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The Coronal Streamer Belt and the Last Two Minima of Activity of the Sun

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Abstract—The structure of the streamer belt and the dynamics of mass ejections during the last two minima of solar activity in 1996–1997 and 2008–2009 are analyzed based on observations from the Solar and Heliospheric Observatory (SOHO) and the Solar Terrestrial Relations Observatory (STEREO). Certain features are revealed in the characteristics of the streamer belt in the last minimum between cycles 23 and 24 compared with the previous minimum between cycles 22 and 23 of solar activity. The connection is considered between the photospheric activity and sector structure of the global solar magnetic field with the topology and dynamics of the streamer belt. Models are briefly discussed that explain the observed phenomena. Data published in scientific journals and on the Internet are used.

Keywords: Sun, corona, streamers, ejections, solar cycle.

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INTRODUCTION

The cycle of solar activity manifests itself in various phenomena, such as sunspot activity, radiation in the centimeter range, the evolution of coronal holes, and the dynamics of the solar corona. Streamers are main large-scale structures of the solar corona. They consist of a series of closed loops located inside the shell of open magnetic field lines and have a helmet shape. Streamers occur along the boundary line of large-scale photospheric magnetic fields of different polarity in active regions, quiet Sun, or along the filament channel.

During the period of minimum solar activity, when the general magnetic field at the source surface (the surface is conventionally assumed to be spherical with a radius of 2.4 R_s separating the inner closed field from the radial direction of the external open field) is well described by a dipole field, a system of streamers is located near the solar equator along the line dividing the global magnetic field of the Sun. It borders the Sun and forms the so-called belt of streamers. The shape of the current sheet is rather flat. In the period of maximum solar activity the magnetic structure is complicated. Coronal streamers can occur at almost any latitude and can be seen everywhere around the solar limb. A current sheet that separates magnetic fields of different polarity forms a corrugated surface. It is assumed that the coronal streamers are the sources of the slow solar wind. The solar plasma escapes into interplanetary space along open magnetic field lines surrounding the streamer belt.

For sunspot cycles 22 and 23, the period of the previous minimum was observed from the last quarter of 1995 until the middle of 1997. The last cycle had some peculiar features in comparison with the previous cycle [1, 2] and it was the longest in the last century. The minimum between cycles 23 and 24, which was predicted to occur in 2006–2007, took longer than expected and continued in 2008–2009. The aim of the present study is to analyze the structure of the streamer belt and the dynamics of the plasma ejected from streamers in the last two periods of minimum solar activity.

1. BELT OF STREAMERS AND SOLAR ACTIVITY

The schematic drawing of a simple streamer is shown in Fig. 1. The inner cavity of the streamer, called the core, is usually less dense than the outer lay-

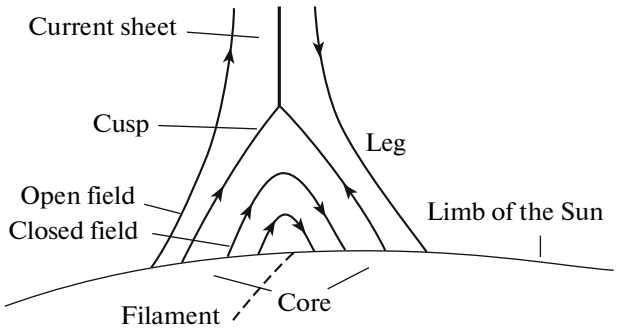

Fig. 1. The schematic drawing of the structure of a streamer.

ers. Loop-like structures in its upper part have a pointed shape in the form of a cusp. Around the current sheet above the cusp there is a fairly dense thin layer of plasma extending over large distances from the solar limb, which is called a coronal ray, formed by magnetic field lines of the outer shell tapering over the cusp .

As can be seen from the images of the solar corona obtained from space in 1997 and 1999 or from the Earth during solar eclipses in 2006 and 2008 (see Fig. 1 in [3], Figs. 1–3 [4], and Fig. 3a in [5]) in the period close to the maximum of solar activity (1999), coronal streamers are located all around the solar disk; at the minimum of solar activity (1997) they may be found in a narrow band near the solar equator. During the last minimum of solar activity (2007–2009) the streamer belt occupied a large range in positional angles.

The form of the streamer belt during the solar minimum is well described by a model in which it is assumed that the scattering electrons are concentrated around a rather flat current sheet surrounding the Sun approximately along the equator. The electron density in the streamer belt in 1996 for the Carrington rotation (CR) 1913, calculated on the basis of maps of the photospheric magnetic field, is shown in Fig. 6 in [6]. The current sheet is thin and has a flat, slightly curved shape.

