the pre-existing field left by the previous solar cycle. In Figure 4a, we show the case when the emerging line current is slightly below the surface. In spite of its apparent complexity this field configuration is strictly potential above the plane z=0 and although it contains neutral layers it has no currents above this plane. Figure 4b shows a similar potential case with the emerging current line at the level z=0. Comparing Figures 4b and 4a it is clear that many field lines are, again, distorted without change in the topology. However two of the field lines (marked A in the Figure) have changed their topology by jumping over the others. This change cannot result from a continuous smooth evolution of the field and thus it would lead to the formation of a current sheet at the neutral layer. The vertical orientation of such current layers will allow the magnetic field to circle around one another in the way it is shown in Figure 5, in which a vertical line currents have been added to describe the current sheet. We suggest that the configuration shown in Figure 5 is an intermediate stage in the evolution of the field from that shown in Figure 4a, as the new field emerges. The slow dissipation of the current layers would, then, bring the configuration to that of Figure 4b through reconnection. Similar formulae to those previously used can be considered to estimate the energy of this configuration, and analogous arguments can be used about its stability and possible flaring.

We stress that in many respects our scenario for the field emergence is similar to that for field "impacting" since they base on approaching currents.

Conclusions

We have presented a scenario for the building up of magnetic stress which in a natural manner leads to a metastable equilibrium in which current sheets result from the strains caused by the large scale motions of sub-photospheric current systems. We show some typical cases which in spite of their highly simplified nature display features commonly observed in coronal images. Our scenario applies to active regions which contain mixed polarity regions in which major solar flares have their origin. In contrast with previous models, our scenario contains vertical current sheets in which the electric current flows vertically. Lateral stresses develop from the predominantly horizontal motions of the upper-photospheric and lower-chromospheric layers. These stresses are released during the impulsive phase of the flare in which the electric currents associated with the current sheet rotate from the vertical to the horizontal direction. The rapid change in the orientation of the magnetic field produces large electric fields capable of accelerating substantial beams of high energy particles. Accompanying this change a large increase in the plasma turbulence allows for an increased rate of current dissipation, heating and reconnection. The realigned currents can result in stable or unstable situations. In the former case the electric currents are maintained subject to a slow dissipation, or in the latter are ejected together with the associated plasmoid of closed magnetic fields.

Our scenario opens a variety of new questions which require both detailed observation and modelling. Detailed observation of the vector magnetic field would reveal the locations and magnitudes of the vertical neutral current layers. Observations of the photospheric motions would give further indication of the locations of the current layers and how they evolve. Modelling is needed to find how these currents interact, how much free energy is stored and what is the stability margin for its release.

Acknowledgements

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Figure Captions

Figure 1. The magnetic field configuration corresponding to the two line currents shown in dashed lines. The currents lie in the plane z=0 and extend parallel to the y axis at x=+1 and x=-1. a) Perspective view; b) front view.

Figure 2. Similar to the previous except that two vertical line currents have been added (shown in dashed line) to mimic the current layers resulting from the approaching of the horizontal currents. a) Perspective view; b) front view; c) top view.

Figure 3. The emergence of an horizontal current line in the field of a deeper seated current. In the case shown in this figure both currents are parallel. A front view is shown here. a) Emerging current below the surface at z=-0.2; b) emerging current right at the surface z=0. Front view.

Figure 4. Similar to Figure 3 but with the emerging current antiparallel to the deep seated current. a) Emerging current below the surface at z=-0.2; b) emerging current right at the surface z=0. Front view.

Figure 5. Similar to Figure 4 but with a vertical line current (dashed line) added to mimic the current layer resulting from the emergence of the upper horizontal current. Notice how some lines remain at the same altitude as before the emergence but move sideways to allow the new field emergence. a) Perspective view; b) front view; c) top view.

