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Energetics of the Magnetosphere

David P. Stern

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ENERGETICS OF THE MAGNETOSPHERE

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San Francisco
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Energy has become a key concept in our society, and for a good reason, because it is a universal currency in which the cost of almost anything we do or make must be paid.

In magnetospheric physics, too, everything must be paid for in this currency, and for that reason, an audit of the magnetospheric energy budget reveals a great deal about the processes which are involved, about their causes and effects. And, just as is the case with finances, any discrepancy uncovered by such an audit constitutes a strong hint of deeper trouble.

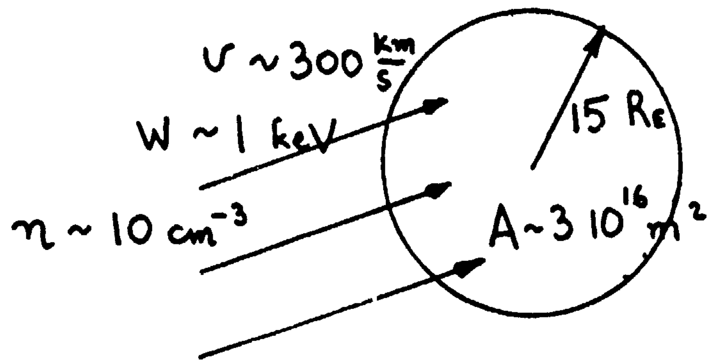
I would like to conduct here a very quick audit of this sort and derive or cite in the next half hour some fundamental energy and power levels associated with the magnetosphere.

(S l i d e 1)

The first quantity is P_1, the power conveyed by a beam of the solar wind with the same cross-section as the dayside magnetosphere, say 30 R_E. It is generally agreed that the solar wind is the energy source of the magnetosphere, and P_1 therefore provides a sort of an upper limit to what can be extracted from it -- it is the power obtained if all solar wind particles hitting the dayside magnetopause gave up their entire energy.

Take a cross section of about $3 \cdot 10^{16}$ m^2, density 10 per cc and speed 300 km/sec (there's more speed but less density ahead of

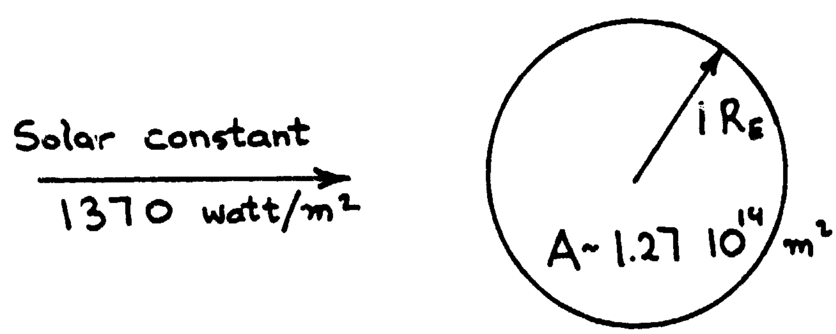
Solar Wind Energy hitting dayside Magnetopause



$$P_1 = n\,v\,W\,A$$

$$P_1 \sim 1.4\ 10^{13}\ \text{watt}$$

Sunshine hitting Earth



$$P_2 \sim 1.75\ 10^{17}\ \text{watt}$$

Figure 1

the bow shock) and you get about

$$P_1 = 1.4\ 10^{13} \text{ watt}$$

1% of this energy is 1.4 10^{11} watt, and that is the widely cited order of magnitude of the energy extracted.

It is interesting to compare this figure to the solar energy input rate P_2 impinging on the Earth. The area available is about 700 times less -- just the cross section of the Earth -- but the energy flux, the so-called solar constant, is big, 1370 watt/m^2. From this

$$P_2 = 1.75\ 10^{17} \text{ watt}$$

This is over 10,000 times P_1 and over a million times the canonical order of energy input into the magnetosphere. It's this huge factor that makes it so difficult to devise a significant sun-weather coupling not involving sunlight.

(S l i d e 2)

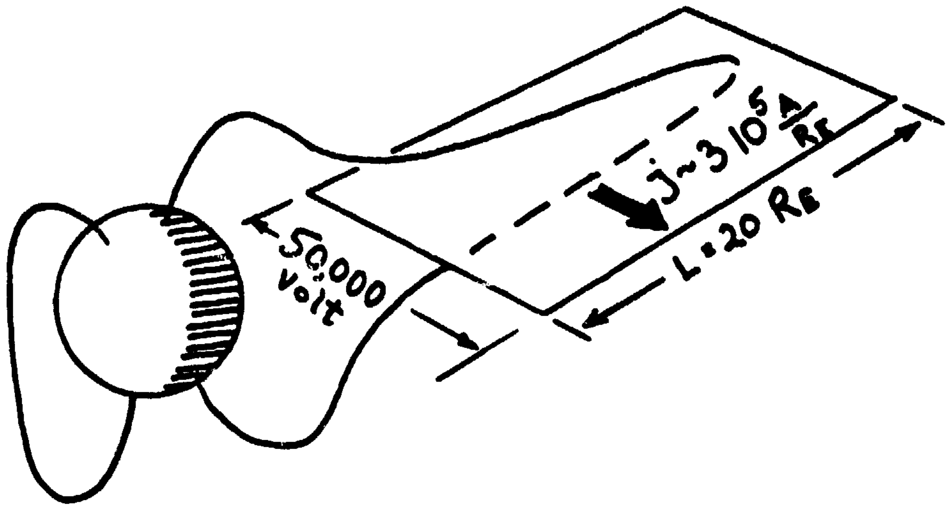
Well, what are the magnetospheric processes that require energy? One prime candidate is the cross tail current. If we take 15γ as the lobe field, the surface current density corresponding to the plasma sheet is $\Delta B/\mu_0$, which comes to about 3 10^5 ampere per R_E of tail length. Taking a length of 20 R_E then gives 6 10^6 amperes, and if the cross-tail voltage is 50,000 volt, we need a power input

$$P_3 = 3\ 10^{11} \text{ watt}$$

or about 2% of P_1.

