Multi-frequency translucency of perturbed stellar corona by signals of discrete space sources

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Received April 30, 2024
Revised July 14, 2024
Accepted October 30, 2024

Boundary-value trajectory problem has been solved for diagnostics of localized plasma ejections of stellar corona based on data from multi-frequency electromagnetic translucency by signals of discrete space sources. System of light equations in spherical case has been taken as original and added by equation for calculation of signal group delay. Solution has been received in approximation of disturbance method with take into account of strong trajectory variations. Functional relations linking of group delays of signals of translucency on various working frequency with parameters of 3d-dimention structure of stellar corona ejection has been received. Opportunity of determination of density of regular frontal part of ejection according to the data of multi-frequency measurements of group delays of signals of translucency is shown. For estimation of parameters of coronal ejection it's recommend to use data of measurements of group delays of signals of translucency in radio-range and data of optical observations.

Keywords: stellar corona, discrete sources, translucency, plasma perturbations, diagnostics, geometrical optics.

DOI: 10.61011/TP.2024.12.60402.342-24

Introduction

Recently, multichannel astronomy methods have been successfully used for the comprehensive study of deep space objects [1]. Due to the intensive development of all-wave precision equipment for the ground and space segments, observations of stellar plasma emissions have become possible [2,3]. Significant results in this direction have previously been achieved for the nearest star — the Sun. The characteristics of solar coronal mass ejections (CME) were mainly obtained using white-light coronographs installed on board of space observatories (SOHO, SDO, PSP, Solo and others). An additional opportunity for CME surveys was the results of radio tracking from spacecrafts and observations of radio emission from remote space sources passing through the corona. To determine the parameters of solar CMEs, approximate analytical formulas for various tracking characteristics were obtained, representing integrals along rectilinear beam trajectories.

In this paper, for the diagnosis of stellar CME based on multi-frequency tracking data from discrete space sources, functional relationships are obtained that take into account significant curvatures of tracking trajectories, which makes it possible, together with optical observation data, to determine the parameters of a stellar ejection with a large gradient of its leading edge.

1. Initial functional ratios and models

To restore the parameters of the coronal ejection from the tracking data, a curved path integral was considered for the group delay of the signal at various operating frequencies:

$$\tau(f) = \frac{1}{c}\int\limits_{(S)} \frac{dS}{\sqrt{\varepsilon(R,\varphi,\delta,f)}}, \tag{1}$$

where $\varepsilon(R,\varphi,\delta,f)$ — dielectric permittivity of the circumstellar plasma; R,φ,δ — radial and angular beam coordinates, respectively; c — light velocity; f — operating frequency of discrete source. In the spherical coordinate system with the origin in the stellar center the arc element dS is expressed as

$$dS = dR\sqrt{1 + R^2(d\varphi/dR)^2 + R^2(d\delta/dR)^2}.$$

Tracking trajectories are solutions to a system of ray equations [4]:

$$\frac{dR}{d\varphi} = R\,\mathrm{ctg}\beta,$$

$$\frac{d\beta}{d\varphi} = \frac{1}{2\varepsilon}\left(1+\sin^2\beta\,\mathrm{tg}^2\alpha\right)\left(\frac{\partial\varepsilon}{\partial\varphi}\,\mathrm{ctg}\beta - R\,\frac{\partial\varepsilon}{\partial R}\right) - 1,$$

$$\frac{d\delta}{d\varphi} = \mathrm{tg}\,\alpha,$$

$$\frac{d\alpha}{d\varphi} = \frac{1}{2\varepsilon}\left(1+\cos^2\alpha\,\mathrm{ctg}^2\beta\right)\left(\frac{\partial\varepsilon}{\partial\delta} - \frac{\partial\varepsilon}{\partial\varphi}\,\mathrm{tg}\,\alpha\right). \tag{2}$$

Here β,α — beam refraction angles. The dielectric constant of the perturbed stellar corona was represented as the sum of:

$$\varepsilon = \varepsilon_0(R) + \varepsilon_1(R,\varphi,\delta),$$

where ε_0 function describe the unperturbed stellar corona, ε_1 characterizes the plasma ejection. As a model ε_0 the dependence was used

$$\varepsilon_0 = 1 - \left(\frac{f_{pl}}{f}\right)^2 \left(\frac{R_m}{R}\right)^2. \quad (3)$$

To assess the possibility of CME survey based on the tracking data, a stationary plasma disturbance was considered at the first stage

$$\varepsilon_1 = \mu \left(\frac{f_{pl}}{f}\right)^2 \left(\frac{R_m}{R}\right)^2 \exp\left[-\left(\frac{R-R_L}{a_R}\right)^2 - \left(\frac{\varphi-\varphi_L}{a_\varphi}\right)^2 - \left(\frac{\delta-\delta_L}{a_\delta}\right)^2\right], \quad (4)$$

where $R_m = 5R_s$ (R_s — stellar radius); f_{pl} — plasma frequency at level R_m; $\mu, R_L, \varphi_L, \delta_L, a_R, a_\varphi, a_\delta$ — accordingly, the intensity, localization coordinates, and scale of the plasma release.