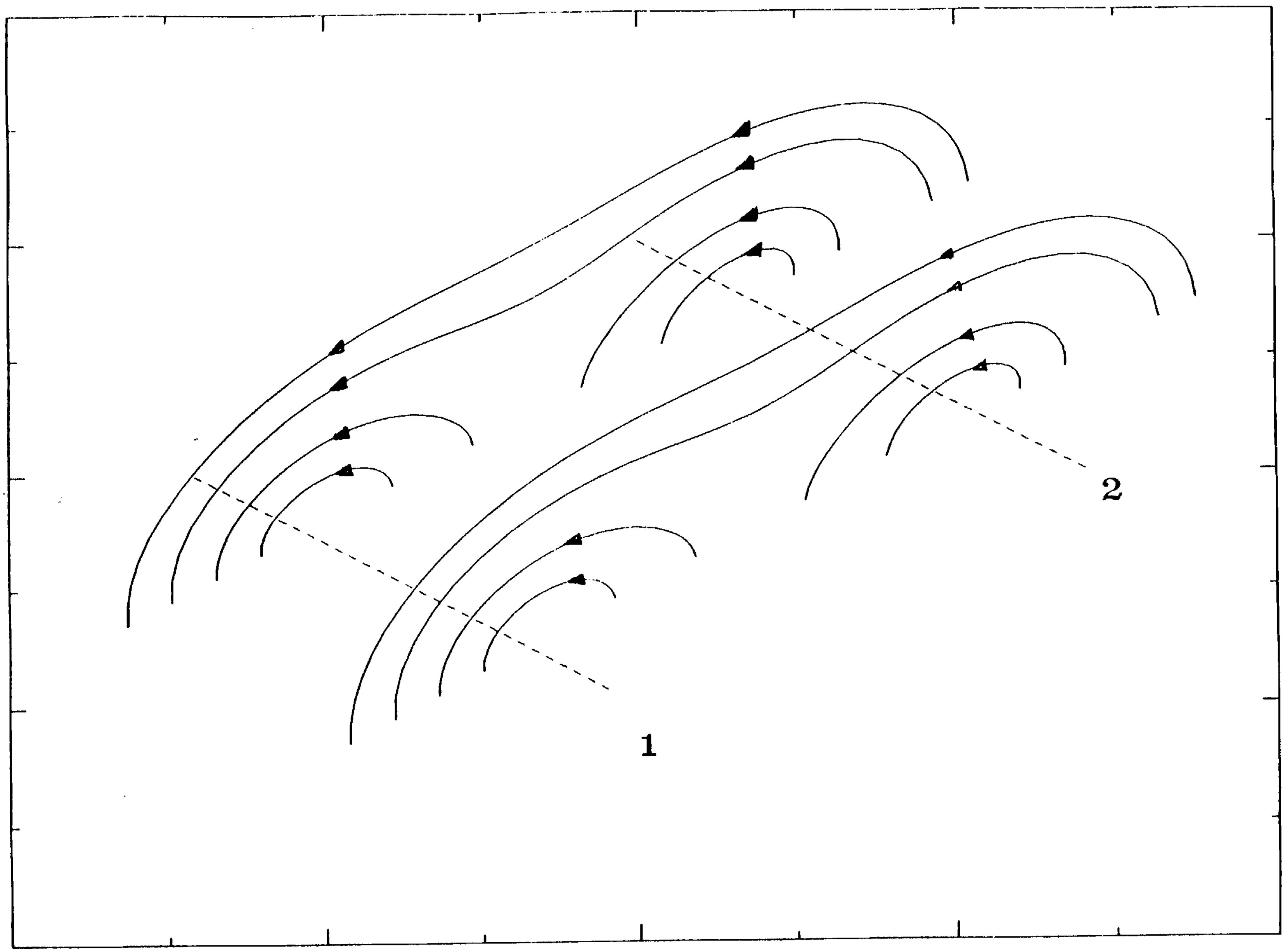
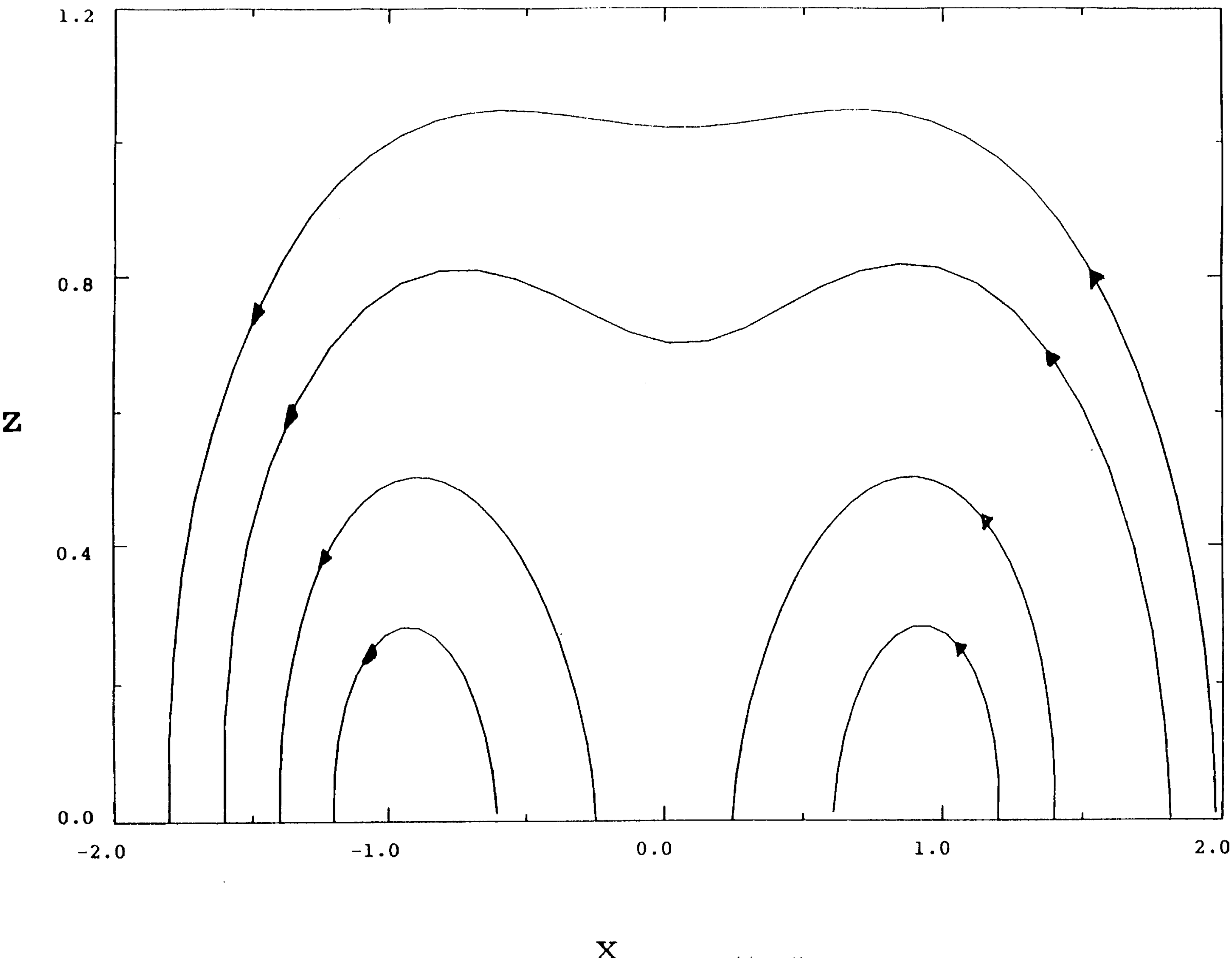


