Weak Transient Activities in the Corona

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Abstract

Weak transient activities of small-scale coronal loops have been reported from Yohkoh and SoHO observations: Active-region transient brightenings (ARTBs), XBP flares, network flares, coronal flashes, and EUV transient brightenings. They are called with different terminology, but no significant differences can be found except for the sizes of energy and the locations where they are observed on the Sun. No differences except for the sizes of energy can be also found between ARTBs and standard flares; The frequency distribution of ARTBs as a function of energy is well represented by a single power-law with a slope similar to that of standard flares, and relatively strong ARTBs are populated by non-thermal electrons. With these observations, although more observations are still required, we currently conclude that weak transient activities of small-scale coronal loops observed not only in active regions but also in quiet regions are just small flares (microflares or nanoflares in terminology), which are located in lower energy extension of standard flares. No reliable evidences suggesting that microflares or nanoflares entirely explain the heating of the corona have been found. However, weak temporal variations seen in quasi-steady long loops are found to be well correlated with the heating level, suggesting that they may be an X-ray signature of the heating process responsible for the heating of the corona.

Key words: Sun:corona – coronal heating – Sun:activity – Sun:flares – Sun:X-rays

1. Introduction

Great advances have been made in the search for microflares and nanoflares in the solar corona after the launch of the Yohkoh satellite. The soft X-ray telescope (SXT) onboard Yohkoh has been providing continuous sequences of soft X-ray coronal images with high temporal/spatial resolutions and high sensitivity, and SXT has shown that the hot (> 3 MK) corona is extremely dynamic with weak transient activities being common phenomena. Rapid heating and mass ejection are included in weak transient activities.

A different aspect of dynamical behaviors in the corona as well as the transition region has been recently observed by Extreme ultraviolet Imaging Telescope (EIT) and Coronal Diagnostics Spectrometer (CDS) on the SoHO satellite. These instruments provide solar images of spectral lines formed in the low temperature (< 2 MK) corona and the transition region, showing that the plasma is more dynamic even in lower temperature atmospheres.

Several kinds of weak transient activities have been reported from the Yohkoh and SoHO observations. They are called with different terminology, because some differences can be found from weak transient activities previously reported, or observations are made with different instruments. It is however uncertain what interrelationships among these weak activities are. This paper reviews properties of weak transient activities which have been reported (§2), and intends to make their similarity and differences clear. The major interest in weak transient activities is whether weak transient activities are responsible for the heating of the corona. In §3, we discuss some results from studies of weak transient activities relevant to the heating of the corona. Finally, in §4, the frequency distribution of weak transient activities is discussed with consideration of their magnetic origins.

2. Properties of Weak Transient Activities

2.1. Active Regions

Yohkoh has found that active regions show soft X-ray transient brightenings of compact coronal loops (Figure 1, Shimizu et al. 1992). They are called active-region transient brightenings (hereafter ARTBs). The energy involved in an ARTB is estimated to be $10^{25} \sim 10^{29}$ ergs, with temperature of $4 \sim 8$ MK, volume emission measure of $10^{44.5} \sim 10^{47.5}$ cm^{-3}, duration of 2-7 min, and loop lengths of (5-40)$\times 10^3$ km (Shimizu 1995a). ARTBs are observed

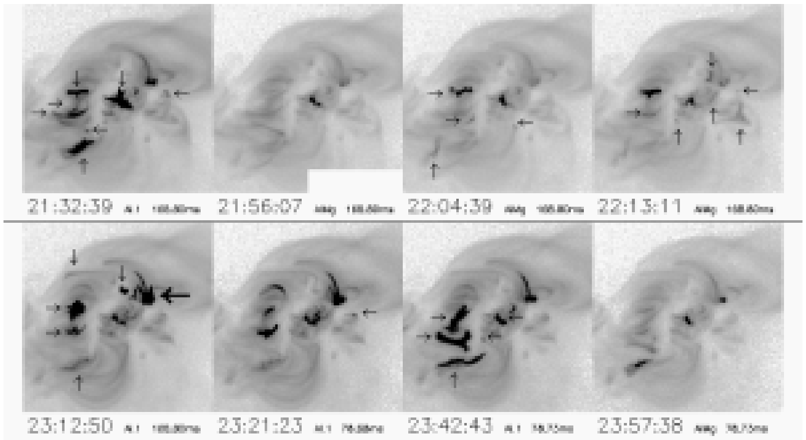

Fig. 1.. Sequence of soft X-ray images of an active region. Active-region transient brightenings are marked by arrows.

