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THE DOUBLE STRUCTURE OF THE CORONAL STREAMER BELT

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Abstract. Increasing the effective spatial resolution when analyzing LASCO-C2/SOHO data helped to reveal the existence of double-ray structure in the streamer belt, both in the absence and presence of belt bends. Streamer-belt rays located in the plane of the sky are demonstrated to deviate poleward (north- and southward, respectively, in the N and S hemispheres) at distances $R < 4$–$5R_{\odot}$ from the Sun center. These new results concerning streamer belt structure are important as the basis for checking a theory claiming to adequately describe physical processes in the corona.

1. Introduction

Streamers are the brightest structures in the "white-light" images of the solar corona. The streamer base is where the helmet is located, represented by a system of arches with a radially oriented ray above it (Vsekhsvyatskii, 1965; Newkirk, 1967). This ray is also called the "stalk" (Strachan *et al*., 2002). Continuous daily observations of the white-light corona on 11 October 1971 – 15 January 1973 by the OSO-7 spacecraft showed (Howard *et al*., 1975) that streamers form a sequence – or the so-called streamer belt – along which runs the neutral line (NL) of the radial component of the Sun's global magnetic field (Svalgaard *et al*., 1974; Korzhov, 1977). At distances over 3–$4R_{\odot}$ ($R_{\odot}$ is the Sun's radius) the angular thickness of the streamer belt is less than 5 degrees (in the heliographic coordinate system) (Sheeley *et al*., 1997). At solar activity minimum only one ray is usually observed at each of the W and E limbs. These rays are located symmetrically relative to the Sun center and are stretched along the solar equator. It is the so-called "minimum" corona. With solar activity rising, rays appear at higher latitudes. At activity maximum they are present almost at all latitudes as well as at the poles. This is the "maximum" corona (Eselevich *et al*., 2000). For more than half a century the question of the nature of these structures was and still is central in the research of the nature of quasistationary slow solar wind (SW) – the core of the streamer belt.

The difficulty in solving this problem is that ray structures observed in the white-light corona are a result of the streamer-belt surface projected onto the plane of the sky. Therefore, the success in solving it depends chiefly on how accurately the spatial picture of the belt can be reconstructed from images of the white-light corona.

A point of view exists that the distribution of plasma concentration along the streamer belt is homogeneous (Wang *et al*., 2000), and rays observed in the corona are a result of belt bends projected onto the plane of the sky (Wang *et al*., 2000; Koutchmy *et al*., 1994). Comparison of the number of bends in a calculated NL running along the belt to the number of rays observed in the white-light corona shows, however, that rays are, as a rule, considerably more numerous than NL bends. In cases when belt surface lies in the plane of the sky ("maximum" corona), possible bends in the streamer belt are theoretically shown (Koutchmy *et al*., 1994; Koutchmy and Molodensky, 2005) do not be likely to result in rays appearing in the plane of the sky. However, it is exactly in this kind of situation that the largest number of rays is registered in the corona. A hypothesis was proposed (Gulyaev, 1992; Eselevich, 1998) to the effect that the significant difference observed between the appearances of the white-light corona at solar-activity minima and maxima is probably due to the orientation of the streamer-belt surface relative to the plane of the sky, and reflects the presence of spatial inhomogeneities in plasma density along the belt. Existence of these inhomogeneities was first proved in Eselevich and Eselevich (1999). It was established there, based on results from analyses of non-calibrated data from the LASCO instrument (processing level 0.5), that the streamer belt at distances $R > 3R_{\odot}$ is inhomogeneous in the absence of coronal mass ejections (CMEs) and represents a sequence of radial rays (or ray pairs) of enhanced brightness. The minimum angular size of all the rays is almost the same: $d \approx 2$–3 degrees; the minimum distance between the rays is $\sim$5–10 degrees.

Latest investigations (Eselevich and Eselevich, 2004; Eselevich and Eselevich, 2005) relying on calibrated data from the LASCO instrument (processing level 1) provided serious indications that the belt is most likely formed by a sequence of, not individual rays, but pairs of rays – generally, of differing brightness. The neutral line, meanwhile, should probably run along the belt between the rays of each of the pairs. In other words, this structure should consist of two closely located (at a distance of d) rows of enhanced brightness rays with opposite signs of the radial component of the Sun's global magnetic field. The question concerning the existence of such an exotic structure in the streamer belt is a matter of interest both in terms of the nature of slow SW flowing in the belt and in terms of a possible development in the rarefied coronal plasma of possible collective processes responsible for forming such structures. The goal of this paper is to prove, based on an improved analysis methodology, that the streamer belt is a sequence of, not individual rays, but ray pairs – generally, of differing brightness.

