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Time Domain Analysis of Solar Coronal Structures Through Hough Transform Techniques

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Abstract. The Hough transform technique is applied to a series of images from the LASCO/C2 coronagraph in order to understand the temporal evolution of radial structures on the solar corona, the so-called "polar plumes". They may corotate with the solar corona and therefore change aspect with time due to projection effects on the plane of the sky. In the images these structures suddenly appear, shift, mix, and fade away on short periods of time. From a long series of images ($\sim$ 100), we determined for each image the polar intensity profile and built up the evolution of such profiles against time. The result is a Time Intensity Diagram (TID) where intensities are plotted with respect to time and position coordinates. Radial structures appear as peak intensities in each profile and therefore as bright points in the TID. The Hough transform techniques are applied to detect coherent trajectories. This technique has been applied successfully to study coronal plumes on coronal images obtained by different instruments aboard the SOHO satellite.

1. Introduction

The solar corona is composed of two components:

1. a highly structured, time variable K-corona due to Thompson scattering of solar light by coronal electrons,
2. a smooth, quasi-stable F-corona due to solar light scattering by interplanetary dust particles.

Both components exhibit an exponential decrease of their radiance with increasing distance from the Sun with the K-component having a steeper gradient than the F-corona. The K-corona structures are tightly linked to the magnetic field of the Sun and their appearance varies with the solar activity (the solar cycle has a period of 11 years). During the minima of activity, the K-corona exhibits two main stable structures, the equatorial streamers and the north and south coronal holes. These holes are filled with quasi-radial ray-like structures, the so-called polar plumes which apparently outline the polar magnetic field lines, a dipole in a first approximation. Plumes are difficult to detect as they appear as faint azimuthal modulations of the radiance of the corona. Their observations has been limited to solar eclipses which are too short to allow a study of their temporal behaviour. The LASCO-C2 coronograph aboard the SOHO satellite has been continuously observing the corona for more than 2 years and its excellent photometric performances are well suited to an in–depth analysis of the nature and temporal evolution of polar plumes and address first two main questions: are they permanent structures, and are they in rigid body rotation with the Sun? If this is so, a movie made of successive images should easily reveal the plumes as oscillating around the polar axis, a result of the projection of the rotation onto the plane of the sky. In practice, such movies are extremely difficult to interpret because of several confusing effects:

1. numerous plumes populate the coronal holes, those in the foreground moving from east to west, those in the background in the opposite direction,
2. phase function of electrons is a strong function of phase angle and heavily biases the visibility of the plumes; low latitude ones rapidly fade out

when they leave the plane of the sky. In addition, any intrinsic variations of the plumes – and we shall see below that they indeed turn on and off – will further complicate the picture.

We present below a novel approach to the problem. We first construct a Time Intensity Diagram (TID) by piling circular profiles extracted from a time-series of images at a given radial distance. Incidentally, the origin of the polar coordinates is not at the center of the Sun but closer to the limb, at the two points (either north or south) of apparent divergence of the plumes. The TID is therefore an image giving the radiance as a function of position angle (x-axis) and time (y-axis) where plumes appear as bright points. Coherent alignments, that is trajectories, are first visually detected and then established using the Hough transform technique. The dotted pseudo-sinusoidal tracks allow to conclude that plumes are recurrent structures, transitory lit, in rigid body rotation with the solar corona.

2. The Construction of the TID

The process of constructing the TID starts with a selection of a set of LASCO/C2 images covering at least half a solar rotation (14 days) with a minimum frequency of 2 images per day to insure interframe continuity. This set is rigorously photometrically equalized by comparing two successive images and correcting for any difference in radiance of more than 0.1 percent. A minimum background image is calculated from the full set after a median smoothing. Then for each equalized image of plumes the following steps are implemented:

1. Subtract the minimum background image.
2. Introduce a polar coordinate system centered at the apparent "divergence point" of the plumes (located at ~ 0.843 solar radius from the center of the Sun on the polar axis).
3. Apply a transform to cartesian coordinates so that plumes now appear as a set of parallel rays.
4. Apply a 1-D median filter, 16 pixels wide and parallel to the plumes direction, to preserve the lateral spatial resolution. This filter was favored over others such as gaussian filters because it better handles impulsive noises and discontinuities which are present in the LASCO images.
5. Estimate and subtract a residual local background.
6. Obtain a mean intensity profile by averaging 128 neighbouring lines.