on the average of once every few minutes in "active" active regions and the occurrence rate goes down to once every hour in small "quieter" active regions. The energy of ARTBs is much smaller than that of standard flares ($10^{29} \sim 10^{32}$ ergs), but the temporal behavior and X-ray morphology is quite similar. From the viewpoint of X-ray morphology, ARTBs can be classified into three categories: multiple loop events, single loop events, and point-like events (Shimizu et al. 1994). For the time evolution, loops tend to brighten from their footpoints or alternatively from the site where loops are apparently in contact in the initial phase of the brightenings, followed by brightenings of the entire loops. Multiple loop configuration is sometimes observed even in standard flares (e.g., Hanaoka 1996; Nishio et al. 1997), and standard flares in some cases show initial brightening at loop footpoints, which may be an X-ray morphological signature for chromospheric evaporation.

ARTBs are not the only weak transient activity observed in active regions. Weak activities can be found even in quasi-steady coronal loops, which connect magnetic polarities surrounding a leading sunspot to opposite polarities near the following spots. Quasi-steady loops are slightly far from steady condition, with slowly changing X-ray intensity accompanied by short-timescale variations (Shimizu and Tsuneta 1997). The time variations are found almost everywhere in active regions and X-ray bright points. Variations are small in spatial size, typically less than a few tens of arcsec, which are much smaller in size than the quasi-steady long loop structures. The duration of the variations is less than 10 min.

2.2. Outside Active Regions

Several types of weak transient activities have been reported from the Yohkoh and SoHO observations of quiet regions, because tiny activities can be more easily detected in quiet regions due to lower background intensity. Weak transient activities reported so far from Yohkoh and SoHO observations are reviewed below.

<u>XBP flares</u> XBP flares are X-ray intensity variations observed in coronal bright points (XBPs) with SXT (Strong et al. 1992). XBPs show intensity variability over a wider variety of time scales from a few minutes to hours as well as rapid changes in their morphology. Relatively intense flare-like brightenings are referred to as XBP flares. Their temperature and volume emission measure are estimated to be 1.4-2.9 MK and $(0.4\text{-}2.5)\times10^{45}$ cm^{-3}, respectively. XBP flares often involve magnetic loops, which are considerably larger than the XBP itself, and which brighten along their lengths (= X-ray coronal jets).

<u>Network flares</u> Network flares are X-ray intensity variations with a duration of roughly 10 min, observed above magnetic networks with SXT (Krucker et al. 1997). The thermal energy content of network flares is estimated $(2\text{-}22)\times10^{25}$ ergs, with temperature of ~ 1.5 MK, volume emission measure of $10^{44.6} \sim 10^{45.9}$ cm^{-3}, and source size of 5 to 8 arcsec (FWHM). These events are more than an order of magnitude in energy smaller than XBP flares. The network flares are produced in compact faint X-ray sources located above magnetic networks. Since faint X-ray sources are basically referred as XBPs, the network flares can be regarded as a lower energy group of XBP flares. Krucker et al. (1997) studied the radio counterpart of the network flares, and found several similarities between standard flares and the network flares.

<u>SXR coronal flashes</u> Coronal flashes are tiny X-ray transient intensity variations found with SXT deep exposure

observations of polar coronal holes (Koutchmy et al. 1997). The soft X-ray flux of coronal flashes is roughly one order of magnitude smaller than the average soft X-ray flux of network flares reported by Krucker et al. (1997), roughly estimating the energy of coronal flashes to be of the order of 10^{24} erg. They are significantly small in size, and brightenings of a single pixel (2.5 arcsec size) are sometimes observed. Coronal flashes last as short as 1.5 min.

EUV transient brightenings/Heating events EUV image sequences obtained with EIT show a large number of small-scale brightenings in small coronal loops located in magnetic networks. Small-scale brightenings are more frequently observed in the He II transition region line (0.08MK) than in low-temperature coronal emission lines (0.9–1.6MK). These coronal brightenings are called EUV transient brightenings (Berghmans et al. 1998) or heating events (Krucker and Benz 1998). Berghmans et al. (1998) estimated that the radiative losses of the brightenings are distributed between 10^{24} and 10^{26} ergs, whereas Krucker and Benz (1998) estimated that the thermal energy content is $10^{25} \sim 10^{26}$ ergs. Their durations are distributed from a few min to 20 min, and their sizes are $10 \sim 100$ Mm^2. Benz and Krucker (1998) found that the heating events are well located at the location of enhanced EUV emission. The EUV transient brightenings may be the low-energy counterparts of the SXT network flares.