2. Initial Data and the Analysis Method

We used white-light images of the solar corona obtained with the LASCO-C2/SOHO experiment as the source data for our analysis, specifically, calibrated

1024×1024 LASCO-C2 images available from *http://lasco-www.nrl.navy.mil*. These data are free of effects such as scattering, vignetting, etc., and the intensity values P are presented in units of the mean solar brightness, P_{msb}.

The essence of the analysis method was as follows: For a chosen range of apparent latitude angles $\Delta\Lambda$, usually not exceeding 60°, distributions of background-subtracted brightness $\Pi(\Lambda, R) = P(\Lambda, R) - P_S(\Lambda, R)$ were constructed in polar coordinates (Λ, R) for sequential times t using the histogram equalization procedure. Here, $P_S(\Lambda, R)$ is the "background" brightness representing the moving average of initial brightness distribution $P(\Lambda, R)$ over the angular interval $\delta\Lambda$ at given t and R (or the running averaging of the number of points located in the angular interval $\delta\Lambda$). The step along R was $0.007 R_\odot$. The goal of the histogram equalization procedure is to intensify the brightness of faintly luminous regions of increased-brightness rays remote from the Sun. Obviously the quantitative information about brightness was thus lost. Usually, when determining $P_S(\Lambda, R)$, the value of $\delta\Lambda = 10^\circ$ (Eselevich and Eselevich, 2004; Eselevich and Eselevich, 2005). In this paper, a diminished value of $\delta\Lambda = 4^\circ$ was used for a number of events. This was done in order to decrease the angular size of the rays to be high-lighted. As a result, closely lying rays become visible as separate, *i.e.* effective spatial resolution of the coronal images increases.

To determine the plasma velocity along individual rays, distributions of the ray brightness amplitude $P_R(R) = P_M(R) - P_S(R)$ were constructed at a given apparent latitude at consecutive moments of time. Here, P_M is the ray brightness maximum. In the process, negative values of brightness $\Pi(\Lambda, R, t)$ in all the images and plots were set equal to $10^{-12} P_{\text{msb}}$. Such a device significantly simplifies the appearance of images and curves to be analyzed, facilitating the process of their analysis (Eselevich and Eselevich, 2004). Generally, the brightness of an individual ray can vary in time due to the following two reasons: solar rotation and non-stationary processes in moving plasma. As a result of solar rotation, the brightness of a chosen ray decreases when moving away from the plane of the sky and, correspondingly, increases when approaching the plane of the sky. The typical scale of such variations is about two to three days. On this background, one can easily distinguish the relatively fast non-stationary changes in brightness at a scale of several hours and less (for example "blobs" and CMEs). Therefore, comparison of ray brightness variation with time, observed under certain conditions, to calculated profiles allows quasistationary rays to be reliably enough identified and their features inspected (Eselevich and Eselevich, 1999).

3. General Appearance of the Streamer-Belt Structure

In order to understand the structure of the streamer belt it is enough to examine it in two mutually perpendicular directions: (1) along the belt surface and (2) perpendicular to it. While observing the white-light corona at the limb, the first situation is

