ISSN 0236-2457

ASTRONOMICHESKII TSIRKULYAR

Published by the Eurasian Astronomical Society
and Sternberg Astronomical Institute

No. 1599, 2013 March 25

CORONAL STREAMERS AND SOLAR ACTIVITY

Корональные стримеры и солнечная активность

Abstract. Анализируется структура пояса стримеров и динамика выбросов плазмы во время двух последних минимумов солнечной активности 1996–1997 и 2006–2009 гг. Используются наблюдения в белом свете с космических обсерваторий SOHO (SOlar and Heliospheric Observatory) и STEREO (Solar TErrestrial RElation Observatory). Рассматривается влияние центров активности и секторной структуры глобального магнитного поля Солнца на топологию пояса стримеров. Скорости выброса плазмы из пояса стримеров в период последнего минимума солнечной активности были на несколько десятков км c^{-1} выше, чем в предыдущий минимум. Используются данные из Интернета и публикаций в научных журналах.

Introduction

Coronal streamers are large-scale structures developing along inversion lines between magnetic fields of opposite polarities on the Sun. Streamers can be located in active regions (ARs), quiet Sun or above filament channels. They consist of closed loops covered by a blade of open magnetic lines and look like helmet-shaped formations if seen along the magnetic inversion line, or like a system of diverging rays if the inversion line is lying in the picture plane or they are visible as a complex superposition of two views. During the minimum of the solar activity streamers lie usually close to the solar equator along the line dividing the general magnetic field of different polarities and form the streamer belt that borders the Sun. The shape of the streamer belt is enough flat. During the solar maximum, when the magnetic field is complicated, streamers arise almost at any latitude and can be seen everywhere around the solar limb forming a highly warped surface. Images of the solar corona during different periods of the solar cycle, registered from the space and on the ground, can be seen, for example, in (Y.-M. Wang, N.R. Sheeley, Jr., D.J. Socker, R.A. Howard, N.B. Rich, J. Geophys. Res., **105**, 25133, 2000; Y.-M. Wang, J.B. Biersteker, N.R. Sheeley, Jr., S. Koutchmy, J. Mouette, M. Druckmüller, ApJ, **660**, 882, 2007; J.M. Pasachoff, V. Rušin, M. Druckmüller, P. Aniol, M. Saniga, M. Minarovjech, ApJ, **702**, 1297, 2009).

Streamers are believed to be a source of slow solar wind (SW). The solar plasma can escape into the space along open magnetic field lines surrounding the narrow current sheet.

The effect of solar activity on the streamer belt structure

Using white-light observations aboard LASCO SOHO Y.-M. Wang et al. (ApJ, **485**, 875, 1997) analyzed the evolution of the streamer belt from April 8, 1996 to September 18, 1996 (CR 1908–1913). The streamer belt preserved rather flat during CR 1908–1910 and became progressively wavier since July 1996 when a low-latitude active complex appeared near the longitude 255°. It was shown that if the emerging AR and background sector magnetic fields have the same sequence of the leading and trailing polarities, i.e., both fields are in phase, then the streamer belt begins to warp at a range of azimuthal angles. Otherwise the two fields are not in phase and the streamer belt remains almost unchangeable. This conclusion was later confirmed by the analysis fulfilled in (F. Sáez, A.N. Zhukov, P. Lamy, A. Llebaria, A&Ap, **442**, 351, 2005; F. Sáez, A. Llebaria, P. Lamy, D. Vibert, A&Ap, **473**, 265, 2007).

During the solar minimum of 2007–2009 the warped shape of the streamer belt was observed to be related also with low latitude ARs (N.R. Sheeley, Jr, D.D.-H. Lee, K.P. Casto, Y.-M. Wang, N.B. Rich, ApJ, **694**, 1471, 2009).