Fig. 1a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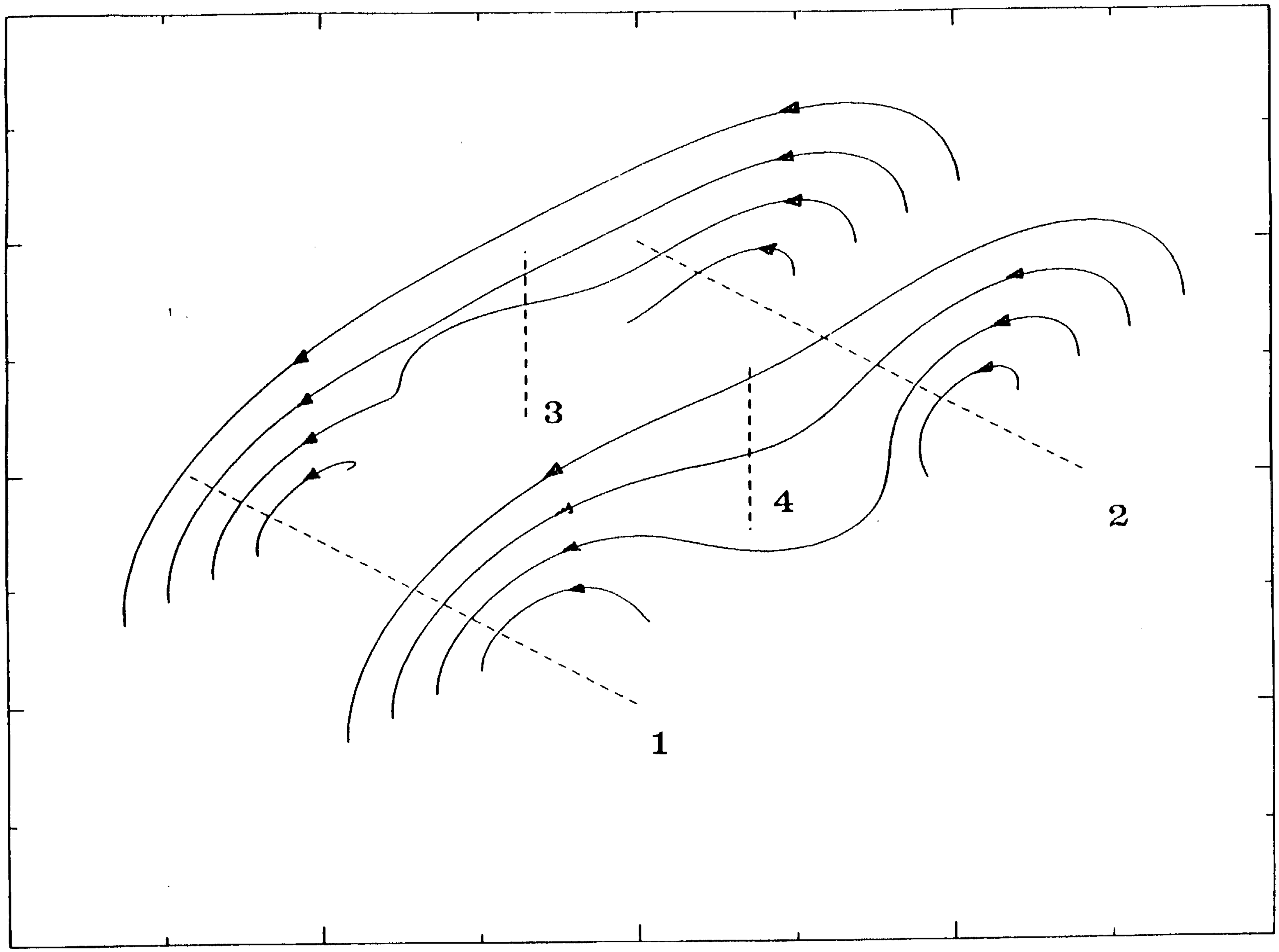

