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Sweet's Mechanism in the Solar Wind

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Abstract

Direct evidence for Sweet's mechanism is presented. This process occurs in the solar wind, at D-sheets near 1 AU. Conductivities on the order of 10^4 esu are obtained, which is on the order of the local plasma frequency, implying that the effective "collision" frequency is on the order of the plasma frequency. The lateral extent of D-sheets is approximately 0.01 AU to 0.001 AU. Hundreds of such D-sheets are probably present between the orbits of Venus and Earth at any instant.

I. Introduction

Sweet (1956, 1958) proposed a mechanism for rapid, steady-state dissipation of magnetic field in a resistive plasma. In his theory, magnetic field is annihilated at a thin current sheet of finite lateral length, 2L, causing a changing gradient in the magnetic field intensity B and giving rise to dissipation of the magnetic field in a region near the current sheet. This dissipation of field is balanced by the convection of magnetic field toward the current sheet. Material that is brought near the current sheet is diverted and flows away, parallel to the current sheet.

Sweet's mechanism has been invoked to explain various astrophysical processes, but there has been no direct evidence for it. This paper shows that Sweet's mechanism operates in the interplanetary medium near 1 AU in structures which Burlaga and Ness (1968) have identified and called D-sheets.

D-sheets are characterized by a "discontinuous" change in the direction of the magnetic field and a broad depression in the magnetic field intensity. The directional discontinuity is the result of a thin ($\lesssim 10^7$m) current sheet. Burlaga and Ness (1968) showed that the minimum magnetic field intensity in the depression is related to the change in the magnetic field direction (which varies and is usually $\lesssim 180°$) in a manner consistent with the hypothesis that magnetic field is annihilated in the current sheet. Burlaga (1968) suggested that the depression is due to a process similar to Sweet's mechanism, but the plasma data needed to establish this were not available at that time.

II. Theory

Parker (1963) reviewed the theory of Sweet's mechanism and gave a specific mathematical model for the case of antiparallel fields and incompressible flow. The basic equations are:

$$\frac{db}{d\xi} = 1 - ub \tag{1}$$

$$\frac{du}{d\xi} = S^2 (1 - b^2)^{\gamma}; \tag{2}$$

here $u \equiv v/v_0$ is the flow speed with respect to the neutral sheet divided by the corresponding speed far from the current sheet; $b \equiv B/B_0$, where B_0 is the magnetic field intensity far from the current sheet; $\xi \equiv -v_0 x/\nu$ $(v_0 < 0)$ where $\nu \equiv (\mu_0 \sigma)^{-1}$, σ is the conductivity in mks units (mhos/m), and $\mu_0 = 4\pi \times 10^{-7}$ henry/m is the permeability of free space; and

$$S^2 = a^2 V_{A_0} \nu / (L v_0^2) \tag{3}$$

where a^2 is a constant on the order of unity, V_{A_0} is the Alfvén speed far from the neutral sheet, and L is the characteristic length of the annihilation region along the current sheet. Eq. (1) is exact and follows from the conditions $\underset{\sim}{J} = \frac{1}{\mu_0}\nabla \times \underset{\sim}{B}$, $\underset{\sim}{E} = -\underset{\sim}{v} \times \underset{\sim}{B} + \underset{\sim}{J}/\sigma$, and $\nabla \times \underset{\sim}{E} = 0$. Eq. (2) is only approximate, and is derived from the conservation of mass, energy, and momentum together with a dimensional argument. The momentum equation can be integrated directly in the steady state to give the additional condition,

$$P = nk\,(T_e + T_p) + B^2/8\pi = \text{constant} \tag{4}$$

here T_p is the proton temperature and T_e is the electron temperature hich we take to be 1.7×10^{5} °K (e.g., see Hundhausen, 1972; Montgomery t al., 1972; Scudder at al., 1973).

Parker showed that the solution of (1) and (2) for $\gamma = 1$ and $b(o) =$ $(o) = 0$, is $u(\xi) = b = \tanh \xi$, $S = 1.0$. He also showed that the solu-ion is insensitive to the choice of γ.

