

EIT waves and coronal magnetic field diagnostics

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Magnetic field in the solar lower atmosphere can be measured by the use of the Zeeman and Hanle effects. In contrast, the coronal magnetic field well above the solar surface, which directly controls various eruptive phenomena, can not be precisely measured with the traditional techniques. Several attempts are being made to probe the coronal magnetic field, such as force-free extrapolation based on the photospheric magnetograms, gyroresonance radio emissions, and coronal seismology based on MHD waves in the corona. Compared to the waves trapped in the localized coronal loops, EIT waves are the only global-scale wave phenomenon, and thus are the ideal tool for the coronal global seismology. In this paper, we review the observations and modelings of EIT waves, and illustrate how they can be applied to probe the global magnetic field in the corona.

coronal mass ejections (CMEs), magnetic field, diagnostics, magnetohydrodynamics (MHD)

Magnetic field plays a vital role in various astrophysical processes. In the solar atmosphere, magnetic field interacts with the plasma, producing abundant eruptive activities, besides the relatively quiescent heating in the atmosphere. Therefore, the measurement of magnetic field in the solar atmosphere is extremely important. For strong magnetic field, Zeeman effect has long been used in the solar photosphere and chromosphere, and is being testified for the transition region. For weak magnetic field measurement, Hanle effect can be utilized^[1]. Spectral lines are formed in a relatively narrow height range in these atmospheric layers, so the local magnetic field can be obtained directly. However, for the corona, where magnetic field directly controls the plasma kinematics, optical emission lines are optically thin, and the traditional

techniques do not work so well^[2]. Although some techniques have been developed to extrapolate the coronal magnetic field based on photospheric magnetograms, the extrapolation is an ill-posed problem anyway. Therefore, it is imperative to develop alternative approaches to probe the coronal magnetic field, such as gyroresonance radio emissions.

Ubiquitous perturbations in the corona would propagate in the form of MHD waves in the quiet Sun or trigger the oscillations of coronal structures, such as prominences and coronal loops, caused by the trapped MHD waves. The phase speeds of the propagating waves or the standing waves are determined by the local magnetic field and/or temperature. Thus, either the propagation speed or the oscillation period provides effective information to diagnose the magnetic field in the corona,

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which gives rise to a new discipline, i.e, coronal seismology^[3].

In the early 1960s, Moreton & Ramsey^[4] discovered a kind of arc-shaped chromospheric perturbations propagating away from big flares to a distance $> 5 \times 10^5$ km, later called Moreton waves. According to Uchida^[5], Moreton waves were due to coronal fast-mode waves sweeping the chromosphere, and they can be used to reconstruct the Alfvén velocity, hence the magnetic field distributions in the corona. In contrast to this large-scale waves, localized MHD waves were also found to be trapped in coronal loops and prominences (see ref. [6] for a review).

Coronal loop/prominence oscillations provide the diagnosis of the local magnetic field, whereas Moreton waves provide the magnetic field information on a relatively larger scale. Both phenomena cover only a small part of the solar surface. However, EIT waves, which were discovered in the coronal mass ejection (CME) event on 1997 May 12, offer a perfect opportunity for the magnetic field diagnosis on a global scale.

1 EIT waves: Observations and modelings

After the launch of the SOHO satellite in late 1995, one of its payloads, the EUV Imaging Telescope (EIT), detected an almost circular front propagating outward from the source active region in the CME/flare event on 1997 May 12^[7]. More frequently, they are present as propagating patches, rather than circular fronts. Such a wave phenomenon is often referred to as “EIT wave”, but occasionally called “coronal wave” by some authors (e.g., ref. [8]). EIT wave fronts, with an emission enhancement ranging from a few to tens of percent, are always followed immediately by expanding EUV dimmings in the base difference images^[9]. Therefore, EIT waves and dimmings are considered symbiotic phenomena which require a common physical process in any theoretical model^[10].

Since EIT waves and dimmings are found visible in several EUV bands, they are believed to result mainly from density enhancement and depletion, respectively, although Wills-Davey & Thompson^[11]

and Chen & Fang^[12] pointed out that the temperature variation also plays a role in determining the EUV intensity. The statistical study by Klassen et al.^[13], using SOHO/EIT observations, indicates that the typical velocities of EIT waves range from 170 to 350 km·s⁻¹, with a mean value of 271 km·s⁻¹. Note that the EIT wave velocity can be as slow as 50 km·s⁻¹ or even smaller^[14]. According to recent research by Long et al.^[15], who analyzed the high-cadence EUV observations by STEREO satellite, the low cadence of the SOHO/EIT observations smoothed the EIT wave velocity evolution, i.e, the maximum velocity was underestimated and the low velocity was overestimated. Therefore, a renewed statistics of EIT wave velocities, based on the high cadence observations of STEREO/SECCHI, is strongly recommended.

