

CHARACTERISTICS OF ANEMONE ACTIVE REGIONS APPEARING IN CORONAL HOLES OBSERVED WITH THE *YOHKOH* SOFT X-RAY TELESCOPE

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ABSTRACT

Coronal structure of active regions appearing in coronal holes is studied, using data that were obtained with the Soft X-Ray Telescope (SXT) aboard *Yohkoh* between 1991 November and 1993 March. The following characteristics are found. Many of the active regions (ARs) appearing in coronal holes show a structure that looks like a sea anemone. Such active regions are called *anemone ARs*. About one-fourth of all active regions that were observed with SXT from their births showed the anemone structure. For almost all the anemone ARs, the order of the magnetic polarities is consistent with the Hale-Nicholson polarity law. These anemone ARs also showed, to a greater or lesser extent, an east-west asymmetry in the X-ray intensity distribution, such that the following (eastern) part of the AR was brighter than its preceding (western) part. This, as well as the anemone shape itself, is consistent with the magnetic polarity distribution around the anemone ARs. These observations also suggest that an active region appearing in coronal holes has a simpler (less sheared) and more preceding-spot-dominant magnetic structure than those appearing in other regions.

Subject headings: Sun: activity — Sun: corona — sunspots — Sun: X-rays, gamma rays

Online material: color figures, mpeg animations

1. INTRODUCTION

The Soft X-Ray Telescope (SXT; Tsuneta et al. 1991) aboard *Yohkoh* (Ogawara et al. 1991) has enabled us to study the detailed structure and evolution of the coronal part of active regions (ARs). Among many findings, one of the interesting discoveries is “sea anemone”-like structure (Shibata et al. 1994a, 1994b; see also Fig. 1). This phenomenon is characterized by radially aligned coronal loops that connect the opposite magnetic polarity of the AR magnetic field and the surrounding region with the unipolar field, and it is physically the same as the X-ray “fountain” originally reported by Tousey et al. (1973) and Sheeley et al. (1975a) in the *Skylab* era. We call these active regions *anemone ARs* in this paper. The appearance of anemone ARs typically lasts for a few days. Figures 2 and 3 present examples of anemone AR evolution. Some ARs stably show anemone structure for a couple of weeks, as shown in Figure 2, and others show anemone structure for a period of the evolution, as shown in Figure 3. Figure 2 also shows jet activity. The Extreme-ultraviolet Imaging Telescope (EIT; Delaboudinière et al. 1995) on board the *Solar and Heliospheric Observatory* (*SOHO*; Domingo et al. 1995) has shown similar features in extreme-ultraviolet images. The appearance of these features is almost the same as that of those seen with the SXT.

Anemone ARs are thought to often appear in coronal holes (CHs) that consist of the global open magnetic field. A bipole emerging within a CH magnetically reconnects with the CH field to produce the characteristic structure (Sheeley et al. 1975b; see also Fig. 4). This situation of magnetic reconnection between the emerging flux and the surrounding field is suitable for generating X-ray jets and/or H α surges (Yokoyama & Shibata 1995, 1996),

and indeed, many jets ejected from anemone ARs have been observed (Shibata et al. 1994b; Vourlidas et al. 1996; Kundu et al. 1999; Alexander & Fletcher 1999). Wang et al. (2006) and Nitta et al. (2006) investigated the solar origins of ³He-rich solar energetic particle (SEP) events and found that the sources of the impulsive SEPs lie next to CHs containing Earth-directed open field lines. These sources further showed the associations with jetlike ejections seen in the extreme-ultraviolet images and with type III radio bursts. Wang (1998) indicates the possibility that even polar plumes may be associated with jets from anemone ARs. A small anemone AR in a CH probably evolves into a polar plume as the flux that has the opposite magnetic polarity to the CH gradually cancels out and thereby generates jets. Anemone ARs sometimes generate filament eruptions (Chertok et al. 2002), and even large flares and/or coronal mass ejections (Verma 1998; Liu & Hayashi 2006; Liu 2007). In these cases, eruptions occurring in CHs easily travel, keeping their speeds by having the advantage of the high-speed solar wind from the CHs. Anemone ARs are probably related to nonradial coronal streamers emanating from magnetically high latitudes (Saito et al. 2000), and attention has been given to their relation with fast solar winds (Takahashi et al. 1994; Saito et al. 1994; Wang 1998). Therefore, understanding the physical and morphological characteristics of anemone ARs is important for space weather studies.