Now this is one of the biggest items in our budget, and it is subject to a great deal of uncertainty. Why 50,000 volts? Because that is the voltage observed across the polar cap in an open magnetosphere, and if the lobes represent open flux, there is no way for the tail current to close without jumping a gap of 50,000

Energy Input to Cross-tail Current



$$P_3 = LJV = (40)(3\cdot10^5)(5\cdot10^4)$$

$$\boxed{P_3 \cong 3\cdot10^{11}\ \text{watt}}$$

If Magnetosphere is closed $P_3 = 0$

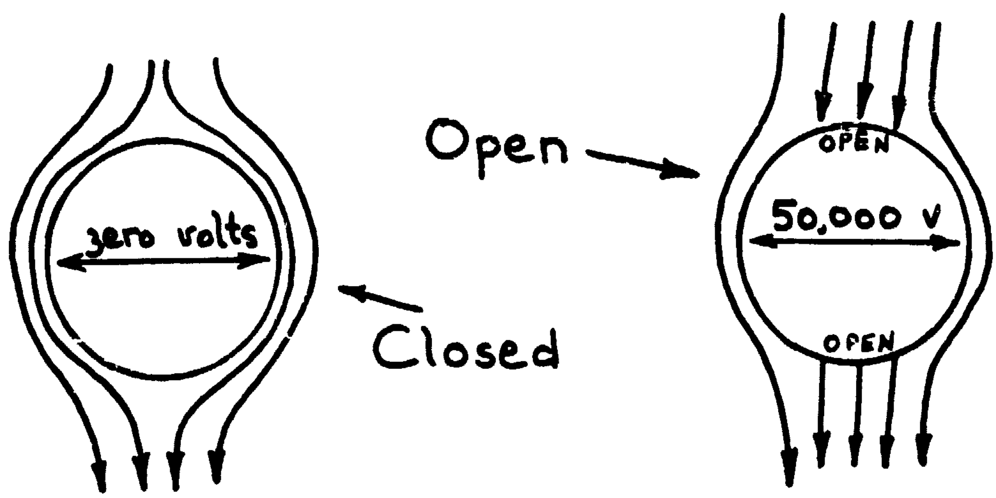


Figure 2

volts or so, as the slide should make clear.

(And by the way, if the magnetosphere is closed, and interplanetary field lines are equipotentials, you get no voltage and no P_3, as the slide also shows.)

In fact, you can devise a reasonable dynamo mechanism by which this voltage is transmitted to the current, and if your imagination is good, you can even regard the boundary layer as "spent solar wind" which has given up most of its energy, something like the relatively slow stream of water that comes out from the exit of a turbine wheel.

Why 3 10^5 amperes per R_E? We get this number from $\Delta\underline{B}$, and it may be argued that it would be more proper to use $\Delta\underline{H}$, i.e. omit contributions by the magnetization current, in the same way as one would do in the presence of ordinary diamagnetic materials. It turns out that magnetization currents do require energy. It is a tricky question, but I lack the time to discuss it.

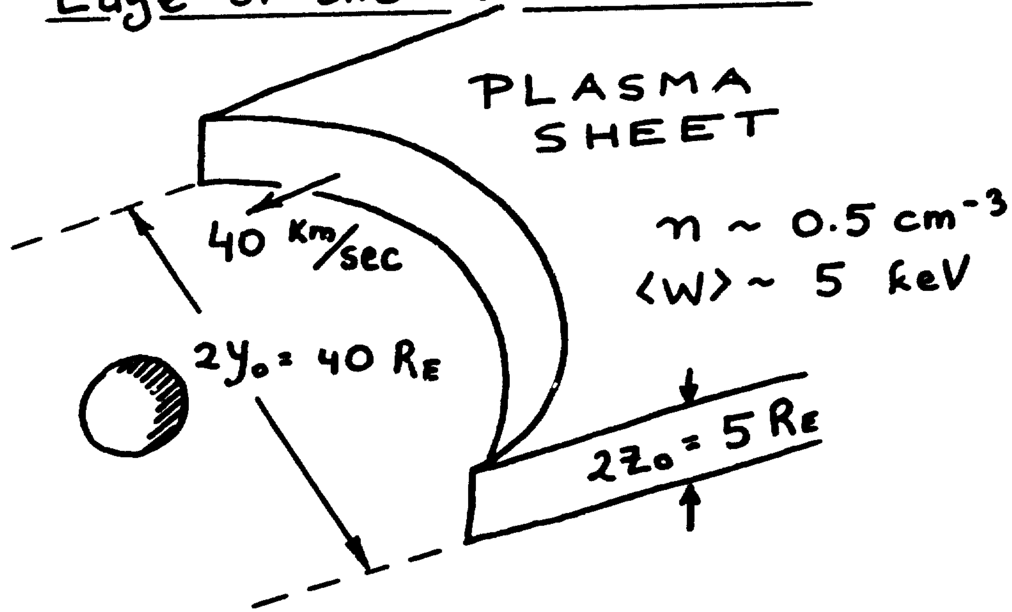
Why 20 R_E? Why not 200? Of course, the voltage and the lobe field intensity may drop off somewhat, but one car still make an estimate of the total tail length and of the associated power requirement. It turns out that the length indeed reaches several hundred R_E, and the power level is 2-3 10^{12} watt, i.e. 7-10 times larger than P_3. This is the figure cited by Siscoe and others.

(S l i d e 3)

I tend to be somewhat suspicious of this figure, though it's more a gut feeling than solid evidence. Most of this energy is deposited past the orbit of the moon, yet the Rice instrument left on the moon has suggested that the plasma sheet may be approaching its end there.

Furthermore, the energy flowing into the inner magnetosphere is far smaller. Consider the inner edge of the plasma sheet--say, 40 R_E wide by 5 R_E thick, 0.5 particles/cc at 5 keV each, that is being generous. A drop of 50,000 volt at $\underline{B}$ = 5γ gives a drift velocity of 40 km/sec, and a power input

Energy Flow past the Inner Edge of the Plasma Sheet



$$P_4 = (2z_0)(2y_0)\, n v \langle W \rangle$$

$$\boxed{P_4 \sim 1.3\ 10^{11}\ \text{watt}}$$

Figure 3

$$P_4 = 1.28\ 10^{11}\ \text{watt}$$

Of course, the tail can store some enery in its magnetic field and release it later in substorms, but I doubt you could get an average power input above 3 10^{11} watt even with this.

So if indeed the energy input into the tail is 20 times P_4, I suspect that almost all of it is returned to the solar wind by spilling out of the flanks or in other ways, and the final result is just some heating of the Earth's wake.