Fig. 2a

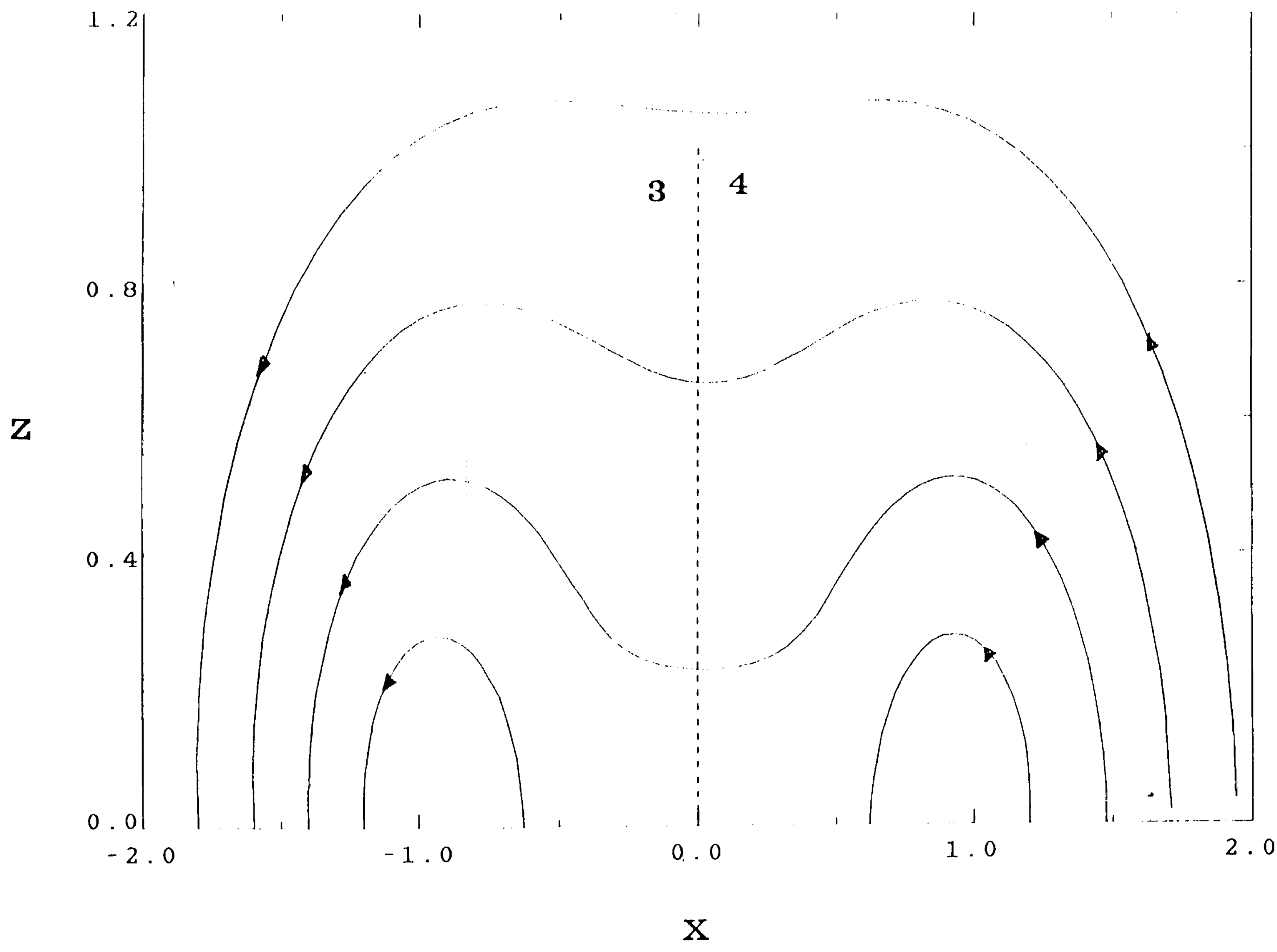

Fig. 2b

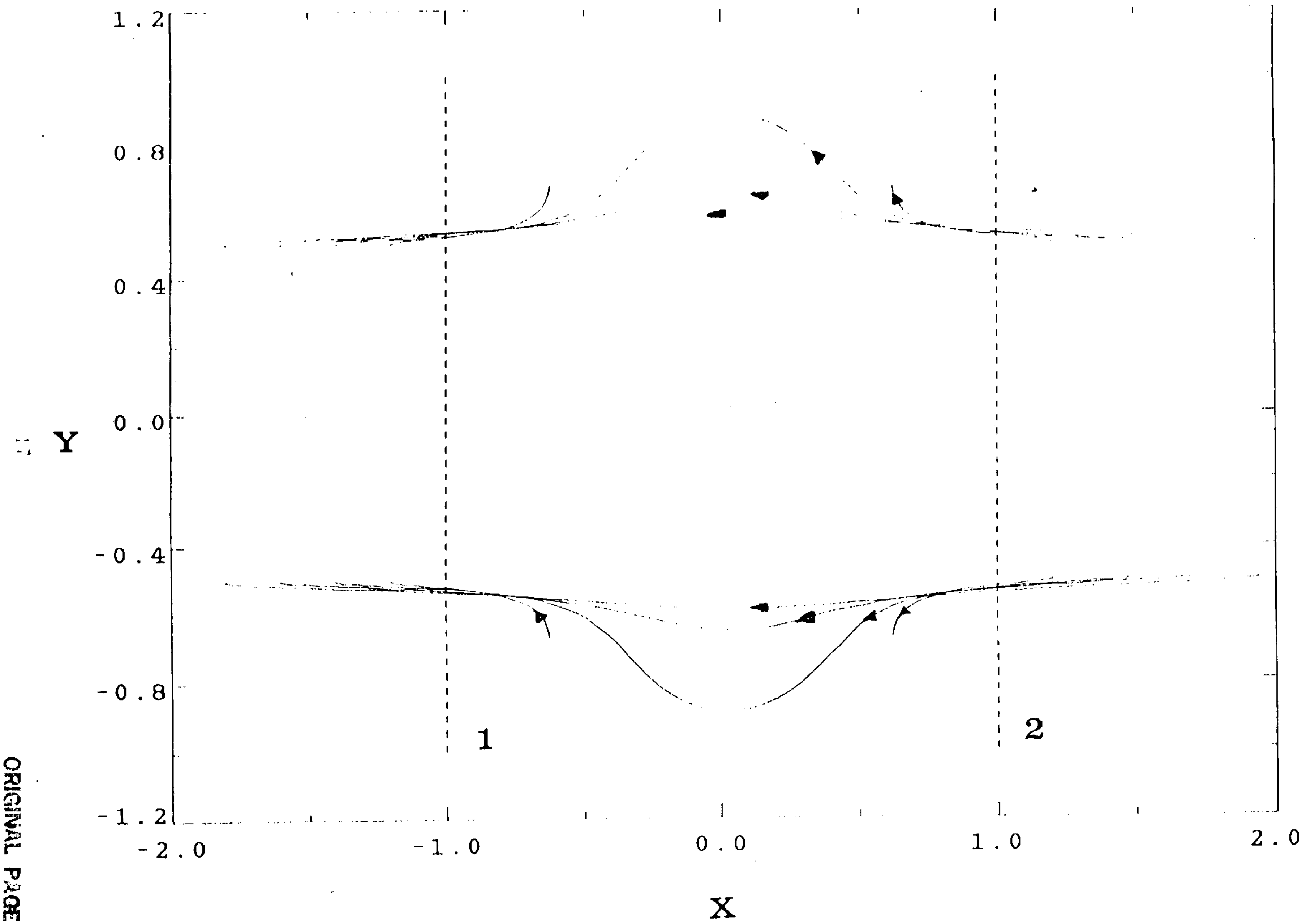