Ejections from streamers

Observations in white-light aboard LASCO SOHO showed that streamers are really more dynamical formations than it was thought earlier. There were revealed numerous plasma clouds ejected from streamers several times a day and called "blobs". Blobs are density enhancements that become visible at distances of 3–4 $R_\odot$ occupying about 1 $R_\odot$ in the length and 0.1 $R_\odot$ in the width and increasing their dimensions while going away. They are only 7–10% more intense than the surrounding corona. To increase the contrast of the images the method of running difference images is usually used (N.R. Sheeley, Jr., D. D.-H. Lee, K.P. Casto, et al. J. Geophys. Res., **104**, 24739, 1999), making possible to follow traces of the blobs and calculate their velocities up to the heliocentric distances of 20–30 $R_\odot$.

As it is shown in Figure 1a, the streamer of February 9, 1997 had a narrow jetlike shape when, the streamer belt was seen edge-on. On January 23, 1997 the streamer seemed to be wider (Fig. 1b), because the wavy streamer belt was inclined to the line of sight.

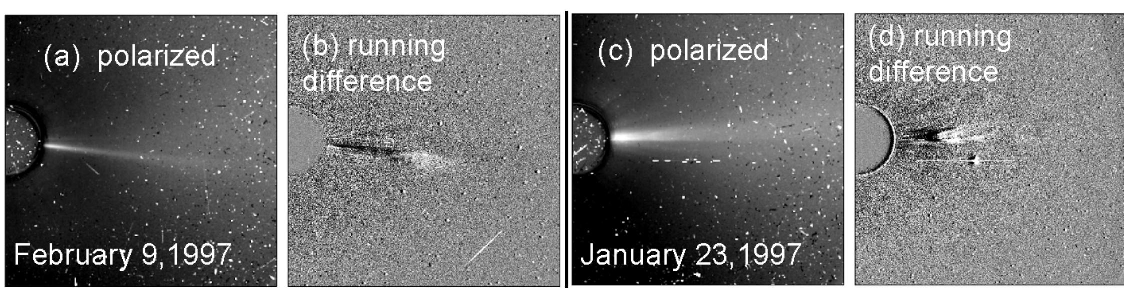

Рис. 1: Streamer belt seen from LASCO C3 (4–30 $R_\odot$) SOHO as a narrow jet on February 9, 1997 (a, b), and having a wider shape on January 23, 1997 (c, d), Fig. 1 from (Y.-M. Wang, N.R. Sheeley, Jr., J.H. Walter, et al., ApJ, **498**, L165, 1998).

Since 2006 observations aboard twin spacecraft STEREO, A and B, gave a possibility to look at the streamer belt from two different points of view in space. The A and B stations are separating with a rate of $\sim 45°$ per year. In June 2008 they were about 56° apart. In 2008 the streamer belt was extended to higher latitudes at the longitude of about 250°–270°, where during a few months an AR existed, as it is discussed in (N.R. Sheeley, Jr, D.D.-H. Lee, K.P. Casto, Y.-M. Wang, N.B. Rich, ApJ, **694**, 1471, 2009).

During June 18 and 19, 2008 sequences of images of three blobs were simultaneously recorded with white-light coronagraphs COR-2 A and COR-2 B when they were moving across the fields of views (2–15 $R_\odot$). In COR-2 B the streamer belt was seen edge-on, and the blobs looked like a fork with two prongs at the west limb (Fig. 2a, b). In COR-2 A the streamer belt was apparently visible face-on, and the blobs on June 18–19 were observed as large arches spanning a range of position angles in the east–south quadrant (Fig. 2c, d). The azimuths of each blob slightly varied. The speeds of the blobs ranged from 300 to 400 km s^{-1} at a heliocentric distance of about 15 $R_\odot$. The event of June 18–19, 2008 was not the only one in 2008. Similar sequences of arched-shaped blobs were also observed on April 25–26, September 7–8, and October 4–5, 2008. The Carrington longitude of the blobs remained approximately the same, about 240°, and the latitude might vary as it can be seen from Figure 10 in (N.R. Sheeley, Jr, D.D.-H. Lee, K.P. Casto, Y.-M. Wang, N.B. Rich, ApJ, **694**, 1471, 2009).

