Thermal Evolution of Coronal Active Regions

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Abstract

We study the thermal evolution of active regions in the corona by analyzing 51 emerging flux regions (EFRs) observed with the soft X-ray telescope aboard *Yohkoh*. We derive the mean temperature and pressure of active regions as a function of time using the filter ratio technique, and found that the mean temperature increases with its expansion. We also studied the relationship between the region size and the temperature, and found that the temperature (T) and the pressure (P) of EFRs increase with increasing region size (L); $T \propto L^{0.42}, P \propto L^{0.25}$. The relation between pressure and region size, however, is strongly influenced by the assumption of the region's thickness along the line of sight.

Key words: magnetic fields — Sun: corona — Sun: evolution — Sun: X-rays

1. Introduction

Newly emerged solar active regions (ARs) are called emerging flux regions (EFRs). Coronal EFRs are important for understanding the heating mechanism of the solar corona because we can see the earliest heating process of plasma in emerging magnetic loops.

The Soft X-ray Telescope (SXT; Tsuneta et al., 1991) aboard *Yohkoh* (Ogawara et al., 1991) has five X-ray filters for obtaining temperature, emission measure, and other plasma parameters. Using the filter ratio technique (Hara et al., 1992), the temperature and emission measure are derived with two filters which have different effective wavelength ranges of soft X-ray. Until now, several studies of temperature structure of active regions have been carried out by many people, which show that active regions have a multi-temperature structure (e.g., Hara et al., 1992; Yoshida and Tsuneta, 1995). Yoshida and Tsuneta (1995) also found that the temperature of a steady plasma component ranges from 3 MK to 5 MK, and high temperature regions ($\geq$ 6 MK) appear to be transiently heated. Sterling et al. (1997) also found that active region corona consists of a steady cool component ($\sim$ 3 MK) and a transient hot component ($\geq$ 5MK) using the Bragg Crystal Spectrometer on board *Yohkoh*. Kano and Tsuneta (1996) studied the temperature structure of steady loops in active regions, and found that temperature and emission measure (pressure) are highest around the loop top. They also found a correlation among the maximum temperature, pressure, and loop length (Scaling Law; e.g. Rosner et al., 1978). Klimchuk and Porter (1995) found that the pressure of loops decrease with loop length, and the temperature is independent of the length.

However, little is known about the evolution of the steady, cool component of active regions. In this paper we would like to examine the time evolution of the steady, cool component of active regions, and the relation between temperature and region size.

2. Observations and Analysis

All data for this study were obtained using the thin Al filter and the AlMg filter in the Full Frame Image (FFI) mode of the *Yohkoh*/SXT. This filter pair can derive the temperatures of 1.5 $\sim$ 10 MK. If we assume a thickness of the region along the line-of-sight for estimating the region's volume, we can obtain the pressure from temperature and emission meassure. The temporal resolution of FFI mode ranges from 8.5 minutes to 30 minutes except for large flares or data gaps. Because the SXT has only Partial Frame Image mode during flare observations, FFI data does not include images of flaring loops. However, X-ray emission from active region is influenced by small flares like transient brightenings.