Fig. 2c

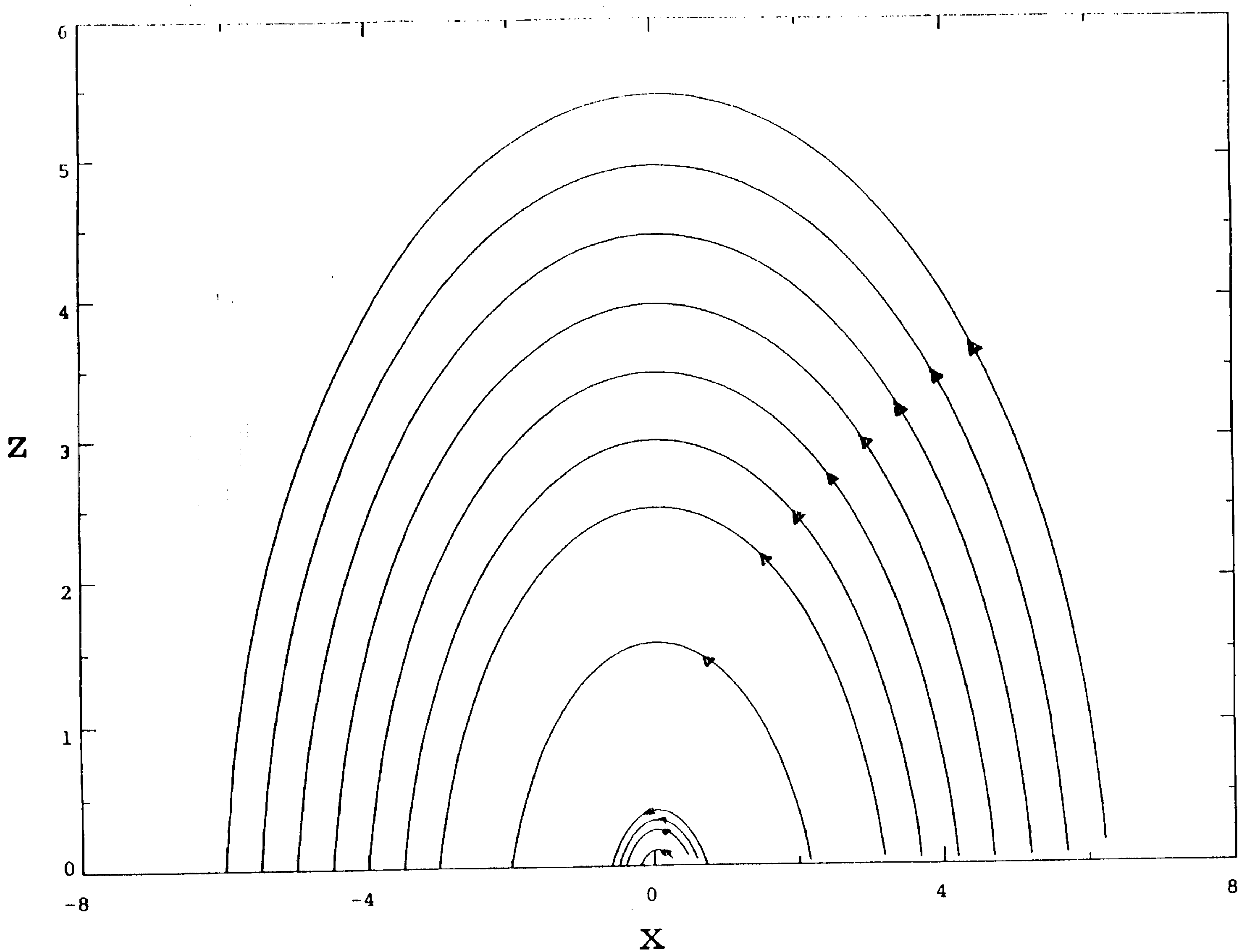

Fig. 3a

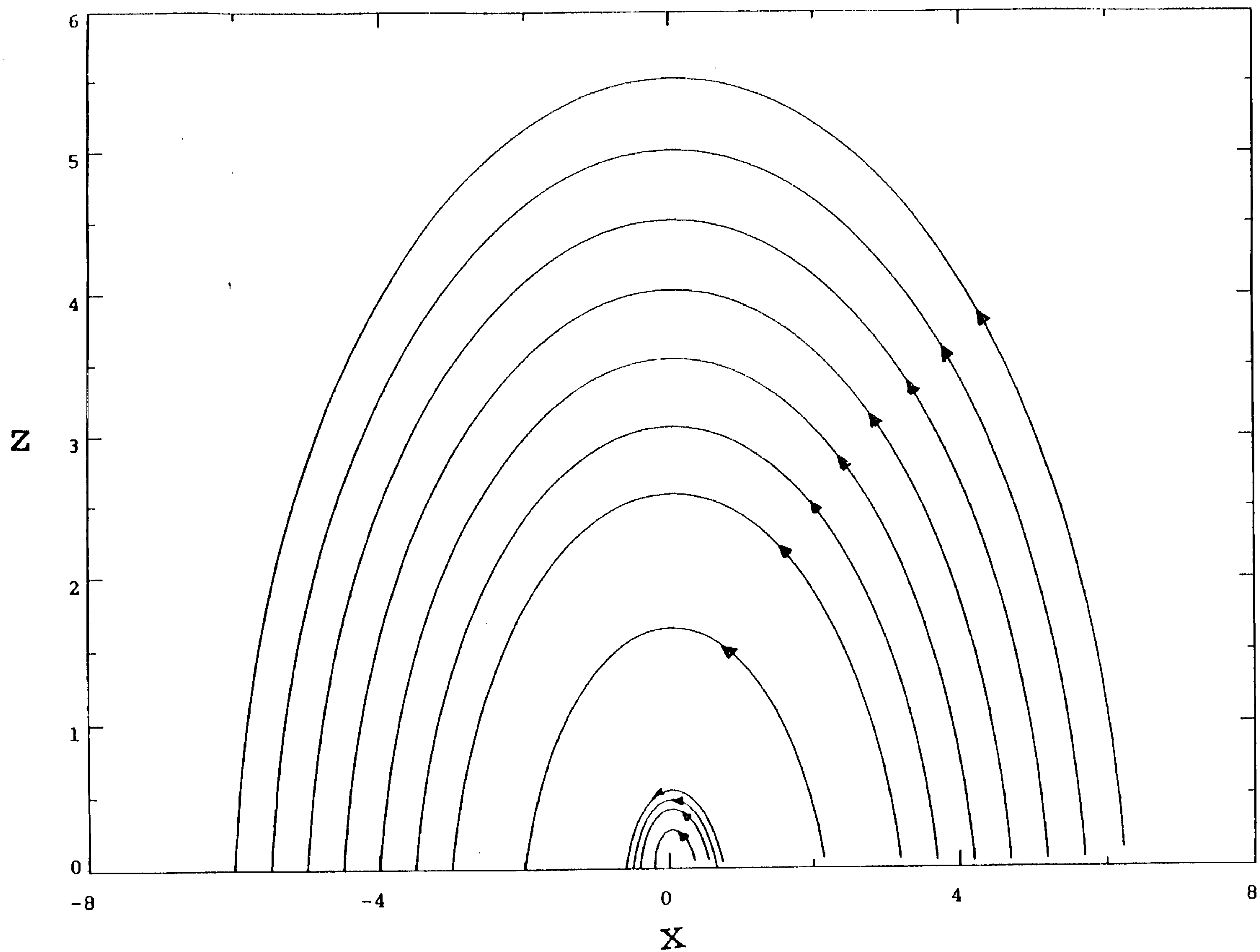