2. Determination of the density of the frontal part of a coronal stellar ejection

The variation of the group delay of the discrete source signal caused by the effect of plasma emission was determined in the approximation of the perturbation method. In equations (1), (2) the following expansions were used:

$$\tau = \tau_0 + \tau_1, \quad R = R_0 + R_1, \quad \delta = \delta_0 + \delta_1,$$
$$\beta = \beta_0 + \beta_1, \quad \alpha = \alpha_0 + \alpha_1,$$

where $\tau_0, R_0, \delta_0, \beta_0, \alpha_0$ — signal characteristics in the unperturbed corona; $\tau_1, R_1, \delta_1, \beta_1, \alpha_1$ — their variations. Given the boundary conditions for variation of trajectory $R_1(\varphi)$ in points of acceptance and radiation $R_1(\varphi_n = 0) = R_1(\varphi_k) = 0$ (here φ_n, φ_k — the angular coordinates of the discrete source and receiver, respectively), as a first approximation, for perturbation of the group delay of the tracking signal from the equation (1) we have

$$\tau_1(f) = \frac{1}{c}\int_0^{\varphi_k}\left(\frac{2\sin\beta_0}{\sqrt{\varepsilon_0(R_0)}}\left(1+\frac{d\beta_0}{d\varphi}\right)R_1 - \frac{R_0}{2\sin\beta_0} \times \frac{\varepsilon_1(R_0,\varphi,\delta_0)}{\varepsilon_0(R_0)\sqrt{\varepsilon_0(R_0)}}\right)d\varphi. \quad (5)$$

As can be seen from (5), to calculate the variation of the group delay, it is necessary to take into account the change in the trajectory $R_1(\varphi)$. This additive was determined by the perturbation method:

$$R_1 = -\frac{1}{Y_1(\varphi_k)}\left[Y_1(\varphi)\int_\varphi^{\varphi_k} DY_2(\varphi)\frac{R_n}{R_0}\,d\varphi + Y_2(\varphi) \times \int_0^\varphi DY_1(\varphi)\frac{R_n}{R_0}\,d\varphi\right], \quad (6)$$

where

$$D = \frac{1}{2}\left[\operatorname{ctg}\beta_0 \frac{\partial}{\partial\varphi}\left(\frac{\varepsilon_1(R_0,\varphi,\delta_0)}{\varepsilon_0(R_0)}\right) - R_0\frac{\partial}{\partial R_0}\left(\frac{\varepsilon_1(R_0,\varphi,\delta_0)}{\varepsilon_0(R_0)}\right)\right],$$

$$Y_1 = \frac{\partial R_0}{\partial\beta_n}(\varphi), \quad Y_2 = \frac{\partial R_0}{\partial\beta_n}(\varphi_k - \varphi),$$

β_n — ray incident angle on the stellar crown; R_n — the radial coordinate of the discrete source. Assuming that spatial scale of the plasma medium between a discrete cosmic source and a receiver significantly exceeds the scale of a stellar CME, the integral (5) taking into account (6) can be approximately calculated by the Laplace method:

$$\tau_1 = \left[B_1(\varphi_s) + 2\frac{B_2(\varphi_s)}{a_R^2}\left(R_0(\varphi_s) - R_L\right)\right]\mu\left(\frac{f_{pl}}{f}\right)^2 \times \left(\frac{R_m}{R_0(\varphi_s)}\right)^2 \exp\left[-\left(\frac{R_0(\varphi_s)-R_L}{a_R}\right)^2 - \left(\frac{\varphi_s-\varphi_L}{a_\varphi}\right)^2\right] \times \sqrt{\pi\left(a_\varphi^{-2} + a_R^{-2}\left(\left(\frac{dR_0(\varphi_s)}{d\varphi}\right)^2 + \left(R_0(\varphi_s)-R_L\right)\left(\frac{d^2R_0(\varphi_s)}{d\varphi^2}\right)\right)\right)^{-1}}, \quad (7)$$

where φ_s — angular coordinate of the largest contribution;

$$P_1(\varphi) = F_1(\varphi)Y_1(\varphi), \quad P_2(\varphi) = F_1(\varphi)Y_2(\varphi),$$

$$F_1(\varphi) = \frac{2\sin\beta_0}{\sqrt{\varepsilon_0(R_0)}}\left(1+\frac{d\beta_0}{d\varphi}\right),$$