At the minimum of solar activity in 1996 on images obtained in polarized light, bright narrow structures with a characteristic width of less than 3°–5° are observed. The streamer belt has a fine structure and a jet-like form if it is seen from the edge. It consists of several rays, if the current sheet is undulating and is seen inclined to the line of sight. Different structures, visible in the streamer belt, are clearly shown in Fig. 1 in [7], where the evolution of the streamer belt for CR 1908–1913 for the period from April 8 to September 18, 1996, is analyzed based on observations in white light using C2 and C3 Large Angle Spectrometric Coronographs (LASCO) of the SOHO. Figure 5 [7] shows the change in the structure of the streamer belt during several months in 1996 in the form of longitude–latitude maps. It is evident that the streamer belt remains narrow at the eastern limb of the Sun and near the western limb the width of the belt is gradually increasing over the course of time. This means that during CR 1908–1910 (from April till June) the surface of the streamer belt remained relatively flat and since July the structure changed, becoming more curved. Discontinuities and the fine structure appeared. The width of the streamer belt grew up to CR 1913. Changes occurred over the low-latitude activity complexes, located at the Carrington longitude of 255°, which is visible on maps of the photospheric magnetic field obtained from observations at the Wilcox Solar Observatory (WSO) and the National Solar Observatory (NSO) at Kitt Peak.

The initial ascent of the active region (AR) during CR 1909 did not cause any change in the topology of the streamer belt. During CR 1911 near latitude 23° N a second magnetic flux appeared and the belt of streamers began to deform [7]. The consideration of the evolution of the streamer belt from April to September, 1996, and comparison with maps of the magnetic field showed that the effect of the photospheric activity on the topology of the streamer belt depends not only on the strength of the emerging magnetic flux, but also on its phase in longitude with respect to the background field. If the sequence of the leading and trailing polarities of the emerging magnetic flux is the same as in the background field (in the longitudinal direction), then these two fields are in phase with each other, otherwise, the fields are in opposition.

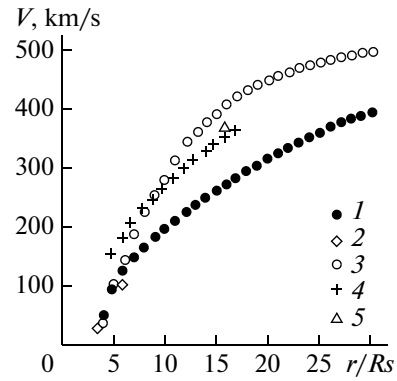

Fig. 2. The dependence of average velocities V of mass ejections from streamers on the heliocentric distance r for (*1*) 80 events in 1997, LASCO/SOHO [3]; (*2*) spectral observations in 1997, UVCS SOHO [14], (*3*) a streamer ejection in 2006, EIT, LASCO SOHO [12], (*4*) 106 events in 2007, LASCO SOHO [15], (*5*) three events in 2008, STEREO [9], 1, 3–5 are the white light, 2 is the ion lines O VI.

If the magnetic field of the active region and the background field are in phase, the shape of the streamer belt becomes wavy and has a larger latitudinal extent (CR 1913) than when the magnetic field emerges in antiphase with the background field. This conclusion, following from observations, was confirmed by model calculations performed in [7] on the intensity of the streamer belt at the heliocentric distance of 3 R_s during the period of minimum solar activity in 1996.

During CR 1909 the magnetic field of the low-latitude active region and the global magnetic field were in opposition and the streamer belt remained flat. The model calculation of the streamer belt intensity for the sequence of polarities for the complex of activity, changed to the opposite, as compared with the observed, shows a more disturbed structure of the streamer belt as compared to the actually observed structure at the longitude of 255°. During CR 1913, the global magnetic field and magnetic field of the active region were in phase with each other and the streamer belt had an undulating form [7, 8].

2. OBSERVATIONS OF THE STREAMER BELT FROM STEREO

Beginning in 2006, observations from space from the space observatory STEREO, which consists of two separate stations A and B, allowed researchers to see the belt of streamers in the white light, both from the edge and from the surface. Having the images recorded simultaneously from two spatially separated space stations, it is possible to obtain more realistic values of plasma velocities. At each station (STEREO/A and STEREO/B) two coronagraphs COR1 and COR2 exist, with a field of view of 1.3–4.0 R_s and 2–15 R_s, respectively. In [9], the streamer belt was investigated on the basis of observations from STEREO over a period of a few months of 2008. Stations A and B separated at a rate of ~45° per year and in June 2008 they were separated from each other by 56°. As may be seen from maps of the photospheric solar magnetic field and maps of the streamer belt intensity at the heliocentric distance of 3 R_S, in 2008 the structure of the streamer belt varied slightly during a few Carrington rotations.