(S l i d e 4)

Next, what is the energy -- call it W_5 -- that is stored in the ring current, in the inner magnetosphere?

You probably all know that the effect of the ring current is to decrease B at the Earth, and that this decrease is characteristic of magnetic storms, amounting to up to hundreds of γ. Now there exists a remarkable formula due to Dessler, Parker and Sckopke, which says that with certain assumptions, if the ring current causes at the origin a decrease ΔB, then

$$W_5 = 1.5\ (\Delta B/B_e)\ U_e$$

where B_e is the surface equatorial field intensity and

$$U_e = B_e^2\ R_E^3/3 \sim 8.4\ 10^{17}\ \text{joule}$$

is the magnetic energy of the main field contained within the Earth. So

$$\text{if} \quad \Delta B = 100\ \gamma \quad \text{then} \quad W_5 = 4\ 10^{15}\ \text{joule}$$

Two things must be noted. One, the formula assumes a certain model for the ring current: for realistic models, the formula may no longer be accurate. Bob Carovillano and George Siscoe, who studied this subject (Rev. Geophys. Space Phys., 11, 289, 1972),

Theorem of Dessler, Parker and Sckopke

$$W_5 = \frac{3}{2} \frac{\Delta B}{B_e} U_E$$

ΔB - field change at $r=0$ due to magnetic storm

$B_e \cong 30000\,\gamma$ Equatorial field at $r = R_E$

$U_E \cong 8.4\ 10^{17}$ Joule - Geomagnetic field energy within $r \leq R_E$

W_5 - total energy of particles that cause the storm

$$U_E = \frac{1}{3} B_e^2 R_E^3$$

Figure 4

concluded that when ΔB is small the formula is pretty good, but when it is large, it overestimates W_5 by a factor from 1.5 to 3.

Secondly, in order to get the baseline for ΔB, we have to remove the entire ring current, and this is not possible. The recent MAGSAT field analysis based on two very quiet days required an external term, corresponding to a baseline value of ΔB of 20γ. If we take this seriously we see that even at very quiet times the ring current contains some 10^{15} joule.

(S l i d e 5)

Suppose now that you have a magnetic storm of $\Delta B = 100\gamma$ and that W_5 is really only 1/2 of what the formula gives. Then

$$W_5 \sim 2\ 10^{15} \text{ joule}$$

Let the energy input from the tail be

$$P_{tail} \sim 4\ 10^{11} \text{ watt}$$

So we need

$$5000 \text{ sec} \sim 1.5 \text{ hours}$$

to build up the magnetic storm. Compare this to the slide, taken from a recent article (Sugiura, EOS, October 1980), where D_{st} may be regarded as the same as ΔB. On the time axis below it each tick mark is 1 day and the whole graph extends over a week:as you see, the magnetic storm indeed builds up gradually, and perhaps you appreciate now the reason why.

One must be careful with these numbers. If a quiet-time equilibrium exists, then trapped orbits and non-trapped ones don't mix, and those 10^{11} watt convected from the quiet-time tail flow by the ring current without adding to it. It is the prime feature of magnetic storms that this separation is broken down -- by transient electric fields from powerful substorms, or

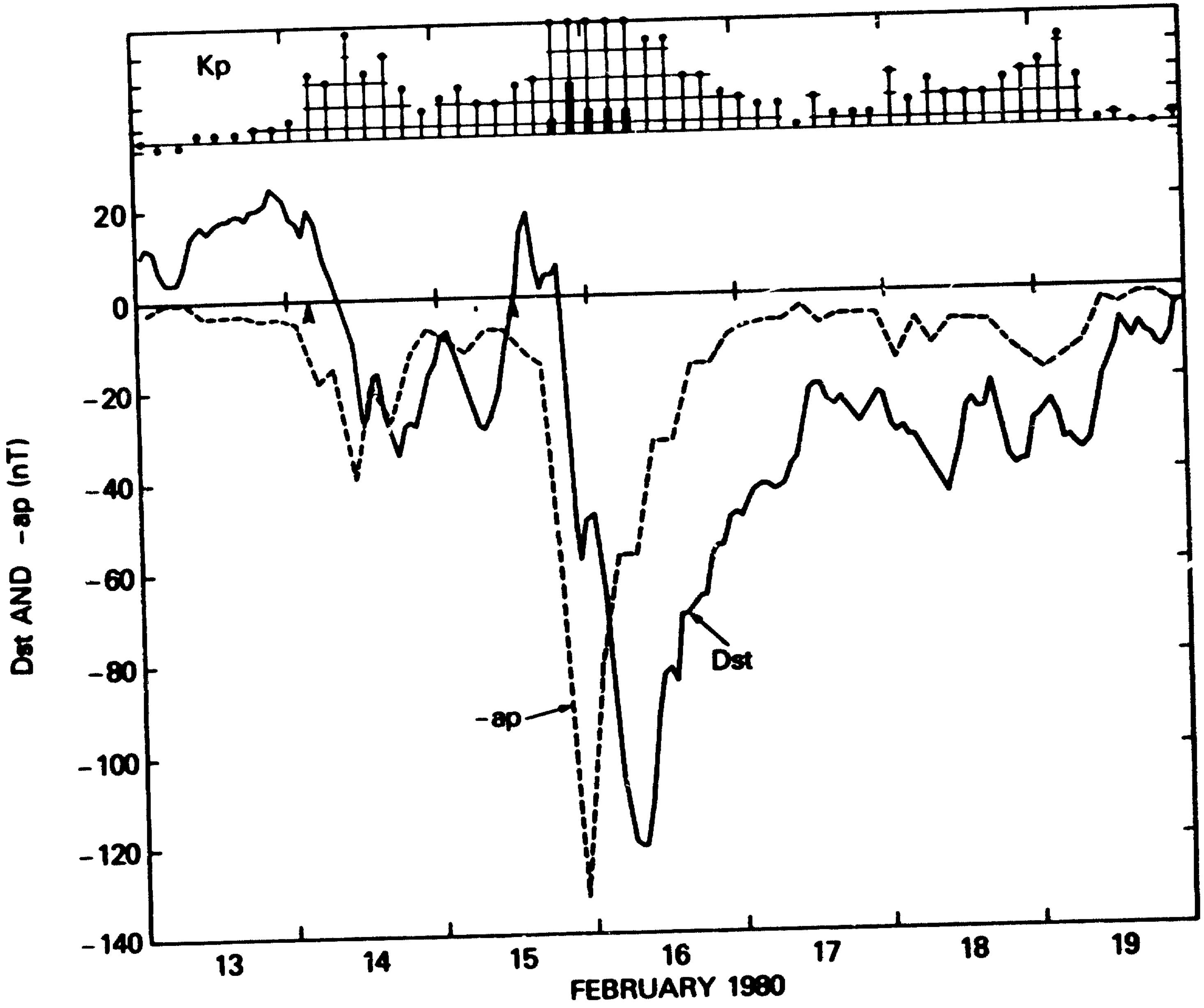

Kp
20
0
-20
-40
-60
-80
-100
-120
-140
Dst AND -ap (nT)
Dst
-ap
13
14
15
16
17
18
19
FEBRUARY 1980

Figure 5

also perhaps in other ways, the debate still goes on -- and the ring current grows.

