Magnetic Fields and Currents in the Corona

by

Yutaka Uchida
Tokyo Astronomical Observatory
University of Tokyo, Mitaka, Tokyo

Abstract

Methods for obtaining information about coronal magnetic fields are reviewed. Estimates using radio data are first discussed with some critical comments, and then, recently-recognized method of evaluating the coronal magnetic fields by using the three-dimensional pattern of X-ray loops together with the photospheric magnetic field is discussed. Current distribution in the corona can also be derived from the magnetic field thus obtained. Some discussion on the significance of the derivation of the current in the corona in relation to the flare theory is given.

1. Introduction

The direct measurement of the magnetic field in the corona by Zeeman effect is difficult due to the smallness of the effect combined with the large Doppler widths of the lines, because the magnetic field in the corona is usually weak and the temperature in the corona is high. We therefore have to recourse to other sources of information at present.

Some information is obtained through radio observations which are often the sole source of information on the magnetic field in the middle to high corona. Another more recently-recognized source of information is the X-ray or EUV observations of the shape of the loops of which the corona is found to be consisted (Vaiana et al 1973, Sheeley et al 1974, Svestka et al 1977). If we reasonably assume that the loops are the frozen-in inhomogeneity of the plasma along the field lines, we can tell with high trustability what the configuration and the strength of the magnetic field in the corona are, by knowing the three-dimensional shape of the loops together with the field strength at one point along each loop, eg , at the photospheric footpoint (Sakurai and Uchida 1976, 1977).

In the following, a brief look at the estimates from radio observations is given in section 2, then the latter method utilizing the coronal loop pattern will be reviewed in section 3, and the discussion is given in section 4.

2. Estimates of the Coronal Magnetic Field from Radio Data

Various methods of obtaining information on the coronal magnetic field from radio observations have been proposed. These include the information from microwave spectra, from the propagation velocity and the band-splitting of type II burst sources, from the polarization of the second harmonics of type III burst, from Razin effect in moving type IV bursts, and so on. Takakura (1971), and more recently, Dulk and McLean (1978) summarized the estimates from radio data as in Figure 1.

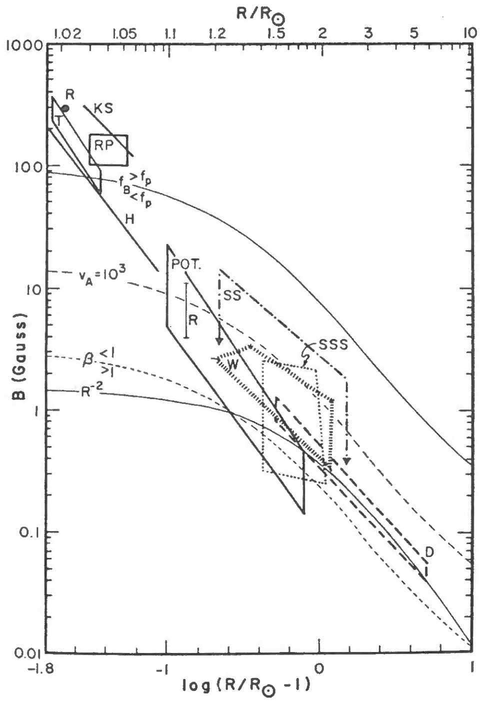


Fig.1.Magnetic field estimates from radio data (Dulk and McLean). T,RP,and KS are from microwave data,SSS,and W from type II burst data,SS from type III burst data,and D from moving type IV burst data,respectively. See original paper for details.

Dulk and McLean deduced an expression

$$B = 0.5\left(\frac{R}{R_\odot} - 1\right)^{-1.5} \quad G \qquad (1)$$

by best fitting the data regions derived by these various methods. The field strength (as given by expression (1)) duely deviates upward on R - B plane from the extrapolated value from in-situ measured field strength in the solar wind (Behannon 1976),