However, it has not been well understood how frequently such an asymmetric magnetic configuration in bipolar spots occurs in CHs. Meanwhile, it has been thought that the reason why the anemone ARs look like a sea anemone is that the average magnetic field strength in one of the bipolar spots is stronger than that of another spot and that the magnetic polarity of the stronger spot is opposite to the ambient polarity of the CHs (unipolar regions), which would be confirmed by investigating the characteristics of CHs and anemone ARs. In this paper we statistically examine the features of anemone ARs observed with the *Yohkoh* SXT. We investigate the birthplaces of anemone ARs and confirm their relations with the CHs. Then we investigate the characteristics of anemone ARs, such as the magnetic configurations of emerging flux regions, those of the surrounding CHs, how anemone ARs appear in CHs, and so on. We also study the relation between

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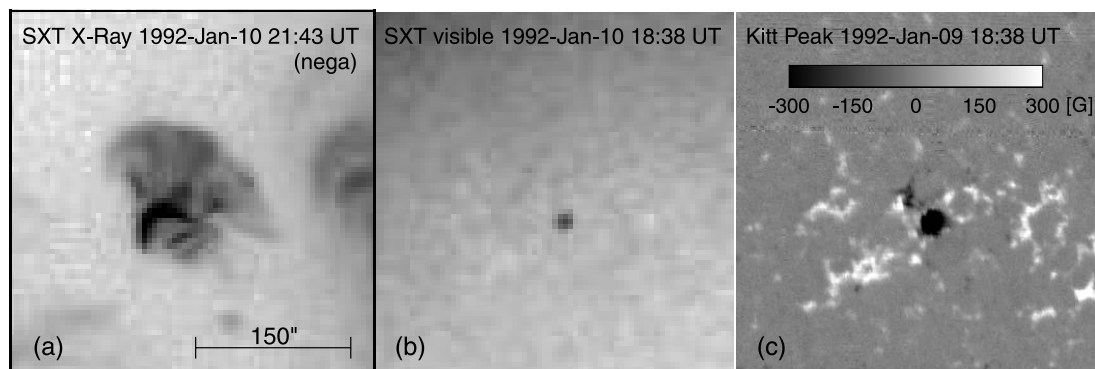


FIG. 1.—Typical example of the anemone AR observed on 1992 January 10 (NOAA AR 7001). (a) SXR image taken with the *Yohkoh* SXT. (b) Visible light image taken with the aspect sensor of the SXT. (c) Magnetogram taken at Kitt Peak.

anemone ARs and X-ray jets, since such a relation has been suggested qualitatively but has been unclear quantitatively. In § 2 we describe our observations and the results, and in § 3 we summarize our results and offer discussions.

2. OBSERVATIONS AND RESULTS

We used soft X-ray (SXR) images taken with SXT full-frame images (FFIs). The spatial resolution of the FFIs is either half-resolution ($\sim 5''$) or quarter-resolution ($\sim 10''$). The time resolution ranges from a few minutes to an hour. The SXT filter used for the FFI events in this paper is either the $0.1 \mu\text{m}$ Al filter or the Al/Mg/Mn filter, both of which are sensitive to SXRs between 3 and 60 \AA .

