THEORETICAL MODEL OF FLARES AND PROMINENCES

I: *Evaporating Flare Model*

T. HIRAYAMA
Tokyo Astronomical Observatory, Mitaka, Tokyo, Japan

(Received 16 April; in revised form 26 November, 1973)

Abstract. A theoretical model of flare which explains observed quantities in Hα, EUV, soft X-ray and flare-associated solar wind is presented. It is assumed that large mass observed in the soft X-ray flare and the solar wind comes from the chromosphere by the process like evaporation while flare is in progress. From mass and pressure balance in the chromosphere and the corona, the high temperature in the soft X-ray flare is shown to be attained by the larger mass loss to the solar wind compared with the mass remained in the corona, in accord with observations. The total energy of 10^{32} erg, the electron density of $10^{13.5}$ cm^{-3} in Hα flare, the temperature of the X-ray flare of $10^{7.3}$ K and the time to attain maximum Hα brightness (600 s) are derived consistent with observations. It is shown that the top height of the Hα flare is located about 1000 km lower than that of the active chromosphere because of evaporation. So-called limb flares are assigned to either post-flare loops, surges or rising prominences.

The observed small thickness of the Hα flare is interpreted by free streaming and/or heat conduction. Applications are suggested to explain the maximum temperature of a coronal condensation and the formation of quiescent prominences.

1. Introduction

The purpose of this paper is to present a theoretical model of the solar flare based on particle evaporation from the chromosphere and to predict various observed quantities obtained in Hα flare, EUV emissions, soft X-ray and the flare associated solar wind. No theory seems to have been presented to explain the mutual relationships among these observations. Theories thus far have concerned mostly with time scale, total energy and accelerations of high energy particles and yet basic difficulties exist. For example Alfvén and Carlqvist (1967) and Takakura (1971) assumed closed magnetic tubes connecting between the opposite polarities. These cannot explain how 10^{32} ergs, mainly in the form of 10^{40} protons to the solar wind, can escape from the corona. Nor how rising prominences, often observed before the flare starts, can pass through the closed tubes. It is essential to have an open field when the flare is occurring. Though the Petschek model (1964) could explain the time scale, the total energy seems not to have been successfully explained. Nor the relationships among various observed parameters have been investigated.

Here we assume the magnetic configuration of a neutral sheet type, as advocated by Petschek (1964), Sturrock (1968), Syrovatsky (1966), and Bruzek (1969). Our model is phenomenological in the sense that we are mainly concerned with relationships among various observed quantities (Section 4).

2. Working Hypotheses

Our theory is based on the following working hypotheses:

Solar Physics **34** (1974) 323–338. *All Rights Reserved*

(1) *Limb flares do not exist if surges, rising prominences and post-flare loops are excluded.* We examined published papers as listed by Tandberg-Hanssen (1967) and found that many 'limb flares' can in fact be identified as either one of the above-mentioned phenomena if enough data such as Hα pictures and/or time history are given. Statistical studies on disk flares have shown that the top height of Hα flare is about 5000 to 10000 km higher than that of the chromosphere (Smith and Smith, 1963). But there is good reason to believe that brighter parts of post-flare loop prominence systems (hereafter called LPS) and/or surges erroneously raised the average height of flare. It is concluded from case studies and statistical studies that there is at present no reason to believe that disk flares are elevated beyond the normal Hα chromosphere. On the contrary we suppose that the top height of Hα flares is lowered compared with that of the normal chromosphere and that there is no limb flare if surges, rising prominences and LPS are excluded. Hereafter the chromospheric flare on the disk is called Hα flare.

(2) *Basic form of Hα flare is a two ribbon flare which runs on both sides of and parallel to the magnetic neutral line.* Hα pictures taken at Mitaka (Moriyama, 1971) were used to check this hypothesis. Out of fourteen flares ten are identified as two ribbon flares, the remaining four are not clearly identified because of bad seeing or small area. Since a magnetic map was not available, neutral line could be identified with Hα fibrils, threads, filamants and/or remnants of filaments. We also studied 43 flares of importance 2 or more using Hα movies obtained at the Sacramento Peak Observatory (33 flares from July 1961 to October 1965) and the Lockheed Solar Observatory (10 flares from September 1959 to June 1962). 30 flares show clear two-ribbon type, 5 are possible two ribbons and 8 are indeterminate because movies do not include later phase or flares are too complicated. There are flares with several two ribbons or knots. Most of the Hα pictures taken under good seeing show that these two ribbons are situated in the active bright region where Hα dark horizontal structures such as fibrils and threads are absent. This would mean that the magnetic field is not horizontal but may extend directly to the corona.

(3) *Particles observed in the corona and the solar wind are evaporated from the chromosphere during the flare.* The content of the often quoted total energy of 10^{32} ergs in big flares is that protons of $10^{7.3}$ K are ejected as the flare-associated solar wind disturbance. Total numbers of protons are estimated to be $\approx 10^{40.3}$ (Hundhausen *et al.*, 1970). Since these are not obtained for the largest flares, they may be even higher. Total numbers of protons in a permanent coronal condensation may be around 10^{38} when the number density of 10^9 cm^{-3} and the total volume of 10^{29} cm^3 are used (Newkirk, 1967). Surrounding normal corona has much lower density so that both of them can not be responsible for the total number of $10^{40.3}$. It is also well known that sporadic coronal condensations (hereafter called soft X-ray flare) show larger mass by about one order of magnitude (Newkirk, 1967). Recent soft X-ray observations confirmed this (Milkey *et al.*, 1971, and Horan, 1971). But these are based on the emission measure ($n^2 V$). If there are density fluctuations, the total number is overestimated. Direct information can be obtained from the continuous spectra in the

corona in the visible wavelength region, which is due to the electron scattering. The flare of November 20, 1960 (Zirin, 1964) shows that 10^{39} electrons and protons are present at the temperature higher than 4×10^6 K. A flare of December 18, 1956 (Zirin, 1959) shows also 7×10^{39} electrons. Hα loops (LPS) often seen beyond the disk show mass flow from the corona (Bruzek, 1964). Rough estimate of mass gives $10^{39} \sim 10^{40}$ particles (Kleczek, 1964), but this may be an overestimate because he assumed that the electron number density is 10^{12} cm^{-3} throughout. Our spectroscopic observations of LPS (Hirayama, 1972) showed that this density was the highest. Summarizing, a large amount of particles seems to come from the chromosphere when a flare is in progress and total numbers of particles ejected to the solar wind is approximately by one order of magnitude larger than those to the corona.