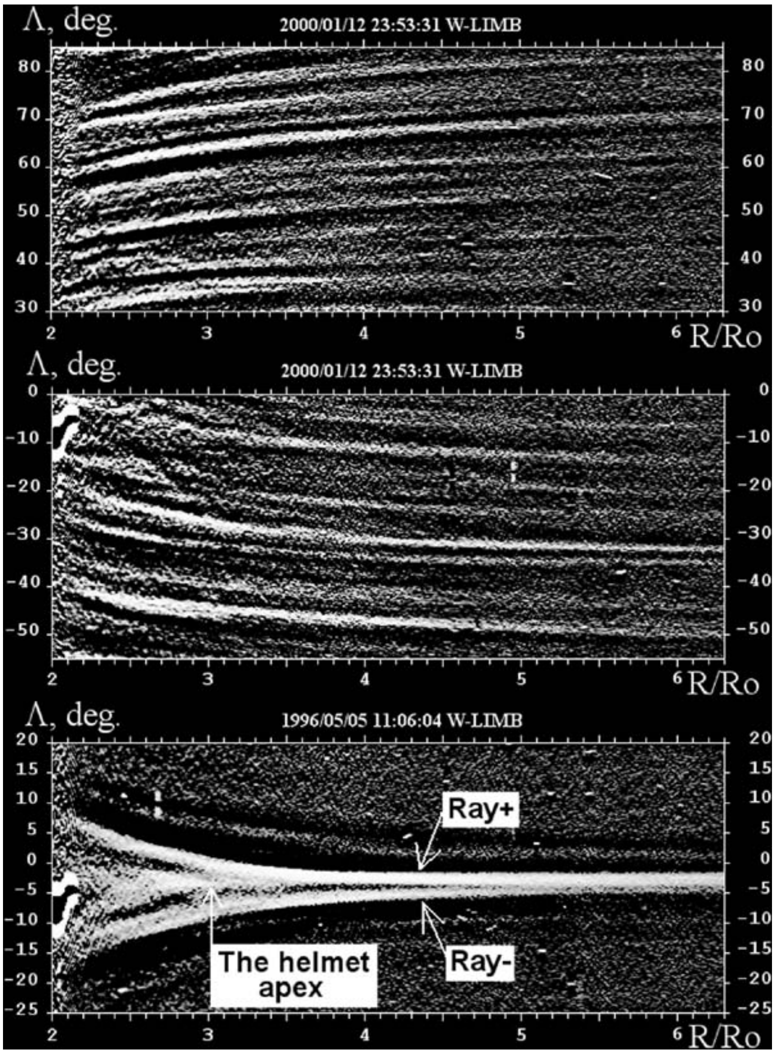

Figure 1. Background-subtracted brightness $\Pi(\Lambda, R) = P(\Lambda, R) - P_S(\Lambda, R)$ distribution in polar coordinates (Λ, R) with $\delta\Lambda = 4^\circ$ in two simplest and typical situations: *top and middle panel* – the belt part is located almost in the plane of the sky (12 December 2000, 20:31 UT), respectively, the northern and southern hemispheres of the Sun, W-limb; *bottom panel* – the part of the belt is normal to the plane of the sky (5 May 1996, 11:06UT), W limb, LASCO-C2.

realized when the surface of the belt is located in the plane of the sky (or close to it); the second, when it is perpendicular to the plane of the sky. Subtracted-background brightness $\Pi(\Lambda, R) = P(\Lambda, R) - P_S(\Lambda, R)$ examples in polar coordinates (Λ, R) are shown in Figure 1: for situation (1), in top and middle panels; for (2), in the bottom panel.

In the top and middle panels, one can see that the structure of the belt along its surface represents a sequence of increased-brightness rays. Here:

– Minimum distance between the rays is 5–10 degrees (maximum distance can exceed 25 degrees);
– *R*-dependent brightness decrease can significantly vary between rays;
– Rays are oriented virtually radially at $R > 4$–$5R_\odot$; while at $R < 4$–$5R_\odot$ they are oriented not radially and deviate poleward when moving away from the Sun;

It should be noted here that the phenomenon of poleward deviation of the rays at $R < 4$–$5R_\odot$ was observed in all the cases (several tens of them were studied) when the belt surface was in the plane of the sky (or near it). This effect is quite unexpected. The unexpectedness is related to the fact that a theory is lacking to adequately describe dynamic processes in the solar atmosphere. Therefore, it is hard to say what the physical causes of this phenomenon are. It is interesting to note that, in the plane perpendicular to the belt, rays in both hemispheres at a latitude below 60 degrees deviate equatorward at $R < 4$–$5\ R_\odot$ (Eselevich and Eselevich, 2002).

These experimental regularities in the streamer-belt ray geometry reflect the physics of dynamic processes in the solar atmosphere. Therefore they can serve as an important basis for checking a theory claiming to adequately describe the coronal processes.

Viewing the streamer-belt ray structure located in the plane of the sky at consecutive moments of time reveals the existence of the streamers' noticeable dynamics (Eselevich and Eselevich, 2004, 2005). One of the typical examples is shown on the left panel in Figure 2, B, C, where the ray formation stage is seen, and the ray's front end is marked by an arrow.

One can see from the figure that here, the process of rays being filled by an additional plasma stream takes place. The dependencies of $(P - P_S)$ on R along the ray axis at $\Lambda \approx -25^\circ$ at consecutive moments of time (Figure 2, right panel) imply that the additional plasma stream moves with a steep front at velocity $V \approx 100$ km s^{-1}. Such a process is typical for the streamer-belt rays. It has been repeatedly registered and inspected before (Eselevich and Eselevich, 2001; Eselevich and Eselevich, 2004). The quasistationary SW velocity in stalk at $R = 5R_\odot$ measured from the ultraviolet O VI line (λ 1032 Å) in Strachan *et al.* (2002) gives $V \approx 90$ km s^{-1} – close to the obtained velocity of the additional plasma flux front.