Fig. 5b

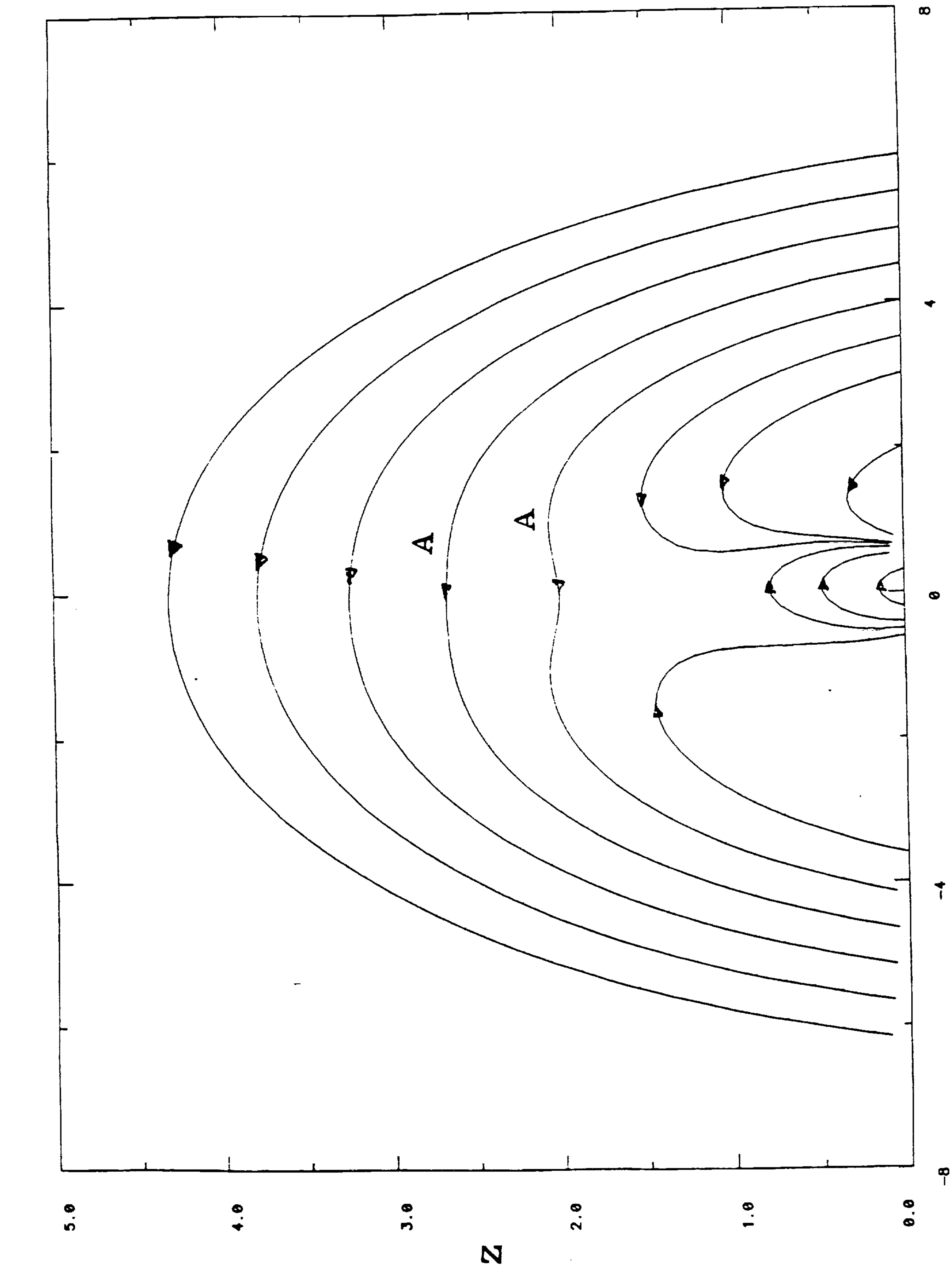

Fig. 1a