(S l i d e 6)

One can also play this game the other way around, noting how D_{st} changes and from this inferring the injection rate P_6 of energy into the ring current. Again certain cautions must be noted -- in a big magnetic storm much of the effect may be due to a temporary growth of a particle population of which only a part may be trapped, or as the term goes, in a "partial ring current." But we ignore this now and assume that the Dessler-Parker-Sckopke relation is valid. During very disturbed times it was then found by Kamide and Fukushima in 1971 (Rep. Ionosph. Space Res. Japan, 25, 125, 1971) that

$$P_6 = 2\ 10^{11} - 2\ 10^{12} \text{ watt} \quad (AE \sim 1000\ \gamma)$$

That's rather big, but these are values for very disturbed times. Neil Davis (JGR 74, 5266, 1969) estimated the annual average of P_6 and got a much smaller value

$$< P_6 > = 1.2 - 1.7\ 10^{10} \text{ watt}$$

I should add that both these articles used the Dessler-Parker Sckopke relation without any discounts, so maybe a further division by 2 is warranted, here and in what follows.

Now it must also be assumed that any energy added to the ring current system at t=0 gradually dissipates again -- if this provision is not made, then W_5 has no way to go but up. Kamide and Fukushima found that an exponential time constant of 40 hours fit the data quite well, and this may or may not be related to loss by charge exchange with neutral hydrogen (Smith et al, JGR 81, 2701, 1976).

The interesting thing is that when this decay is taken into

Typical Magnetic Storm

$\Delta B = 100\,\gamma$

$W_s \sim 2 \cdot 10^{15}$ joule

Input from tail: $P_6 \sim 4 \cdot 10^{11}$ watt

$\tau \sim 5000$ sec ~ 1.5 hours

Since ΔB and τ are observable, it is possible to derive P_6 :

Kamide & Fukushima:

$$P_6 = 2 \cdot 10^{11} - 2 \cdot 10^{12} \text{ watt}$$

(AE ~ 1000 γ, very disturbed)

Neil Davis:

$$\langle P_6 \rangle = 1.2 - 1.7 \; 10^{10} \text{ watt}$$

(annual average)

Akasofu:

$$P_6 \text{ watt} \sim 10^9 \cdot AE\,(\gamma)$$

Figure 6

account, P_6 is approximately proportional to the auroral electrojet index AE, which is a good measure of the level of substorm activity (see Rostoker, Rev. Geophys. Space Phys., 10, 935-960, 1972). Akasofu (Planet. Space Sci., 28, 495, 1980; top col. 2, p. 501) puts

$$P_6 = AE(\text{in } \gamma).10^9 \text{ watt}$$

which is inside the range given by Kamide and Fukushima, and he then compares this to his proposed solar wind-magnetosphere coupling index ϵ, which has similar values. It is this fact that P_6 seems to be proportional to AE which suggests that a magnetic storm is pumped up by a series of substorms, and that each substorm is one stroke of the pump that inflates the magnetosphere. However, there exist those who disagree, or who claim that this is part of the story but not the entire story of magnetic storms.

(S l i d e 7)

Next input: how much energy goes into the Birkeland currents?

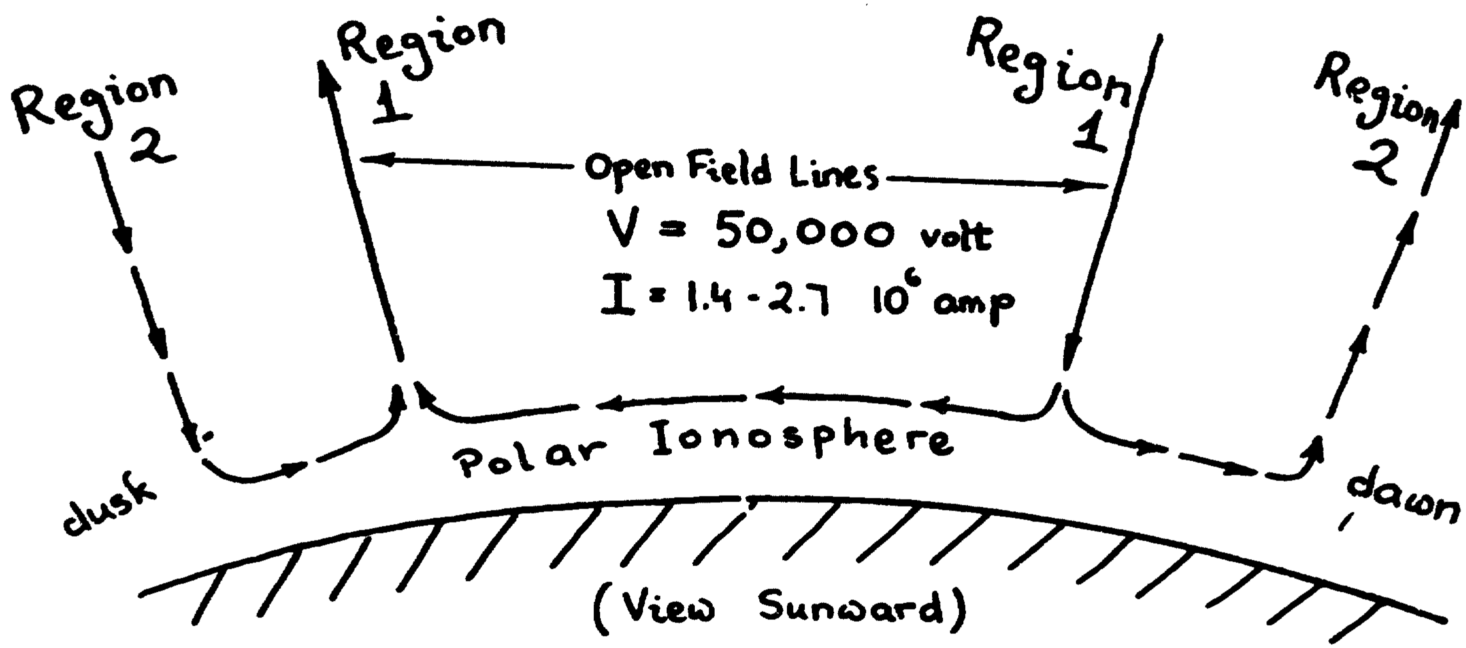
Let us count only the poleward "region 1" currents, because presumably the second (and weaker) system of currents located further equatorward is drained by them as well. Iijima and Potemra estimate for them