There are 49 ARs whose births were observed with SXT from 1991 November to 1992 May. We examined the birthplaces of those ARs and categorized them into the following three types according to their appearances: (A) anemone type, (B) two-sided loops type, and (C) other types. We summarize the results in Table 1. The two-sided loops structure consists of large-scale loop brightenings that occur at both sides of the emerging fluxes. The

structure suggests a magnetic reconnection between the emerging flux and an overlying coronal magnetic field that lies nearly horizontally (Shibata et al. 1994a). Figure 4 shows schematic illustrations of an anemone AR and a two-sided loops structure. A newly emerged magnetic flux interacts with the surrounding fields and generates the characteristic configuration. If the surrounding fields stand vertically, such as those for a CH (Fig. 4, *top and middle*), the interaction leads to an anemone structure. On the other hand, a two-sided loops configuration is generated if the surrounding fields lie nearly horizontally. Among the newly emerged ARs, 12 ARs showed clear anemone structure. Therefore, anemone ARs were not rare phenomena, and about one-fourth of all newly emerged ARs belonged to the class of anemone ARs. Ten of the anemone ARs (type A) appeared in CHs, and only one anemone AR appeared in a quiet region (QR). On the other hand, the ARs that appeared in QRs usually did not show anemone structure, but mainly the two-sided loops structure. The difference between the magnetic field configurations of the CHs with nearly vertical fields and those of the QRs with

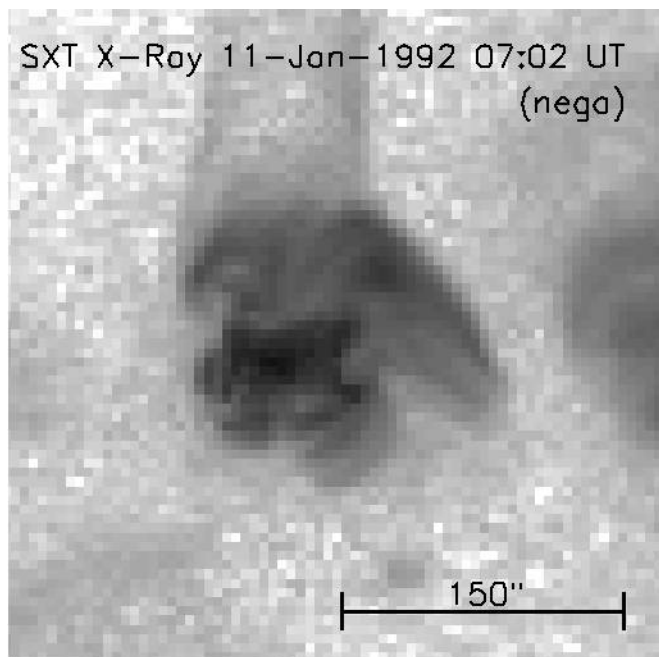


FIG. 2.—Typical example of anemone AR evolution. The movie of SXR images for NOAA AR 7001 shows jet activity. [See the electronic edition of the *Journal* for a color version of this figure, as well as an associated mpeg animation.]

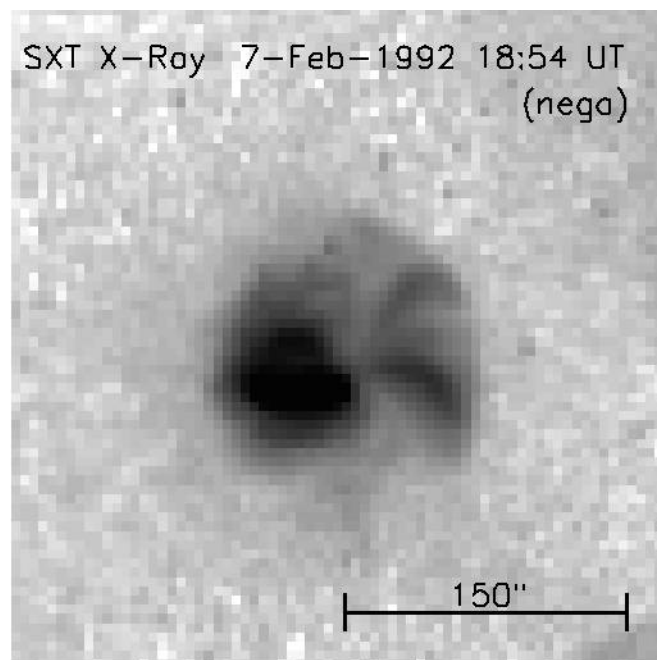


FIG. 3.—Typical example of anemone AR evolution. The movie of SXR images for NOAA AR 7051 shows that the anemone feature appears in the course of the evolution. [See the electronic edition of the *Journal* for a color version of this figure, as well as an associated mpeg animation.]