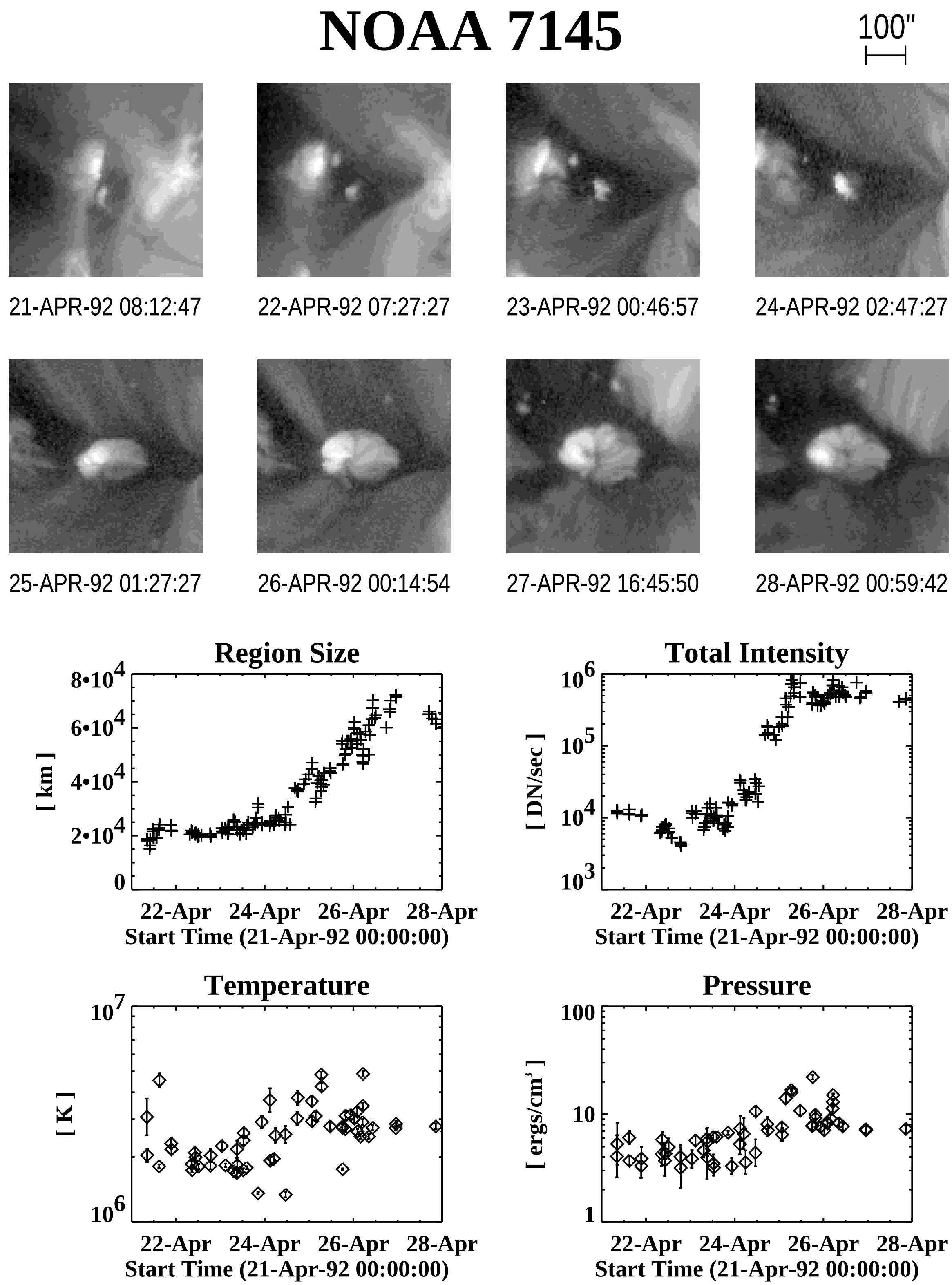

Fig. 1.. Soft X-ray images of typical emergence of active region 7145. Lower panels show the time development of the region size, total X-ray intensity, temperature, and pressure.