(4) *Rising prominences and/or fast expanding coronal arches are possible candidates of the trigger of flares.* About half of the major flares are known to be associated with pre-existing dark filaments on the neutral line and preceded by their sudden disappearances (Smith and Ramsey, 1964). Ascending motion detected by Doppler shift is found to occur some 20 min prior to the start of the flare. A similar conclusion was obtained by inspecting Hα movies obtained at the Sacramento Peak Observatory. Out of 16 flares with pre-existing dark filaments on the neutral line as judged from Hα pictures, 10 erupted, 5 remained and 1 was indeterminate. When prominences do not rise or do not exist, fast expanding coronal arches observed in the green coronal line (Bruzek and Demastus, 1970) could be the substitute. Future studies of spectroheliograms of, say, Mg X obtained in space observations would be very interesting if prominence-like features seen in Mg X in the magnetic neutral line are found and rise prior to flares.

3. Overall Picture of the Model

Figure 1 shows the time history of the present model. Differences from the Bruzek's model (1969) are mass flow from the chromosphere to the solar wind and lowered top height of the Hα flare. Figure 1a shows the pre-flare stage where a prominence of 10^4 K or a fast expanding coronal arch of 10^6 K lies on the neutral line. When for example the gradient of magnetic field increases, the field encircling the prominence is increased and this means that electric currents running parallel to the long axis of prominence increase. Due to the kink instability the currents start to bend and the prominence begins to rise (Hirayama, 1974). This occurs $20 \sim 30$ min prior to the start of the flare (Smith and Ramsey, 1964), the initial rising velocity being small, $\lesssim 10$ km s^{-1}. A magnetic cavity will appear just after the prominence. And collapse will take place from both sides. After the collapse the heat flow which is generated at and near the reconnecting point X, presumably by Joule dissipation, goes down to the chromosphere and it makes the top of the chromosphere brighten and evaporate (Figure 1b). Figure 1b′ shows a side view of 1b.

The larger numbers of particles thus evaporated would escape passing through X point where the heat flow is still being generated. After a pair of magnetic lines of force reconnects, particles can no longer escape from a magnetic loop which bridges the Hα two ribbons. This is observed as the soft X-ray flare with a temperature of $10^{7.3}$ K. The observed temperature of the Hα flare are found to be $8000\text{K} \leqq T_0 \leqq$ $\leqq 10000$ K (Švestka, 1972). The pressure balance is held between the soft X-ray flare ($nT = 10^{10.2} \times 10^{7.3}$) and the Hα flare ($n_0 T_0 = 10^{13.5} \times 10^4$). The top height of chromo-

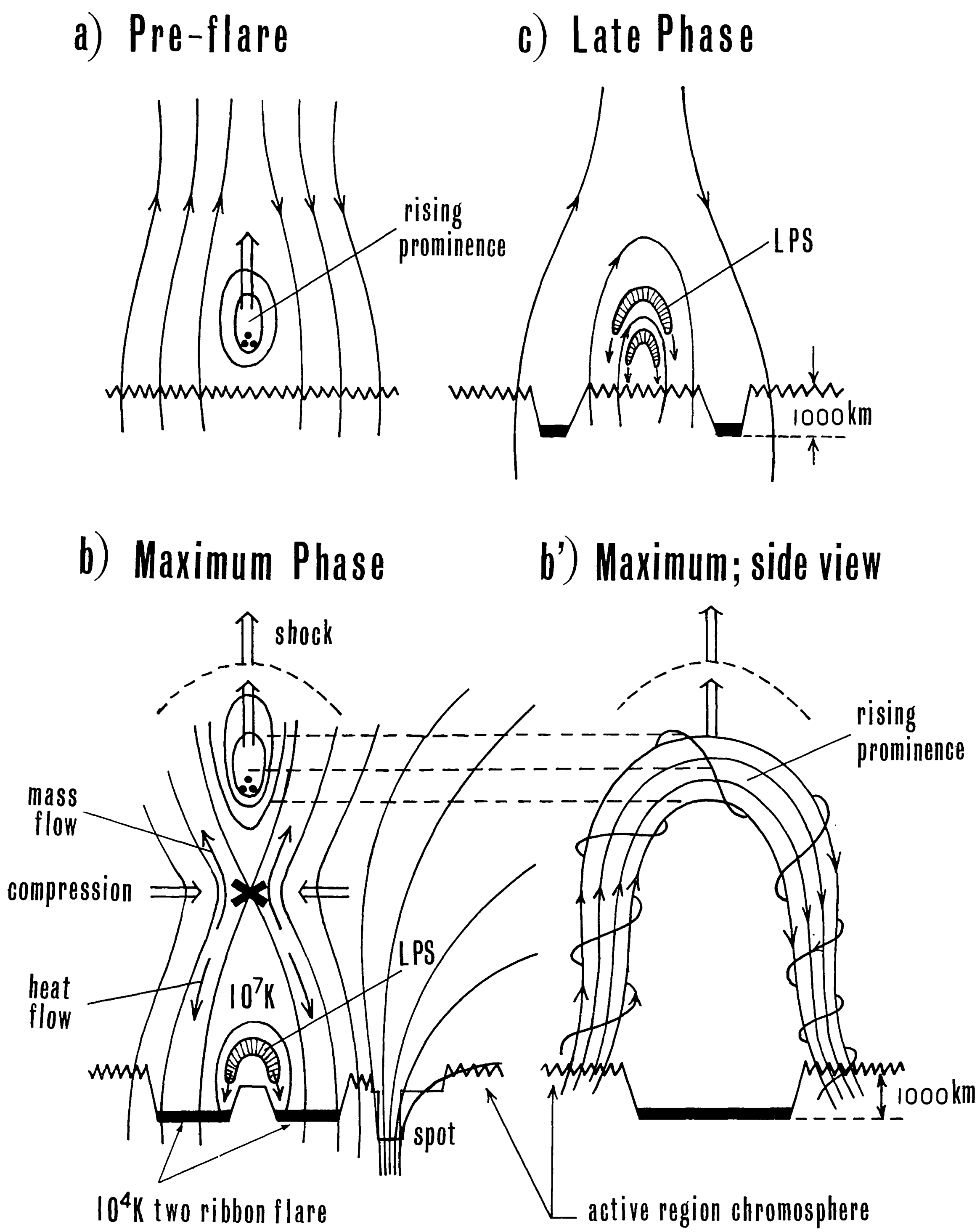

Fig. 1. Time history of the flare. Thin lines denote magnetic lines of force. Note that Hα flare is lowered by 1000 km compared with the top height of the initial active chromosphere because of evaporation to the corona and the solar wind (mass flow).

sphere is now by 1000 km lower than pre-flare active region because of evaporation and just above this comes the corona with very thin transition regions in between.