For D-sheets, the magnetic field does not simply reverse direction cross the current sheet; consequently, $b(0) \equiv b_{min} \neq 0$, but one still equires $u(o) = 0$. Furthermore, in general, ${}^{+}B_o \equiv B(\xi \rightarrow +\infty) \neq$ ${}^{-}B_o \equiv B(\xi \rightarrow -\infty)$, so that one must consider the regions $\xi > 0$ and $\xi < 0$ separately. This can be done simply be setting $b = B/{}^{+}B_o$ in the egion $\xi \geq 0$ and $b = B/{}^{-}B_o$ in the region $\xi \leq 0$. An approximate solution f (1) and (2) for these conditions and with $\gamma = 1$ is,

$$ {}^{+}B = {}^{+}B_o \tanh \xi + B_{min} \operatorname{sech} \xi \;;\; v = v_o \tanh \xi \,,\; \xi > 0 \qquad (5) $$

$$ {}^{-}B = {}^{-}B_o \tanh \xi + B_{min} \operatorname{sech} \xi \;;\; v = v_o \tanh \xi \,,\; \xi < 0 \qquad (6) $$

$$ S = 1 $$

his satisfies (1) exactly, and is a good approximation to (2) when $_{min}/{}^{+}B_o$ is small. This solution is rigorously valid only for incom-ressible flow, i.e., when the ambient pressure p_o is much greater than he magnetic pressure $B_o^2/8\pi$. Nevertheless, if the compression factor, $_o/n_c \gtrsim 1$ where n_o is the ambient particle density and n_c is the ensity near the current sheet, then the above results are expected to e applicable.

III. Observations

To relate the above theory to the interplanetary observations, one must consider that a D-sheet is convected past the spacecraft with the solar wind velocity $\underset{\sim}{V}_w$. Let t_o be the time at which the current sheet passes the spacecraft, and let $\tau \equiv t - t_o$, where t is the time of a measurement. Then $x = \underset{\sim}{V}_w \cdot \hat{n}\tau$, where $\hat{n}$ is the normal to the current sheet, and $\xi = \alpha\tau$ where,

$$\alpha = -v_o \underset{\sim}{V}_w \cdot \hat{n} / \nu \qquad (v_o < 0) \tag{7}$$

The value of α can be obtained from the observed half-width of the measured magnetic field profile, τ_w, by solving the equation

$$\frac{B_{min}}{{}^+B} + \frac{1}{2}\left(1 - \frac{B_{min}}{{}^+B_o}\right) = \tanh(\alpha\tau_w) + \frac{B_{min}}{{}^+B_o}\,\mathrm{sech}\,(\alpha\tau_w)$$

Only three measured parameters, B_{min}, ${}^+B_o$, and τ_w are needed to determine ${}^+B\ (\tau)$, and just one additional measured parameter, ${}^-B_o$, is needed to determine ${}^-B(\tau)$. There are no adjustable parameters.

The merging speed, v_o, can be computed from the bulk velocity $\underset{\sim}{V}(\tau)$ measured outside of the depression as follows. In general, $\underset{\sim}{V}(\tau) = V_w(\tau)\hat{w} + v_o\ (\tau)\ \hat{n} + v_t\ (\tau)\hat{t}$, where $\underset{\sim}{V}_w = V_w\hat{w}$ is the solar wind velocity or the velocity with which the current sheet moves, $v_o\hat{n}$ is the velocity toward the current sheet along the normal direction $\hat{n}$, and $v_t\hat{t}$ is the velocity parallel to the current sheet. Since the discontinuity in a D-sheet is a tangential discontinuity, $\hat{n}$, can be computed from the relation $\hat{n} = {}^+\underset{\sim}{B} \times {}^-\underset{\sim}{B} / |{}^+\underset{\sim}{B} \times {}^-\underset{\sim}{B}|$. Assume that $v_o\ (\tau) = -v_o(-\tau)$. This is not exactly true when ${}^+B \neq {}^-B$, but the resulting error in v_o is small.