$$I \sim 1.4\ 10^6 \text{ ampere at quiet times } (AE<100\gamma)$$
$$I \sim 2.7\ 10^6 \text{ ampere at disturbed times } (AE>100\gamma)$$

I shall again assume a voltage of 50,000 volts, because the particles associated with these currents flow along open field lines, so they must complete a circuit of about this voltage.

Actually, the current contains 2 components. Part of it closes across the polar cap, and then 50,000 volts is certainly appro-

The Power associated with the Flow of $J_{\parallel}$



$$P_T = 2VI = 1.4 - 2.7 \; 10^{11} \text{ watt}$$

Figure 7

priate. The other part comes from convected charges via the region 2 sheets, and there the value may be an overestimate, because such particles already have soaked up some energy during their trip earthwards, and we have already counted that energy as part of the input into the cross-tail current.

So the energy input we get this way is really more of an upper limit. We must further multiply by 2, because the above figures are per polar cap, and this gives

$$P_7 \sim 1.4\ 10^{11}\ \text{watt} \quad \text{(quiet)}$$
$$P_7 \sim 2.7\ 10^{11}\ \text{watt} \quad \text{(disturbed)}$$

Nisbet et al. (JGR 83, 2647, 1978) get 1.2 10^{11} watt, but they assume only half as much power in the summer hemisphere as in the winter hemisphere, because their model fields are weaker. In any case, all this is just an order of magnitude.

(Slide 8)

Finally, let's take the aurora. The only global assessment of auroral energy input was performed by Sharp and Johnson (JGR 73, 969, 1968) who used total energy detectors, sensitive down to 80 ev. That was 12 or 13 years ago and I hope someone will check it with new data when DE goes up next year. Their result is shown on the slide and ranges over the values

$$P_8 = 4\ 10^{9}\ \text{watt} \quad (K_p=1)$$
$$= 6\ 10^{10}\ \text{watt} \quad (K_p=4)$$
$$= 2\ 10^{10}\ \text{watt} \quad \text{(weighted average)}$$

This is a global average for both hemispheres and is surprisingly small, only $\sim$ 1/7 of the Birkeland input P_7.

Of course, P_8 is really part of P_7, because the auroral beam is part of $j_\parallel$, it just differs in that part of its driving voltage is in the form of $E_\parallel$. The remaining 6/7 of P_7 end up as

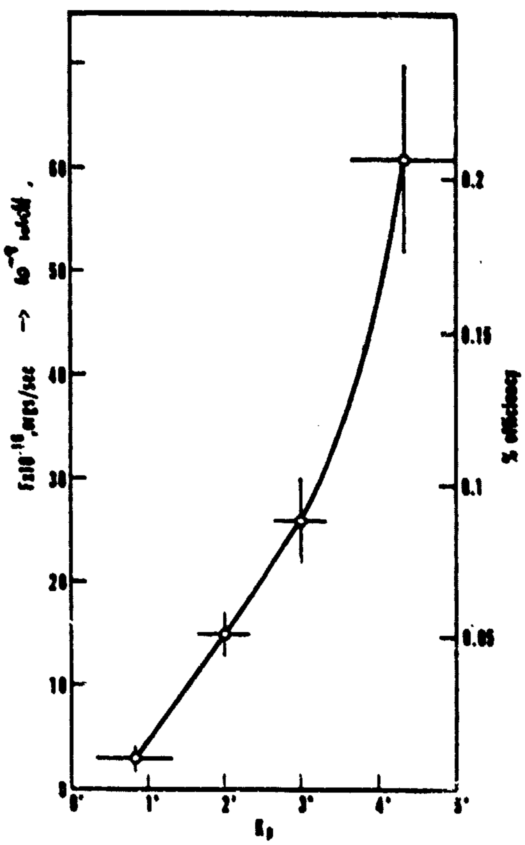


Figure 8

joule dissipation in the ionosphere and (as noted) it is possible that part of it has already been counted before. Still, the aurora is a small part of the total budget.

We note that the power of the <u>kilometric radiation</u>, as cited to me by Mike Kaiser (who ought to know) is

$$P_9 \sim 10^7 \text{ watt} \quad \text{(quiet)}$$
$$\sim 10^9 \text{ watt} \quad \text{(peak)}$$

which fits with about 1% of the auroral energy.

