REMOTE SENSING STRUCTURE AND DYNAMICS OF SOLAR PROMINENCES USING HIGH-RESOLUTION IMAGING DATA

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1 Statement of Problem and Background

The solar corona, the outermost part of the sun's atmosphere, is a highly dynamic region prone to eruptive instabilities many of which are driven by magnetic reconnection. Coronal Mass Ejections (CMEs) are among the most dramatic solar eruptions accompanied by a significant release of plasma, energy and momentum into the interplanetary space. Located in the interior of CMEs are prominences, dense and relatively cool objects embedded in a hotter surrounding plasma [1, 2]. Prominences are best observed in the solar limb in emission in Hα, the first spectral line of the Balmer series of neutral hydrogen. A prominence typically forms over timescales of about one day, with stable prominences persisting in the corona up to several months, looping hundreds of thousands of miles into space. When seen projected against the solar disk in H-alpha, prominences appear in absorption as dark features called filaments.

Prominences can differ by their morphology and the effects they cause in the surrounding coronal plasma. They can also support various types of magnetic topologies leading to several distinct scenarios of magnetic reconnection. Due to this diversity, prominences are important to classify. In this project, I will use prominence classification scheme developed by Gilbert et al [1] who placed these coronal structures into two main categories – active prominences and eruptive prominences (EPs). An active prominence is a prominence in which a motion is observed but no portion of the material appears to escape the solar gravitational field. An EP, the primary subject of the proposed study, is an event in which all or some of the material manages to escape the gravitational field.

I will pay special attention to EPs because these prominences show a particularly strong connection with CMEs [1–4]. EPs can take a form of complete eruptions, partial eruptions, and failed eruptions [5, 6], and are described in terms of several prominence support models, such as the normal polarity dip model, the normal polarity flux rope model, and the inverse polarity model in which the flux rope is assumed either to emerge from below the solar surface or to be created by normal stress from the sides of the helmet structure that induce reconnection at the X-type neutral line. During the time evolution of the inverse polarity flux rope model, the prominence breaks into two portions, separated by an X-type neutral line creating conditions for internal magnetic reconnection [5].

Many important aspects of prominence formation, eruption and subsequent evolution remain to be understood. Prominence eruptions are highly energetic events which may involve a variety of triggering scenarios. Since most of the observed EPs are partial eruptions [5], it is essential to study this class of prominences. High resolution solar coronal imaging is instrumental for analyzing structure and dynamics of partial EPs. Since prominences are embedded in the surrounding coronal plasma, their study can shed new light on fundamental physical mechanisms underlying instabilities, magnetic topologies and flow patterns shaping this dynamic solar region. Investigation of solar corona in general has astrophysical implications as it can lead to a better understanding of physics of stellar coronas of Sun-type stars. Reconstructing structure and dynamics of solar prominences is also important for predicting extreme space weather events and mitigating their impact on human technologies.

2 Research Objectives

This project aims at quantitative analysis of structure and dynamics of magnetically driven coronal events such as partial EPs using high-resolution images from the Solar Dynamic Observatory (SDO) and the Solar TErrestrial RElations Observatory (STEREO) missions, addressing the following scientific questions:

1. Which scenario of prominence support and evolution does coronal observations support? The majority of the EPs exhibit separation of escaping material from the bulk of the prominence, initially accelerated by the reconnecting magnetic field and then returning toward the solar surface. In other words, most EPs are partial. Several different models have been suggested to explain how cool, dense objects such as prominences can be supported in and thermally isolated from the surrounding hot, tenuous coronal plasma. Of the three basic prominence support models listed above, the observed disconnection of many prominences seems most consistent with the flux rope models of prominence support. I will verify this tendency based on an analysis of a representative set of partial EP events.

2. How are partial EPs driven after the initial eruption? While the general scenario of EP evolution is well known, many details remain to be understood. In particular, relative contributions of the three main magnetohydrodynamic forces (pressure, gravity and magnetic) acting on prominence material may vary from event to event and change during different phases of the same eruption. Using feature tracking and density estimation techniques, I will reconstruct the local coronal force field and identify the leading drivers of different types of EPs.