$$B = 3\times10^{-5}\left(\frac{R}{216 R_\odot}\right)^{-2} \quad G \qquad (2)$$

corresponding to the effects of the presence of the higher pole components of the fields in the neighborhood of the sun. Expression (1) is, of course, a very crude expression because it is based on information sources very inhomogeneous in quality, referring characteristically different points in the corona, and also relying upon information of other quantities like the density distribution which we have to infer from the data obtained from observations of other points and other instances. For example, information of the magnetic field from microwave spectra is coupled with the energy spectrum of the high energy particles emitting it which is not known, and that from the propagation of type II bursts is coupled with the model of the density distribution along their paths of propagation. The deduction of the field strength from the band spitting of type II bursts requires the information of shock strength in addition to that of density. Razin effect gives us the information of the magnetic field again only when information about the density is given. For example, Dulk and McLean assumed the density distribution of 2 x or 8 x Newkirk's model coronal density, but this, of course, does not represent the density in active region corona. Further, the motion of the source may well sample out both closed and open part of the magneteic field along the path. These arguments envisage the problems with such expression as expression(1), especially for highly structured low corona. Namely,some of the information comes from active regions and others from non-active regions (or from closed field regions and from open field regions), and so on, but all mixed together to give an averaged expression (1). This suggests that the information derived from radio data, at least at the present stage, should be taken merely as a rough measure of the magnetic field strength in the corona. In the outer part of the corona where there is no other way of measuring the magnetic field, however, expression (1) may serve as the only existing measure of the magnetic field and is useful.

3. Geometrical Method for Calculating the Coronal Magnetic Field from the Shape of the Coronal Loops

In the inner part of the corona ($R \lesssim 1.5 R_\odot$), X-ray and EUV observations from Skylab have revealed that the corona is consisted of highly inhomogeneous structures, mainly of loop shape. It was noticed that this allows a rather solid way of estimating the magnetic field in the corona (Sakurai and Uchida 1977). Namely, if we know the three-dimensional shape of the loops which are safely assumed to be the frozen-in inhomogeneities of the plasma along the field pattern, we can calculate the detailed distribution of the magnetic field in the corona by specifying the field intensity at, eg , the photospheric footpoints.

Complete determination of the three-dimensional pattern of the loops from observations with a suitable time separation should in principle reveal the field configuration in the corona , and further, the configuration of the electric current in the corona. The determination of the location and the configuration of the coronal electric current in the vicinity of the flare site and the change of it before and after the flare are extremely important in relation to the investigation of the mechanism of the flare. We give some comments about this direct method of determination in section 4.

More practicable alternative is to use models and determine parameter values in them by comparing the projection of the calculated pattern of the field with the observed loop shape. This approach followed the method initiated by Schmidt (1964) to calculate the potential field in planar geometry, and has been extended later by several authors to global potential field, and further, to non-potential fields.

3.1. Model Fitting by Potential Field

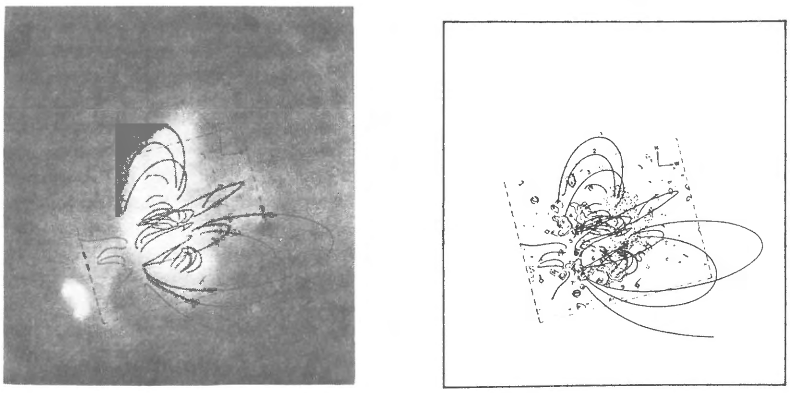
Schmidt's problem was to calculate the extention of the magnetic field into the corona by knowing the distribution of the field on the bottom boundary, the photosphere. Assuming a potential field, he obtained the solution by using Green function method in which the photospheric field distribution is replaced by the distribution of unit monopoles,

$$\phi(\mathbf{r}) = \int G(\mathbf{r}, \mathbf{r}') B_n(\mathbf{r}') d\mathbf{r}' \qquad (3)$$

$$G(\mathbf{r}, \mathbf{r}') = \frac{1}{2\pi |\mathbf{r} - \mathbf{r}'|} \qquad (4)$$

$$\mathbf{B} = -\nabla\phi \qquad (5)$$

where B_n is assigned on the bottom boundary surface, the photosphere. This method is widely used both in pre-Skylab days (eg., Rust 1972 for loop prominences) and in post-Skylab days (eg., Poletto et al 1975 for soft X-ray loops (Figure 2a, b)). It is seen that a rough agreement is obtained.



a b

Fig 2 a) X-ray loop structure of Jun 15,1973 observed by AS and E experiment on Skylab.
b) Field lines calculated by Poletto et al (1975) using the photospheric magnetic field distribution of that day. (Sorry for bad reproduction of X-ray picture. Original is quite good).