2.3. *Coronal X-Ray Jets*

X-ray jets have been discovered by SXT as transitory X-ray enhancements with apparent collimated motion (Shibata et al. 1992). They are associated with XBP flares in XBPs, ARTBs or small flares in active regions or emerging flux regions. Coronal jets are reported to be associated even with coronal flashes (Koutchmy et al., 1998). The lengths lie in the range of a few $\times 10^4 \sim 4 \times 10^5$ km. Their durations range from a few min to 10 hours. The apparent velocities are 10–1000 km/s with an average velocity of about 200 km/s (Shimojo et al. 1996), providing an estimate of the kinetic energy in $10^{25} \sim 10^{28}$ ergs. The total (kinetic plus thermal) energy of jets is about one order of magnitude smaller than the thermal energy involved in the associated small flares (Shimojo 1999), and therefore the detection of jets is greatly affected by the intensity of the background in which jets occur; X-ray jets can be found when the intensity enhancements of jets exceed about 30 % of the background.

2.4. *Interrelationship of Weak Transient Activities*

Figure 2 summarizes weak transient activities observed in the corona as a function of involved energy in the vertical axis and the location of occurrences in the horizontal axis. Newly observed coronal weak activities are distributed between 10^{29} and 10^{24} ergs. Weak transient activities are more easily found in quiet regions because of low quasi-steady X-ray background level. No significant differences except for the involved energy and occurrence location may be found among ARTBs, XBP flares, network flares, coronal flashes, and EUV transient brightenings. The durations of these activities are all less than roughly 10 min, and they show soft X-ray light curves with sudden increase at the beginning and slowly decrease in the late phase, which are temporal behaviors similar to that of standard flares. The coronal loops showing these activities are compact, and smaller energy activities appear to be confined into more compact loops.

Coronal jets are observed in a wide range of weak transient activities, as illustrated by a hatched region in Figure 2. Note that the hatch does not correctly illustrate the total energy involved in jets themselves. Because of lack of observations, it is currently uncertain whether small variations in quasi-steady long loops are similar to the other weak transient activities. However, they appear to be small variations at the limited parts within coronal loops, whereas the other weak activities are X-ray brightenings of the entire compact loops.

2.5. *Weak Transient Activities in Transition Region*

Harrison (1997) reported 'blinkers' which are temporal variations observed in the EUV quiet Sun with CDS. The thermal energy content of blinkers is of the order of 10^{-6} of a standard flare. Their durations range from 1 to 30 min with an average duration of 13 min. The brightenings are contained within areas of about 6000×6000 km which appear to be at magnetic network cell junctions.

Blinkers are well observed in emission lines from transition region temperatures, and emission lines from higher (low-temperature corona) and lower (upper chromosphere) temperatures observed at the same time do not display the same variations in brightenings, indicating that the blinkers appear to be pretty much confined to transition region temperatures. Therefore the blinkers can be considered to be a weak transient phenomenon in the transition region rather than in the corona. Several weak microflare activities in the transition region have been reported so far: EUV microflares (Porter et al. 1987), explosive events and EUV jets (Brueckner and Bartoe 1983), and so on. The blinkers may be a member of these weak transient activities.