A cross-section of the streamer belt observed at the limb when the streamer belt is perpendicular to the plane of the sky (Figure 1, lower panel) represents, in the general case, two rays of increased brightness: Ray+ and Ray−, which, at $R > 4$–$5\ R_\odot$, are oriented practically radially, and at $R < 4$–$5R_\odot$ when approaching the Sun, round the helmet on both sides. The increased-brightness rays represent magnetic

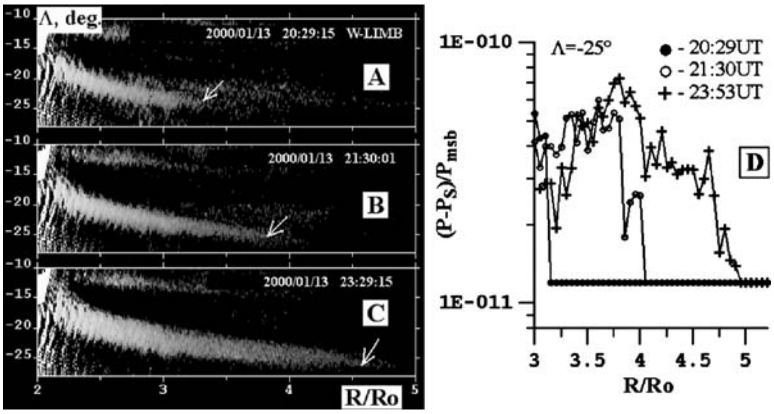

Figure 2. Distributions of the background subtracted brightness $\Pi(\Lambda, R) = P(\Lambda, R) - P_S(\Lambda, R)$ in polar coordinates (Λ, R) with $\delta\Lambda = 10^\circ$ for the separate ray, in the case when the part of the belt is located almost in the plane of the sky: A, B and C – ray formation in time (13 January 2001); D – ray brightness dependency on the distance R at the latitude $\Lambda = -25^\circ$ at consecutive moments of time on 13 January 2001.

tubes with plasma of increased density moving from the Sun along them, and the helmet represents a system of arches (loops) of magnetic field filled by plasma moving within. The magnetic field's radial component is known to have opposite directions at different sides of the helmet. The helmet top is located between Ray+ and Ray− (see Figure 1, bottom panel) and corresponds to the location of the neutral line dividing the regions of opposite polarity in the Sun's global magnetic field. In the case in question, the plus (+) polarity (direction from the Sun) takes place north of the NL, with the minus (−) polarity occurring south of the NL. That is why the rays are called Ray+ and Ray− – according to the supposed sign of magnetic field in them. Such was the preliminary conclusion first made in Eselevich and Eselevich (2005). However, as was noted in that paper, the streamer-belt cross-section is often visible as one ray, while the helmet can be absolutely invisible. This is related to the fact that, when considering things in time, we deal with a dynamic picture, *i.e.* brightnesses in individual rays and the helmet significantly vary in time independently of each other.

It should be noted that, while observing the corona in the light of the ultraviolet O VI line (λ 1032 Å) in Strachan *et al.* (2002), two luminosity peaks (legs) were found below the top of the helmet, rounding it on the sides. Our additional examinations of 23–27 April 1997 – the dates used in Strachan *et al.* (2002) – showed that the location of the peaks of the O VI 1032 Å line emission approximately coincides with the location of the ray brightness peaks in the LASCO C2 data. Thus, Ray+ and Ray− may very probably be called the "legs". In the light of the Ly α line (λ 1216 Å), however, the legs are not observed. Therefore this statement requires additional research.

4. Cross-Section Structure of the Streamer-Belt

To investigate the structure of the streamer-belt cross-section in more detail, let us examine a part of the streamer belt both typical for a solar-activity minimum and quite long (about 15 days or longitude range $\delta\Psi_L \approx 180°$) – from 27 April to 11 May 1996 – near the equator (latitude $\lambda \approx (-2)$–(-5) degrees) at the W limb, perpendicular to the plane of the sky, in the absence of CME influence. In the cases when temporal variations in ray brightness and latitude location due to non-stationary processes are to be distinguished from similar changes produced by solar rotation, we shall compare the measured dependencies of the ray brightness amplitude $P_R(\Psi_L)$ and apparent latitude of ray location $\Lambda(\Psi_L)$ at $R = 4R_\odot$ to corresponding dependencies for these cases computed using formulas (3), (4), with $\alpha \approx 5$, from Eselevich and Eselevich (1999) and formula (5) from Eselevich and Eselevich (2004).