A direct extention of Schmidt's approach to the global case was attempted by Schatten et al (1969), but a more legitimate way in the global case was developed by Altschuler and Newkirk (1969) in spherical harmonic expansion technique,

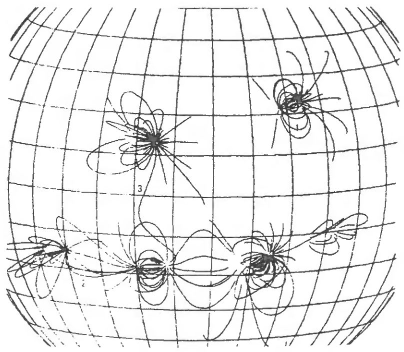
$$\phi(\mathbf{r}) = R_e \sum \left\{ C_{\ell m}\left(\frac{a}{r}\right)^{\ell+1} + D_{\ell m}\left(\frac{r}{a}\right)^{\ell} \right\} Y_\ell^m(\theta,\varphi) \qquad (6)$$

$$\mathbf{B} = -\nabla\phi \qquad (7)$$

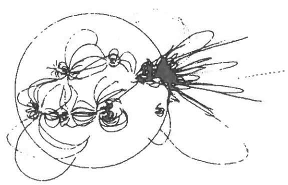
and the coefficients are fixed by matching the expression with the observed field given on the inner boundary, the photosphere. Their treatment was in pre-Skylab days, and the comparison with the observation was made with the eclipse or K-coronagraph results in which the structure can only be observed beyond the limb, and the detail of the coronal structure can not be separated and obscure due to the overlap in the projection of the structure on the sky.

In trying to reproduce the X-ray loop pattern obtained by Skylab, Sakurai and Uchida (1977) developed another method based on Biot-Savart's law by replacing the active region flux tube by subphotospheric current in the form of solenoids, and calculating vector potential.

a



b



HIGH SURFACE RESOLUTION
STRONG FIELDS
(90 POLYNOMIALS)

c

Fig 3 a) Coronal loop structure of Sep 5,1973 observed by NRL experiment on Skylab.
b) Calculated model of the magnetic field lines of the same day by Sakurai and Uchida(1977).
c) The same by Altschuler et al(1977),for the preceding day. (Sorry for bad reproduction of EUV pictures. Original is superb.)

$$\mathbb{A}(\mathbf{r}) = \frac{1}{c}\int \frac{\mathbf{j}(\mathbf{r})}{|\mathbf{r}'-\mathbf{r}|} d\mathbf{r}' \quad (8)$$

$$\mathbb{B} = \mathrm{rot}\,\mathbb{A} \quad (9)$$

It may be said that the global-scale features as well as loop structures above active regions are reasonably well reproduced by this model (Figure 3a, b). Altschuler et al (1977) developed their own method to include very high order terms in spherical harmonic expansion, and also tried to reproduce the Skylab result (Figure 3c).

The result of such a comparison using potential field models indicates the following ; (i) the rough structure of the loop-shaped corona can be reproduced already by potential field models, but (ii) marked deviations are often seen especially near the flaring active regions, and (iii) a better fitting of local and global features observed in X-ray is obtained by Sakurai-Uchida method rather than by elaborated extention of Altschuler and Newkirk's method with very many terms of expansion. Items (i) and (ii) suggest that most part of the coronal field is relaxed to the current-free state (the lowest energy state), but at some special part like the neighborhood of the flaring active regions , the deformation of the field is seen, suggesting the presence of the local current in the corona. Item (iii) reflects the fact that the brightest corona is closely related to the active region fields which is difficult to take into account in detail in Altschuler et al's method . Sakurai-Uchida method concentrates attention on strong fields and is advantageous in reproducing the brightest loop structures of the corona which are due to the active region fields.