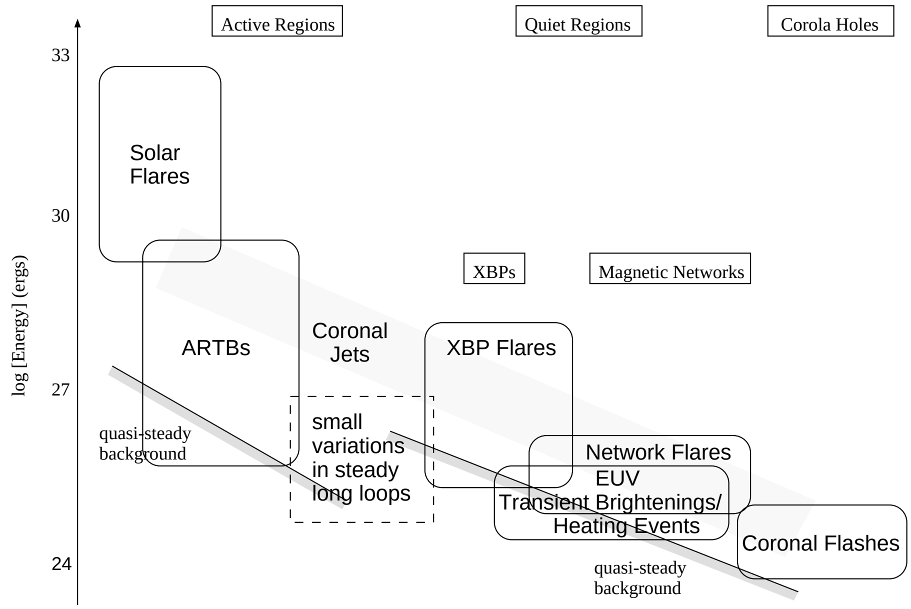

Fig. 2.. Coronal Weak transient activities as a function of energy in vertical axis and occurrence location in horizontal axis. The significant differences among weak transient activities are their energy and the locations where they are produced.

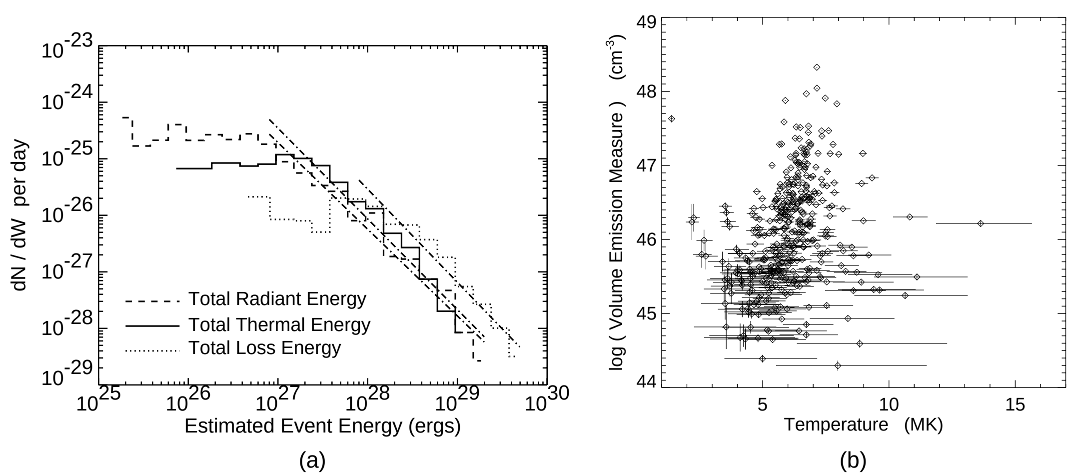

Fig. 3.. (a) Frequency distribution of ARTBs as a function of the total energy, and (b) volume emission measure of ARTBs at the X-ray peak intensity as a function of temperature (Shimizu 1995a). A combination of Al 1265Å and Al 12μ m filters is used with the assumption of soft X-ray emission from isothermal plasma.

3. Implication for the Heating of the Corona

3.1. Frequency distributions

Figure 3a shows the frequency distribution of ARTBs, which is well represented by a single power-law function with a slope of $1.5 \sim 1.6$, in the energy range larger than 10^{27} erg. This slope is same as that of standard flares (e.g., Crosby, Aschwanden, and Dennis 1993), meaning that the flare power-law distribution is maintained over five orders of magnitude in energy ($10^{27} \sim 10^{32}$ ergs). Since a slope steeper than 2 is necessary for working as the major heating source, it is concluded that ARTBs cannot provide all the energy for the heating of the active-region corona. The total thermal energy supplied by ARTBs is estimated to be at most a factor of 5 smaller than the heating rate required for the active-region corona. The energy is used to generate > 5 MK hot plasma in the corona (Watanabe et al. 1995; Yoshida and Tsuneta 1996).

Recently the frequency distributions of EUV transient brightenings/ heating events are published; Krucker and Benz (1998) give a single power-law with a slope of between 2.3 and 2.6, whereas Berghmans et al. (1998) obtain a slope of 1.35 for the single power-law distribution. The difference in slope might be partly explained by the different source sizes of the events determined by the different search algorithms used in these studies, although we need to wait for further investigations.