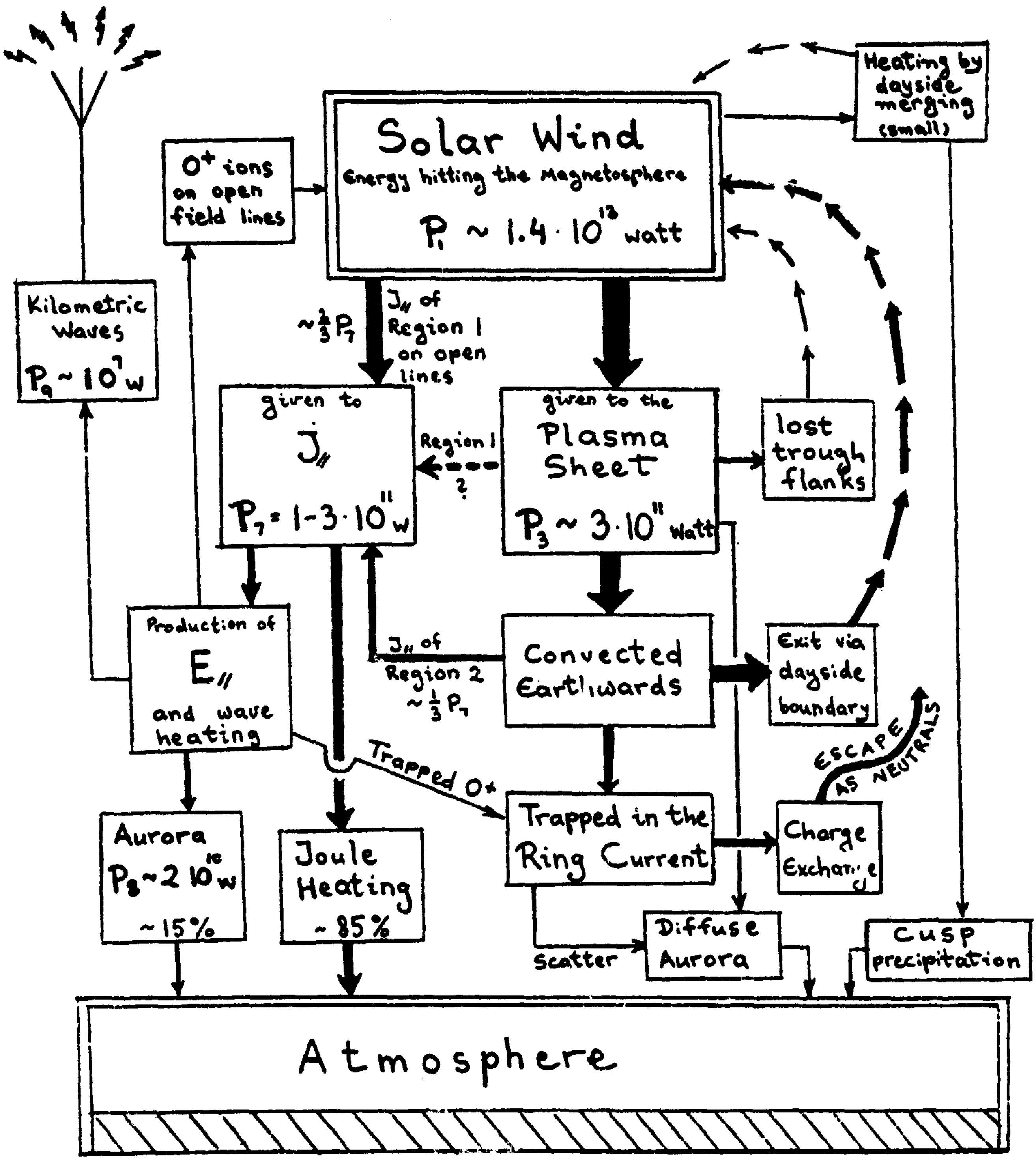
(S l i d e 9)

This slide gives a tentative summary of the average energy flow in the magnetosphere. It's somewhat intricate-looking, so I would not encourage you to try to assimilate it here -- there exist copies for distribution, which you can study later in more detail.

As you can see, most energy inputs are pretty much in agreement with each other. Maybe it's a bit of an anticlimax, because there has been so far very little mention of the more exotic processes involved, such as <u>merging</u> and <u>substorms</u> (I prefer "merging" to "reconnection" because it's 2 syllables shorter, though "reconnection" is always appropriate to describe the re-unification of two sections of a field line which has been earlier torn apart).

Actually, as has been already noted, merging on the dayside is essential for an open magnetosphere, and unless the configuration is open, there exists no voltage between opposite flanks of the tail.

However, when people discuss merging, they frequently have in mind additional things besides change of topology. In particular, reconnection is often viewed as a way of energizing the plasma.



Heating by dayside merging (small)
Solar Wind
Energy hitting the Magnetosphere
$P_1 \sim 1.4 \cdot 10^{13}$ watt
O^+ ions on open field lines
Kilometric Waves
$P_9 \sim 10^7$ w
$J_{\parallel}$ of Region 1 on open lines
$\sim \frac{2}{3} P_7$
given to $J_{\parallel}$
$P_7 = 1\text{-}3 \cdot 10^{11}$ w
Region 1
?
given to the Plasma Sheet
$P_3 \sim 3 \cdot 10^{11}$ watt
lost trough flanks
Production of $E_{\parallel}$ and wave heating
$J_{\parallel}$ of Region 2
$\sim \frac{1}{3} P_7$
Convected Earthwards
Exit via dayside boundary
ESCAPE AS NEUTRALS
Trapped O+
Aurora
$P_8 \sim 2\ 10^{10}$ w
~15%
Joule Heating
~85%
Trapped in the Ring Current
Charge Exchange
Scatter
Diffuse Aurora
Cusp precipitation
Atmosphere

Figure 9

(S l i d e 1 0)

On the slide here you have a 2-dimensional merging configuration, in which case the electric field E is constant and perpendicular to the figure. What these people have noted (and this idea can be extended to include details such as shocks etc.) is that since the flow velocity v along the x and y axes is E/B, as B goes to zero v gets rather large. So one may expect fast jets to be squirted out from the merging region, and experimenters have searched for such jets near the magnetopause, getting very unhappy when they don't appear and very happy on those rare occasions when they do.

However, only very few particles will pass right where they are speeded up, and the jets may only occur where B is very weak. In the overall scheme of energy transfer, compared to P_3 or P_6, this does not seem to be a significant input.

(S l i d e 1 1)

There also seems to exist merging in the tail during substorms, at least according to one school of thought. Let me stress here, the e x i s t e n c e of neutral points or lines in the tail does not by itself assure merging, such points or lines can also exist in a stagnant field. What makes it a process of merging is that the plasma is flowing through the neutral point or line.

