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High-order shock-capturing methods for modeling dynamics of the solar atmosphere

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Abstract

We use one-dimensional high-order central shock-capturing numerical methods to study the response of various model solar atmospheres to forcing at the solar surface. The dynamics of the atmosphere is modeled with the Euler equations in a variable-sized flux tube in the presence of gravity. We study dynamics of the atmosphere suggestive of spicule formation and coronal oscillations. These studies are performed on observationally derived model atmospheres above the quiet sun and above sunspots.

To perform these simulations, we provide a new extension of existing second- and third-order shock-capturing methods to irregular grids. We also solve the problem of numerically maintaining initial hydrostatic balance via the introduction of new variables in the model equations and a careful initialization mechanism.

We find several striking results: all model atmospheres respond to a single impulsive perturbation with several strong shock waves consistent with the rebound-shock model. These shock waves lift material and the transition region well into the initial corona, and the sensitivity of this lift to the initial impulse depends nonlinearly on the details of the atmosphere model. We also reproduce an observed 3 min coronal oscillation above sunspots as well as 5 min oscillations above the quiet sun.

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1. Introduction

This paper investigates the response of the solar atmosphere to impulsive forcing at the solar surface using initial conditions derived from observationally based atmosphere models. Impulsive forcing is studied because it provides insight into the natural modes of oscillation of the solar atmosphere, and because there are occasional observed impulsive phenomena, such as small solar flares, spicules, etc. Impulsive forcing is believed to be mostly caused by magnetic stresses, such as those resulting from magnetic reconnection, local dynamo action, the emergence of magnetic flux tubes from the solar interior and interaction between flux tubes and granular convection. We look at a range of parameters that define the forcing function for each atmosphere model. We simulate the response of previously published observationally based model atmospheres above the quiet sun and above sunspots. Various phenomena that appear in our simulations correspond to observed phenomena on the sun. Specifically, our simulations show behavior corresponding to *spicules*, narrow, jet-like features observed in the solar atmosphere, and oscillations in the upper atmosphere. We find that the details of these phenomena depend on the atmosphere model.

The dominant feature in our simulations is strong shock waves that propagate upward, lifting material from the lower atmosphere and causing oscillations of atmospheric materials. Because of these strong shocks, we perform our simulations using high-resolution central shock-capturing schemes. These schemes provide reliable approximations to solutions of the model equations in the presence of strong shocks while avoiding spurious numerical oscillations. We extend existing methods to computational meshes which have variable grid spacing. We also use new variables defined to facilitate numerical maintenance of hydrostatic equilibrium.

One important result of our simulations is the observation that the height of the lifted material depends nonlinearly on the details of the initial atmospheric model. A second result is that when we use the quiet sun atmosphere model, we observe a period of particle oscillations is in the 6 min range while if we initialize our simulations using a sunspot model we see oscillations in the 4 min range. This is strikingly similar to observations of coronal oscillations in the solar atmosphere [2].

Our simulations are based on the quasi-one-dimensional Euler equations applied to an initially hydrostatic atmosphere in a magnetic flux tube whose area increases with height. This model ignores heating, except for the input background heating needed to maintain the initial atmosphere contained in the initial conditions. This model also ignores radiative energy loss, ionization terms, and thermal diffusion. We neglect magnetic fields beyond their role in defining the geometry of the flux tube. Our lack of inclusion of energy loss precludes the study of continuous forcing, because without energy loss terms such forcing would increase the energy of the atmosphere, causing it to expand without bound. We therefore restrict our study to impulsive forcing. We will add energy loss terms and study continuous forcing in a future work.

The structure of this paper is as follows: In Section 1.1 we discuss basic properties of the solar atmosphere, describing its structure and summarizing the observed phenomena of interest to this paper. Section 2 presents the physical model that underlies our simulation. Section 3 introduces our numerical method, including a discussion of initial and boundary conditions, and the computational mesh. New second- and third-order reconstructions on irregular meshes are presented in Section 3.2. In Section 3.4 we present a new technique for maintaining initial hydrostatic equilibrium. Section 4 presents our results, focusing on the match between our simulations and observed properties of the solar atmosphere. We speculate on physical interpretations of our results in Section 4.2.1.

1.1. *The solar atmosphere*

The solar atmosphere is a dynamic environment with high-energy phenomena occurring on many scales. At the base of the solar atmosphere is the *photosphere*, the surface of sun's convective outer layer. The photosphere is roughly divided into two types of regions, *quiet* and *active*. The dominant features of the quiet photosphere are its temperature, about 6000 K, and *granulations*, which are currently understood as the surface of convective cells