3. Is the force-free condition valid in the post-eruption solar corona? I will check whether the force-free assumption commonly used in coronal simulations can be applied for the post eruption solar corona. The conducted analysis will provide information relevant to the dynamics of the moving parts of the prominence as well as to the plasma medium in which they move. Using a set of image processing techniques (see the next section), I will evaluate at what stages and locations of the eruption the force-free assumption is approximately valid, and where/when it fails. The results will help identify appropriate numerical models for reconstructing the coronal magnetic field around the EP region.

4. How does the balance of forces during a partial eruption affect the dynamics of the escaping material and the morphology of the resulting CME? I will determine what fraction of studied EPs evolves into successful CMEs, and identify a plausible physical scenario of this transition based on the reconstructed forces and the available EP/CME models. The results of this study will improve our ability to predict timing and physical properties of CMEs which are one of the most important drivers of the space weather in the solar system.

3 Data and Methodology

A representative set of EP events observed by STEREO and SDO missions will be compiled. I have already put together a preliminary set of events for initial tests, which includes 15 events. This database will be expanded up to at least 50 events to cover a broader range of solar conditions.

Time evolution of partial EPs will be explored using a spatiotemporal feature tracking method developed earlier by V. Uritsky [7, 8]. Detectable pieces of falling prominence material will be represented by subvolumes in a three-dimensional space time made up of spatial positions and observing times of relevant image pixels. These subvolumes will be defined as connected sets of pixels with the emission flux below a specified level representing the absorption of the background UV radiation by the EP.

I will estimate angular accelerations of individual prominence pieces using a technique of V. Uritsky and B. Thompson [9]. In this technique, Keplerian trajectory analysis is used to evaluate angular accelerations experienced by the fragmented prominence material at different locations and times. To convert accelerations into torques and reconstruct the effective force field constraining the eruption, the mass density of the EP pieces will also need to be estimated.

The evaluation of mass density of the moving prominence pieces will be conducted using a single wavelength remote sensing method of H. Gilbert [10] and a multi-wavelength method of D. R. Williams [11]. In Gilbert's method, observations of coronal radiation in the Fe XII (19.5 nm) spectral line, which is observed by prominence material, are used. This method has two versions based on the"spatial-interpolative" and the "temporal-interpolative" approaches, and requires one to consider the effects of both foreground and background radiation. Both versions, however, can be applied only when the prominence material crosses the limb. Williams et al. extended this technique to enable measurements of prominence density on a regular basis and at arbitrary locations. In this project I will use the multi-wavelength implementation of their method – the "polychromatic opacity imaging," which is a powerful way to track the partially ionized gas of the EP as it propagates through the solar atmosphere, providing realistic mass-distribution estimates for models of erupting structures.

Using the obtained values of angular acceleration and mass densities of the fragmented prominence material, I will check the validity of the force free approximation by estimating whether or not the magnetic forces are negligible. The results will be used to clarify the geometry and choose appropriate coronal field models.

In order to investigate the EP/CME relationship, I will study a subset of prominence events in which significant CMEs have been observed and their morphology could be analyzed. These events will be investigated further in order to identify which force configurations can lead to successful CMEs.

Proper attention will be paid to analysis of measurement errors of all the methods used in this project. The algorithms will be written in Python language and made available to the solar physics community.

3.1 Research Milestones

1. Selection of representative prominence events; preprocessing image files.
2. Analysis of kinematics of prominence material using the available feature tracking method.
3. Estimation of mass densities of prominence pieces using single and multi wavelength techniques.
4. Analysis of the balance of the forces acting on the prominence material based on the obtained results.
5. Development of a qualitative physical model of prominence evolution consistent with the conducted analysis.
6. Presentation and publication of the obtained results.

4 Contribution and Originality

Joint application of feature tracking and density evaluation techniques to partial prominence eruptions will be performed for the first time. This analysis will contribute to answering the long-standing question of how solar eruptions are driven. It will also help identify appropriate numerical models for reconstructing the coronal magnetic field tracing the EP region, and improve our ability to predict timing and physical characteristics of CMEs.

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