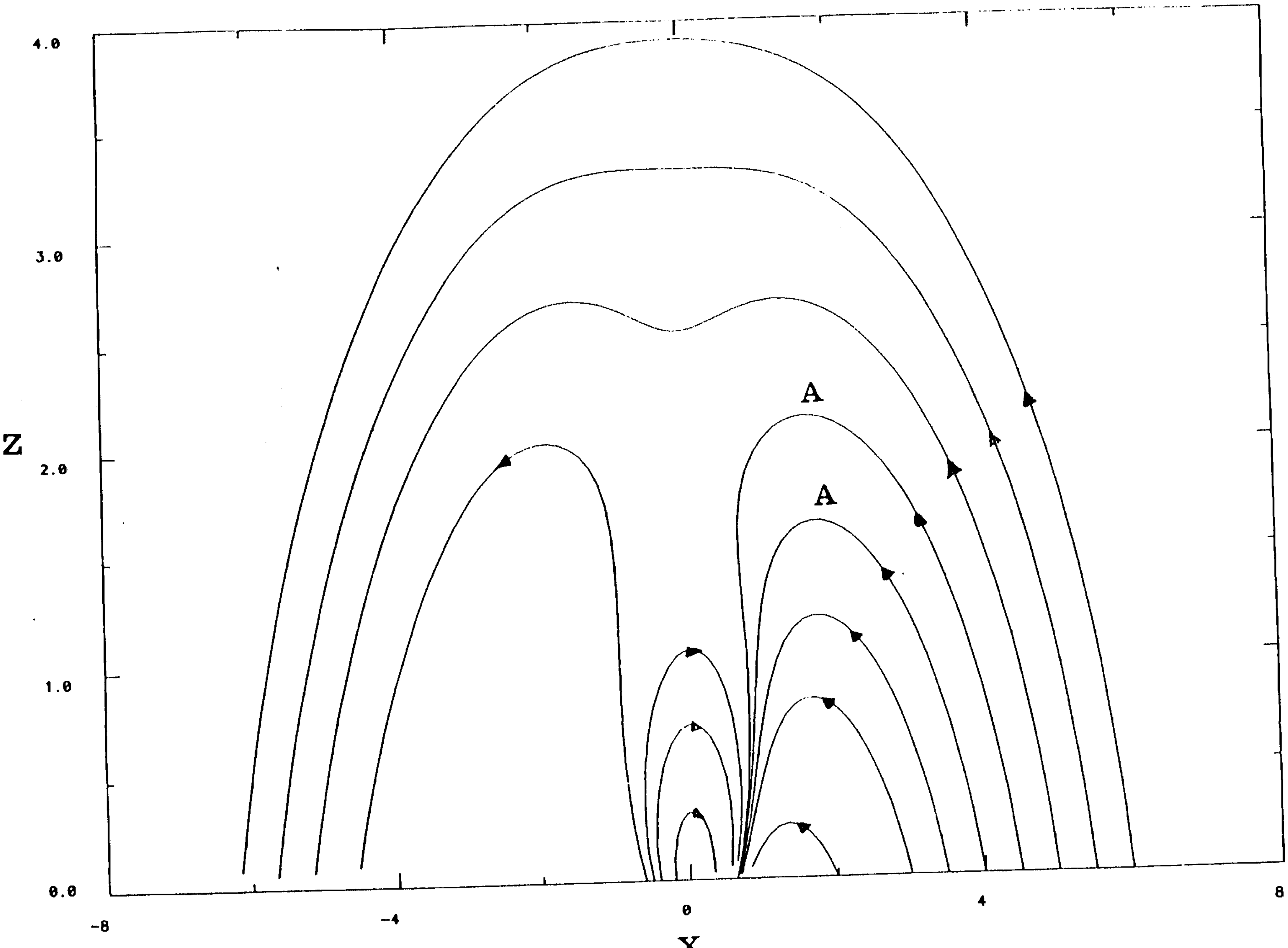

Fig. 4b

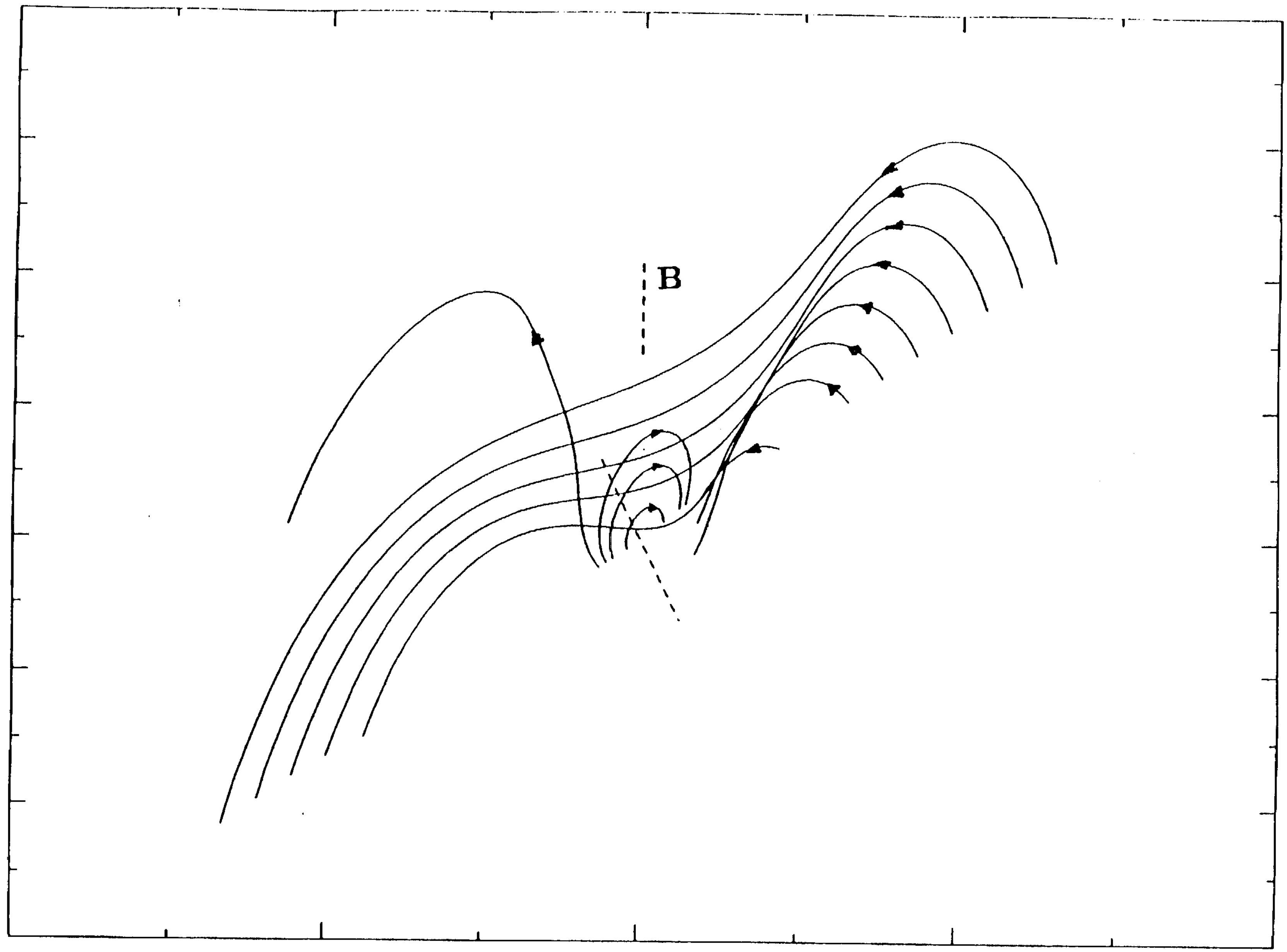

Fig. 5a