When the prominence rises further, X point goes higher and heat flows further apart from the neutral line. Hence expansions fo Hα two ribbons are observed. In the lower central region cooling from 10^7 K to 10^4 K proceeds earlier, presumably because density is higher (radiation cooling), length of loop is shorter (conductive cooling), or cooling of any process has begun earlier. LPS is then seen first in soft X-rays, next Fe XIV 5303 Å and Hα. Because of small scale height for $T \approx 10^4$ K, particles cannot float and flow down through both legs of loops. Later LPS are seen higher up to 10^{10} cm (Bruzek, 1964) and widths of both of the two ribbons become narrower (Figure 1c).

Most of the recovering mass would come slowly from the lower chromosphere because only the small portion of mass remained in the soft X-ray flare region. It is to be noted that the evaporating process would not be seen in Hα since evaporating gas will be already too hot.

Jefferies and Orrall (1965) interpreted the extended wing of Hα observed at the LPS of February 19, 1962 as caused by super-thermal particles which they considered responsible for the formation of LPS. It is also possible to interpret their observed profile of Hα by the Stark effect only if $n_0 \leqslant 5 \times 10^{15}$. They neglected the sign of inequality. Other observations of typical LPS (Hirayama, 1972) show clear-cut Stark broadenings for all the Balmer lines. Hence LPS can be considered as a manifestation of simple cooling process without compression.

In front of the prominence a shock wave may be generated and this might be the cause either of type-II or moving type-IV burst.

4. Evaporating Flare Model

We now consider a column of unit area with length H anchored at the base of the chromosphere. This length H is *not* pressure scale height but is determined by magnetic configuration. Magnetic line of force is assumed to be parallel to this column. The top of this column is at the X point in Figure 1b. Pressure balance between the top of chromosphere (Hα flare) and the base of the corona (soft X-ray flare) can be written as

$$nT = n_0 T_0, \tag{1}$$

and

$$n_0 = n_{00} \exp \{(2000 \text{ km} - z)/H_0\}. \tag{2}$$

Subscript 0 denotes the value at the top of the flaring chromosphere. z is the height from the photosphere, where $z = 0$ is taken at optical depth of unity at 5000 Å. n_{00} is the number density of hydrogen at the height of $z = 2000$ km from the photosphere. H_0 is the scale height of total density of the chromosphere, taken to be 200 km (Noyes and Kalkofen, 1970, and Figure 2). The temperature of the Hα flare is taken to be $T_0 = 10^4$ K throughout this paper. Since there must be a region of 10^4 K between the lower chromosphere and the transition region, this value is not considered to be

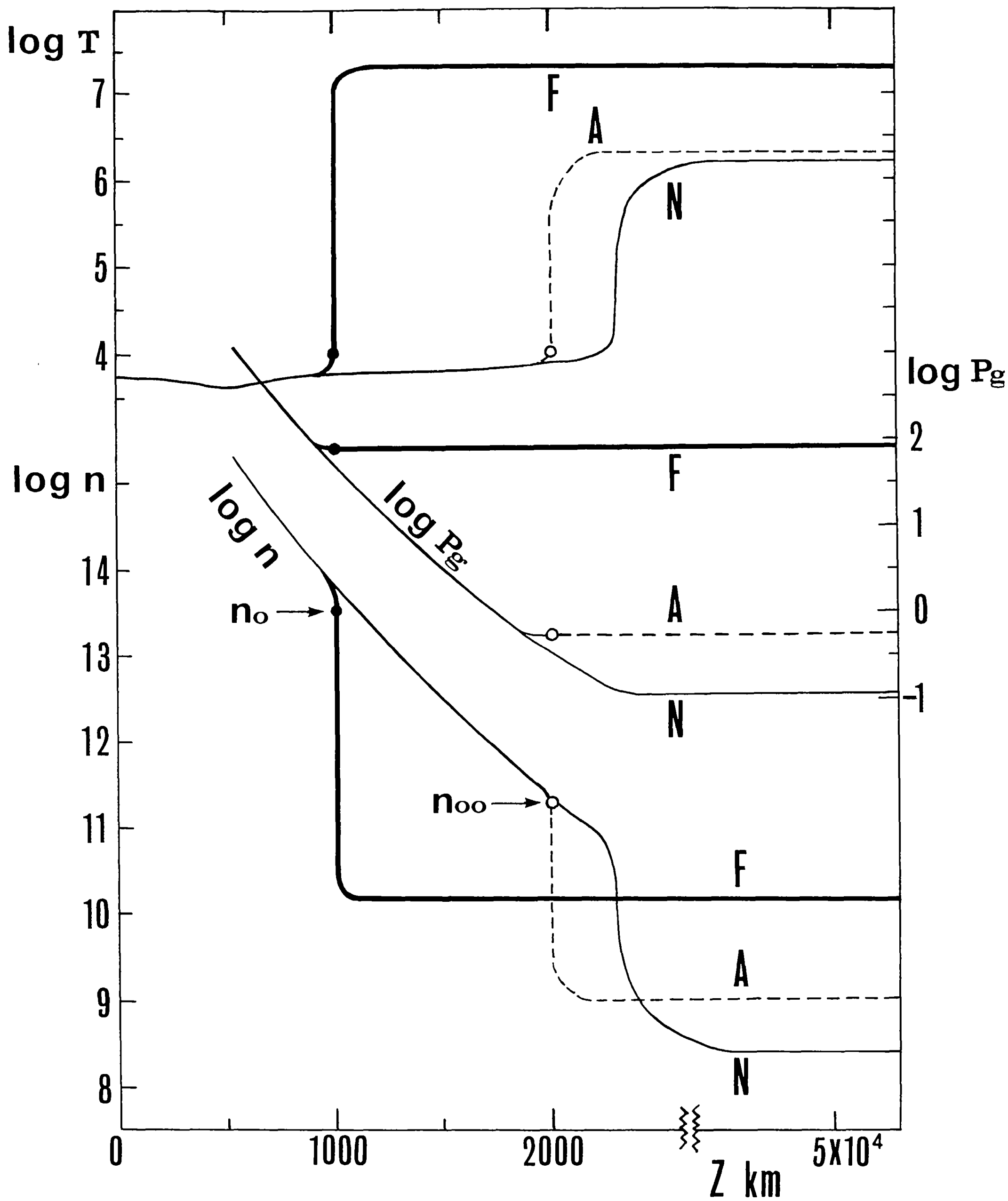

Fig. 2. A schematic model of flare (*F*), active region (*A*) and normal region (*N*) against the height from the photosphere. Top height of Hα flare (filled circles) is lowered compared with that of active chromosphere (open circles) by the amount required from the pressure difference, which in turn is due to heating and to evaporation by heating.

a variable parameter. At the very top of the chromosphere the contribution of neutral hydrogen to the pressure is neglected.

