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Synthetic Images of the Solar Corona from Octree Representation of 3-D Electron Distributions

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Abstract. Empirical and theoretical modeling of 3-D structures in the solar corona is confronted by the tremendous amount of data needed to represent phenomena with a large dynamic range both in size and magnitude, and with a rapid temporal evolution. Octree representation of the 3-D coronal electron distribution offers the right compromise between resolution and size, allowing computation of synthetic images of the solar corona.

1. Introduction

The photometric representation of coronal structures is based on a geometrical model of the spatial electron density in the corona and computation of the corresponding scattered light. The purpose is to generate synthetic photometric images which can be compared directly with images of the corona obtained either during eclipses or with space coronagraphs.

Density models for the coronal structures have traditionally been obtained by inversion of the Thomson scattering integral, assuming *a priori* shapes of the modeled structures. Later, Bohlin & Garrison (1974) adopted the direct approach in the form of a general program based on numerical integration along specified lines of sight to find the emergent Thomson scattered white light.

Today, the coronal plasma model involves MHD processes. However, numerical physical models of the corona cannot be implemented for high resolution in size and magnitude with classical finite element methods, due to the amount of data one has to cope with. In order to be able to simulate images of the corona at high resolutions we concentrate on the simulation program, improving the methods of Bohlin & Garrison, and incorporating an octree representation of the electron density.

In this paper, we first explain the coronal spatial electron density model and the equations to compute the scattered white light. We then describe the octree representation and coding used, and the algorithms used to integrate along a line of sight through the octree data structure. Finally, we present a sequence of computed images displaying the corona over a solar rotation.

2. The Model

2.1. Principle

Given the electron density in the coronal plasma, we compute the photospheric light scattered by the coronal electrons:

$$B(x,y) = C \int_{-\infty}^{+\infty} N_e[2A - (A - B)\sin^2\theta]dz \qquad (1)$$

where N_e is the electron density, C is a constant depending upon electron scattering cross-section and mean solar brightness, A and B are two coefficients derived from the limb-darkening of the Sun and the distance from the electron to the Sun center, dz is a path element along the line-of-sight, and θ is the scattering angle—that is, the angle between the line-of-sight and the line from Sun center to scattering point.

2.2. The Models

The models attempt to explain the observed coronal streamers as structures associated with the neutral magnetic sheet of the Sun, seen edge-on (Saito et al. 1993).

The corresponding electron density is written as a product of two independent functions:

$$N_e = N_{radial}(r) \times N_{shape}(d). \qquad (2)$$

N_{radial} is the radial decrease along the axis of the streamer and depends only upon r, the distance from the considered point to the Sun center. This function has been derived from eclipse observations of streamers. N_{shape} represents the shape of the neutral sheet and is restricted to a variation with the distance d from the considered point to the neutral sheet. We have chosen for N_{shape}:

$$N_{shape}(d) = e^{-(d/d_0)^4}, \qquad (3)$$

a smooth function sharper than a simple Gaussian. The parameter d_0 represents half the "thickness" of the streamer.

The shape of the neutral sheet is then defined as the radial extension of the neutral line observed on the photosphere, for one Carrington rotation.

3. The Octree Representation

3.1. Octree Structure Description

An octree is a tree-structured representation that can be used to describe a set of volumetric data enclosed by a bounding cube. The octree is constructed by recursively subdividing each cube into eight sub-cubes, starting at a single large cube represented by the root-node in the tree. A cube will have descendants only if its associated volume of object space is not homogeneous. The recursion continues until either all sub-cubes are homogeneous or until the required resolution is achieved.

