Astronomical Data Analysis Software and Systems X
ASP Conference Series, Vol. 238, 2001
F. R. Harnden Jr., F. A. Primini, and H. E. Payne, eds.

Projective Transform Techniques to Reconstruct the 3-D Structure and the Temporal Evolution of Solar Polar Plumes

A. Llebaria, A. Thernisien, P. Lamy

Laboratoire d'Astronomie Spatiale (CNRS) Marseille

Abstract. A sequence of 400 images obtained over three days with the C2-LASCO/SOHO coronagraph was used to disentangle the complex evolution of the structures observed on the corona of the Sun's North pole. Projective transforms were used to find and delimit the elusive linear structures on each image ($< 1 : 1$ of SNR). From frame to frame, these structures show strong brightness variations as well as lateral shifts which are linked to rotation of the Sun. Taking advantage of solar corona rotation as a rigid body (of ∼28 days period), we are able to extract short sinograms to obtain a 3-D reconstruction with few hypotheses. The whole procedure is described, emphasizing the role of the bilinear transform as a new tool in this process.

1. Introduction

Polar plumes appear in images of the Sun's corona as faint linear enhancements in radial directions emanating from the North and South polar regions during the period of minimal solar activity. For each pole, the plumes seem to diverge from a virtual point located on the polar axis not far from the solar surface. They overlay the smooth and very bright background due to the F-corona.

What are polar plumes? Solar light is scattered by the coronal electrons moving outward from the polar regions at about 500 km/s (solar K-corona). Local enhancements of electron density, outlining the 3-D polar magnetic field, appear to the observer as polar plumes by projection onto the sky. Due to the exponential decrease of electron density with increasing radial distance from the Sun and to projection effects, the plumes parallel to the sky plane outshine the tilted ones, thus bringing up a selection effect. Recent studies (Lamy et al. 1997; Deforest 1998; Llebaria et al. 1998) have shown that plumes are enduring recurrent structures showing a transient activity. We present here the image processing methods used to obtain these results.

Even if plumes seems to be in rigid body rotation with the solar magnetic field, classic inversion with Radon transform is unable to reconstruct such 3-D structure due mainly to transient phenomena. In this paper, the 3-D distribution must be deduced from the temporal analysis using a variant of sinograms called TID (Time Intensity Diagram) introduced in previous works (Lamy et al. 1997; Llebaria & Lamy 1999). The TID is a variation of the classical sinogram of the Radon transform, where angle has been replaced by time and sections are

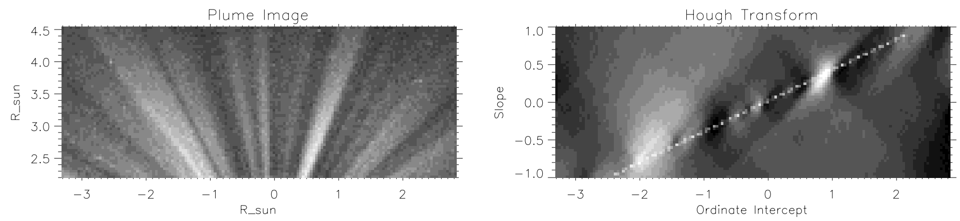

Figure 1. Plume images (left) and correlative picks in the dual plane(right). The dotted line shows a fit to maxima positions. Fit parameters reveal the position of divergence point in image plane.

replaced by the accumulated flux of the plumes along radial directions. We will describe some properties of TID and of its derivatives for the first time.

To improve the TID accuracy, we have extended the concepts developed in these works using the *bilinear dual transform* or BDT. This transform is a member of the projective transforms family, as Radon and Hough transforms are. These points are discussed in detail by Ballester (1994), who introduced the BDT as a variant of Hough transform. We have applied such techniques to an outstanding sequence of high rate C2-LASCO frames obtained in the interval from 1997/03/21 at 22:10:35 UTC to 1997/03/24 at 16:22:41 UTC. This entails a sequence of 402 frames for 66 hours of uninterrupted observations, i.e., a frame every 10 minutes. For 3-D reconstruction, the problems so far have been:

1. Inaccurate exposure times.
2. All plumes have a very low SNR, so the divergence point is poorly defined.
3. Combined motion and transient activity leading to a very confusing effects.

We address points 2) and 3), solved with projective techniques.

2. Bilinear Dual Transform

Plumes appear in coronal images as linear features with few or no structures on the radial direction. As a result of this, and at least for this preliminary approach, we assume that the shape of the radial profiles of solar plumes is constant from one image to the next. Some of these changes are caused by lateral displacements due to coronal rotation.

The increase of SNR is obtained by summing up intensities along radial directions centered on the virtual divergence point. Finding this point in the original images is the role of the *bilinear dual transform* (BDT), defined below.

The BDT is a dual transform which projects lines on points, like the standard Hough transform, and points in lines, unlike the Hough transform (Jain 1989). A straight line $y = x/q + p/q$, defined by slope $1/p$ and shift point p/q in the original plane of (x, y) coordinates, is converted to a point (q, p) in the transformed (or dual) space, also called the plane of parameters. Conversely, a line $q = p/d + c/d$ on the plane of parameters corresponds to a point (c, d) on the image plane.