Mass balance between the chromosphere and the corona can be described as

$$\frac{\mathrm{d}(nH)}{\mathrm{d}t} = -\gamma n_0 \frac{\mathrm{d}z}{\mathrm{d}t}. \tag{3}$$

γ is the ratio of numbers of protons remained in the soft X-ray flare to those of all the evaporated protons from the chromosphere. This equation states that particle loss or evaporation of chromospheric protons increases the total numbers of protons, nH, in the corona by an amount of $-\gamma n_0 \mathrm{d}z/\mathrm{d}t$. The portion, $-(1-\gamma)\, n_0 \mathrm{d}z/\mathrm{d}t$, goes to solar wind through the top of the column where, at the same time, energy is being released presumably by Joule dissipation. When the energy release is in progress, the top height of the chromosphere in the flaring region, z, decreases. Since the maximum depression is below ≈ 1000 km, H ($\geqslant 10^4$ km) is assumed not to be influenced by the change of z, but it can vary through the change of the top height X presumably due to magnetic compression. Upon integrating (3) by using (1), (2) and $P = 2nkT$, we get

$$T(t) = \frac{T_0 H(t)}{\gamma H_0} \frac{P(t)}{P(t) + \alpha P(0)}, \tag{4}$$

where $\alpha = \{T_0 H(0)/\gamma H_0 T(0)\} - 1$. Here we assumed constant γ. $T(0)$ and $H(0)$ denote initial values in the corona. If $\alpha > 0$, $T(t)$ increases when $P(t)$ is increased and vice versa. Taking $T(0) = 2 \times 10^6$ K for the active region from line widths (Billings, 1966), we can expect temperature increase if $5 \times 10^9 \gamma < H(0)$. Since observed value of γ is ≈ 0.1 or so, we can expect temperature increase with increasing gas pressure when $H(0) > 4000$ km. If the transition region is included in (1) and (3), main feature will not be changed since pressure balance still holds and since the mass in the transition region is considered to be small (see Section 5).

We consider hereafter bigger flares of importance 3 or 4. $H = H(t)$ is assumed to be constant and is taken to be 5×10^9 cm from the height of sporadic coronal condensations and LPS (Newkirk, 1967, and Bruzek, 1964). In bigger flares pressure in the soft X-ray flare region becomes so large that we can approximate

$$T = \frac{T_0 H}{\gamma H_0}. \tag{5}$$

The meaning of Equation (5) is as follows: when $\gamma = 1$, namely in case of no escape of particles to the solar wind, maximum temperature is given by $T_0 H/H_0$. This holds irrespective of the form and the amount of input energy to the corona. When the energy is deposited in the corona and the corona becomes hotter, particles in the top of the chromosphere become hot due to increased heat conduction and/or direct bombardment of coronal particles and evaporate to the corona to the point where pressure balance is held at the corona-chromosphere boundary. Therefore temperature of the corona cannot rise indefinitely because of pressure balance and $n \sim n_0$ in the limiting case as in (5). After maximum temperature is attained, the input energy is used only to increase the number of particles in the corona. In the present case the maximum temperature is $T = 2.5 \times 10^6$ K. We propose that the temperature of a permanent coronal condensation within a closed magnetic field ($\gamma = 1$) is controlled by the above limiting value. This is in good agreement with observations (Newkirk, 1967, and Noyes, 1971). This conclusion will be valid only when stationary state is established. It may be valid even if magnetic pressure is much higher than gas pressure because pressure balance was considered parallel to the magnetic lines of force.

One might argue that evaporation would not occur and the chromosphere would be compressed in order to maintain pressure balance due to high temperature in the corona. But this may not be the case: First if the appreciable amount of mass would not evaporate, high density in the soft X-ray flare and large mass to the solar wind would not be observed. Another argument can be given in favour of evaporation hypothesis. If the chromosphere ($\leqslant 10^4$ K) is compressed without evaporation, the scale height of density of the compressed portion of the chromosphere becomes much larger than H_0. In order to maintain large density scale height it is necessary to assume large turbulent velocity. This is against observations which indicate 6 km s^{-1} or less (Dinh and Hirayama, 1974). If $\gamma < 1$, namely an open magnetic field, the maximum temperature can be larger than 2.5×10^6 K by a factor of $1/\gamma$.

What can we expect for flares, using only mass balance and pressure balance, (1) and (5)? We assume $T = 2 \times 10^7$ K (for example see Milkey *et al.*, 1971) and $n_0 = 3 \times 10^{13}$, which is the observed electron (=proton) number density in larger Hα flares (Švestka, 1972). Then we obtain $\gamma = 0.125$ and $n = 1.5 \times 10^{10}$ cm^{-3}. These values are in good agreement with observations; observed value of averaged n is given by Newkirk (1967) and Zirin (1959 and 1964). In this example an Hα flare is located at the top of the chromosphere which is now by 1000 km lower than the initial height of the top of the active chromosphere: $(nT)_{\text{active}} = 5(nT)_{\text{quiet}} = 10^{15.3}$ (Noyes, 1971). Figure 2 shows a schematic model. The chromospheric model is due to Noyes and Kalkofen (1970). We note here that the use of the approximate formula (5) is justified since $P \sim nT \gg \alpha (n_{00} T_0)_{\text{active}}$, where α is 11.5.

If we take the total area of Hα flare to be $S = 3 \times 10^{19}$ cm^2 we obtain following quantities:

The total energy to solar wind:

$$U_w \equiv \frac{3nkTHS(1-\gamma)}{\gamma} = 1.3 \times 10^{32} \text{ erg},$$

total number of protons to solar wind:

$$N_w \equiv \frac{nHS(1-\gamma)}{\gamma} = 1.6 \times 10^{40},$$

total energy in the corona: $U \equiv 3nkTHS = 1.9 \times 10^{31}$ erg,
total number of protons in the corona: $N \equiv nHS = 2.3 \times 10^{39}$,
emission measure in the soft X-rays: $\text{EMX} \equiv n^2 HS = 3.4 \times 10^{49}$.