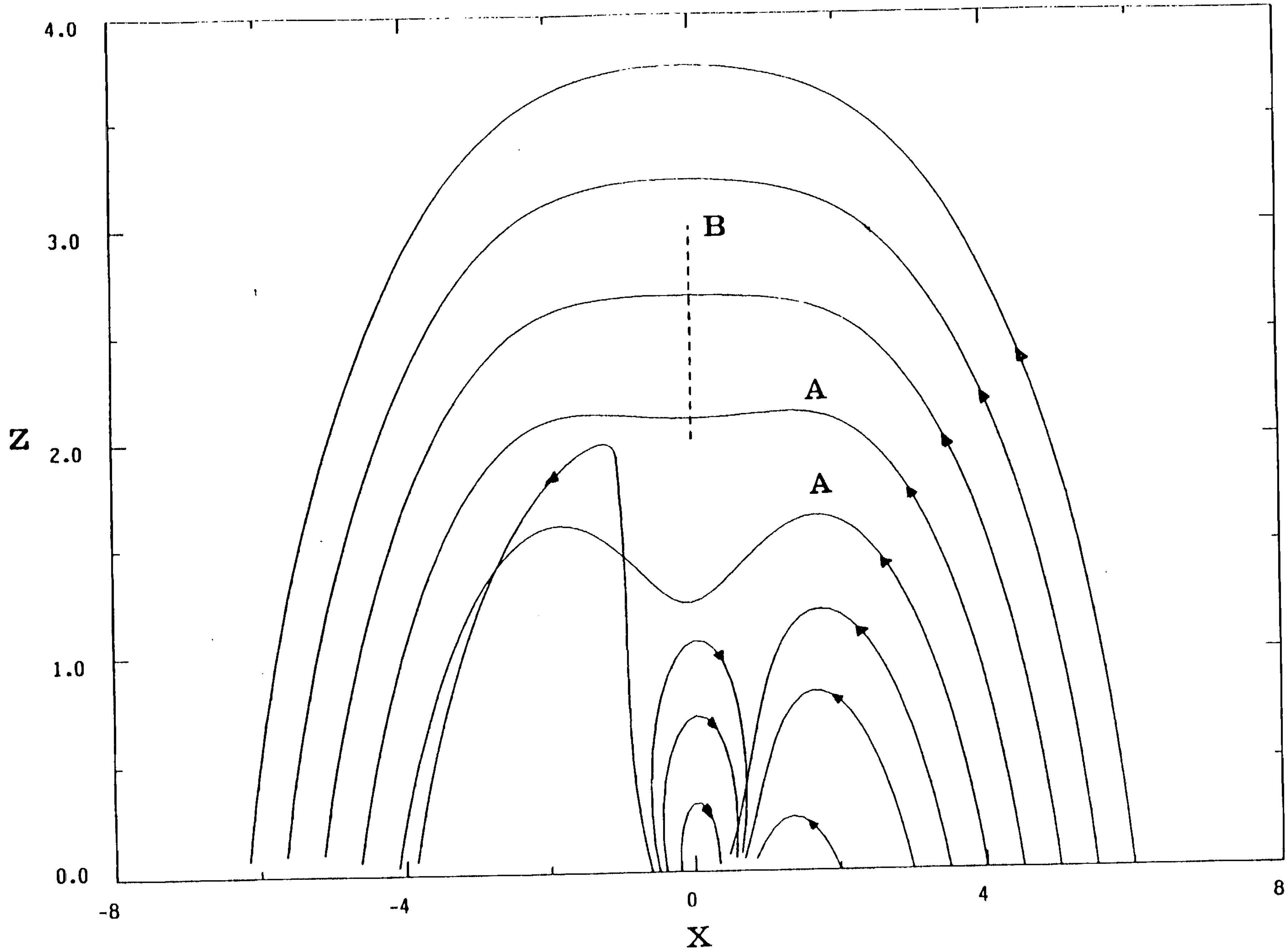

Fig. 5b

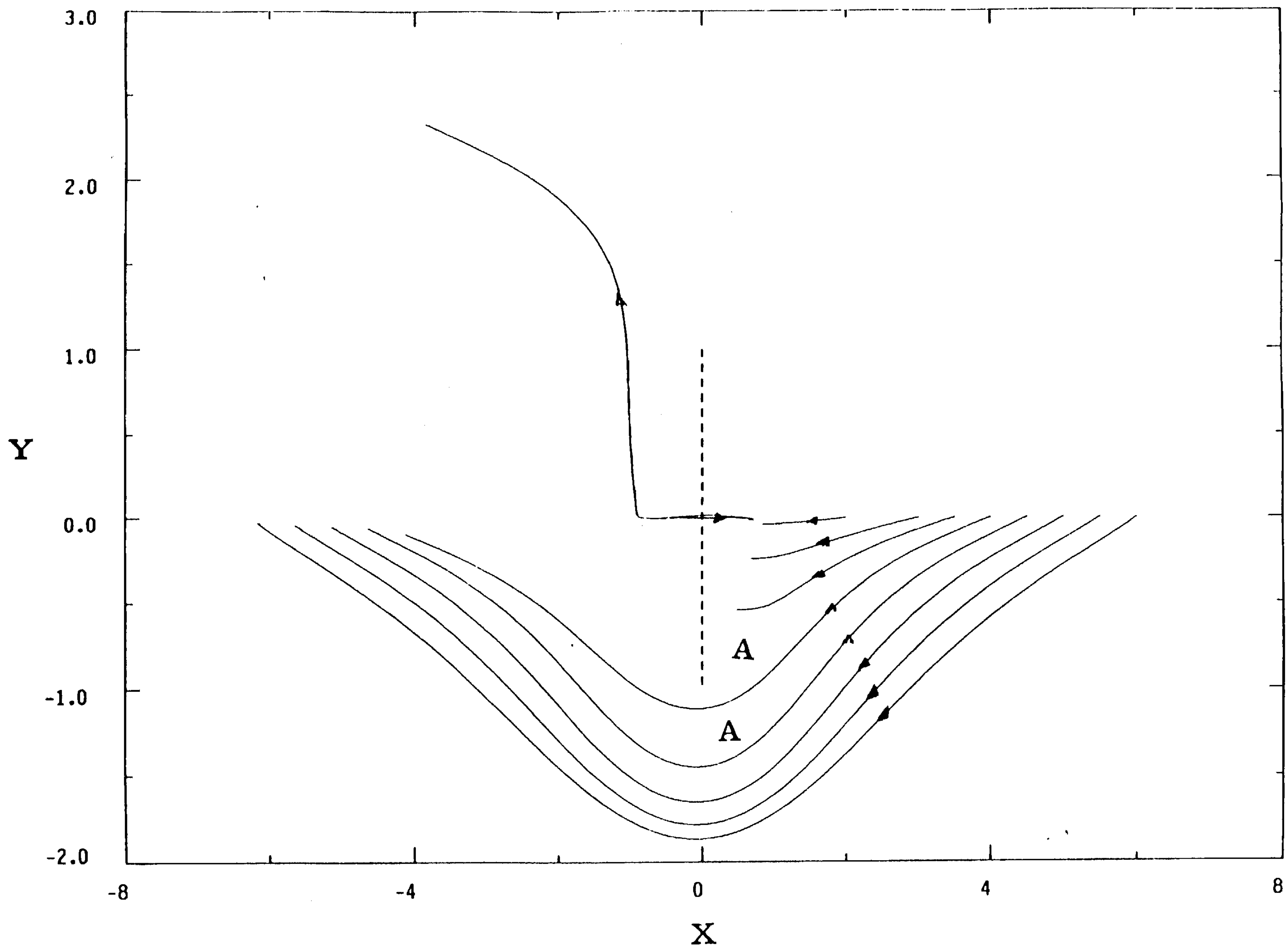

Fig. 5c