A unique equation defines this symmetric conversion:

$$qy = x + p$$

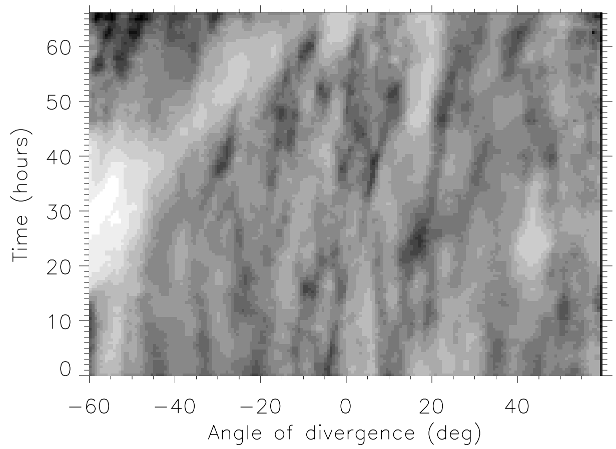

Figure 2. The TID generated from 402 images ($\sim$ 66 hours). The bright feature at left is a high latitude solar jet, moving quickly to the East (right), and crossing normal plume paths. Plume traces of variable thickness with different lifetimes appear as obvious features.

where (q, p) is a pair of parameters defining a line in the image plane and a single point in the dual plane. Conversely, (x, y) refers to a point in the original image and they are parameters of a line on the dual plane. The main advantage of BDT is this symmetry. It is clear that deducing the divergence point is easier in the dual plane than in the image plane. Once transformed, the plumes appear as a set of aligned peaks on the parameter plane. We obtain the divergence point fitting a straight line to the set of positions of these peaks. The straight line coefficients define the position of the divergence point on the image plane. Moreover the clustering of positions on BDT reflects interesting geometrical properties of the plumes which are not addressed here.

3. TID Construction and Properties

We recall here the main steps of the TID construction algorithm:

- For each frame, from a center located at the divergence point, and for a regular set of angular positions, plumes are radially integrated.
- A profile of integrated brightness values as a function of angle is generated for each frame.
- The sequence of profiles compose a Flux=F(angle,time) diagram, here called the time intensity diagram (TID)

The TID reveals how plumes behave. Bright pixels delineate continuous paths in the time direction indicating the presence of enduring plumes over this time interval. Interrupted paths show intermittent plumes and local brief brightenings are clearly visible as distinct from crossings of plume paths.

The derivative of TID with respect to angular position ($d\ TID/d\alpha$) shows strong correlations in the time direction. The $d\ TID/d\alpha = 0$ condition corresponds to ridges and valleys of intensity extrema. Paths of positive extrema define the sites with lateral shift. Projecting paths following a family of parametric sinusoids determine the best parameters (phase and amplitude) defining the 3-D position of each plume (we follow a Hough-like transform procedure).

The derivative of TID with respect to time emphasizes the intrinsic intensity behavior. In particular, sudden intensity increases followed by quick decreases reveal "bursts" of plume activity (corresponding to polar "jets" of the solar literature). The plumes rise and fall appear diffuse over the image and correspond in fact to relatively slow changes in activity.

4. Plume Paths and Temporal Activity

Once paths have been defined as described above, it is possible to return to the original image sequence in order to isolate a plume for all the observing time and isolate the corresponding temporal profile. The latter is obtained as an image of integrated brightness depending on time and radial distance to the Sun surface. This temporal profile allows the finest analysis of how plumes evolve. Using projective techniques, once again, with this temporal profile, the apparent radial speed has been found for a significant set of plumes.

5. Conclusions

The bilinear dual transformation, a member of the Radon-Hough family, has been successfully applied to detect converging linear structures in a low SNR environment. An outstanding feature is its linearity in both *a quod* and *ad quem* spaces. Points are converted into straight lines and reciprocally. The latter has successfully been used to find linear convergent structures in presence of strong noise. This algorithm, as well as the modified Radon transform, has been crucial in determining several solar plume characteristics like their mean radial flow speed or the frequent outburst of short-lived "polar jets" (1–2 hours) over a long-term background activity (Llebaria et al. 2000).

References

Ballester, P. 1994, A&A, 286, 1011

Deforest, C. E. 1998, in ESA ESP SP-421 Conf. Ser. ed. T. D. Guyenne, 63

Jain, A. K. 1989, Fundamentals of Image Processing (Englewood Cliffs, N.J.: Prentice Hall)

Lamy, P., Llebaria, A., Koutchmy, S., Reynet, P., Molodensky, M., Howard, R., Schwenn, R., & Simnett, G. 1997 in ESA ESP-404 Conf. Ser. ed. A. Wilson, 487

Llebaria, A., Lamy, P., Deforest, C. E., Koutchmy, S. 1998, in ESA ESP SP-421 Conf. Ser. ed. T. D. Guyenne, 87

Llebaria, A. & Lamy, P. 1999, in ASP Conf. Ser., Vol. 172, Astronomical Data Analysis Software and Systems VIII, ed. David M. Mehringer, Raymond L. Plante, & Douglas A. Roberts (San Francisco: ASP), 46

Llebaria, A., Thernissien, A., & Lamy, P. 2000, in COSPAR Conf. Ser. (in press)