Then, subtracting $\hat{n} \cdot \underset{\sim}{V}(\tau)$ from $\hat{n} \cdot V(-\tau)$ and noting that $\hat{n} \cdot \hat{t} = 0$, one obtains

$$v_o = ({}^{+}\underset{\sim}{V} - {}^{-}\underset{\sim}{V}) \cdot \hat{n}/2 \tag{8}$$

Similarly, one obtains,

$$\underset{\sim}{V}_w \cdot \hat{n} = ({}^{+}\underset{\sim}{V} + {}^{-}\underset{\sim}{V}) \cdot \hat{n}/2 \tag{9}$$

Now consider the data. Burlaga and Ness (1968) and Burlaga 1968) identified 8 D-sheets in the Pioneer 6 GSFC magnetic field observations. The plasma data needed for this study (from the MIT plasma analyzer on Pioneer 6) were available for only 5 of these. One case was rejected because $\hat{n}$ could not be computed due to large fluctuations in the magnetic field direction, and another was rejected because of fluctuations in the velocity. For one of the remaining three events (on December 27, 1965), $B_{min}/{}^{+}B_o$ was not small and hence the above theory is not applicable to it. Nevertheless, this is included in the discussion that follows. The other two events, which are identified in Table 1 and shown in Figure 1a and Figure 1b will be examined in more detail.

To compute v_o from (8) for the three events under consideration, one must use velocities measured at τ sufficiently large that $u \ll 1$, but sufficiently small that they represent phenomena associated with the D-sheet. We chose two successive (within a few minutes) measurements made at the edge of the depression in ${}^{+}B(\tau)$ (where $B/{}^{+}B_o \gtrsim$ 95) and the two corresponding measurements at the edge of ${}^{-}B(-\tau)$. The average v_o computed from (8) using these two pairs and Δ, equal to half the difference of the two values of v_o obtained in this way, are shown in Table 1. The small Δ obtained from the two independent pairs of measurements is a measure of the relative uncertainty of the two corresponding values of v_o for each event. The absolute error in v_o is larger, and is estimated to be a few km/sec. For all three of the D-sheets in Table 1, the observations indicate motion toward the current sheet with a speed of several km/sec, which is $\approx$ 10% of the Alfvén speed. This is consistent with Sweet's mechanism.

Now consider the variation of $B(\tau)$. For the April 3, 1966, event one obtains $\alpha = 5.6 \times 10^{-3}$ which gives the magnetic field profiles $\pm B(\tau)$ shown in the top panel of Figure 1a. Similarly, for the Jan. 21, 1966, event, one obtains $\alpha = 3.25 \times 10^{-3}$ which gives the magnetic field profiles $\pm B(\tau)$ shown in the top panel of Figure 1b. In both cases, the observed $B(\tau)$ profiles are fitted very well by the theoretical curves.

The total pressure, P, for the April 3 and Jan. 21, events is shown in the bottom panels of Figure 1a, b. P is approximately constant, within the experimental uncertainties, consistent with (4).

The above results, indicating a subalfvénic flow toward the current sheet, and a depression in the magnetic field intensity profile which is accurately described by a solution of the equations for Sweet's mechanism, constitute strong evidence for the operation of Sweet's mechanism at D-sheets in the solar wind.

In Sweet's mechanism, magnetic field is dissipated by the finite conductivity of the plasma. This can be computed for each of the D-sheets in Table 1 using (7) which gives $\sigma = -\alpha/(\mu_0 \; v_o \; \mathbf{V}_w \cdot \hat{n})$, where $\mathbf{V}_w \cdot \hat{n}$ is given by (9), and α and v_o are given in Table 1. The resulting conductivities, which are listed in Table 1, range from 1.7×10^4 esu to 9.3×10^4 esu. The magnetic Reynold's number is ≈ 100.

The theoretical conductivity given by the Spitzer-Harm formula (Spitzer, 1962) with $T = 2 \times 10^5$ °K gives $\sigma \sim 5 \times 10^{14}$ esu, which is $\gtrsim 10^{10}$ times larger than our empirical value. Evidently, one or more micro-instabilities have developed to produce the anamalous conductivity. Scarf (1970) has suggested that ion sound wave turbulence can greatly alter the effective collision time; this theory would predict $\sigma \lesssim 5 \times 10^6$ esu under the conditions in D-sheets, which is still a factor of 100 larger than the observed value. If the effective electron-ion collision frequency, ν_{ei}, eff, is much greater than ω_{ec}, then $\sigma_{esu} \sim \omega_{ep}^2/(4\pi \nu_{ei},\text{eff})$, where ω_{ep} is the electron plasma frequency (e.g. Chapman and Cowling, 1970, p. 366). Thus, $\sigma_{esu} \sim \omega_{ep}/2$, if $1 \lesssim \nu_{ep}/\nu_{ei}$, eff; this is the case for the D-sheets under consideration, as shown in Table 1.