If such a flow takes place, then the energy released is generally believed to be the magnetic energy of the high-latitude tail lobes. How much is that? Regard the tail lobes as two half-cylinders, 20 R_E in radius and 50 R_E long. This gives 20,000 π cubic earth radii, each of them 2.6 10^{20} m^3: if the lobe field is 15 γ, we get

$$W_{10} = 1.45\ 10^{15} \text{ joule}$$

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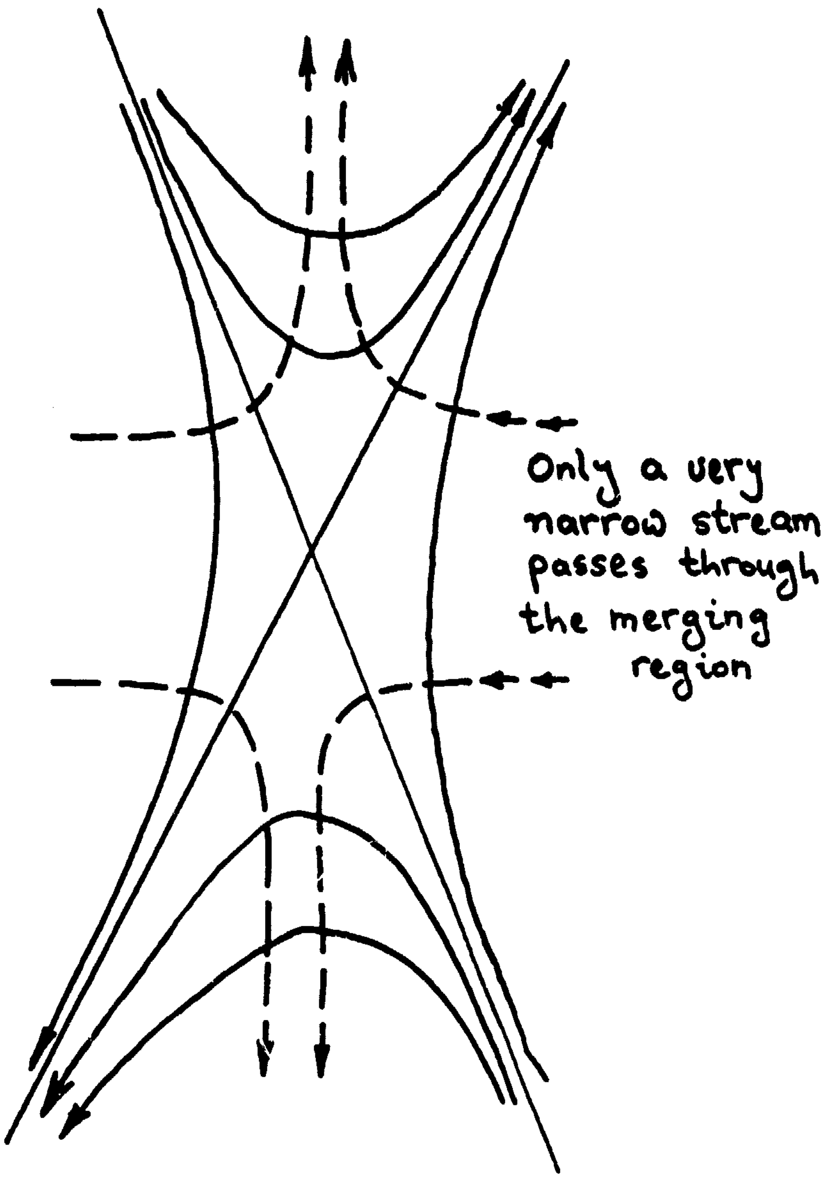
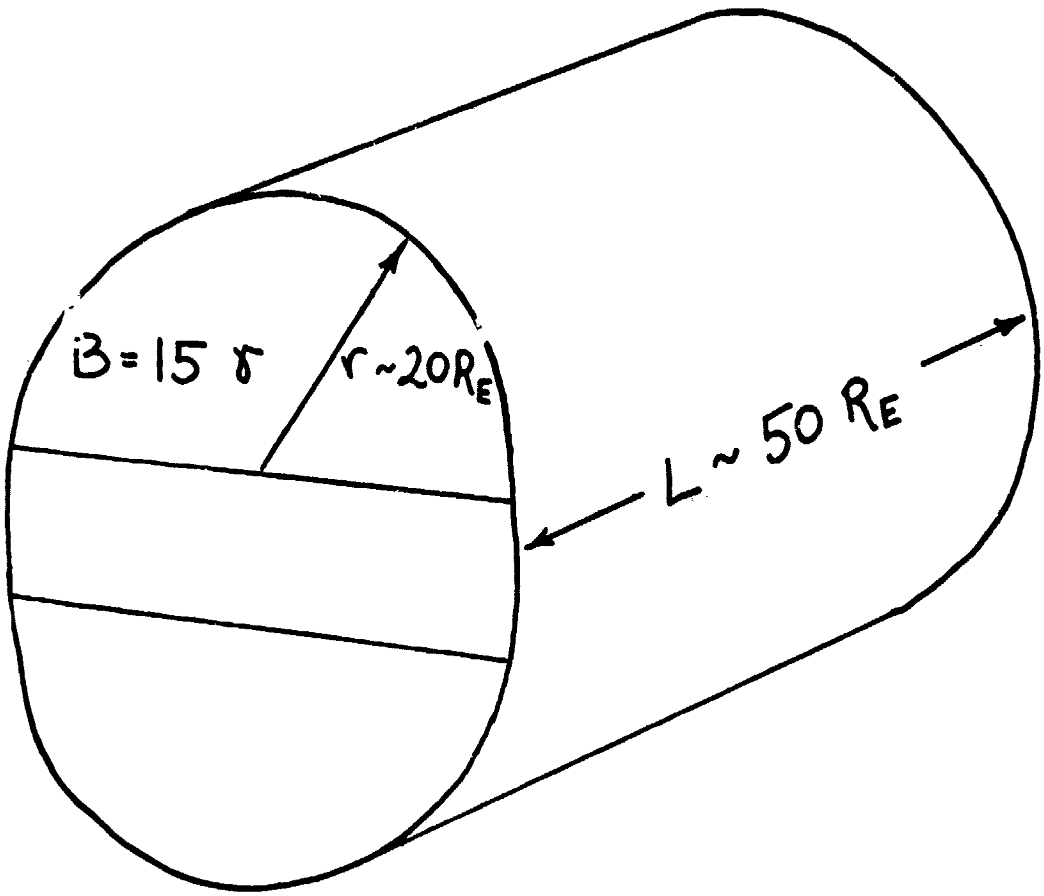


Figure 10

Magnetic Energy Stored in the Tail



$$W_{10} = (\pi r^2 L)(B^2/2\mu_0) \sim 1.45\ 10^{15}\ \text{joule}$$

If $0.1\ W_{10}$ is released in 1000 sec

$$P_{10} \sim 1.45\ 10^{11}\ \text{watt}$$

Figure 11

or about 1/3 of what's in the ring current.