TABLE 1
BIRTHPLACES OF ACTIVE REGIONS WHOSE BIRTHS WERE OBSERVED
BY THE *Yohkoh* SXT BETWEEN 1991 NOVEMBER AND 1992 MAY

Type	Total	QR	CH	QR/CH ^a	Jet ^b
A (anemone)	12	1	10	1	7
B (two-sided loops)	13	13	0	0	9
C (other).....	24	18	5	1	7

^a Boundary between the QR and the CH.

^b Number of ARs that were associated with jets or jetlike phenomena.

nearly horizontal fields leads to the difference of the appearances. Table 1 also presents the association of anemone ARs with X-ray jets. About 58% of the anemone ARs (7 out of 12) showed jet-like ejections, and therefore, we can confirm that anemone ARs are suitable to generate X-ray jets, as Shibata et al. (1994b) reported.

We also sought anemone ARs in the SXT FFIs between November 1991 and March 1993, and we found 28 anemone ARs. All of these anemone ARs appeared within CHs. Here an anemone AR is defined by the following rules: (1) it shows a configuration of loops fanning out almost symmetrically in the SXT images, and (2) it looks like an isolated active region in the SXT images. A typical example of an anemone AR, which was observed on 1992 January 10, is presented in Figure 1. Figure 1 shows a SXR image (Fig. 1a) and a visible light image (Fig. 1b) taken with the *Yohkoh* SXT, as well as a magnetogram (Fig. 1c) obtained at Kitt Peak National Observatory. Figure 1a clearly shows that many loops fan out symmetrically from the center of the anemone. We can also see a following-preceding (east-west) asymmetry in the brightness of the loops; in this case, the loops in the following

(eastern) part of the AR are brighter than those in the preceding (western) part. Table 2 lists all 28 of the anemone ARs with their SXR and magnetic field characteristics. Column (5) of Table 2 gives the following-preceding asymmetry. We can see that almost all of the anemone ARs show this asymmetry. By using full-disk magnetograms taken at Kitt Peak, we further statistically studied the characteristics of the anemone ARs, such as the magnetic polarities of the surrounding CHs (col. [6]) and those of bipolar spots/regions (col. [7]). We also added the sunspot magnetic classification from Solar Geophysical Data⁶ (col. [8]) to Table 2.

From Table 2, we deduced some characteristics of anemone ARs. First of all, although anemone ARs mainly showed simple structure, they were not always α -type sunspots. We found that β -type or even more complex sunspots can also generate anemone structure by interacting with the surrounding magnetic field after the sunspot emergence. Then we found that 71% of all anemone ARs (20 out of 28) appeared in the northern hemisphere. There were more sunspots in the southern hemisphere during this time period, and therefore anemone ARs showed a tendency toward antisolar activity. This is consistent with the fact that almost all anemone ARs appeared within CHs. Almost all the surrounding CHs in the northern hemisphere had positive magnetic polarity during this period. Among the anemone ARs in the northern hemisphere, about 80% (16 out of 20) had the characteristic that the magnetic polarity of the preceding spots was negative, which was, therefore, opposite to that of the surrounding CHs. We call these ARs *normal* anemone ARs (see the left half of Table 3). The order of the magnetic polarities for most of the normal anemones, that is, negative (positive) polarity for the preceding

⁶ See <http://www.ngdc.noaa.gov/stp>.