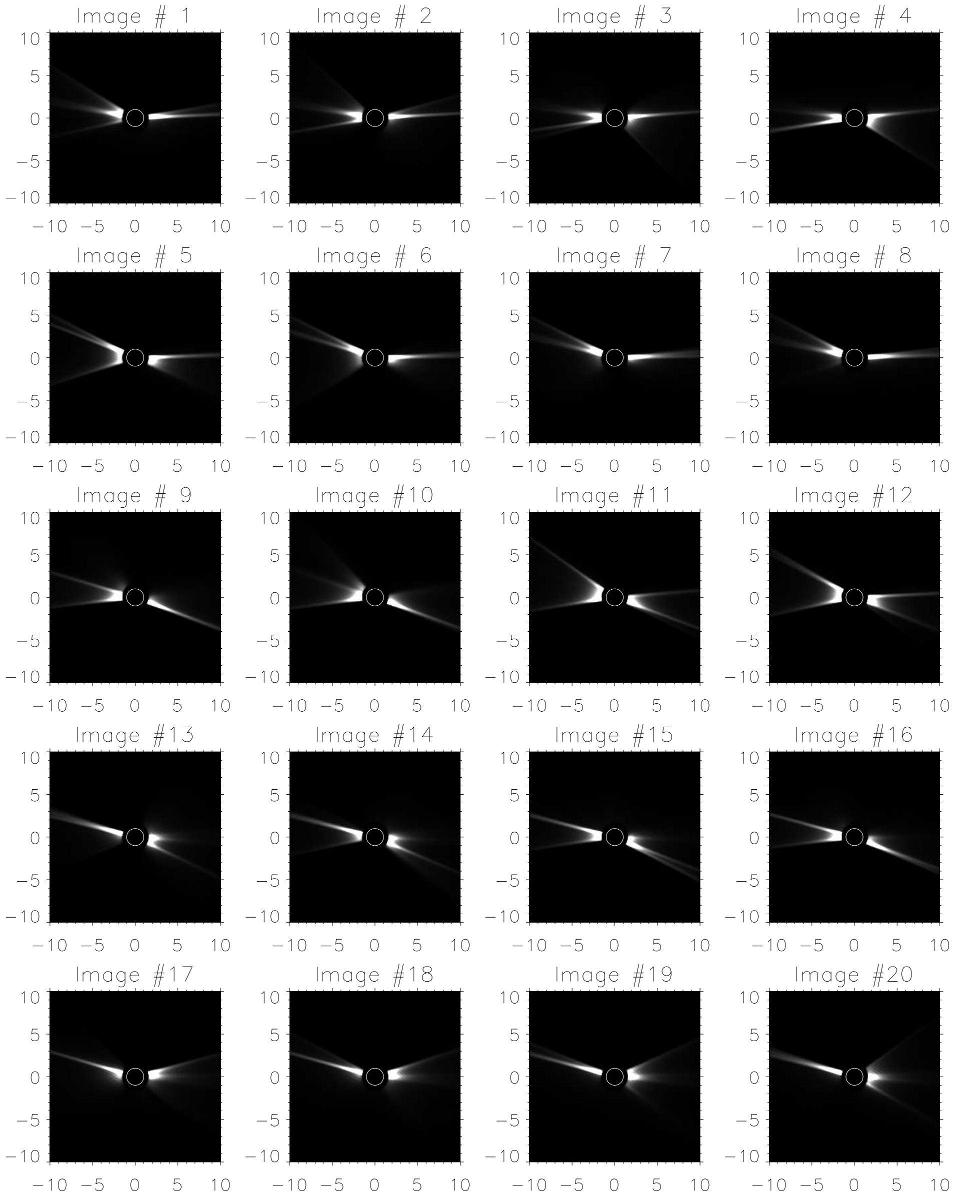

Figure 1. Sequence of 20 simulated images with the electron density based upon the neutral sheet for Carrington rotation 1901 (20 Sep–27 Oct 1995). Frame increases first from left to right and second top to bottom. The time interval between images is one day. The rapid radial decrease in brightness has been compensated. Source for the neutral line: Solar Geophysical Data, no. 617 (January 1996), synoptic chart of the source surface field on p. 39.

3.2. The Octree Encoding

A number of efficient schemes have been developed to represent and encode octrees. The S-tree type (Jonge, Scheuermann, & Schijf 1994) linear encoding was implemented in this work. The tree is built directly from the continuous expression of the coronal electron density given by the mathematical expressions (Eq. 2). The subdivision criterion for a cube is the variation of the electron density within the cube.

4. The Octree Ray-tracing Algorithm

The traversal of the octree data structure to determine the leafs hit by a line-of-sight relies on the HERO algorithm (Agate, Grimsdale, & Lister 1991). At each level of the octree, the algorithm generates the addresses of child voxels (volume elements) in the order they are penetrated by the ray, avoiding the time consuming test of determining the intersection between the ray and the eight children for every node in the tree.

5. Results

Such octree coding and ray-tracing methods lead to significant improvements in terms of resolution, compression, and speed. The generation of an octree of size $1024 \times 1024 \times 1024$, based on smallest voxel size, with 4 byte floating point values, takes approximately two hours (using a standard low cost workstation with 64 MB of memory) and requires 60 MB of disk space. The same data uniformly sampled at the same resolution would have required 4096 MB.

The ray-trace reconstruction of the former octree-based data produces white light images with a resolution of 512×512 pixels, in less than half an hour. A uniform sampling (e.g., by 1024) of every line-of-sight (every pixel) would have led to a far longer computing time for the same output.

This relatively short time necessary to compute one image allows to compute a temporal sequence of images showing corona aspect variations with Sun rotation (Figure 1).

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