During the period of minimum solar activity the streamer belt is usually confined to a narrow region near the equator, as it was 12–13 years ago in 1997. In 2008, the streamer belt had an undulating form and a large latitudinal extent at the latitude of 270°, where during a few months there was an active region according to maps of the photospheric magnetic field made by the NSO. Over June 18–19, 2008, a series of simultaneous images was obtained on the COR2 A and COR2 B coronagraphs, when the three clouds of plasma (blobs) ejected from the streamers moved through the field of view. In the images recorded by COR2 B the clouds, when observed from the edge, had the shape of a fork with two prongs. A series of clouds, seen from above in the images made by COR2 A, appeared as a series of large arches, each of which had its own azimuth.

Observations in white light with the wide-angle coronagraphs C2 and C3 LASCO/SOHO discovered the ejection of plasmoids from coronal streamers and allowed us to determine their speeds projected onto the plane of the sky. These multiple ejections, which occur several times a day during the period of minimum solar activity and with a greater frequency when the Sun is active, are the so-called blobs. They are clouds of plasma ejected from the Sun along the axis of a streamer. Blobs become visible at the heliocentric distance of 3–4 R_s and occupy ~1 R_s in length and ~0.1 R_s in width. As the distance from the Sun increases, their size grows. The intensity of these formations is only about 7–10% of the intensity of the corresponding streamer. Since the ejected clouds of material are denser than the surrounding corona, they can serve as tracers of the slow solar wind, because their motion is associated with the solar wind velocity, and trajectories may be traced.

The intensity of the white corona decreases rapidly with the heliocentric distance r. The investigated events seem to have a low brightness. To increase the image contrast a special difference image method was used. To select a moving phenomenon, from the image received at a given instant the image corresponding to some previous point in time is subtracted. The resulting images are called "running" difference images. A moving object looks like a "bipolar" phenomenon with a white spot, preceding the dark one in the direction of motion. The intensity increases in areas where the density of matter is greater at a given time and decreases where the density is less (see Fig. 3 in [10]).

Based on these difference images, maps are constructed. From the difference images obtained by LASCO/SOHO C2 and C3, radial strips of a width of about 10° are cut, centered along the axis of the streamer, and arranged vertically one after another in a time sequence to form the map of time–altitude with the time given along the x axis and the heliocentric distance set along the y axis. This method was proposed by J.H. Walters [11]. Maps show distinct tracks (Fig. 6 in [3], Fig. 2 in [12]). Analyzing such tracks, we can calculate the velocities and accelerations of the moving phenomenon depending on the heliocentric distance. In fact, this method may only provide the full speed component in the plane of the sky. However, events whose trajectories strongly deviate from the plane of the sky are not visible due to their low intensity.

Streamer ejection belongs to a special class of coronal events when, as a result of the magnetic reconnection near the Sun, the streamer suddenly breaks up and separates, with subsequent ejection into interplanetary space. Due to magnetic tension, power lines located below the reconnection point are drawn back to the Sun [12, 13] and the streamer separates and ejects into interplanetary space. In [12], the streamer ejection was studied during July 1–2, 2006 on the solar limb in the NW quadrant of the Extreme Ultraviolet Imaging Telescope (EIT), which gives the image of the solar disk and the lower corona in the far ultraviolet region of the spectrum, and the LASCO/SOHO coronograph, which registers images of the solar corona in white light at distances of up to 30 R_s. As the distance from the Sun increased, the speed grew from 20 to 500 km/s; the maximum acceleration was 12 m/s^2.

3. THE RATE OF MATTER EJECTION FROM STREAMERS

We systematized the data on the velocity of plasma in streamers and compared the dynamics of the streamer belt in the last two minima of solar activity. The results are shown in Fig. 2. The data for 80 blobs is presented, which were observed in 1997 in white light by the LASCO/SOHO (●). On the average, velocities increased from 50 km/s on 3–4 R_s to 300 km/s on 20 R_s and the average acceleration was of the order of 4 m/s^2. The average velocities at distances

of 1.7–5 R_s were calculated according to the spectral observations made by the SOHO Ultraviolet Coronograph Spectrometer (UVCS) in 1997 (◇) [14]. The velocities of the streamer that was ejected on July 1–2, 2006 and registered on the EIT and LASCO/SOHO coronagraph (○) were followed up to a distance of about 30 R_s [12]. According to [15], we calculated the average values of velocities for 106 blobs that were observed in the period from February 14 to September 29, 2007 on the LASCO/SOHO (+). The average acceleration was 6.8 m/s^2. The velocities of plasma clouds detected on June 18–19, 2008, at STEREO COR2-A and COR2-B (△) ranged from 300 to 400 km/s [9].