3.2. Implication of the Deviation from the Potential Field and the Extention to the Model-Fitting by Non-Potential Fields

Potential field in the corona is nothing but the field due to the source current outside the region under consideration, ie, in the invisible subphotospheric layers in our case. Since observations of the photospheric magnetic field at the time of flares generally indicate that there is no appreciable change in the magnetic field observed at the very moment of the flare occurrence (Rust 1972), it is required that the electric current responsible for the releasable magnetic energy available for the flare should preexist in the corona or in the chromosphere . The detection of the presence of such a current in the corona was simply beyond the range of capability of observation before Skylab, but now it is, so to say, made visible by X-ray or EUV observations as the deviation of the coronal magnetic field from the potential field, if we identify the coronal loops with the field-aligned plasma inhomogeneity. Potential field is the lowest energy state (without any current in the corona) for the given distribution of the normal component of the field on the boundary, and the deviation from this is produced by the presence of the coronal current. Naturally, such a current is held only in those cases in which the distortion of the field lines can not be continuously relaxed by the motion in the corona alone. In such cases, the work done on the footpoint of the flux tube by the photospheric motion is stored in the form of excess magnetic energy, or,

$$\Delta W = -\frac{1}{2c}\int \mathbf{A}\cdot\mathbf{j}\, dv \qquad (10)$$

providing the energy of flares (Uchida and Sakurai 1977).

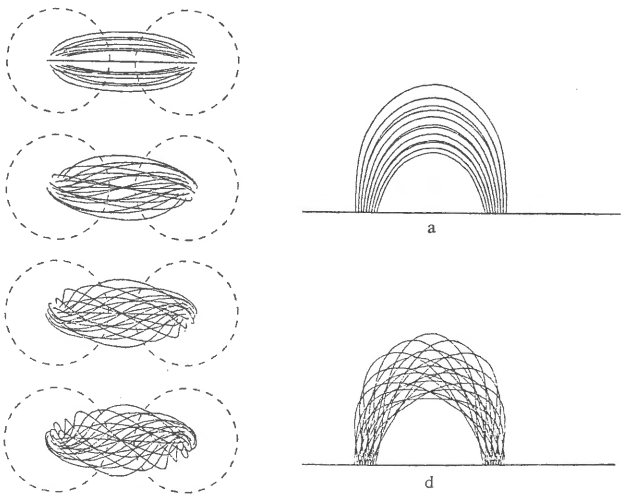
Two fundamental cases of such current configurations widely considered in relation to flares are (a) field-aligned (force-free) current which may be built up, eg , by the twisting at the footpoint of the magnetic flux tubes, and (b) the sheet current which may be produced at the boundary of two regions of plasmas with magnetic fields frozen to them. This occurs at the boundary of plasmas with different pressures (and different field strengths to compensate the difference in pressure) in general. The polarities of the field on both sides of the sheet may be the same, but an important situation appears when the polarities of them are opposite from each other. So-called neutral sheet is a special case of this.

Field-aligned current (a) may be characterized by the helical winding of the loops. Since $\beta \equiv 2\mathcal{R}\rho T/(B^2/8\pi)$ is small in the corona except at the neutral sheet, we deal with this case in terms of force-free field in which the Lorentz force disappears, ie,

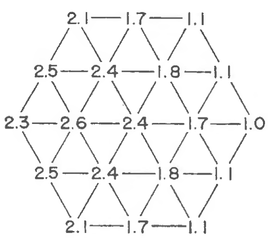
$$\mathbf{j}\times\mathbf{B} = 0 , \qquad \mathrm{rot}\,\mathbf{B} = \alpha\mathbf{B} \qquad (11)$$

α = const along the lines of force by its nature, but can vary from a line to another. A constant-α field signifies the one in which α takes a common value for all field lines, and can be tackled with (eg, Woltje 1958). Nakagawa and Raadu (1972) applied this to the sunspot field and claimed that the cyclonic appearance of the fibrils around the sunspots may represent the presence of the current. Levine and Altschuler (1974) formulated the global constant-α field, and found that the constant field with constant everywhere is too restrictive to reproduce the observation.

Non-constant-α field has been discussed by Sturrock and Woodbury (1967), Barns and Sturrock (1972), Chiu and Hilton (1977) and other people, in the expression using the Euler potentials, but the equation is very complicated and difficult to deal with. Recently, however, Sakurai (1979) has developed a variational method of dealing with this problem. His method is to treat the eneryg integral(the variation of which gives out the Lorentz force equation (10) as the Euler's equation for the minimization in a special case in which other terms are negligible) and minimize the integral by varying the shape parameters (finite element method). Figure 4 shows examples of the results of his calculations of non-constant-α force-free field produced by the motion of footpoints.



a



b

Fig. 4. Model Calculation of non-constant-α field by Sakurai(1979).
a) Magnetic field before and after applying twist motion.
b) Distribution of induced α value inside the spot.

$$\delta W(\mathbf{r}) = \delta \int \left\{ \frac{\mathbf{d}_3^2}{8\pi J} + \bar{p}(\mathbf{r}) J \right\} d^3u = 0 \tag{12}$$

$$\mathbf{B} = \nabla u_1 \times \nabla u_2 = \frac{\mathbf{d}_3}{J} \tag{13}$$

$$\mathbf{d}_3 \equiv \frac{\partial \mathbf{r}}{\partial u_3}, \quad J \equiv \frac{\partial(x_1, x_2, x_3)}{\partial(u_1, u_2, u_3)} \tag{14}$$

He also developed another approach in which the current is assigned for each tube and obtained the configuration which minimizes the energy (Sakurai 1980). An example of the result of the calculation is shown in Figure 5.