The discovery of EIT waves immediately reminded the researchers of the coronal counterparts of H α Moreton waves, and so they were explained in terms of fast-mode MHD waves in the corona^[9,16,17], though there were arguments whether the fast-mode waves originate from the flare or the CME^[18,19]. However, the fast-mode wave model can not account for the following observational features: (1) Even considering that the high-cadence observations may upgrade the statistical results made by Klassen et al.^[13], the EIT wave velocities are still significantly smaller than those of Moreton waves, which are truly fast-mode; (2) EIT waves may stop at the footpoints of the magnetic separatrix^[20]; (3) EIT wave velocities are anti-correlated with the speeds of the corresponding type II radio bursts^[13]; (4) EIT waves accelerate from ~ 20 km·s⁻¹ near the source active region to more than 400 km·s⁻¹ in the quiet region^[15].

In order to reconcile these discrepancies, Chen et al.^[21,22] proposed a field-line stretching model, i.e, as the strongly twisted flux rope erupts to form a CME, a fast-mode piston-driven shock propagates outward, which corresponds to the coronal counterpart of H α Moreton wave. At the same time, the erupting flux rope pushes the overlying magnetic loop successively. The stretching of each magnetic loop leads to an EIT wave front on the outer side and density depletion inside the magnetic loop.

Therefore, the model explains the EIT waves and dimmings simultaneously. The field-line stretching model can account for all the four features mentioned above, and was supported by imaging and spectroscopic observations^[23].

3 EIT waves as a tool for coronal seismology

Since EIT waves propagate across almost the entire solar disk in many events, they are the ideal tool for the global magnetic field diagnosis. As for other wave phenomena, how EIT waves are used for coronal seismology depends on the identification of the wave mode. If they are fast-mode MHD waves, the magnetic field reconstruction would be the same as used for Moreton waves. Within such a framework, several groups tried to reconstruct the global magnetic field distribution^[24]. Considering the discrepancies between the fast-mode wave model and the observations, we have proposed a magnetic field-line stretching model, as described in Sec. 2. In this section, we discuss how EIT waves can be used for coronal seismology in the framework of our field-line stretching model.

The sketch of our model is depicted in Figure 1, where the thick curved lines are the initial magnetic field lines. As the flux rope (*the circles*) moves upward, it pushes the top part of the first field line near point *A*, and this local part expands outward. As shown in Figure 1(a), the expan-

sion would be transferred along the field line to its footpoints *C* and *E*, with the Alfvénic velocity v_A . The expansion near the footpoints *C* and *E* compresses the plasma on the outer side, which produces the first EIT wave front. At the same time, the local expansion near point *A* would also be transferred upward to the top part of the second magnetic field line, near point *B*, with the fast-mode wave velocity ($v_f = \sqrt{v_A^2 + v_s^2}$, where v_s is the sound speed) since it is perpendicular to the field lines, as illustrated by the right panel. Thus the top part of the second field line near point *B* expands. Again, the local expansion, as a kind of perturbation, would be transferred along the second field line to its footpoints *D* and *F*, with the Alfvénic velocity v_A . Thereby, a second EIT wave front is formed near points *D* and *F*. With such a repeating circle, progressing EIT wave fronts are formed as outer field lines are pushed to expand successively. Note that the successive expansion of the magnetic loops naturally leads to expanding dimming regions behind the EIT wave fronts. The apparent velocity of the EIT wave in the model is the distance between two successive EIT wave fronts, e.g., *CD*, divided by the time difference between the formation of the two successive EIT wave fronts, Δt . This is to say, the EIT wave apparent velocity near points *C* and *D* is related to the magnetic field by $v_{\text{EIT}} = CD/\Delta t$, where $\Delta t = \int_A^B 1/v_f ds + \int_B^D 1/v_A ds - \int_A^C 1/v_A ds$.