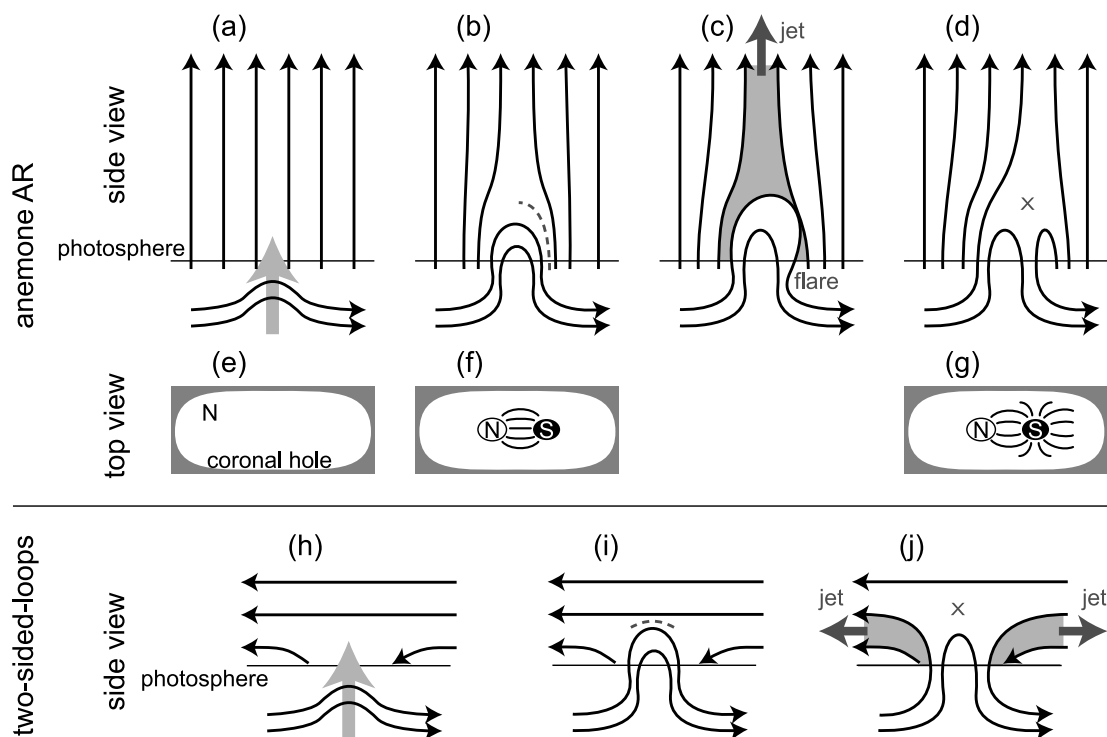


FIG. 4.—Schematic illustrations of an anemone AR from a side view (*top*) and a top view (*middle*), and those of a two-sided-loops structure from a side view (*bottom*). (a) Magnetic flux newly emerges within a unipolar region such as a CH. (b) A current sheet is generated between the emerged field and the surrounding field, as shown with the dashed gray line. (c) A magnetic reconnection occurs there, which generates jets and flare brightenings. (d) and (g) An anemone structure is formed. The gray cross represents an X-point. (h), (i), and (j) Magnetic flux newly emerges within a quiet region that consists of horizontal magnetic fields, and magnetic reconnection between them generates jets ejected from both sides of the X-point. The shaded gray region in panels (c) and (j) is filled with hot plasma that emits SXR.