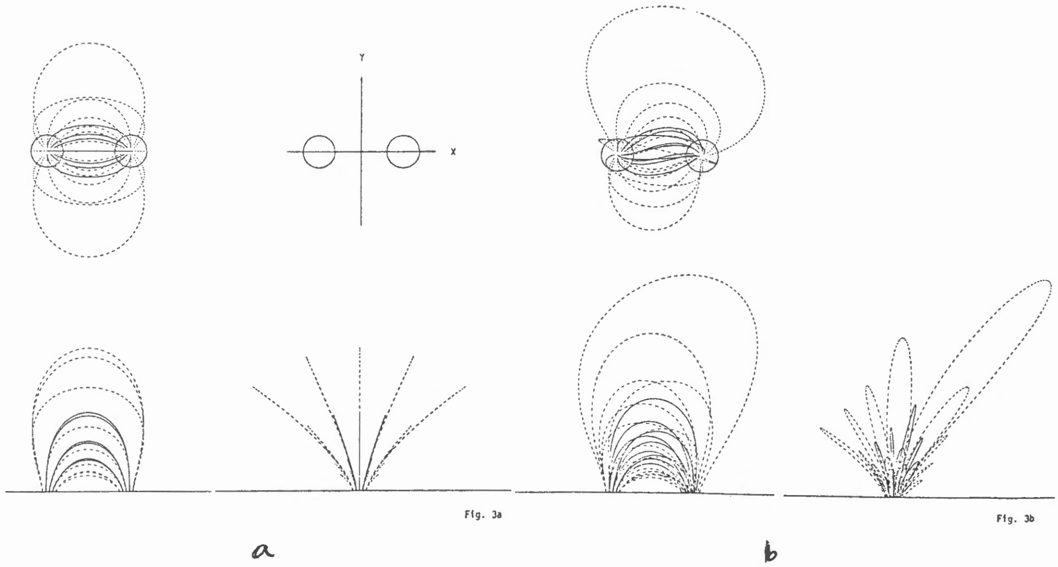


Fig. 5. A result of model computation in which the distributions of $B_n(\mathbf{r})$ and $\alpha(\mathbf{r})$ are given in the region of one(+) polarity in the photosphere. a) Before twisting. b) After twisting. Solid lines are those to which $\alpha(\mathbf{r})$ is assigned and are twisted as the result.

The effect of the sheet current,on the other hand,may be characterized by the "insulation" of the nearby regions of opposite polarities which are otherwise expected to connect to each other. The presence and the drastic change at a flare of such an "insulation" are seen in EUV monochromatic pictures obtained by Skylab. Calculation of the field with sheet current can be done in cases in which the sheet is singly connected . Sakurai and Uchida (1977) calculated the current sheet models and an example of calculation is given in Figure 6.

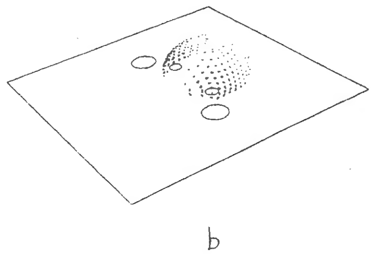


Fig 6 An example of magnetic field with and without current sheet.
a) Small pair of spot emerged in the preexisting active region,producing current sheet.
B) Distribution of the current on the sheet.
c) Magnetic field after relaxation of the current sheet.

Reconfiguration of this type is certainly seen in some flares observed in X-rays or EUV lines (Sheeley et al 1974b). Purely field-aligned current and purely sheet current, however, are idealizations and both may coexist more or less in actual cases. It is, however, important to establish which is the main mechanism of flare energy storage, in order to pin down the flare mechanism. More observation in X-ray and EUV lines which cover the build-up and release phases of flares is highly desirable.