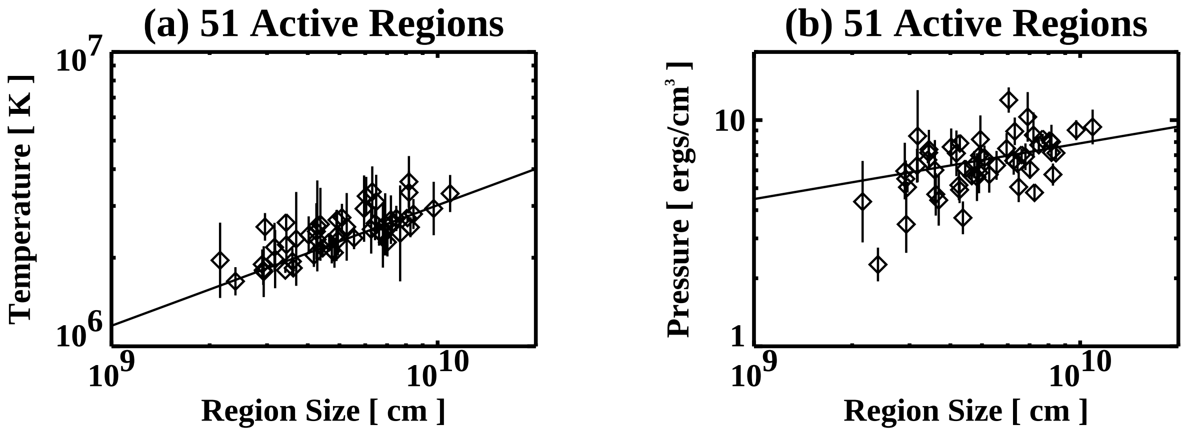

Fig. 2.. (a) Temperature (T) vs. region size (L) for 51 active regions. Solid line shows $T \propto L^{0.42}$. (b) Pressure (P) vs. region size for 51 active regions. Solid line shows $P \propto L^{0.25}$. We assume that the line-of-sight thickness is 20,000 km for deriving the pressure.

In previous work using *Yohkoh* data, many people summed images over the observation time ($\sim 30 - 60$ min) to increase the signal-to-noise ratio. Because we want to know the time development of the temperature of EFR, we do not use this method. To increase signal-to-noise ratio, we integrated the soft X-ray emission over the entire region. Therefore our temperature is a mean temperature weighted by soft X-ray brightness. Because the brightest part of SXT images is near the center of active regions, our temperatures are representative of the temperature around the top of emerging magnetic flux. We are not concerned with the spatial variations of temperature within active regions.

We define the *core region* as the portion of the active region radiating the brightest 80% of the total integrated soft X-ray intensity of the EFR. Because the core region shows emerging magnetic loops directly (Yashiro, Shibata, and Shimojo, 1998), we apply this definition for determination of the boundary of EFRs. Please note that we studied only the core of active regions. We define the size of an EFR as the square root of area of the core region.

3. Results

Figure 1 shows the time evolution of a typical active region, NOAA 7145, observed with the *Yohkoh*/SXT. The upper panel shows the soft X-ray images. It appeared at 8:10 UT on 21 April 1992, and had a size $\sim$ 20000 km until 7:52 UT on 24 Apr (Figure 1). At this stage, the temperature of the AR is 2.0 ± 0.5 MK except for some high temperature components (≥ 5 MK) resulting from flare heating. The mean pressure of the AR is $\sim$ 4 ergs/cm^3. NOAA 7145 grows to $\sim$ 70000 km between 10:57 UT on 24 Apr and 17:03 UT on 26 Apr. After the rapid growth, the temperature of the AR is 2.6 ± 0.4 MK, and the pressure is $\sim$ 6.4 ergs/cm^3. We found that the temperature and pressure increase with the expansion of the active region.

Figure 2a shows the relationship between the region size and the temperature for 51 EFRs. Using the least square fitting, we found the relationship between the region size (L) and the temperature (T) to be $T \propto L^{0.42}$ (Solid line in figure 2a). Figure 2b also shows the relationship between the region size and the pressure (P) for the 51 EFRs. We found that the pressure increase with the region size ($P \propto L^{0.25}$), but this result is strongly influenced by the assumption of line-of-sight thickness. If we assume the line-of-sight thickness is proportional to the region size, the relationship changes to $P \propto L^{-0.25}$.

4. Discussion

We found that the mean temperature of the steady (i.e. non-flaring) component ranges from 1.7 MK to 3.6 MK, and also found the temperature increases with the region size; $T \propto L^{0.42}$. Because a large active region consists of long loops, our result means that the temperature of steady loop increases with loop size. Klimchuk and Porter (1995) studied steady coronal loops using *Yohkoh* data, and found the temperature is independent of loop size. Sterling et al. (1997) found that the temperature of active regions decreases with height using limb observations.