Let us consider the behavior in time of the background-subtracted brightness $\Pi(\Lambda, R) = P(\Lambda, R) - P_S(\Lambda, R)$ in polar coordinates (Λ, R) for the chosen 15-day period. Its evidence is that the streamer belt cross-section represents, in the general case, two rays, whose brightnesses change independently in time.

Indeed, during the whole study period, two rays of increased brightness rounding the helmet on both sides are seen in Figures 3, 4 and 5 at distances $R < 4R_\odot$: Ray+ and Ray−. However, at distances $R > 4R_\odot$ these two rays are not always seen at the same time. Thus, at the start of this period – on 27 April 1996 (00:15UT) – in Figure 3, the streamer belt cross-section at distances $R > 4R_\odot$ represents a single Ray+ at latitude $\lambda \approx -3.5°$ (marked by an arrow labeled Ray+).

On 28 April at 03:03UT a single Ray− is seen at latitude $\lambda \approx -5°$. On 28 April at 08:52UT one can see a bright Ray− and a gradually brightening Ray+. On the bottom panel – 28 April at 14:40UT – the brightness of Ray+ is already higher than that of Ray−. As was already noted above, ray brightness increase within such short times is related to an additional plasma flux from the Sun flowing at velocity of $V \approx 100$ km s^{-1} along the magnetic tube forming a ray.

The process of gradual intensification of Ray− brightness (or the ray being filled by plasma) is very clearly seen in Figure 4. Brightness of Ray+ practically does not change in all the four images. In the top image (07:02UT), the brightness of Ray− is almost the same at all distances $R \leq 5R_\odot$, decreasing abruptly at $R \approx 5R_\odot$. At $R > 5R_\odot$ the ray is almost invisible. In the images below the brightness at $R \leq 5R_\odot$ almost does not change, and the brightness at $R > 5R_\odot$ gradually increases, *i.e.* this part of the Ray− is being filled by plasma.

Starting from 8 May 1996 (Figure 5) the angular distance between Ray+ and Ray− increases. The cause of this can be understood from analysis of time (longitude Ψ_L) – dependency of the latitude location of Ray+ (black circles) and Ray− (light circles) brightness maxima and their brightness P_R/P_{msb} amplitude, shown, respectively, on the upper and lower panels in Figure 6 from Eselevich and Eselevich (2005).

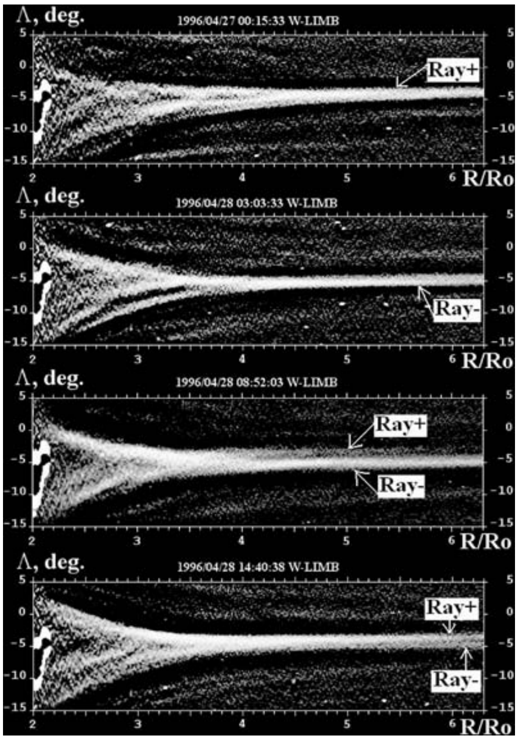

Figure 3. Distributions of the background subtracted brightness $\Pi(\Lambda, R) = P(\Lambda, R) - P_S(\Lambda, R)$ in polar coordinates (Λ, R) with $\delta\Lambda = 4°$ at consecutive moments of time from 27 April (00:15 UT) up to 28 April (14:40 UT) 1996. Streamer belt is normal to the plane of the sky, W limb, LASCO/C2.