Here we point out a possibility that EIT data may give a slope slightly steeper than that of standard flares. Coronal plasmas in narrow temperatures of $0.9 - 1.6$ MK are selectively observed with EIT. The energy produced by weak transient activities may be used to heat plasma up to higher temperatures, so that some amount of plasma can exist above 2 MK. Since EIT is less sensitive to plasmas above 2 MK, EIT may provide an underestimated energy. Moreover, a possible correlation can be found between temperature and emission measure for standard flares (Yuda et al. 1997) and ARTBs (Figure 3b). If this correlation can be applied to EUV transient brightenings, the slope of the frequency distribution can be changed because the energy is more underestimated for larger events.

3.2. Existence of Non-thermal Electrons

Several studies have been done to search for non-thermal electrons involved in coronal weak transient activities, using radio and hard X-ray observations. Radio counterparts of ARTBs are presented by Gary (1998) in these proceedings, showing the existence of non-thermal electrons. Nitta (1997) shows that some strong ARTBs are accompanied by hard X-ray emission, and that the scatter plot between the peak soft X-ray flux and the time-integrated hard X-ray flux indicates that these ARTBs are not particularly hard X-ray-rich or -deficient in comparison with standard flares. For network flares in the quiet Sun, Krucker et al. (1997) found tiny radio signals probably from non-thermal population of electrons. Radio counterparts of EUV transient brightenings are reported by Benz and Krucker (1999).

3.3. Small Variations in Quasi-Steady Loops

Most of the radiation from the corona comes from quasi-steady long loop structures, although weak transient activities discussed above are confined into compact loop structures. Even these quasi-steady loops have weak temporal variations (§2). An intensity correlation is found between the magnitudes of the time variations and the intensities of the persistent corona (Figure 4), indicating that the variations are apparently related to the heating mechanism of the persistent corona. Since the intensity correlation between the magnitudes of variations and the corresponding background intensities is not found for ARTBs (Shimizu and Tsuneta 1997), weak variations observed in quasi-steady loops can be physically different from weak transient activities like ARTBs. However, the radiative response against the input of the same amount of energy may be different between long loops and compact loops, and thus further studies to compare them are required.

4. Single Power-law Distribution

Observations in active regions have revealed that the frequency distribution is represented by a single power-law function with a slope of $1.5 \sim 1.6$ from the largest flares ($\sim 10^{32}$ erg) down to smaller energy. The single power-law distribution is maintained at least over 5 orders of magnitude in energy, suggesting that the energy released by these transient activities may be controlled by an unique physical condition, such as the size and strength of the current at magnetic reconnection site.

Several kinds of magnetic origins appear to exist in flare-like transient activities. Yohkoh observations have suggested that at least two types of magnetic field configuration exist in the occurrence of solar flares: loop-with-a-cusp and emerging-flux-type configuration. Loop-with-a-cusp configuration appears to be more dominant in larger flares, and emerging-flux-type configuration is more frequently involved in smaller flares. A small-scale emerging flux is found to be associated with the onset of pointlike ARTBs (Shimizu 1995b), which can be well explained with emerging-flux-type configuration. Going down to XBP/network flares, canceling magnetic bipoles are involved rather than emerging bipoles in their occurrence; Harvey (1998) shows that 64% of XBPs are associated with canceling magnetic bipoles. Considering the variety of magnetic field configuration in addition to the single power-law distribution, a common physical condition should be involved in these different magnetic field configurations.