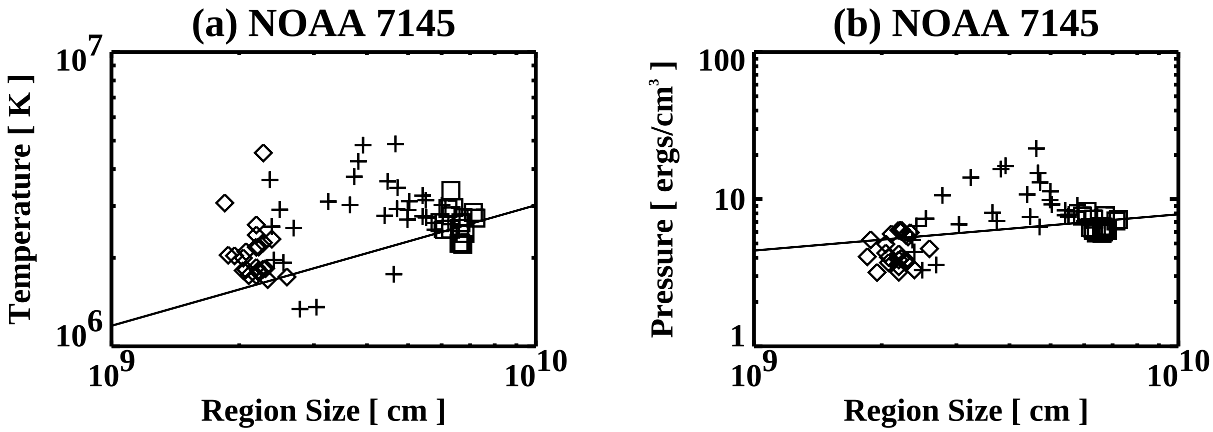

Fig. 3.. (a) Temperature vs. region size for NOAA 7145. (b) Pressure vs. region size for NOAA 7145. Diamond, crosses, and squares show the different observing time, 21-Apr 08:17 UT $\sim$ 23-APR 14:11 UT, 23-APR 20:25 UT $\sim$ 26-APR 05:15 UT, 26-APR 08:22 UT $\sim$ 28-APR 09:28 UT, respectively. Solid lines are same as figure 2.

This result implies that the temperature decreases with the loop size. What is the cause of the discrepancy between our result and these previous works ?

During the early phase of active regions, coronal magnetic field strength (B) correlates with the region size (L) (Yashiro and Shibata, 1999). If the temperature increases with magnetic field strength, we can explain the discrepancy. In our case, the magnetic field strength of the loop increases with size. (This is the property of emerging flux regions.) So the temperature increases with loop size. In the case of Sterling et al. (1997), magnetic field strength of the loop decreases with size because outer loops of active region have weaker magnetic fields. In the case of Klimchuk and Porter (1995), their loops seem to be independent of magnetic field strength because of random sampling. So the temperature is independent of the loop size. Therefore, the temperature of active region depends on magnetic field strength rather than the region size.

Lets us discuss the evolutionary effect of EFR. Figure 3a shows the relationship between the region size and the temperature of AR 7145. We mark diamonds, crosses and squares for early phase, growing phase and maximum phase, respectively. We can clearly see the temperature increase with the region size. Solid line which is the same as in figure 2a shows the relationship determined from the maximum phase of 51 ARs. Figure 3b shows the relationship between region size and pressure of AR 7145. Solid line is also the same plot as in figure 2b. The temperature and the pressure during the expansion phase (marked by crosses) are higher than the average values determined from the maximum phase of 51 ARs. In this phase, many transient phenomena occurred because the AR often interacted with outer coronal magnetic field (see figure 1). Our result suggests that active regions at different phases have different properties. If we want to know the universal properties of active regions, we should consider the evolutionary effect.

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