Given σ we can now estimate the lateral extent, 2L, of the D-sheets from (3) with S = 1, viz., $L \approx V_{A_0} \nu / (v_0^2)$, which gives L ranging from 10^{-3} AU to 10^{-2} AU (see Table 1). The relatively small occurrence rate, R, of D-sheets ($R \approx 2$/month in the Pioneer 6 data) is due in part to the small extent of the D-sheets. The number of D-sheets which intersect the ecliptic plane between the orbits of Venus and Earth at any instant is $N \gtrsim 2\pi \times 1\ \text{AU} \times 0.3\ \text{AU} \times R/(2L V_w)$ which is between 10 and 500. Thus, there may be hundreds of D-sheets near 1 AU at any instant. It is likely that this is only a lower limit, for only very broad D-sheets could be resolved in the Pioneer 6 data; many much thinner D-sheets might be present.

Table 1

Data and Derived Parameters for D-sheets

	12/27/65*	1/21/66	4/3/66
t_o (UT)	1050	0915	0819
v_o (km/sec)	-8.7	-3.1	-4.5
Λ (km/sec)	.3	.1	.8
v_o/V_A	.12	.03	.26
α	$\sim 10^{-2}$	3.23×10^{-3}	5.6×10^{-3}
σ (mks)	$\sim 7 \times 10^{-6}$	1.9×10^{-6}	10×10^{-6}
σ (esu)	$\sim 6 \times 10^{4}$	1.7×10^{4}	9.3×10^{4}
$\nu_{ep}/\nu_{ei,eff}$	~1	.27-.18	1.2
ωp (hz)	$\sim 12\times10^{4}$	$17\times10^{4}-23\times10^{4}$	16×10^{4}
L (AU)	$\sim 7\times10^{-4}$	3×10^{-2}	4×10^{-4}
N	~332	8	500

* Theory not expected to be strictly applicable.

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Dr. Lazarus provided the plasma data from the MIT plasma analyzer on Pioneer 6 and discussed them with us. The magnetic field data are from the GSFC magnetometer of Ness on Pioneer 6.

Figure Captions

Fig. 1 Magnetic field and plasma observations of the two D-sheets which were observed by Pioneer 6. The theoretical curve for each event is a solution to the equations for Sweet's mechanism. The bottom panel shows that the total pressure is approximately constant across each of the D-sheets.

References

1) Burlaga, L. F. 1968, Solar Physics, 4, 67.

2) Burlaga, L. F., and Ness, N. F. 1968, Canadian Journal of Physics, 46, S 962.

3) Chapman, S. and Cowling 1970, The Mathematical Theory of Non-Uniform Gasses, Cambridge University Press.

4) Hundhausen, A. J. 1972, Coronal Expansion and the Solar Wind Springer-Verlag.

5) Montgomery, M. D. 1972, Solar Wind, Sonett, Coleman, and Wilcox, eds., NASA SP-308, 208.