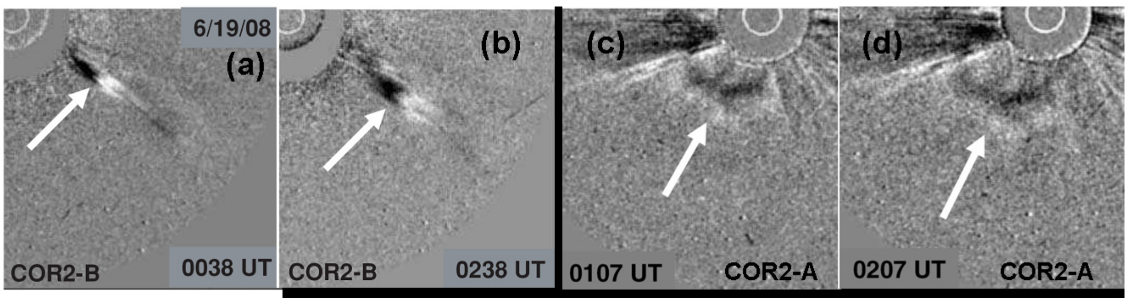

Рис. 2: A blob on June 19, 2008 seen as a fork aboard COR2 B STEREO (a, b) and appearing as a large expanding arch aboard COR2 A STEREO (c, d), Figs. 3 and 4 from (N.R. Sheeley, Jr., D.D.-H. Lee, K.P. Casto, Y.-M. Wang, N.B. Rich, ApJ, **694**, 1471, 2009).

Coronal streamer ejections

A streamer ejection is a special class of coronal events, when as a result of magnetic reconnection close to the Sun the streamer is suddenly torn with subsequent detachment and ejection into the interplanetary space. The low magnetic lines retract to the Sun (Y.-M. Wang, N.R. Sheeley, Jr., ApJ, **650**, 1172, 2007; N.R. Sheeley, Jr., Y.-M. Wang, ApJ, **655**, 1142, 2007). The streamer ejection observed on July 1–2, 2006 in the N–W quadrant with the EIT and LASCO C2 and C3 SOHO was investigated by N.R. Sheeley, Jr., et al. (N.R. Sheeley, Jr., H.P. Warren, Y.-M. Wang, ApJ, **671**, 926, 2007). In Figure 3 difference images of the ejected streamer are shown. The rising streamer loops were stretched and then the legs of the streamer were pinched together. The reconnection occurred at 1.3–1.4 $R_\odot$. The light arch in front of the streamer seems to arise as a sheath of material swept up by the moving streamer (Fig. 3d).

The streamer ejection of May 23–24, 2008 was observed simultaneously from STEREO A and B. In Figure 4 face-on and edge-on views obtained with COR-2 A and COR-2 B coronagraphs are presented (Fig. 11 from N.R. Sheeley, Jr., D.D.-H. Lee, K.P. Casto, Y.-M. Wang, N.B. Rich, ApJ, **694**, 1471, 2009). The pinch of streamer loop arcades formed the concave outward shape of the blob (forklike structure), which is distinctly seen.

The ejection is much greater than in cases of streamer blobs. As it is discussed by Sheeley and Wang (2007), the bigger events are connected with reconnection processes that occur