These values are again in very good agreement with observations: solar wind (Hundhausen *et al.*, 1970) and corona (Newkirk, 1967; Milkey *et al.*, 1971; Hudson and Ohki, 1972; and Horan, 1971). It may first seem curious that we have successfully predicted even the total energy only from T, n_0, H and S. But it will become apparent in the following discussion that electron density in the Hα flare (n_0), is closely related to the magnetic field strength. There are indications that the maximum of total emission measure in soft X-rays, EMX, is preceded by the peak coronal temperature (Horan, 1971, and Milkey *et al.*, 1971). In our model, total number of particles nHS and accordingly EMX would increase until Hα flare area becomes maximum. But at the outer edges of two ribbons pressure in the corona would not become so large that it would be necessary to use Equation (4) instead of (5). Therefore average temperature would start decreasing while emission measure is still increasing.

Exact formula for γ would be complicated but if we denote the duration of energy release as τ, γ is given as a ratio of time required for particles to escape from the column of height H to τ. After τ is elapsed, we assume that the magnetic line of force will be reconnected with another one on the other side of neutral sheet and particle escape becomes impossible

$$\gamma = \frac{H/v_p}{\tau}, \tag{6}$$

where $v_p = \sqrt{(3kT/\pi m_p)}$ is the mean velocity of protons. Using above values we obtain $\tau = 615$ s. This is in turn considered to be the rise time of Hα intensity in a fixed position of a flare. According to Smith and Smith (1963) the observed rise time of Hα intensity is approximately the same as the time from the onset to the Hα area maximum and it is from 300 to 600 s and in some cases up to 1000 s in larger flares.

Now we add two equations: energy equation and definition of τ. We assume that available total magnetic energy $HSB^2/8\pi$ is mostly converted into the energy in the solar wind and the soft X-ray flare, $3nkTHS/\gamma$, with an efficiency factor $\eta(<1)$.

$$\eta \frac{B^2}{8\pi} = \frac{3nkT}{\gamma}. \tag{7}$$

For simplicity we neglect here the radiated energy from the Hα flare, which is presumably the second largest outgoing energy ($\leqslant 10^{31}$ erg). τ might be taken as Joule dissipation time. But since the mechanism of the energy conversion is not known, we adopt that τ is the same as the duration from the onset of a flare to the time of the area maximum in accordance with the observation as stated above. As shown in Section 2, at least half of major flares are preceded by the rising prominence which is situated along the neutral line at the onset. Then the duration of energy release in a flare as a whole would approximately be given by the height of the soft X-ray flare, H, devided by the mean rising velocity of prominence. The mean rising velocity is, in turn, given by the Alfvén velocity (≈ 100 km s^{-1}) of inside the prominence if the theory due to the kink instability is adopted (Hirayama, 1974). Even apart from this specific theory, this value is not only consistent with observed velocities but also Waldmeier (1939) reported that rising prominence in the active region (larger magnetic field) is faster than in the quiet region. Now Alfvén velocity inside the rising prominence in the neutral sheet, v_a, would be related to that outside the sheet, Mv_a. Hence

$$\tau = \frac{H}{Mv_a}. \tag{8}$$

Here M is another parameter and v_a is the Alfvén velocity in the soft X-ray flare region. This expression is formally identical to that given in the Petschek model (1964) where $M \leqq 0.1$. Using previous values and adopting $B = 500$ G, we get $\eta = 0.1$ and $M = 0.01$ from Equations (7) and (8). Since v_a becomes 8.9×10^8 cm s^{-1}, $Mv_a \approx 100$ km s^{-1}. This value is exactly the one we would like to have for the velocity of rising prominence. If one adopts the Petschek theory, this value of M is also consistent with this theory.

We solve Equations (1) and (5)–(8) in terms of B, H, η and M.

$$\begin{aligned}
\gamma &= c_1\, \xi^{1/3} \\
T &= \frac{T_0}{c_1 H_0}\, \xi^{-1/3} H \\
n &= \frac{c_1^2 H_0}{24\pi k T_0}\, \eta \xi^{2/3} H^{-1} B^2 \\
n_0 &= \frac{c_1}{24\pi k T_0}\, \eta \xi^{1/3} B^2 \\
\tau &= \left(\frac{c_1^2 H_0}{6RT_0}\right)^{1/2} \xi^{-1/6} H^{1/2} \\
z &= 2000\ \mathrm{km} - H_0 \ln \frac{n_{00}}{n_0}
\end{aligned} \tag{9}$$

where $\xi = M^2/\eta$ and $c_1 = (3/4\pi)^{1/3}$, R being gas constant. Apparently if we assume $H = 5 \times 10^9$ cm, $B = 500$ G, $\eta = 0.1$ and $M = 0.01$, we get the values of γ, T, etc. exactly the same as those already obtained and these were all in good accordance with observations. These equations are only pertinent to a flare as a whole, but if P and H are considered to be time-dependent, time history of T, n and n_0 for each column can be guessed when proper modifications due to Equation (4) are made. Here we assumed that M and η are universal constants for all the flare. Even if they are not constant, $\xi^{1/3}$ or $\xi^{1/6}$ term shows that we could safely neglect dependence of these upon B, H or other unknown parameters. η cannot be smaller than 0.001 because this requires original magnetic energy of more than 10^{35} erg. η may be between 0.1 and0.01. Also M cannot be changed by more than one order of magnitude. Therefore predicted values of γ, T, etc. do not change much for allowed η and M. Observations show that T ranges only from 0.8 to 4×10^7 K. This seems reasonable because H could not possibly be changed beyond a factor of ten (1–10×10^9 cm) and T is not related to B which would vary much among various flares. Smith and Smith (1963) report that rising time to the maximum area of Hα flare does not change very much from flare to flare (5–10 min). This is again consistent with $\sqrt{H}$ dependency.

Very long rise time of 30–100 min in flare-like plages (Bruzek, 1957) can be predicted from our theory: $\tau = H/(v_p \gamma) \sim H/\sqrt{T} \sim \{H\,(P\,(\tau) + P\,(0)\,\alpha)/P\,(\tau)\}^{1/2}$ gives right order of magnitude if $P\,(\tau)$ is not very much higher than $P\,(0)\,\alpha$ in Equation (4).