6) Parker, E. N. 1963, Astrophys. Journal Suppl. Ser 77, 8, 177

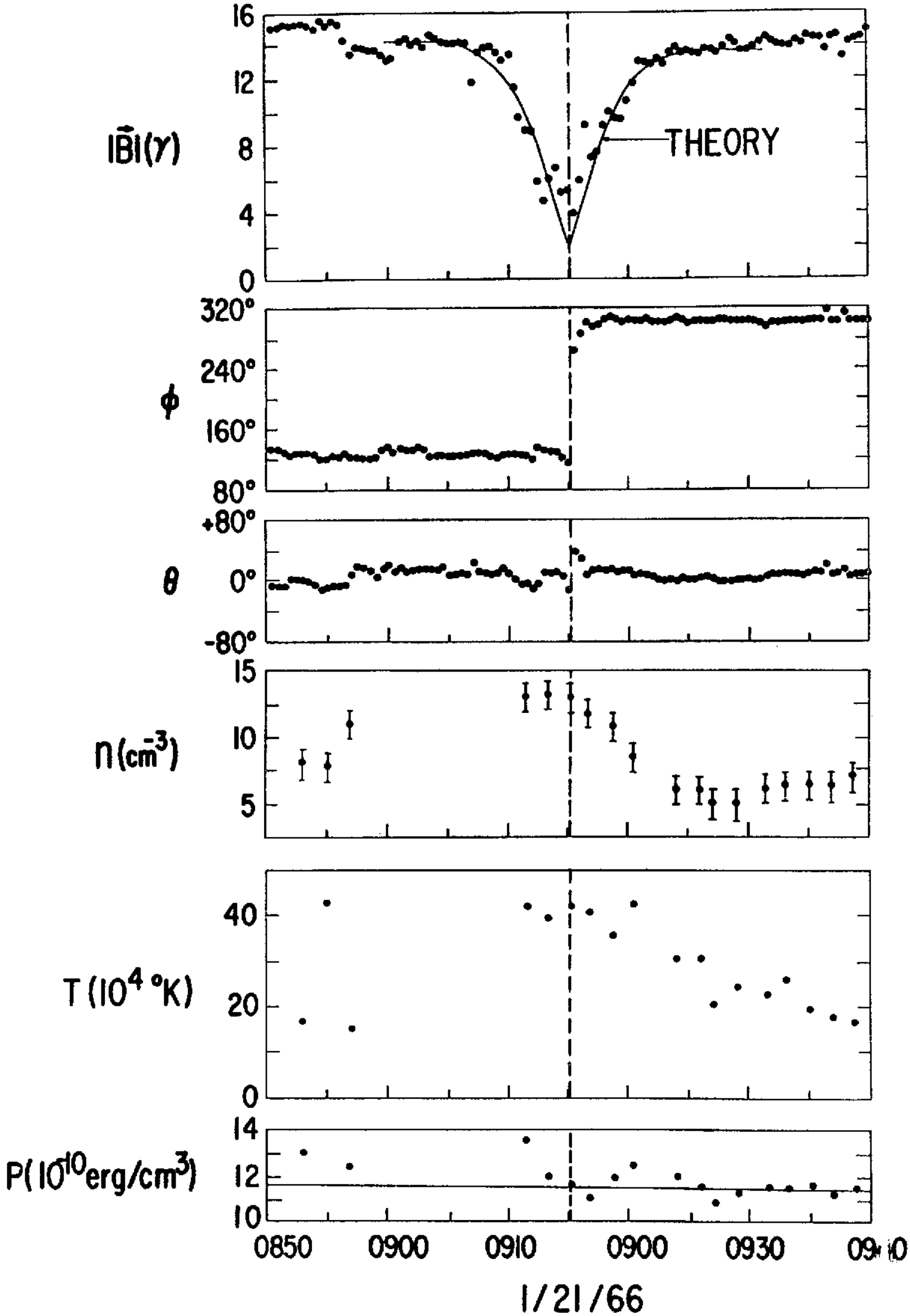
7) Scarf, F. L. 1970, Space Science Rev., 11, 234.

8) Scudder, J. D., Lind D., and Ogilvie, K. W. 1973, J. Geophys. Res., 78, 6535.