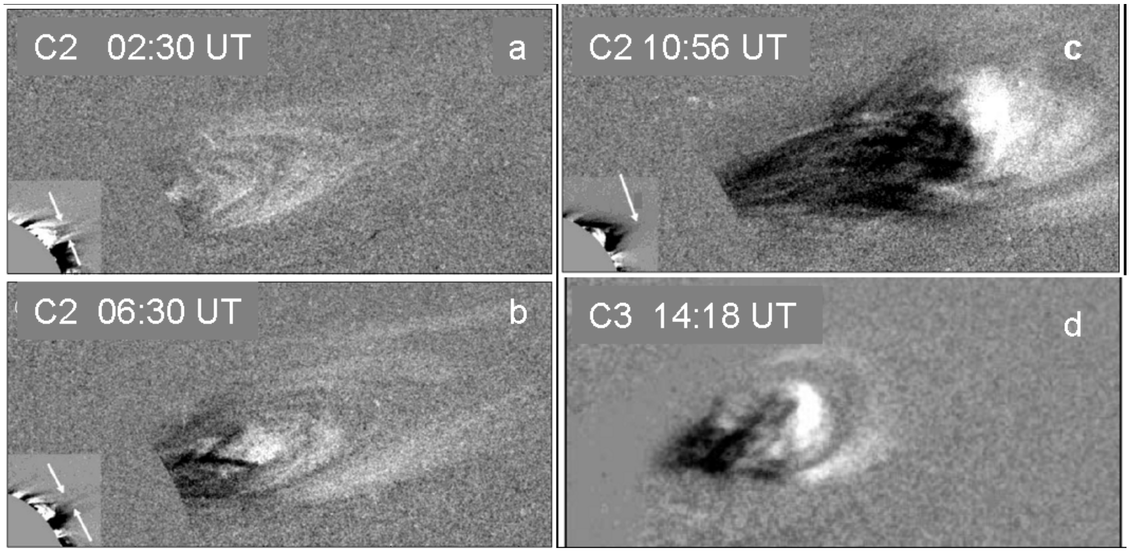

Рис. 3: Streamer ejection on July 1 and 2, 2006: composite EIT/ LASCO C2 SOHO running difference images on July 2 (a, b and c). Features pinching together are shown by white arrows, a dark cusp below the rising loops is seen at 10:56 UT (d). A side of the embedded EIT image is $1.0\,R_{\odot}$. A light arch in front of the ejected streamer is visible at 14:18 UT; Figs. 1 and 3 from (N.R. Sheeley, Jr., H.P. Warren, Y.-M. Wang, ApJ, **671**, 926, 2007).

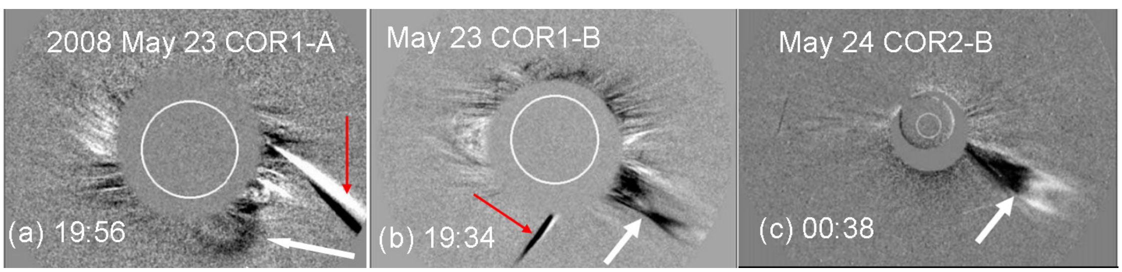

Рис. 4: Streamer disconnection and ejection on May 23–24, 2008 observed from STEREO A and B. Red arrows indicate a sungrazing comet, Fig. 11 from (N.R. Sheeley, Jr., D.D.-H. Lee, K.P. Casto, Y.-M. Wang, N.B. Rich, ApJ, **694**, 1471, 2009).

closer to the Sun. Streamer ejections disrupt the streamer belt structure. Streamer blobs seem to do no harm to the streamer and its cusp.

Results

The data on velocities of plasma outflowing from the streamer belt have been systemized by us for the last two solar minima. The period of activity minimum for 22–23 cycles observed from the last quarter of 1995 to the first half of 1997 and minimal activity between 23–24 cycles was predicted in 2006–2007, but lasted longer till 2009.