Interesting point is $n_0 \sim B^2$. Larger n_0 produces larger central intensity in Hα (Jefferies, 1957) and wider wing of Hα due to the Stark broadening. Since bigger flares may generally be related to stronger magnetic fields, our theory predicts that bigger flares or flare knots in a strong magnetic field show larger intensity and/or wider wing in Hα or Ca^+ K. Bumba and Howard (1965) in fact reported that the Ca^+ K brightenings in smaller flares occur only in the K network (strong B), while they occur even inside the network in larger flares.

We can also test our theory with the EUV observations of flares obtained with the OSO 6 satellite (Wood and Noyes, 1972). Since they treated only smaller flares, Equation (4) may be utilized instead of Equation (5), but some qualitative argument can be made by using Equations (9). Heat flux to the chromosphere is given by

$$F = \eta \frac{B^2}{8\pi} H/\tau .$$

F is found to be 10^{10} ergs cm^{-2} s^{-1}, which is 2000 times larger than the conduction flux in the active region (Dupree, 1972). Gas pressure is 150 times larger. Observation shows that active regions and flares near and after maximum phase are supposed to be governed by conduction in 10^5–10^6 K temperature region (Wood and Noyes, 1972). In this case the intensity of EUV lines (I^{EUV}) is proportional to $(nT)^2/F$, which can be converted into

$$I^{EUV} \sim \frac{B^2}{\tau} . \tag{10}$$

This is, qualitatively, exactly what Wood *et al.* (1972) gave in their Figure 2 for $I^{EUV} - \tau$ relations though rise time was for EUV. We can also predict that I^{EUV} is stronger when Hα intensity, reported in terms of b, n and f, is stronger (large B). This is again the observed fact (their Table IV).

We calculate the apparent expansion velocity of separating two Hα ribbons, assuming that width of one of two ribbons is given by $D \approx \sqrt{S}/4$ in accordance with observations

$$V_{sep} = \sqrt{S}/4\tau = 22 \text{ km s}^{-1} . \tag{11}$$

Direct observations give 10–60 km s^{-1} (Ogir, 1967).

If we adopt $B = 1500$ G, with the same values of η, M and H as before, we get $n = 1.4 \times 10^{11}$, $n_0 = 3 \times 10^{14}$ and $\Delta z = 1400$ km and others are not changed. The total energy to the solar wind becomes 1.2×10^{33} erg. In this case n_0 would not be the proton density but the total hydrogen density and a fraction of n_0 would be observed as the electron density through the Stark broadening.

Finally we predict some qualitative relations like Equation (10) derived from Equations (9). These should be tested by already existing data and/or future observations.

$$\begin{aligned} n_0 &\sim B^2 , \\ n &\sim n_0/\tau^2 , \\ \text{EMX} &\sim n_0^2 S/\tau^2 , \\ U_w &\approx U/\gamma \sim n_0 \tau^2 S , \\ v_p &\approx \text{velocity of solar wind near the Sun} \sim \tau . \end{aligned} \tag{12}$$

All the values are observable. For example n_0 can either be obtianed directly from spectral observations of Hα flares or qualitative estimations of n_0 could be given from central intensity and/or width of Hα line. Larger U_w is believed to be related with longer τ as in the case of driven wave and smaller U_w with shorter τ as in the blast wave (Hundhausen and Gentry, 1969, and Hundhausen *et al.*, 1970). Larger Hα brightness and hence larger n_0, and larger importance, S, are reported to be connected with larger EMX (Drake, 1971).

In concluding this section it is to be emphasized that the essential point in our whole argument stems from Equations (1), (2) and (3).

5. Small Geometrical Thickness of Hα Flares

Spectroscopic analyses of flares show that the geometrical thickness of emitting Balmer lines is quite small, 10–100 km, (Suemoto and Hiei, 1959, and Švestka, 1972). In accordance with the previous section we assume that the region emitting Balmer lines is a single thin sheet covering on the top of the lowered evaporating chromosphere. This sheet may not necessarily be even as shown in Figure 1, but must be very much ragged because of inhomogeneous strength of magnetic field, $(n_0 \sim B^2)$.

There are two possible ways of transporting energy from the X-point to the chromosphere: heat conduction and direct bombardment.

(a) Direct bombardment hypothesis: We apply direct bombardment of particles at the initial phase of a flare column. Since the temperature of the corona will finally become $10^{7.3}$ K, the bombarding particles would have higher equivalent temperature than this, for example $T_b = 10^{7.5}$ K. Mean free path of the bombarding particle is given by $\lambda_b = 10^4 T_b^2/n$ (Spitzer, 1962). For the density of $n_0 \sim 10^{13}$ at the Hα flare, λ_b becomes 10 km. At the onset of the flare the corona in 10^5–10^6 K region is governed by heat conduction and the temperature scale height, H_T, is given by

$$H_T \equiv \frac{\mathrm{d}z}{\mathrm{d}\ln T} = \frac{10^{-6} T^{7/2}}{F_c}. \tag{13}$$

Taking the conductive flux F_c in the active corona as 5×10^6 ergs cm^{-2} s^{-1} and $T = 10^{6.3}$, we have $H_T = 10^{9.4}$ cm. Here the density is around $n = 10^{9.2}$. λ becomes $10^{9.8}$ cm, which is larger than H_T. Since λ_b/H_T is proportional to $T^{-5/2}$ (because F_c = const and nT = const), λ_b/H_T becomes even larger in the lower temperature region, hence free bombardment. In the temperature region of 10^4–10^5 K, constancy of conducting flux does not hold. But H_T can be estimated from the Dupree model (1972) for the normal region to give 45 km at $T = 10^{4.7}$ K. It would be smaller in the active region. λ_b for $nT = 10^{15.5}$ at this temperature is 1000 km. Since $10^{7.5}$ K particles seem to penetrate down to 10^4 K region, the thickness of the Hα flare would be determined by $\lambda_b = 10$ km at the earlier phase of the Hα flare element.