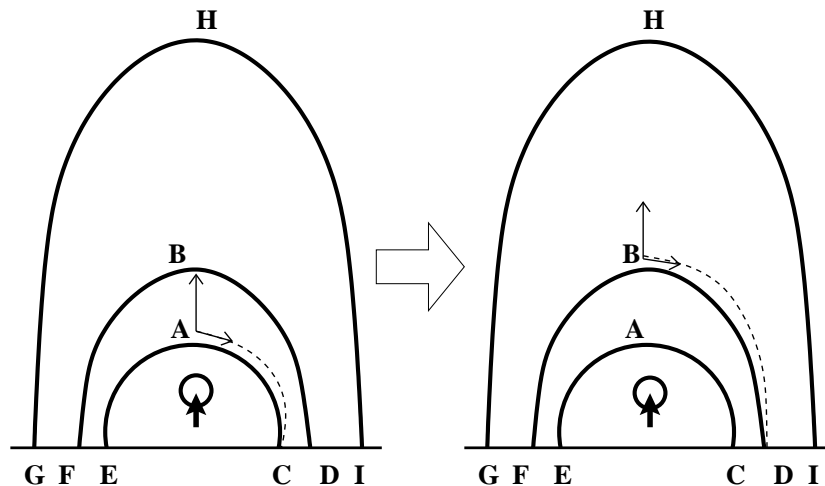


Figure 1 The sketch of our field-line stretching model for EIT waves^[21].

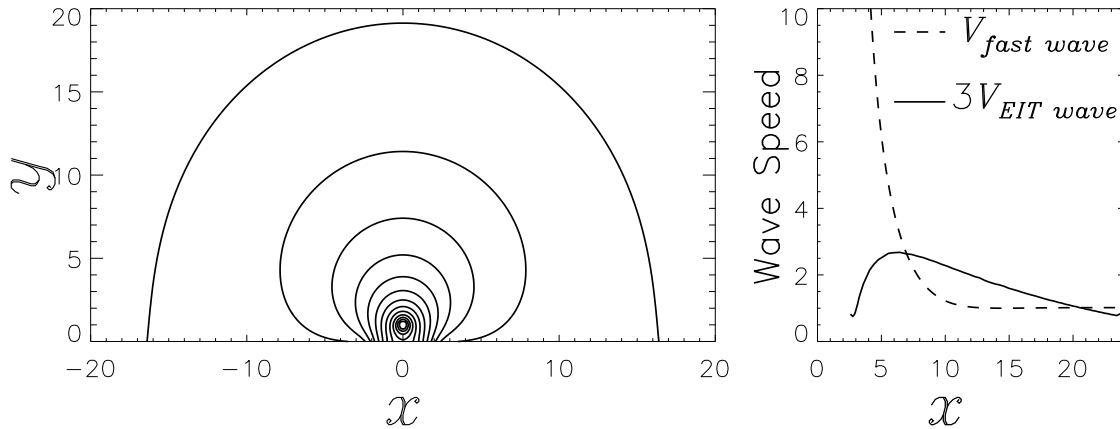


Figure 2 (a) A magnetic configuration with an active region surrounded by potential field; (b) the corresponding distributions of the fast-mode wave and EIT wave velocities along the surface. The unit of the velocity is $900 \text{ km}\cdot\text{s}^{-1}$.

As demonstrated by Chen et al.^[21], if the magnetic field lines are concentric semicircles, the resulting v_{EIT} is about $0.34v_f$. For any given magnetic configuration, the EIT wave velocity distribution can be analogically derived by the above formula. For example, Figure 2(a) depicts the magnetic configuration for an active region surrounded by a potential bipolar field. The corresponding EIT wave velocity and the fast-mode wave velocity distributions are plotted in the Figure 2(b). The EIT waves are seen to accelerate near the boundary of the source active region. This feature is consistent with the recent observation^[15], but which cannot be interpreted by the fast-mode wave model.

We can adjust the coronal magnetic configuration so that the resulting EIT wave velocity distribution can best match the observational one. In this way, the coronal magnetic field distribution can be reconstructed. This procedure, which is forward modeling, is demonstrated here to be eligible. The inverse modeling, i.e., to derive the 3D coronal magnetic field directly from the observed

EIT wave velocity distribution, similar to the techniques used in helioseismology, deserves substantial further studies.

4 Prospects

As the largest-scale wave phenomenon in the corona, EIT waves offer an ideal opportunity to probe the coronal magnetic field. As proposed in our field-line stretching model, the formation of each EIT wave front conveys the magnetic information in 3D space, all the way from the erupting flux rope to the top of each field line, and then along the field line to its footpoints. Therefore, similar to the p -mode waves in the helioseismology, EIT waves can be used to probe the 3D distribution of the coronal magnetic field, providing that high-cadence EUV imaging observations are available. In this paper, we demonstrated the feasibility of the forward modeling of the coronal seismology based on EIT wave. However, the inverse modeling, i.e., the direct inversion from EIT wave velocity evolution to the coronal magnetic field, deserves further investigation.

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