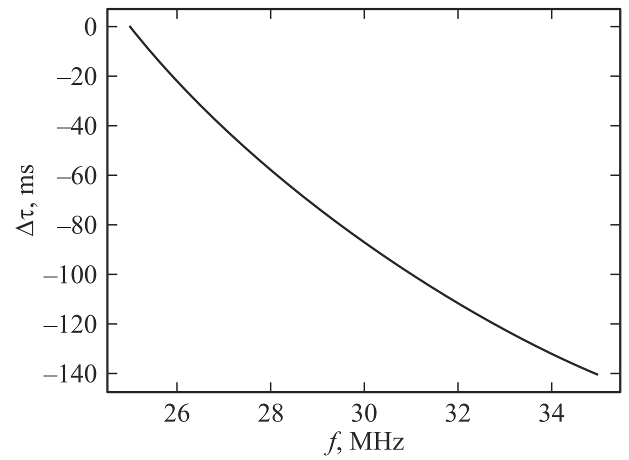
$$F_2(\varphi) = \frac{R_0}{2\sin\beta_0\varepsilon_0(R_0)\sqrt{\varepsilon_0(R_0)}},$$

$$B_1 = F_2 + VQ, \quad B_2 = \frac{VR_2}{2\varepsilon_0\sin^2\beta_0},$$

$$V = \frac{1}{Y_1(\varphi_k)R_0}\left(Y_2(\varphi)\int_0^\varphi P_1(\varphi')d\varphi' + Y_1(\varphi)\int_\varphi^{\varphi_k} P_2(\varphi')d\varphi'\right),$$

$$Q = \frac{1}{2}\frac{R_0}{\varepsilon_0^2}\frac{\partial\varepsilon_0}{\partial R_0}.$$

The spatial parameters of CME included in (7) can be determined based on optical observation data. Then, ejection tracking by signals at different frequencies of the radio band allows us to determine the parameter μ, characterizing maximum disturbance of the ejection, in terms of difference in group delays. When there's a strong gradient in the front part of ejection, this difference will not be zero, since radio waves experience significant refraction at the perturbation front. As for characteristics of the undisturbed trajectories included in (7), they can be calculated using ray equations(2) for a given model of an undisturbed stellar corona (3). From formula (7) It follows that variation of the group delay time decreases with increasing operating frequency. At lower frequencies, maximum variations τ_1



Relative group delays of CME tracking signals of a sun-like star at various radio frequencies.

occur, corresponding to trajectories passing near the leading edge of the coronal ejection. The increase in group delay variations directly follows from formula(5), which includes the perturbation of the trajectory $R_1(\varphi)$ and the dielectric constant function of the ejection $\varepsilon_1(R_0, \varphi, \delta_0)$. The trajectory integral over perturbation ε_1 depends on the length of the beam path inside plasma ejection and increases as it grows. Correction $R_1(\varphi)$ depends on the function $D(\varphi)$, which, in its turn, is defined by spatial gradients $\varepsilon_1(R_0, \varphi, \delta_0)$. For the coronal disturbance model (4) the greatest variation $R_1(\varphi)$ occurs in case of ejection tracking near its leading edge, rather than inside it, where the dielectric permittivity gradient is significantly lower.

As an example, the figure shows the results of calculations of differences in variations of the group delays of CME tracking signals of a sun-like star at various frequencies and the variations in the signal delay at a certain reference frequency of $f = 25$ MHz. The following model (3), (4) parameters are selected: $f_{pl} = 15$ MHz; $\mu = 1.7$; $R_L = 5R_s$ (R_s — star radius); $\varphi_L = 0.4$ rad; $a_R = 0.15R_s$; $a_\varphi = 0.63$ rad. Angular coordinate of the receiver was $\varphi_k = 1.74$ rad.

It is easy to see that the relative group delays of radio signals vary significantly even within a narrow frequency band 25–35 MHz. This indicates a high sensitivity of the radio transmission signals to CME parameters.

Conclusion

The boundary trajectory problem of stellar CME tracking by signals from discrete space sources has been solved. Approximate analytical relations linking the group delays of the signals with the CME parameters are obtained. The possibility of determining the density of the regular frontal part of an injection based on multi-frequency measurements of the tracking signals group delays in the radio band is shown. The combined use of optical observations of the stellar CME spatial structure and radio measurements of the group delays of tracking signals makes it possible to estimate the disturbance parameters.

Funding

The study has been supported by the Ministry of Education and Science of Russia (projects FZZE-2023-0004, FZZE-2024-0005).

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] A.M. Cherepaschuk (rev.) *Mnogokanalnaya astronomia* („Vek 2“, Fryazino, 2019) (in Russian)
[2] C. Argiroffi, F. Reale, J.J. Drake, A. Ciaravella, P. Testa, R. Bonito, M. Miceli, S. Orlando, G. Peres. Nature Astronomy, **3**, 742 (2019). DOI: 10.1038/s41550-019-0781-4
[3] J.D. Alvarado-Gómez, J.J. Drake, O. Cohen, S.P. Moschou, C. Garraffo. Astronom. J., **862** (2), 12 (2018). DOI: 10.3847/1538-4357/aacb7f
[4] Yu.A. Kravtsov, Yu.I. Orlov. *Geometrical Optics of Inhomogeneous Medium* (Springer-Verlag, Berlin, 1990)

Translated by T.Zorina