From Figure 6 (upper panel) one can see that: Latitude location of the Ray+ curve (black circles) at the 30 April–11 May part is approximately constant: $\Lambda \approx -2° \pm 1°$. It has some small bends $\approx 1°$ (smaller than the ray's angular size *d*) and significantly differs from the calculated curve for an individual ray, whose latitude in the plane of the sky $\lambda = -2°$ (on the upper panel in Figure 6, dotted lines show the calculated curves for an individual ray for the five values $\lambda = 0°, 1°, 2°, 3°, 4°, 5°$). It means that in this case the streamer belt represents a sequence of rays with close values of brightness P_R amplitudes, the distance between which is close to $\approx 5°$ – apparently, of the type presented in Figure 1 (top and middle panel). In the 27–29 April part, Ray+ is absent. That is a situation is likely to take place here when, near the plane of the sky and several tens of degrees both sides of it, bright rays are absent along the belt.

A situation analogous to the curve for Ray+ takes place also for the curve for Ray− (light circles) in the 27 April–7 May part: the ray latitude location experiences only small bends $\pm 1°$ close to $\Lambda \approx -5°$. However, in the 8–11 May part, the run of this curve agrees well with the calculated curve for an individual ray with

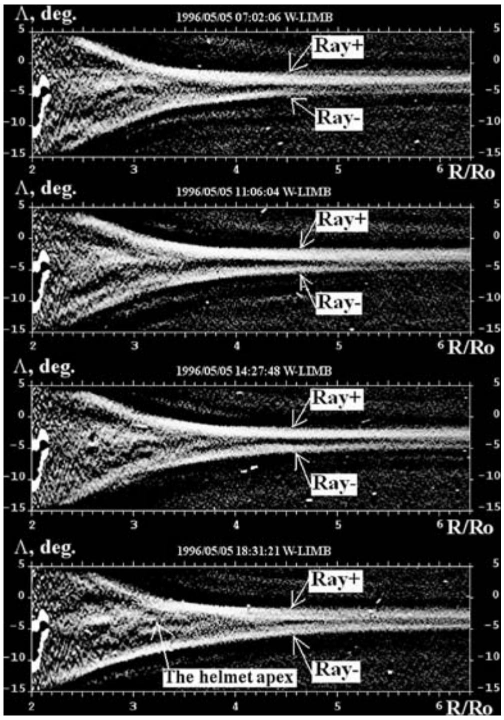

Figure 4. The same as in Figure 3 for the time interval from 5 May (07:02 UT) up to 5 May (18:31 UT) 1996.

$\lambda = (-5) - (-4)$ degrees (accuracy $\pm 1^{\circ}$). It may mean that, starting from the moment of time on 8 May, only one bright ray practically exists near the plane and several tens degrees on both sides of it along the belt. Comparison of the 8–11 May segment of the Ray− brightness amplitude curve (light circles in the lower panel) with calculations for an individual ray with (dotted line) $\lambda = -5^{\circ}$ shows their noticeable difference (Figure 6, bottom panel). It means that in the 8–11 May segment, an individual Ray− is characterized by non-stationary brightness.

Remarkably, at the end of 30 April 1996 apparent latitude increases by approximately 2 degrees simultaneously for Ray+ (black circles) and Ray− (light circles) (upper panel Figure 6). Apparently, it can be treated as a true bend in latitude of the streamer belt as a whole.

To see the streamer belt bends manifesting themselves, let us compare the background-subtracted brightnesses $\Pi(\Lambda, R) = P(\Lambda, R) - P_{S}(\Lambda, R)$ in polar coordinates (Λ, R) in Figure 7 upper and bottom panels.

In upper panel Figure 7 for 5 May 1996 (18:31UT), one can clearly see Ray+ and Ray− in the entire range between $R \approx 2.1R_{\odot}$ to $R \approx 6.3R_{\odot}$ and their location agrees with the location of ray brightness maxima in Figure 6 at $R = 4R_{\odot}$. Near the 30 April 1996, according to Figure 6, an approximately two-degree equatorward

