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Possible Method for Determining Direction of Motion of Coronal Mass Ejections

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1. Abstract

This article presents a possible method of determining the direction of motion of a coronal mass ejection (CME) by measuring the secular (perspective) acceleration and radial velocity. The method is already used in stellar astronomy for measuring the proper motions of stars. In solar physics the direction and propagation of CMEs is one of the most discussed topics in space weather phenomena. Using the appropriate methodology is crucial for finding different approaches to estimate the direction and position of Earth directed CMEs.

Keywords: Coronal mass ejections (CMEs), kinematics, secular (perspective) acceleration.

2. Introduction

In many astronomical fields, there is the underlying problem of determination of the real velocity and direction of movement of a heavenly body. The problem is difficult to solve, especially in case of CMEs. The ejected material is not a point-like so the morphology cannot be clearly identified from a series of photographs which is the case for other celestial bodies. Additional problems are generally a non-uniform motion, changes in morphology and internal motions. Several methods have been developed to determine CME kinematics to an extent, such as: the Point-P [Howard et al., 2006], Fixed-Φ [Kahler and Webb, 2007], harmonic mean-HM [Lugaz et al., 2009] and visual fitting method [Wood et al., 2009; Maloney et. al., 2009]. Satellites, for example Solar and Heliospheric Observatory (SOHO) [Brueckner et. al. 1995], Solar Terrestrial Relations Observatory (STEREO) [Kaiser et al., 2008] and Parker Solar Probe [Fox et al., 2016], are a source of observational data. Two STEREO spacecrafts provide stereoscopic imaging of the solar phenomena, which enables more accurate forecasting of CMEs interaction with Earth.

3. The method based on secular acceleration

This method does not require stereoscopic observations. Observations by one satellite are sufficient, based on the assumption that by observing a certain feature of a CME, it is possible to determine its position on the celestial sphere and its radial velocity very accurately. Assuming that a recognizable feature at a given time interval of the observations moves uniformly, the problem is uniquely solvable. The method is related to a study of the proper motion of stars and the effect of perspective (secular) acceleration [Green, 1988; Perryman, 2009].
Figure 1 shows the observing body (or any of its recognizable features) uniformly moving along a straight line with velocity V from position X' to position X. The coordinate system was chosen in such manner that its origin O (in which is the observer) and the velocity vector V are in the same plane. Coordinate x-axis is perpendicular to the velocity vector of the body. The distance of body in its position X' is r. That distance and the angle θ indicated in Figure 1, define the position of the body in the selected coordinate system.

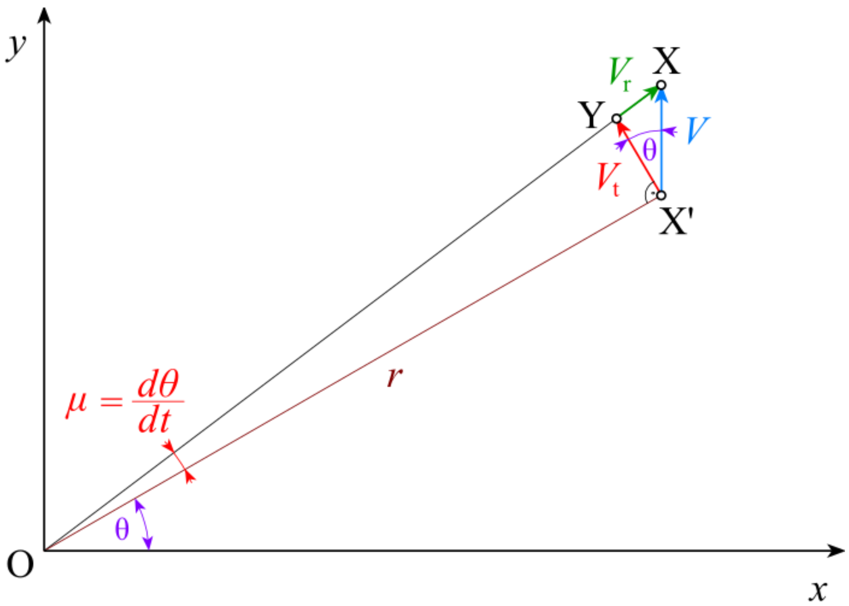

Figure 1. *Radial (V_r) and transversal (V_t) velocity component of the body.*

Distance X'X which body traverses over a selected time interval of observations is very small in comparison to the distance *r*. Therefore, in the first approximation, the velocity of angular displacement of the body on the celestial sphere (μ) can be considered constant:

$$\mu = \frac{d\theta}{dt} = \text{const.}$$

We can decompose the velocity of the body into the radial component V_r that is given as:

$$V_r = \frac{dr}{dt} \tag{1}$$

and transversal component given with expression:

$$V_t = r\frac{d\theta}{dt} \tag{2}$$

From the Figure 1 we see that these components relate to the velocity *V* of the body with following expressions:

$$\begin{aligned} V_r &= V\sin\theta \\ V_t &= V\cos\theta \quad . \end{aligned} \tag{3a, b}$$

Assuming that the angle μ is small, the transversal component is:

$$\mathrm{tg}\mu \approx \mu(\mathrm{rad}) = \frac{\overline{\mathrm{YX'}}}{r}$$

Distance YX' can be expressed as the product of the transversal velocity component (V_t) and the associated time □*t*. Than we have:

$$\mu(\mathrm{rad}) = \frac{V_t \Delta t}{r} \tag{4}$$

Let us find now the expression for change of angular displacement. Taking into account the expression (2), we can rewrite the equation (3b) in the form:

$$V \cos\theta = r \frac{d\theta}{dt}$$

By differentiating, we get:

$$-V \sin\theta \frac{d\theta}{dt} = \frac{dr}{dt}\frac{d\theta}{dt} + r\frac{d^2\theta}{dt^2}$$

As $\mu = d\theta/dt$ and $V\sin\theta = dr/dt = V_r$, we easily derive an expression:

$$\frac{d\mu}{dt} = -\frac{2\mu}{r}V_r \tag{5}$$

The expression (5) represents a change of angular displacement that is called secular or perspective acceleration. If we are able to perform sufficiently accurate measurements of the displacement of the body and to determine the amount of the secular acceleration ($\Delta\mu/\Delta t$), then it is possible to exactly determine the velocity and direction of motion of the body. Let us suppose that μ is the measured average displacement of the body in the observed time interval Δt. Using the expression (5) we find the distance to the body is:

$$r = |r| = \frac{2\bar{\mu}V_r}{\frac{\Delta\mu}{\Delta t}}$$

where the radial velocity is determined from the spectral measurements. Knowing the distance, we can find (using the expression (4)) the tangential velocity component (V_t). Direction of the motion is determined by the angle θ, which can be found using the formula:

$$\theta = \arctan\left(\frac{V_r}{V_t}\right) \tag{6}$$

which follows from the expression (3a, b). The velocity V is given by expression:

$$V = \sqrt{V_t^2 + V_r^2} \tag{7}$$

which follows directly from Figure 1, or from the expressions (3a, b).

4. Conclusions

The method based on secular acceleration makes it possible to determine the real velocity of the observed feature, its distance and direction of motion, which is important for space weather forecasting. The difficulty is that the method requires accurate astrometric and spectroscopic measurements. In the following research, we will try to apply the method to specific observational data.

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