The resulting profiles are piled up with increasing time to construct the TID diagram. A sample TID appears in Fig. 1. with its x-axis corresponding to the

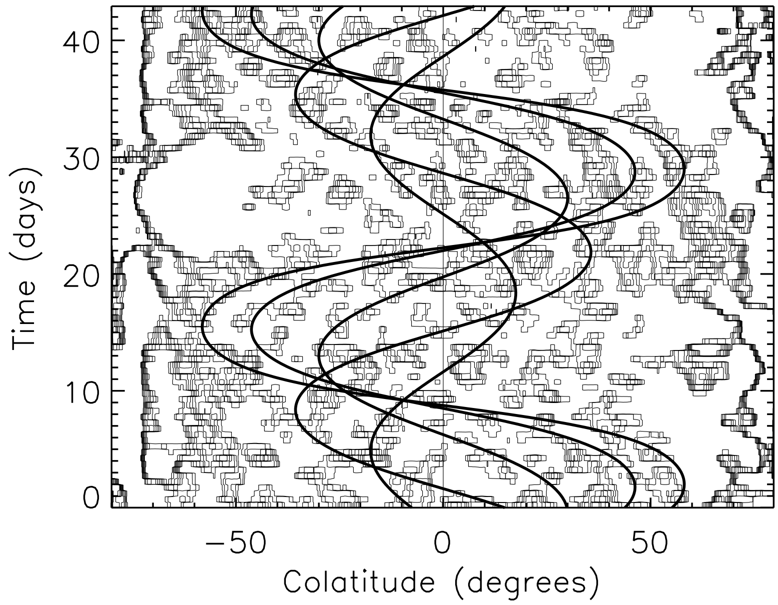

Figure 1. TID diagram for a sequence of 86 images (43 days).

position angle and the y-axis, to the time.

Under the assumption of rigid body rotation, individual plumes will follow sinusoidal curves on the TID with a common axis corresponding to the polar direction. The instantaneous position angle can be written as a function of time. The maximum elongation (or colatitude), the period and the initial phase angle are the three parameters which define a particular trajectory. The exact equation, including a corrective term for the apparent variation of the polar axis with respect to the plane of the sky can be found in Lamy et al. (1998).

3. Analysis of the trajectories using a Hough-like transform

The TIDs built from white light images do not display continuous tracks for the plumes, except at high colatitudes. Their patchy appearance immediately suggests that identified plumes are not permanent structures. However dotted sinusoidal paths are suggested and must further be explored. Their reality will indicate that plumes are enduring, recurrent structures that are transiently lit.

In order to find objective tracks, we introduce a variant of the Hough transform, a method derived from the Radon transform, which makes it possible to detect many kinds of geometric alignments in an image. The specific advantage of the Hough method is its ability to detect alignments of disjoint tracks and points as a single entity. A discussion of this method can be found in Ballester (1994, 1996) and astrophysical applications, for instance in Ragazzoni & Barbieri (1993, 1994).

In our case, alignments would coincide with the sinusoidal tracks of the plumes. The method consists in summing the TID levels along the expected trajectory for each combination of colatitude, initial phase and period. In theory, the track profile over the TID is a Dirac function, but for practical situations the Dirac kernel is replaced by a so-called influence curve. It must be positive, integrable and with a finite support. We chose a normalized truncated gaussian curve corresponding to the estimated uncertainty in the plumes position over time.

Each sum defines a point in the 3-D parameter space. The result is a 3-D intensity function of the synodic rotation period which ranges from 27 days at the equator to 35 days at the poles, with a half day uncertainty, the colatitude which varies from 0° to 80° with a reasonable resolution of 2° and the phase which covers the whole period, with a half day resolution.

For an initial estimation, this function was reduced to a more tractable 2-D function, by fixing the period to the mean synodic solar rotation. The standard technique consists in determining first the coordinates of the absolute maximum, which defines the most conspicuous track, then to subtract from the TID all the points corresponding to the track and then to restart the whole process and look for the next maximum. In practise, we do not follow this procedure because the same point of TID can belong to two distinct trajectories. Instead, we select the most prominent set of local maxima at once as indicators of most probable trajectories.

4. Results

We built the TID corresponding to a time interval of 43 days centered on December 1997, as shown in Fig. 1. We found 7 reliable trajectories with a period of 27 days and with colatitudes ranging from 14° to 54°; five of them are overplotted in the figure. This method has been effective to track the dotted trajectories of the white light polar plumes establishing for the first time their temporal evolution and their correlation with the extreme ultra-violet plumes present in the solar polar regions (Llebaria et al. 1998).

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