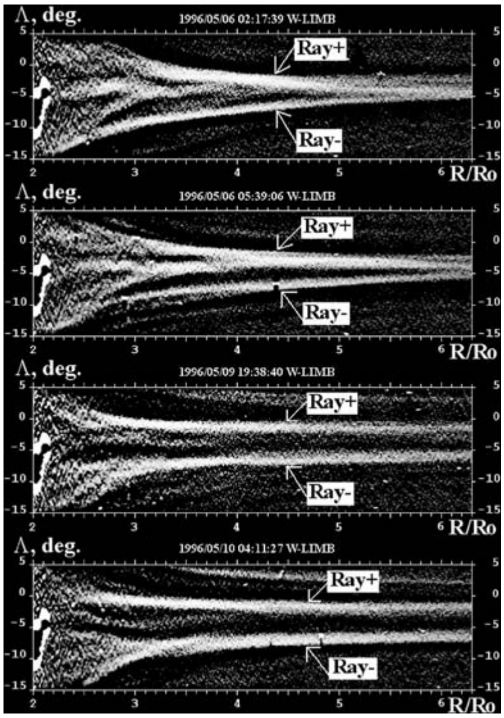

Figure 5. The same as in Figure 3 for the time interval from 5 May (02:17 UT) up to 10 May (04:11 UT) 1996.

belt-bend takes place. A consequence is that in the image in bottom panel Figure 7, one can see, apart from Ray+ and Ray−, reflecting the streamer belt cross-section up to the bend, rays shifted approximately 2 degrees equatorward relative to them – Ray+C and Ray−C. These correspond to a belt cross-section located after the bend. The double-ray structure of the belt section meanwhile is observed in both cases and is seen, at least, up to $R = 4R_{\odot}$. At larger distances, because of the faster drop in brightness in Ray− and Ray−C, one can see primarily Ray+ and, to a lesser extent, Ray+C. It should be noted that such a clear picture of two rays manifesting themselves in the belt cross-section and, moreover, in the presence of a bend, is not often observed. This is related to dynamical processes in rays, whose brightnesses can significantly change within hours.

Thus, the performed analysis allows one to single out:

– Two rows of rays – Ray+ and Ray− – in most of the belt (from 30 April to 11 May).
– A bend in latitude of the streamer belt as a whole (at the end of 30 April 1996 in the upper panel of Figure 6).

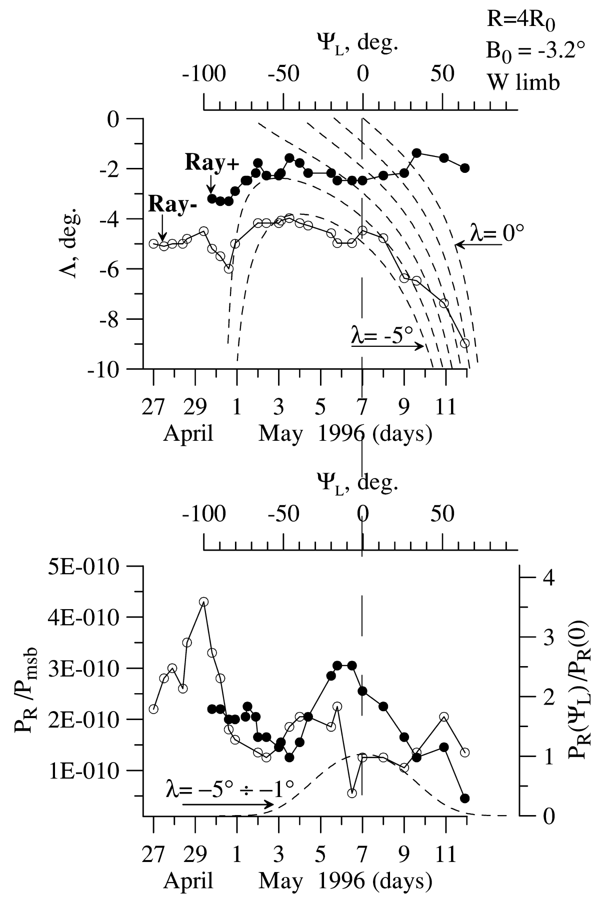

Figure 6. Top: observed apparent latitudes Λ of the Ray+ and Ray− brightness maxima (solid and open circles, respectively) as a function of time (*lower horizontal axis*) or angular deviation from the plane of the sky Ψ_L (*upper horizontal axis*) at $R = 4.5R_\odot$(Ψ_L is positive in the direction of solar rotation). The *dashed curves* were calculated for $\lambda = 1°, 2°, 3°, 4°, 5°$; $B_0 = -3.2°$ and are close to the observational points. *Bottom*: same for the ray-brightness amplitude. The *dashed curve* was calculated for $\lambda = -5°$, $B_0 = -3.2°$, $R = 4.5R_\odot$. From Eselevich and Eselevich (2005).

It is important to note that the double-ray structure of the streamer belt (two rows of rays – Ray+ and Ray−) is observed both in the absence of belt bends and in their presence.