According to observations made in 1996–1997, the spread of velocities of the blobs was within 150 km/s and from observations made in 2007 it was within 250 km/s. Perhaps such a difference in the behavior of velocities was caused by the variation in the conditions in which blobs near the Sun are originated. The large spread in velocities in 2007 compared with the spread in 1996–1997 indicates the increased solar activity in the last minimum of cycles 23 and 24. The velocity of the streamer ejected as a whole, is greater than the average velocity of the limited volumes of plasma, such as blobs, formed over the cusps of streamers and leaving the Sun. Apparently, there is an additional driving force in the events of the first type.

CONCLUSIONS

During the periods of minimum solar activity streamer belt is usually confined to a narrow region near the solar equator, as observed in 1996–1997. During the last solar minimum in 2007–2009, the belt of streamers had an undulating form and a large extent in heliographic latitude. In 2008, phenomena, such as the events of June 18–19, were also observed in April, May, and October. All of them were visible from STEREO A as large arches, which occupied a large range of angles in longitude [9]. These observations can be explained by assuming that the streamer belt had a curved form. The streamer belt in April–June, 1996, was quite flat.

Ejections of streamers, such as the event observed in June of 2006, occurred during the minima of 1996 and 2008, with streamer belt break down and further reappearance after some time. Blobs that leave the Sun from the region above the cusp do not destroy the structure of the streamers. Apparently, the ejection of such plasma clouds has a different origin compared with the separation of the streamer as a whole. It is believed that the ejection of plasmoids, such as blobs, is the result of the reconnection of magnetic lines that make up the "legs" of the streamer (Fig. 1) with open field lines of the surrounding magnetic field.

Streamer ejection may be explained by a model that is similar to the model of a "leaky faucet" proposed in [16], or the model proposed by J.A. Linker in [17], when in some point of time the plasma pressure begins to exceed the tension of the magnetic field, resulting in rising and stretching of loops. The legs of stretched loops start to pinch together and reconnect at distances close to the Sun up to 1.3–1.4 R_s, and the volume of plasma of the streamer are released and detach from the Sun. The sudden separation of the streamer into two components may be observed, i.e., plasma, ejected in outer space at speeds of 400–500 km/s and returning to the Sun at a speed of 100 km/s [12, 18]. Apparently, the streamer belt was more dynamic in 2006–2009 than in 1996–1997. At the heliocentric distances of 3–15 R_s during the last minimum solar activity, the velocities of the plasma ejected from streamers were a few dozen (up to a hundred) km/s greater than during the previous minimum in 1996.

It seems that the difference in the nature of the dependencies of the ejection velocities of blobs on the heliocentric distance, which were derived from observations in 1996–1997 and 2007–2008, reflect real differences in the dynamics of the ejected plasma. In [15] data on recurrent ejections from 10 streamers are presented. Depending on the specific situation from each streamer from 9 to 10–13 ejections occurred during 3–4 days (on the average 3–4 ejections per day). Altogether 106 events were analyzed. The streamer belt was located in the equatorial region and occupied about 40° in latitude. From maps of tracks (time–distance) from [15] and speed–distance dependencies it is evident that ejections from the same streamer occurred with a slight difference in time. However, the velocities of successive ejections could vary by 1.5–2 times. For example, this can be clearly seen in Fig. 1 in the ejection tracks that were observed at the beginning of June 13 and at the middle of June 15 (Case A) [15].

Figure 3 [10] shows trajectories of ejections, which were repeated for 8 days, from 19 to 27 April, 1997, from the streamer on the west limb of the Sun. It is seen that trajectories of ejections are more uniform in nature and do not have such significant differences, as observed in 2007. The velocity diagram with heliocentric distances for the ten clearest cases depicted in Fig. 4 in [10] shows a velocity spread of about 150 km/s, which is consistent with the scatter of velocities derived from observations of 60 events in 1996 [19].

According to observations in 1996–1997 and 2006–2007, the difference in the velocities of plasmoids ejected from the cusp of streamers by separate portions most likely was caused by the fact that during the last minimum solar activity the level of general solar activity, including the dynamics of the streamer belt, was higher, i.e., the streamer belt extended to higher latitudes and heliocentric distances.

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