(b) Conduction hypothesis: When the density of the corona increases due to evaporation from bombardment, the bombarding particles would not penetrate down to the chromosphere. In the lower temperature region $\leqslant 10^5$ K, heat conduction will be balanced with radiation if steady state is assumed near and after the end of energy release

$$An^2T^r = \frac{\mathrm{d}}{\mathrm{d}z}\left(KT^{5/2}\frac{\mathrm{d}T}{\mathrm{d}z}\right), \tag{14}$$

where K, A and r are constant. If $T = G(z - z_0)^{1/m}$ is assumed with pressure constancy, we get $r = 5.5 - 2m$ and $A = K(3.5 - m)\,G^{2m}/(nT)^2m^2$. Since A is a constant determined by radiating processes of various ions, G^m should be proportional to nT. As the temperature scale height turns out to be mT^m/G^m at a given temperature it is proportional to $(nT)^{-1}$. Since the Vernazza and Noyes model (1972) predicts $H_T \sim \sim 470$ km at $8000 \sim 9000$ K, we assume $H_T \approx 200$ km at 10^4 K for the normal chromosphere (n.c.). We then obtain

$$H_T\,(\text{flare}) = 200\ \text{km} \times \frac{(nT)_{\text{n.c.}}}{(nT)_{\text{flare}}}. \tag{15}$$

For $(nT)_{\text{n.c.}} = 10^{14.8}$ and $(nT)_{\text{flare}} = 10^{17.5}$, H_T becomes 0.4 km. For smaller flares H_T would be ten to hundred times larger. Therefore we can conclude that heat conduction hypothesis also reads to the small geometrical thickness of Hα flares.

We finally check whether the neglect of transition region for the mass loss in Equation (3) can be justified. In a region where the heat conduction is constant along the height, the number of particles in this region is estimated to be

$$\int_{T_1}^{T_2} n\mathrm{d}z = \frac{2K}{5F_c}(nT)\,[T_2^{5/2} - T_2^{5/2}],$$

where $nT = \text{const}$ is assumed.

In the region of $10^5 \leqslant T \leqslant 10^6$ K, $\int_{T_1}^{T_2} n\mathrm{d}z$ is found to be $\approx 10^{16}$ which is much smaller than $nH = 10^{19.9}$ in the $10^{7.3}$ K region. In the lower temperature region Equation (14) should be utilized.

$$\int_{T_1}^{T_2} n\mathrm{d}z = \frac{1}{1-m}\{K(3.5 - m)/A\}^{1/2}\,[T_2^{m-1} - T_1^{m-1}].$$

In this Equation $T_2 \approx 10^{4.5}$ K and $T_1 \approx 10^5$ K. If m does not change very much, $\int_{T_1}^{T_2} n\mathrm{d}z$ does not vary among normal chromosphere, plage and flare. Since the model for the normal region (Dupree, 1972) predicts that the total numbers are small in this temperature range, we can safely neglect the contribution of particles contained in this region also for flares.

6. Applications

(1) One application was already mentioned: The maximum temperature of a coronal condensation in a closed magnetic configuration would be given by Equation (5) with $\gamma = 1$. The maximum temperature in the normal corona in an *open* magnetic field

would be inferred from the condition that thermal energy does not exceed gravitational potential energy. This condition and Equation (5) both lead to the same dependence of $T_{\max}$ on the surface gravity, g, and scale length H: $T_{\max} \sim gH$.

(2) Moustaches: Moustaches with rather symmetrical profile would be small flare-like phenomena discussed in Section 4. If extended wings are caused by macroscopic motion of $\approx 100 \text{ km s}^{-1}$ (Severny, 1964), it is very difficult to understand the long lifetime of some 30 min and very small scale observed near the limb and on the disk (Bruzek, 1972). Geometrical extension of moustaches would become $100 \text{ km s}^{-1} \times 30 \text{ min} = 2 \times 10^5$ km or so, while Bruzek's picture near the limb indicates 500–1000 km. If wings are interpreted in terms of the Stark broadening and/or collision broadening, only requirement is large number density. This is easily accomplished by the same argument given in Section 4: A moustache is a tiny but deep 'well' whose surface has large electron density of, say, 10^{13} cm^{-3} because overlying portions of low density have evaporated. When the amount of evaporation is large, it would be seen in white light as a facular granule beautifully shown by Bruzek (1972). Although flare and moustache may be independent as Bruzek suggests, there is a good deal of similarity, which deserves further study.

(3) Formation of quiescent prominences: To make prominences an essential point is to get large mass in the corona. It is usually assumed that mass comes from the corona (Kuperus and Tandberg-Hanssen, 1967). We propose here that the mass would come directly from the chromosphere due to a slow flare-like process discussed in Sections 3 and 4. Case A: If we take $\gamma \approx 1$ in Equation (4), namely not much escape of particles, we get the temperature of the corona not very much higher than in the normal corona but the pressure and hence the density can become larger. Radiation loss ($\sim n^2$) would be larger, but the normal heating of the corona would decrease because shock strength would not grow due to high densities. Cooling and condensation would then take place in the small dip of the reconnected magnetic field and a prominence is formed. If dips cannot be formed, it would appear as a coronal rain. Case B: Also the case where temperature decreases with increasing pressure, $\alpha < 0$ in (4), is very interesting. This would happen even in a big flare, since the region close to the neutral line cannot have large $H(0)$. Then a new prominence parallel to the neutral line could be formed under the tunnel of LPS. This is often observed. In the quiet region one rising prominence (either of 10^4 or 10^6 K) could produce a very faint flare as reported by Bruzek (1957). After the flare-like brightening, another prominence could be formed. In short, it is suggested that a prominence could trigger a flare due to eruption and a flare could produce a prominence due to evaporation. The very first prominence must be either a 10^6 K prominence which does not require much mass inside, or a very low fibril in the active region whose formation would be entirely different.

7. Conclusions

A theoretical model of the flare is presented to explain mutual relationships observed at Hα, EUV, soft X-ray and flare-associated solar wind. Four working hypotheses are made with some supporting evidences (Section 2): (1) so-called limb flares are nothing but either rising prominences, surges or post flare loops and the top height of Hα flares is lower than that of pre-flare active regions. (2) Basic form of the Hα and soft X-ray flares is a two ribbon flare. (3) Large amount of gas evaporates from the top of the Hα flare while the flare is in progress. (4) The trigger of the flare would be pre-flare rising prominences or coronal fast expanding arches. Time history of our flare model was briefly discussed (Section 3 and Figure 1).

When mass, pressure and energy balance among the evaporating chromosphere, the corona and the solar wind are assumed, following quantities are deduced all in conformity with observations (Section 4, particularly Equations (9)): The electron number density of the Hα flare ($10^{13.5}$) and the soft X-ray flare ($10^{10.2}$), the temperature of the soft X-ray flare ($10^{7.3}$K), the duration to maximum Hα area (600 s), mass ratio of X-ray flare to the solar wind (0.1). Assumed critical parameters are the magnetic field strength (500 G) and the height of soft X-ray flare ($10^{9.7}$ cm). If the area of the Hα flare is assumed ($10^{19.5}$ cm^2), the total energy released ($10^{32.1}$ erg), the total number of particles ejected to the solar wind ($10^{40.2}$) and the emission measure in the soft X-ray flare ($10^{49.5}$ cm^{-3}) are also predicted.
It is found that high temperature in the soft X-ray flare can only be attained by the larger mass loss to the solar wind compared with the mass remained in the corona, irrespective of the form or the amount of the energy released in the corona (Equation (4) or (5)). It is shown that the top height of the Hα flare is lowered about 1000 km compared to the original height in the active region chromosphere because of evaporation (Figure 2). Some of the qualitative theoretical relationships among Hα flare, soft X-ray flare, EUV and solar wind are found to be consistent with observations: Equations (10), (11) and (12).