Some authors (Wang *et al.*, 2000; Wang *et al.*, 2000), based on calculations and their comparison to observations, suggested that the frequently observed double structure of the streamer belt can be a result of the belt's small-scale bends. In this case the neutral line should run along the maxima of rays' brightness, following those bends. However, the above results allow, in our opinion, a safe enough separation of the belt-bend cases from a situation when the streamer-belt cross-section

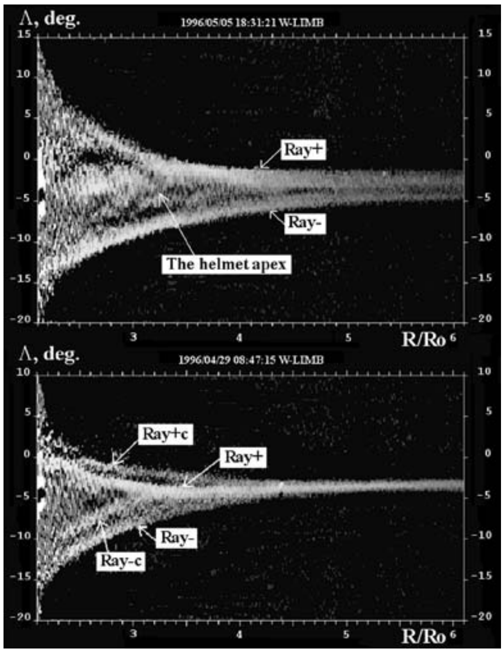

Figure 7. The background-subtracted brightness distribution $\Pi(\Lambda, R) = P(\Lambda, R) - P_S(\Lambda, R)$ for the situations when: (*upper panel*) – there is no the bend of a segment of the streamer belt, which is normal to the plane of the sky; (*bottom panel*) – there is the small bend of a segment of the streamer belt, which is normal to the plane of the sky.

represents two rays of increased brightness, with the neutral line running between two closely located rows of these rays. The suggested spatial ray structure of the streamer belt on the basis of the above results is schematically shown in Figure 8 from Eselevich and Eselevich (2005).

As suggested in Eselevich and Eselevich (2005) the double-ray structure of the streamer belt may result from the development of an instability. In particular, Gubchenko *et al*. (2004) have shown in a kinetic approach that, in streamer belt-type current systems, the development of the so called stratification instability can lead to the formation of a set of magnetic-tube (ray) pairs along the belt, which resemble the observed rays. If this is correct, we are dealing with collective properties of rarefied plasmas manifest via the formation of structures on cosmic scales.

5. Conclusions

1. Increasing the spatial resolution when analyzing LASCO-C2/SOHO data helped to reveal the existence of double-ray structure in the streamer belt, both in the absence and presence of belt bends.

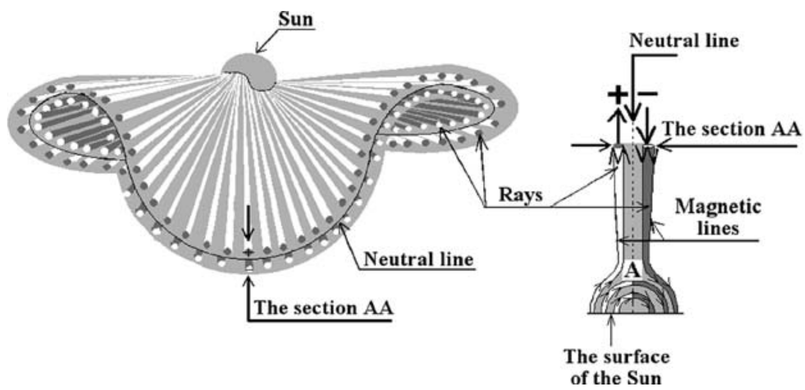

Figure 8. Schematics of the spatial ray pattern of the coronal streamer belt (*left*) and the cross section (AA) of the streamer belt (*right*). The magnetic field is directed away from the Sun (+) in the light rays of the upper row of the streamer belt and toward the Sun (−) in the dark rays of the lower row. The apex of the helmet is labeled A in the right-hand schematic. From Eselevich and Eselevich (2005).

2. Streamer-belt rays located in the plane of the sky are demonstrated to deviate poleward (north- and southward, respectively, in the N and S hemispheres) at distances $R < 4–5 R_\odot$ from the Sun's center.
3. These new results concerning streamer belt structure are important as the basis for checking a theory claiming to adequately describe physical processes in the corona.

Acknowledgements

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