Caan et al. (JGR 78, 8087, 1973) have estimated from before-and-after comparisons that something like 10% of the lobe energy is released in a substorm, and if this output is spread over 1000 seconds, we get

$$P_{10} = 1.45\ 10^{11}\ \text{watt}$$

If the time scale is faster, you get a higher level. Even if you believe that substorms get their energy by some direct coupling to the solar wind, unless there exists a flaw in Caan's study, you must add P_{10} to the sum of energies released during a substorm.

(Slide 12)

Let me end on a somewhat exotic note. You can see that neutral lines forming inside the plasma sheet are created in pairs -- an X-type line and an O-type line (actually, they are probably connected in the 3rd dimension).

The X-type line is the place where field lines pass as they are convected earthward -- and the plasma on these lines ultimately receives most of the released energy, as it moves into stronger magnetic fields near Earth and its particles are adiabatically energized.

The plasma flowing into the O-type line, however, is accelerated much more efficiently along that line, because that line acts like a sinkhole, sucking in particles from all around it. Once a particle is drawn towards the O-line, it does not rest until it is very close to the axis, where its motion is non-adiabatic and where it is rapidly accelerated by whatever voltage is available.

Vasyliunas (to be published) has argued that the vc age

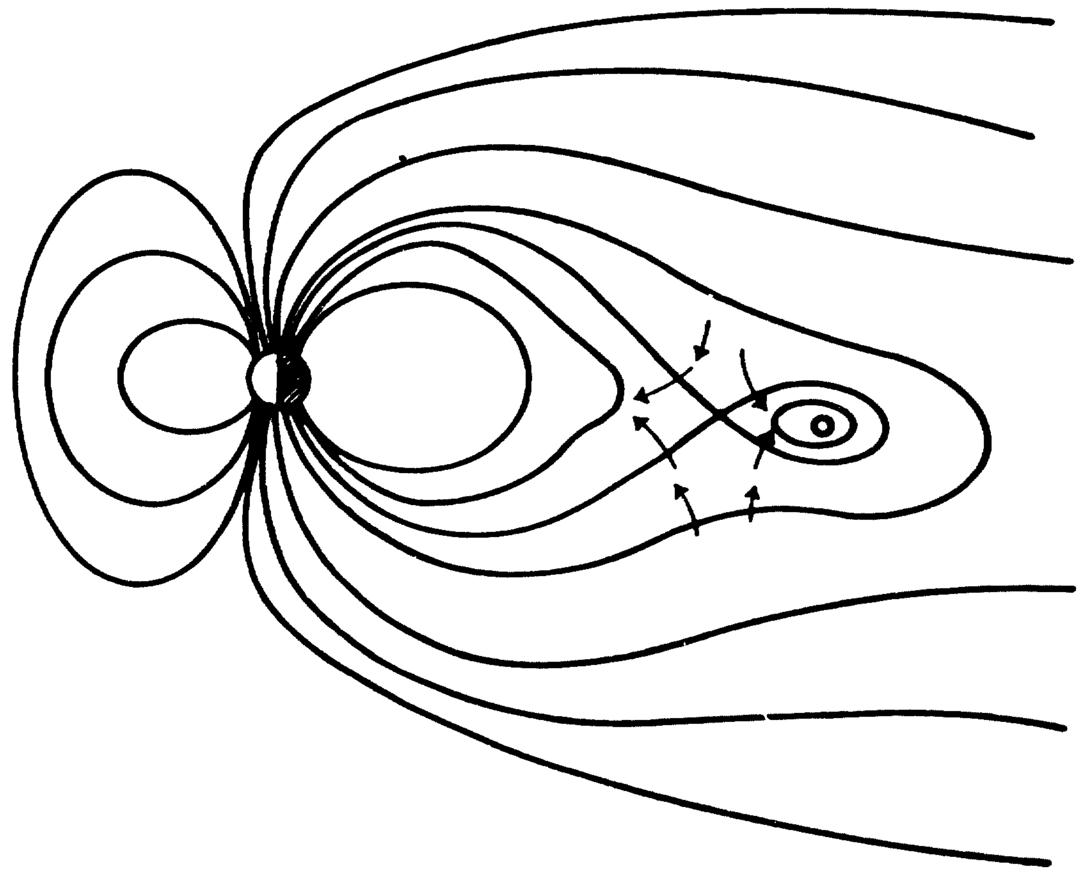


Figure 12

available here cannot be too big, and his argument can be rephrased as follows. What you have here is really a very efficient mechanism for "annihilation of magnetic fields." The plasma and its magnetic field flow together into the sinkhole and out comes the plasma alone, so the magnetic energy must be given to the particles. How much will each particle get?

It all depends on the beta of the plasma. If beta ≈ 1 — a good approximation for the plasma sheet — then the average particle energy can at most double. But if during the "thinning" that accompanies substorms, the plasma sheet is completely squeezed out and the two high-latitude lobes merge directly, then beta is about 1/100 and a hunderdfold energization is quite possible. In other words, there exist so few particles in the lobe plasma, that if the energy of their surrounding magnetic field is transformed to provide them with additional kinetic energy, each of them receives quite a lot. In the total energy budget this is probably a small item, but it could account for the high-energy bursts observed in the tail by APL's instruments.

(S l i d e 1 3)

In summary, here are somesome of the numbers concerned with the energy budget of the magnetosphere, and if they do not seem to be unusually surprising, it may be mainly because they are not too sensitive to the details of the driving processes. There still exists a lot about these processes that we do not know, and in particular, even at this late stage, I would not at all discount the possibility that given all popular theories for explaining the substorm, the correct answer is still "none of the above."

(e n d)

Magnetospheric Power Levels

in units of 10^{10} watt

Impinging Solar Wind Energy	$P_1 \sim 1400$
Sunshine on Earth	$P_2 \sim 1{,}750{,}000$
Cross-tail power input, in 20 R_E	$P_3 \sim 30$
Inflow at inner edge of Plasma Sheet	$P_4 \sim 13$
Input during Magnetic Storms	$P_6 \sim 20 - 200$
	$\langle P_6 \rangle \sim 1.5$
Birkeland Current input	$P_7 \sim 14 - 27$
Auroral input	$P_8 \sim 0.4 - 6$
	$\langle P_8 \rangle \sim 2$
Kilometric Radiation	$P_9 \sim 0.001$
	$(P_9)_{peak} \sim 0.1$
Stored tail energy released during Substorm	$P_{10} \sim 15$

Figure 13

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