The results are presented in Figure 5 based on the white light observations from LASCO SOHO and STEREO and observations in EUV spectral lines with UVCS SOHO. On the left

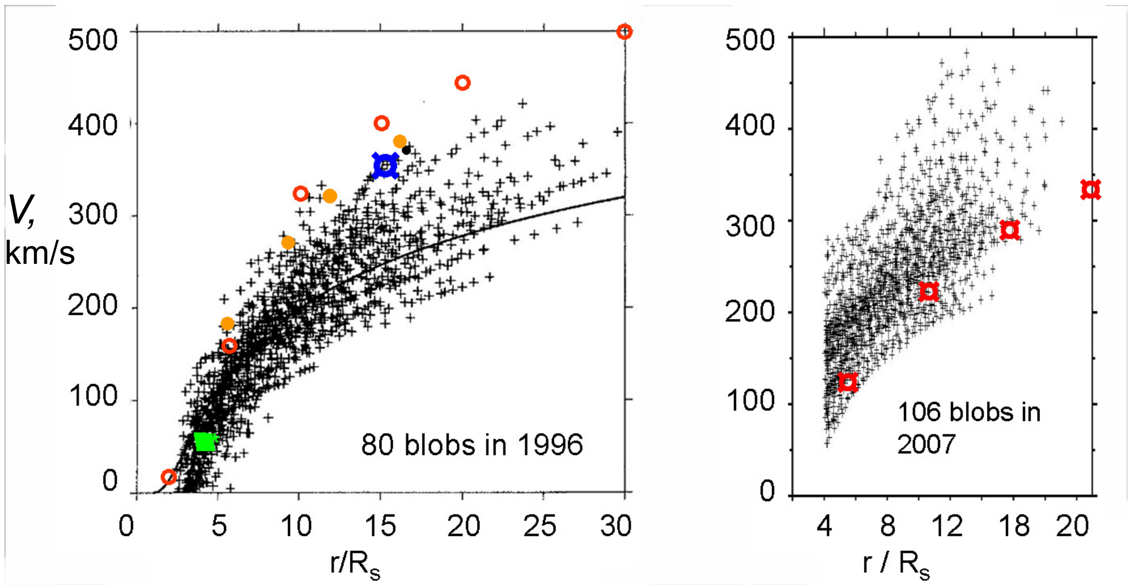

Рис. 5: Streamer plasma outflow velocities. Left: black pluses 80 blobs in 1996, LASCO SOHO (Wang et al., 2000); green squares average velocities at 1.7–5 $R_\odot$ in 1997, UVCS/SOHO (Strachan et al., 2002); red circles streamer blowout, 2006 July, LASCO SOHO (Sheeley et al., 2007); orange dots average for 106 blobs in 2007, LASCO SOHO (Song et al., 2009); blue ¤ symbol blobs in 2008, COR2 A and COR2 B STEREO (Wang et al., 2009). Right: black pluses 106 blobs in 2007, LASCO SOHO (Song et al., 2009); red ¤ symbols average for 80 blobs in 1996, LASCO SOHO (Wang et al., 1997).

diagram data for 80 blobs observed with LASCO C2 and C3 SOHO in 1996 are shown with black pluses. The velocities increase in average from 30–50 km s^{-1} at 3–4 $R_\odot$ to 300 km s^{-1} at 20 $R_\odot$, and the average acceleration is ∼4 m s^{-2}. The corona expansion according to Parker at $T \sim 10^6$ K is shown with a solid curve (Y.-M. Wang, N.R. Sheeley, Jr., D.J. Socker, R.A. Howard, N.B. Rich, J. Geophys. Res., **105**, 25133, 2000). The average velocities at 1.7–5 $R_\odot$ observed during 1997 with UVCS SOHO, are presented with a green square (L. Strachan, R. Suleiman, A.V. Panasyuk, et al., ApJ, **571**, 1008, 2002). The velocities of the streamer ejected on July 1–2, 2006 and observed with the EIT and LASCO SOHO (N.R. Sheeley, Jr., H.P. Warren, Y.-M. Wang, ApJ, **671**, 926, 2007), are shown with red circles. The streamer velocity increased from 20 km s^{-1} to 500 km s^{-1}, the maximum acceleration was ∼12 m s^{-1}. The average velocities as a function of the distance were calculated by us using the data of observations of 106 blobs from February 14 to September 14, 2007 according to (H.Q. Song, Y. Chen, K. Liu, S.W. Feng, L.D. Xia, Solar Phys., **258**, 129, 2009) and are shown with orange dots in the left diagram. The initial results of the authors are presented with pluses in the right-hand diagram of Figure 5. The average acceleration was evaluated by us to be ∼6.8 m s^{-2}. The blobs' speeds observed on June 18–19, 2008 with the COR-2 A and COR-2 B STEREO range from 300 to 400 km s^{-1}. The mean value is shown with a blue ¤ symbol.