TABLE 2
LIST OF ANEMONE ARs WITH THEIR SXR AND MAGNETIC CHARACTERISTICS

Date (1)	NOAA AR (2)	Helio. Lat. ^a (3)	Carr. Rot. ^b (4)	X-asym. ^c (5)	CH Pol. (6)	AR Pol. ^d (7)	Mag. Class ^e (8)
1991 Nov 10.....	6921	N	...	F	+	+−	B
1992 Jan 10.....	7001	N25	1851	F	+	+−	A
1992 Feb 07.....	7051	N21	1852	F	+	(+−)	B
1992 Mar 07.....	7085	N23	1853	F	+	+−	A
1992 Mar 07.....	7095	N16	1853	F	+	+−	A
1992 Apr 04.....	7124	N14	1854	F	+	+−	B
1992 Apr 25.....	7145	N11	1855	F	+	+−	B
1992 May 02.....	7146	N08	1855	F	+	+−	A
1992 May 21.....	7174	N14	1856	F	+	+−	B
1992 Jun 20.....	7205	N11	1857	F	+	+−	B
1992 Aug 15.....	7263	N16	1859	F	+	+−	B
1992 Sep 11.....	7276	N15	1860	F	+	+−	BGD
1992 Dec 19.....	7375	N14	1863	F	+	+−	B
1992 Dec 24.....	7381	N07	1863	F	+	+−	B
1993 Jan 26.....	7409	N18	1865	F	+	+−	B
1991 Dec 18.....	6973	N	...	Unclear	+	+−	B
1992 Jan 31.....	7029	N18	1852	P	−	+−	B
1992 Jun 07.....	7192	N09	1856	P	−	+−	B
1991 Nov 12.....	6918	N	...	F	−	−+	A
1993 Feb 09.....	East of 7417	N	...	Unclear	+	−+	No data
1991 Nov 20.....	6928	S	...	P	+	−+	A
1992 Apr 25.....	7143	S05	1854	P	+	−+	BGD
1992 May 02.....	7150	S07	1855	P	+	−+	B
1992 May 16.....	7167	S07	1855	P	+	−+	B
1992 May 21.....	7167new	S07	1856	Unclear	+	−+	B
1992 May 21.....	7176	S12	1856	Unclear	+	−+	A
1992 Jun 15.....	7195	S08	1857	F	+	−+	A
1991 Nov 03.....	6900	S	...	F	−	−+	A

^a Heliographic latitude, from Solar Geophysical Data.
^b Carrington rotation number, from Solar Geophysical Data.
^c X-ray asymmetry. The letter F (P) means that the following (preceding) part of the anemone structure is brighter.
^d Magnetic polarities of anemone ARs. The left and right signs show the polarities of the following and preceding spots, respectively.
^e Sunspot magnetic classification, from Solar Geophysical Data.

(following) spots, is consistent with the Hale-Nicholson polarity law (Hale et al. 1919) in the northern hemisphere. On the other hand, only four anemone ARs (20%) had different magnetic configurations; there was one anemone in which both the polarity of the preceding spot and that of the CH were positive, and only three anemone ARs that appeared in CHs with negative magnetic polarity (see Table 2). We call these cases *abnormal* anemone ARs. These anemone ARs also showed, to a greater or lesser extent, an

east-west asymmetry in the SXR intensity distribution. We examined the relation between the normal and abnormal features with the following-preceding asymmetry, and we found that 75% of all normal anemone ARs (15 out of 20) showed a clear tendency for the following (eastern) parts of the ARs to be brighter than their preceding (western) parts. We summarize these features in Table 3, according to the magnetic polarities (the left half) and the asymmetry of the loop brightnesses (the right half).

TABLE 3
SUMMARY OF ANEMONE ARs ACCORDING TO THE MAGNETIC POLARITIES (*left*) AND THE ASYMMETRY OF THE LOOP BRIGHTNESSES (*right*)

Magnetic Polarity		Asymmetry	
Northern hemisphere.....	20	Northern hemisphere.....	20
CH + AR +− (normal).....	16	Following (eastern) bright X-loops.....	16 ^a
CH + AR −+.....	1	Preceding (western) bright X-loops.....	2
CH − AR +−.....	2	Unclear.....	2
CH − AR −+.....	1		
Southern hemisphere.....	8	Southern hemisphere.....	8
CH + AR +−.....	0	Following (eastern) bright X-loops.....	2
CH + AR −+.....	7	Preceding (western) bright X-loops.....	4
CH − AR +−.....	0	Unclear.....	2
CH − AR −+.....	1		
Total of anemone ARs.....	28	Total of anemone ARs.....	28

^a Of these, 15 of them are normal type, and 1 is abnormal type.

In the southern hemisphere, on the other hand, the magnetic polarity of the preceding spots of all the anemone ARs was positive, although the total number of anemone ARs was much smaller (8). The order of the magnetic polarities for the preceding and following spots is again consistent with the Hale-Nicholson polarity law in the southern hemisphere. Interestingly, most of these anemone ARs (7 out of 8) appeared in CHs with positive magnetic polarity. During the period from 1991 November to 1993 March, there were both CHs with positive polarities and those with negative polarities on the solar surface. Therefore, we can say that anemone ARs tended to occur in CHs with positive magnetic polarity in this period. The preceding (western) parts of the loops were dominantly brighter in the SXR than were the following parts in half (4 out of 8) of these ARs. We also summarize these ARs in Table 3.