Very small effective thickness of Hα flare was interpreted either by mean free path of hot ($T > 10^{7.3}$ K) particles in the evaporating chromosphere or by small thickness of heat conducting region (Section 5).

An application to explain the maximum temperature of the permanent coronal condensation in a closed magnetic field is suggested. Further an application to the formation of prominence is indicated (Section 6). It is suggested that large mass in the quiescent prominence can be expected by the evaporation from the chromosphere as a slow flare-like process. In this picture, a rising prominence produces a flare and a flare produces a prominence.

The second paper of this series will treat a theory of the rising prominence. Subjects of later papers will be acceleration of particles, mechanism of energy release, refinements of the present paper and prominence formation.

Acknowledgements

I am very much indebted to Dr J. W. Evans and the staff of the Sacramento Peak Observatory for their hospitality where a part of this work was done in the winter of 1971–1972. I am also grateful for stimulating discussions with Drs R. W. Noyes,

H. U. Schmidt, Z. Suemoto and U. Uchida. This research has been supported in part by the Asia Foundation.

References

Alfvén, H. and Carlqvist, P.: 1967, *Solar Phys.* **1**, 220.
Billings, D. E.: 1966, *A Guide to the Solar Corona*, Academic Press, New York.
Bruzek, A.: 1957, *Z. Astrophys.* **42**, 76.
Bruzek, A.: 1964, *Astrophys. J.* **140**, 746.
Bruzek, A.: 1969, in D. G. Wentzel and D. A. Tidman (eds.), *Plasma Instability in Astrophysics*, Gordon and Breach, Sci. Publ., New York–London–Paris, p. 81.
Bruzek, A.: 1972, *Solar Phys.* **26**, 94.
Bruzek, A. and Demastus, H. L.: 1970, *Solar Phys.* **12**, 447.
Bumba, V. and Howard, R.: 1965, *Astrophys. J.* **142**, 796.
Dinh, Q. V. and Hirayama, T.: 1974, in preparation.
Drake, J. F.: 1971, *Solar Phys.* **16**, 152.
Dupree, A. K.: 1972, *Astrophys. J.* **178**, 527.
Hirayama, T.: 1972, *Solar Phys.* **24**, 310.
Hirayama, T.: 1974, in preparation.
Horan, D. M.: 1971, *Solar Phys.* **21**, 188.
Hudson, H. S. and Ohki, K.: 1972, *Solar Phys.* **23**, 155.
Hundhausen, A. J. and Gentry, R. A.: 1969, *J. Geophys. Res.* **74**, 2908.
Hundhausen, A. J., Bame, S. I., and Montgomery, M. D.: 1970, *J. Geophys. Res.* **75**, 4631.
Jefferies, J. T.: 1957, *Monthly Notices Roy. Astron. Soc.* **117**, 493.
Jefferies, J. T. and Orrall, F. Q.: 1965, *Astrophys. J.* **141**, 505.
Kleczek, J.: 1964, in *The Physics of Solar Flares*, AAS-NASA Symp., NASA SP-50, p. 77.
Kuperus, M. and Tandberg-Hanssen, E.: 1967, *Solar Phys.* **2**, 39.
Milkey, R. W., Blocher, N. K., Chambers, W. H., Fehlau, P. E., Fuller, J. C., and Kunz, W. E.: 1971, *Solar Phys.* **20**, 400.
Moriyama, F. (ed.): 1971, in *IASY Report on Solar Phenomena in 1969*, Tokyo Astron. Obs.
Newkirk, G.: 1967, *Ann. Rev. Astron. Astrophys.* **5**, 213.
Noyes, R. W.: 1971, *Ann. Rev. Astron. Astrophys.* **9**, 209.
Noyes, R. W. and Kalkofen, W.: 1970, *Solar Phys.* **15**, 20.
Ogir, M. B.: 1967, *Izv. Krymsk. Astrofiz. Obs.* **37**, 44.
Petschek, H. E.: 1964, in *The Physics of Solar Flares*, AAS-NASA Symp., NASA SP-50, p. 425.
Severny, A. B.: 1964, *Ann. Rev. Astron. Astrophys.* **2**, 363.
Smith, S. F. and Ramsey, H. E.: 1964, *Z. Astrophys.* **60**, 1.
Smith, H. J. and Smith, E. v. P.: 1963, *Solar Flares*, MacMillan Co., New York.
Spitzer, L.: 1962, *Physics of Fully Ionized Gases*, 2nd ed. Interscience Publ., New York–London–Sydney, p. 131.
Sturrock, P. A.: 1968, in K. O. Kiepenheuer (ed.), 'Structure and Development of Solar Active Regions', *IAU Symp.* **35**, D. Reidel Publ. Co., Dordrecht-Holland, p. 470.
Suemoto, Z. and Hiei, E.: 1959, *Publ. Astron. Soc. Japan* **11**, 185.
Švestka, Z.: 1972, *Ann. Rev. Astron. Astrophys.* **10**, 1.
Syrovatsky, S. I.: 1966, *Soviet Astron.* **10**, 270.
Takakura, T.: 1971, *Solar Phys.* **19**, 186.
Tandberg-Hanssen, E.: 1967, *Solar Activity*, Blaisdell Publ. Co., Waltham, Mass.–Toronto–London.
Vernazza, J. E. and Noyes, R. W.: 1972, *Solar Phys.* **22**, 358.
Waldmeier, M.: 1939, *Z. Astrophys.* **18**, 241.
Wood, A. T. and Noyes, R. W.: 1972, *Solar Phys.* **24**, 180.
Wood, A. T., Noyes, R. W., Dupree, A. K., Huber, M. C. E., Parkinson, W. H., Reeves, E. M., and Withbroe, G. L.: 1972, *Solar Phys.* **24**, 169.
Zirin, H.: 1959, *Astrophys. J.* **129**, 414.
Zirin, H.: 1964, *Astrophys. J.* **140**, 1216.