To visualize better the difference between two last minima of the solar activity the average velocities for 80 blobs observed in 1996 with the LASCO SOHO are plotted with red ¤ symbols in the right-hand diagram of Figure 5, where data for 106 events observed in 2007 are presented. Blobs' velocities are scattered from the average value within ±75 km s^{-1} for

1996 and $\pm$125 km s^{-1} for 2007. Such variability in blobs' velocities is thought to be due to variability of the conditions of blobs' origin near the Sun. The greater velocity scatter in 2007 in comparison with the velocity range in 1996 gives evidence for a stronger solar activity during the last minimum in comparison with the previous one, as it is discussed in (G.A. Porfir'eva, G.V. Yakunina, A.B. Delone, Moscow University Bulletin, **65**, 516, 2010, doi: 10.3103/S0027134910060160).

Discussion

At the solar minimum the streamer belt was confined to a narrow region around the equator, and from April to July 1996 it remained flat enough. During the last solar minimum in 2007–2009 the streamer belt had a wavy appearance and larger latitudinal extension. Events similar to blobs of June 18–19 were also observed in April, September and October 2008. All of them were seen from STEREO A as large arches spanning a wide range of position angles. It means that streamer belt had a warped structure.

Streamer blowouts similar to the event of June 1–2, 2006 occurred during the solar minima in 1996 and 2008, but they are observed more frequently during maximal solar activity. Such streamer ejections disrupt the streamer belt for some interval with later reconstruction. The blobs are believed to be the results of magnetic reconnection occurring at heliocentric distances of 1.5–5 $R_\odot$. The streamer ejection can be explained by a so-called "leaky faucet" model proposed by E.W. Hones, Jr. (Austral. J. Phys., **38**, 981, 1985) or a model by J.A. Linker & Z. Mikić (ApJ, **438**, L45, 1995), when the plasma pressure would exceed the magnetic field tension and as a result the loops would rise and stretch. Their pinching together legs would reconnect close to the Sun at $\sim$1.3 $R_\odot$ and a streamer plasma bulk would be released and escape to the space. A sudden split into inflowing component and ejected streamer leaving the Sun could be seen (Y.-M. Wang & N.R. Sheeley, Jr., ApJ, **650**, 1172, 2006; N.R. Sheeley, Jr., H.P. Warren, & Y.'M. Wang, ApJ, **671**, 926, 2007).

The streamer belt appears to be more dynamic in 2006–2009 than in 1996–1997. At heliocentric distances of 3–15 $R_\odot$ the streamer plasma outflow velocities seem to be from several dozens of km s^{-1} to a hundred of km s^{-1}, greater during the last minimum of the solar activity than during the previous solar minimum in 1996. It is not so surprising, because in 2007–2009 the Sun in all its characteristics was more dynamic and its corona looked more impressive and stretching to higher latitudes and heliocentric distances.

M.V. Lomonosov Moscow State University
P.K. Sternberg Astronomical Institute
University avenue 13, Moscow 119991, Russia
galina-porfirieva@yandex.ru
osmir@yandex.ru
yakunina@msu.sai.ru

A.B. Delone
А.Б. Делоне
G.A. Porfir'eva
Г.А. Порфирьева
O.B. Smirnova
О.Б. Смирнова
G.V. Yakunina
Г.В. Якунина

Received March 20, 2013