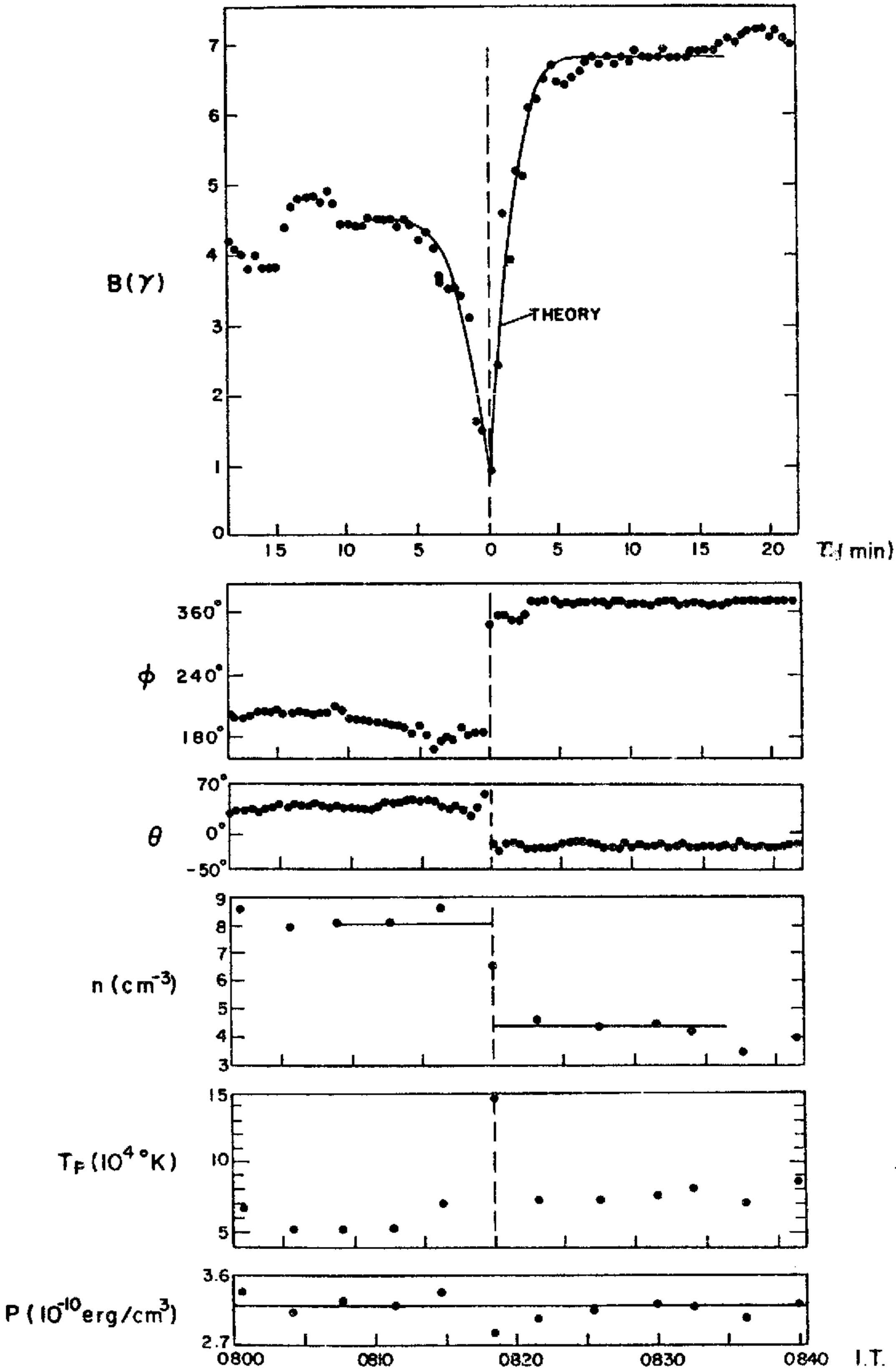
9) Spitzer, L. 1962. Physics of Fully Ionized Gases, Interscience, New York.

10) Sweet, P. A. 1956, Proceedings of the International Astronomical Union Symposium on Electromagnetic Phenomena in Cosmical Physics, Stockholm.

11) Sweet, P. A. 1958, Nuovo Cimento, Suppl 8, Ser. X, 188.



|B|(γ)
THEORY
φ
θ
n(cm⁻³)
T (10⁴ °K)
P(10¹⁰erg/cm³)
0850
0900
0910
0900
0930
09·0
1/21/66



B(γ)
THEORY
T (min)
φ
θ
n (cm⁻³)
T_F (10⁴ °K)
P (10⁻¹⁰ erg/cm³)
0800
0810
0820
0830
0840
I.T.

4/3/66