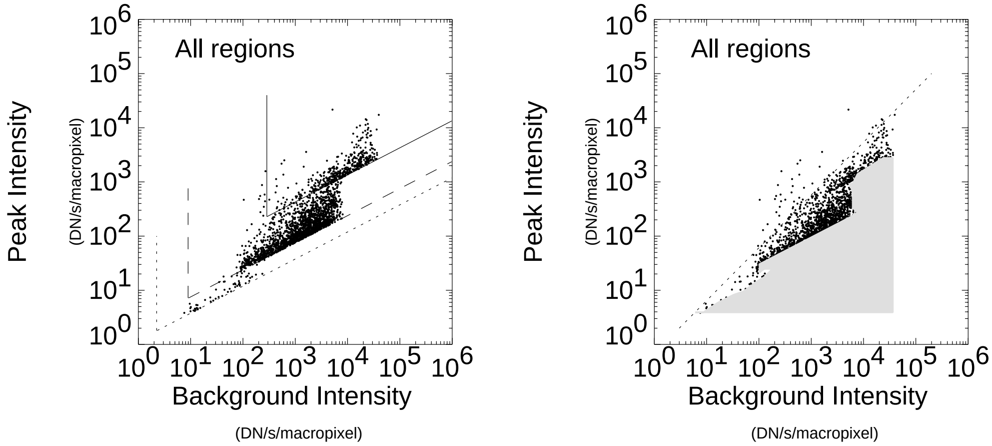

Fig. 4.. The magnitude of weak variations in quasi-steady loops is plotted against the corresponding persistent-coronal intensity. Each point corresponds to each X-ray variation detected with the position-dependent light-curve analysis. The three regions with different X-ray emission level (the active-region bright core, the active-region outer region, and a quiet region) are examined. Each data set has its own lower detection limit, depending on the number of incident photons (solid, dashed, and dotted lines in the left panel). Smaller variations below the photon noise would exist in the hatched region of the right panel. The upper envelope of the distribution says that the intensity of the largest time variability observed is correlated with the intensity of the persistent corona over a wide intensity range.

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References

Benz, A.O. and Krucker, S. 1998, Sol. Phys. 182, 349
Benz, A.O. and Krucker, S. 1999, A&A 341, 286
Berghmans, D., Clette, F., Moses, D. 1998, A&A 336, 1039
Brueckner, G.E., Bartoe, J.-D.F. 1983, ApJ 272, 329
Crosby, N.B., Aschwanden, M.J., Dennis, B.R. 1993, Sol. Phys. 143, 275
Gary, D.E. 1998, in these proceedings
Hanaoka, Y. 1996, Sol. Phys. 165, 275
Harrison, R.A. 1997, Sol. Phys. 175, 467
Harvey, K.L. 1998, in Magnetic Reconnection in the Solar Atmosphere, eds. R.D. Bentley et al. (ASP conf. vol.111) p.9
Koutchmy, S., Hara, H., Suematsu, Y., Reardon, K. 1997, A&A 320, L33
Koutchmy, S., Hara, H., Shibata, K., Suematsu, Y., Reardon, K. 1998, in Observational Plasma Astrophysics: Five Years of Yohkoh and Beyond, eds. T.Watanabe et al. (Kluwer: Dordrecht) p87
Krucker, S., Benz, A.O., Bastian, T.S., Acton, L.W. 1997, ApJ 488, 499
Krucker, S., Benz, A.O. 1998, ApJL 501, L213
Nishio, M., Yaji, K., Kosugi, T., Nakajima, H., Sakurai, T. 1997, ApJ 489, 976
Nitta, N. 1997, ApJ 491, 402
Porter, J.G., Moore, R.L., Reichmann, E.J., Engvold, O., Harvey, J. 1987, ApJ 323, 380
Shibata, K., Ishido, Y., Acton, L.W., Strong, K.T. et al. 1992, PASJ 44, L173
Shimizu, T., Tsuneta, S., Acton, L. W., Lemen, J. R., Uchida, Y. 1992, PASJ 44, L147
Shimizu, T., Tsuneta, S., Acton, L. W., Lemen, J. R., Ogawara, Y., Uchida, Y. 1994, ApJ 422, 906
Shimizu, T. 1995a, PASJ 47, 251
Shimizu, T. 1995b, Ph.D. thesis, The University of Tokyo
Shimizu, T., Tsuneta, S. 1997, ApJ 486, 1045
Shimojo, M., Hashimoto, S., Shibata, K., Hirayama, T., Hudson, H.S., Acton, L.W. 1996, PASJ 48, 123
Shimojo, M. 1999, Ph.D. thesis, The Graduate University of Advanced Studies
Strong, K. T., Harvey, K. L., Hirayama, T., Nitta, N., Shimizu, T., Tsuneta, S. 1992, PASJ 44, L161
Watanabe, T., Hara, H., Shimizu, T., Hiei, E. et al. 1995, Sol. Phys. 157, 169
Yoshida, T., Tsuneta, S. 1996, ApJ 459, 342
Yuda, S., Hiei, E., Takahashi, M, Watanabe, T. 1997, PASJ 49, 115