3.3. Possibility of Direct Geometrical Determination of Magnetic Field

Lastly, a brief remark for the possibility of the direct geometrical determination of the field and current is given. We discussed in the above the parameter-fitting by using models, but it would be better if the field can be calculated model-free. This may in principle be possible if we obtain the three dimensional shape of the loops purely geometrically from the comparison of photographs taken with appropriate time separation (long enough to produce stereo effect but short enough compared with the life of a loop). Three dimensional shape of the loop can be obtained as the intersection of two cylindrical(non-circular) surfaces, each of which contains the loop itself and the projection of it on the solar surface at the relevant time, one being rotated back by the angle corresponding to the solar rotation during the time separation. Computor programs are now being prepared in order to do this from the time sequence of X-ray photographs of AS and E experiment on Skylab.

4. Summary and Discussion

At present, it is still impossible to say that the knowledge about the coronal magnetic field is established. It is still difficult to have decisive information about the coronal magnetic field from radio observations since most of them as they are, involve with other unknown entities of which we have to make some assumption. Compared with these, the method using the geometry of loops observed in X-ray or EUV lines is rather naive one, and the only assumption is that these loops are frozen-in inhomogeneities to the magnetic field. This assumption seems to be safe except for the transiency during the flare time,for example. The state of the matter with this method is pretty far from being complete but there is a hope to do this first in the model-fitting method and gradually in full to determine the current as well as the magnetic field on computors.

References

Altschuler,M.D., and Newkirk,G.,1969, Solar Phys. 9, 131.
Altschuler,M.D. ,Levine,R.H ,Stix,M. , and Havey, J., 1977, Solar Phys.51, 345.
Barns,C.W., and Sturrock,P.A.,1972, Astrophys.J.174, 659.

Behannon,K.W ,1976, in Physics of Solar and Planetary Evironment, ed, Willioms,D.J. (Am. Geophys. Union), p 332.
Chiu,Y.T. and Hilton,H.H.,1977, Astrophys.J. 212,873.
Dulk,G.A., and McLean,D.J.,1978, Solar Phys. 57, 279.
Levine,R.H., and Altschuler,M.D.,1974, Solar Phys. 36, 345.
Nakagawa,Y., and Raadu,M.A.,1972, Solar Phys. 25, 127.
Poletto,G.,Vaiana,G.S.,Zombeck,M.V.,Krieger,A.S., and Timothy,A.F., Solar Phys. 44, 83, 1975.
Rust,D.M.,1968, in IAU Symp. No 35,Structure and Development of Solar Active Regions, ed.Kiepenhener, K.O. (D.Reidel),p77.
Rust,D.M.,1972, Solar Phys. 25, 141.
Sakurai,T. , and Uchida,Y. ,1976, Abstract, US-Japan Cooperative Seminar High Eenergy Phenomena in Solar Flare, Tokyo Japan, p V 3.
Sakurai,T., and Uchida,Y.,1977, Solar Phys. 52, 397.
Sakurai,T.,1977, Publ. Astron. Soc. Japan, 31, 209.
Sakurai,T.,1980, CFA Reprint No 1316, Harvard.
Schatten,K.H.,Wilcox,J.M. and Ness,N.F.,1969, Solar Phys. 6, 442.
Schmidt,H.U.,1964, in NASA Symp. on Physics of Solar Flares, ed. Hess,W.N., (NASA) p 107.
Sheeley,N.R.,Bohlin,J.D.,Brueckner,G.E.,Purcell,J.D., Scherrer, V. and Tousey,R.,1974, Solar Phys. 40, 103.
Sheeley,N.R. ,Bohlin,J.D. ,Brueckner,G.E. ,Purcell,J.D., Scherrer,V.,Tousey,R.,Smith,J.B.,Speich,D.M., Tandberg-Hanssen,E.,Wilson,R.M., de Loach,A.C., Hoover,R.B., and McGuire,J.P.,1975, Solar Phys. 45, 377.
Sturrock,P.A., and Woodbury,E.T.,1967, in Plasma Astrophysics, ed. Sturrock,P.A.,(Academic Pr.), P155.
Svestka,Z.,Krieger,A.S.,Chase,R.C., and Howard,R., Solar Phys. 52, 69.
Takakura,T.,1967, Solar Phys., 1, 304.
Uchida,Y.and Sakurai,T.,1977, Solar Phys.,51, 413.
Vaiana,G,Krieger,A.S., and Timothy,A.F.,1973 Solar Phys. 32, 81.
Woltjer,L.,1958, Proc. Nat. Acaad. Sci. USA, 44, 489.