3. SUMMARY AND DISCUSSION

We statistically studied the characteristics of anemone ARs observed with the *Yohkoh* SXT. First, we surveyed 49 ARs whose births were observed with the SXT between 1991 November and 1992 May, and we found the following feature: (1) About one-fourth of all newly emerged ARs (12 out of 49) were anemone ARs. Moreover, almost all anemone ARs appeared within CHs, and the ARs that appeared in QRs did not show anemone structure, but mainly showed the two-sided loops structure. We also confirmed that anemone ARs usually generate X-ray jets. Next we examined 28 anemone ARs observed between 1991 November and 1993 March. We found the following characteristics: (2) About 71% of all anemone ARs appeared in the northern hemisphere, although the number of sunspots was larger in the southern hemisphere, in this period. This means that the number of anemone ARs is a feature of antisolar activity. Furthermore, almost all the anemone ARs were not located on or near the global neutral line where active longitudes were situated. (3) Among the anemone ARs in the northern hemisphere, about 80% had the characteristic that the magnetic polarity of the preceding spots was negative, which is consistent with the Hale-Nicholson polarity law. The magnetic polarity is thus opposite to that of the surrounding CHs, since almost all the surrounding CHs in the northern hemisphere had positive magnetic polarity during this period. In the southern hemisphere, on the other hand, the preceding spots of all anemone ARs had positive polarity, which is again consistent with the Hale-Nicholson polarity law. The magnetic polarity of the surrounding CHs was, interestingly, mainly positive, while there are both CHs with positive polarities and those with negative polarities in the southern hemisphere during this period. (4) Anemone ARs showed, to a greater or lesser extent, a following-preceding (east-west) asymmetry in the SXR intensity distribution. In particular, the “normal” anemones in the northern hemisphere had following (eastern) parts of the ARs that were brighter than their preceding (western) parts. For half of the anemone ARs (4 out of 8) in the southern hemisphere, on the other hand, the preceding (western) parts of the loops were brighter in the SXRs than were the following parts.

The first, second, and third observational features detailed above suggest that anemone ARs have a simpler (less sheared) magnetic structure than other ARs. The “anemone” shape itself shows a potential-like magnetic configuration; that is, the lowest energy state. This is also consistent with the fact that α - and β -type spots, which are less active ARs, are observed at the center of anemone ARs. Moreover, the observed anemone ARs showed the preceding-spot–dominant magnetic structure more clearly than did those appearing in other regions. We also followed the evolution of the anemone ARs and found that a typical anemone AR does not change its appearance even when it approaches the solar limb (Saito et al. 2000). The fourth observational feature showed that the following-preceding asymmetry in the SXR intensity distribution depends on the order of the magnetic polarities of the anemone ARs and the CHs.

We can see a clear tendency for anemone ARs to appear within CHs with positive polarity. However, we cannot conclude it, since the period studied in this paper is restricted to part of a solar cycle (from 1991 to 1993). In the northern hemisphere, almost all CHs have positive polarity, and for the CHs in the southern hemisphere, the number of observed anemone ARs is too small during this period. Moreover, although we found a tendency of antisolar activity for anemone ARs, we need more samples covering a longer term before we can conclude it. We will survey anemone ARs with data that cover one full solar cycle observed with the *Yohkoh* SXT for future works. A survey of anemone ARs covering one solar cycle will also make clear the variation of these features through the solar cycle and any association with fast solar winds.

We also have to clarify whether emerging fluxes that generate anemone ARs have special characteristics or not on their own merits, as well as how they are related to the origin of magnetic fields. More detailed examinations of anemone ARs and the structure of the emerging fluxes, using data that have a higher spatial resolution and greater sensitivity, will be required in order to answer these questions. For example, the X-Ray Telescope on board *Hinode* has observed many similar (and smaller) features, and analyzing them will be appropriate.

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