

# Doppler effect, speed of the light, stellar velocity and distance

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## Abstract

Calculating the distance of a star from Earth using stellar parallax makes sense only in two cases. In the first case, this is possible if the object we are observing is stationary in relation to the Sun and in the second case if the measurements are made simultaneously, but from two different locations. We will consider the case when the star moves uniformly with respect to the Sun. By measuring the Doppler effect at three different points, we will be able to determine the speed of light emitted from the star in the direction of the observer, the velocities at which the star and Sun move regarding the referential coordinate system and finally we will calculate the distance between the star and the observer.

**Keywords:** *Doppler effect, speed of light, stellar velocity, stellar distance*

## 1. Introduction

Suppose that the sender  $S$  and receiver  $A$  of the signal move uniformly at velocities  $\mathbf{u}$  and  $\mathbf{v}$ , respectively regarding to the coordinate system  $(K)$ .

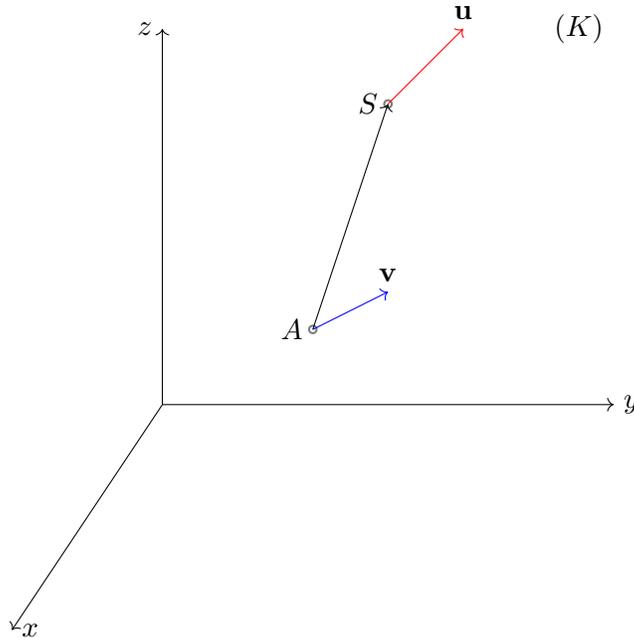


Figure 1: The sender  $S$  and the observer  $A$  move uniformly with respect to the coordinate system  $(K)$

Referring to Fig[1] we have that:

$$\mathbf{a} = [a_x, a_y, a_z] = \frac{\mathbf{AS}}{\|\mathbf{AS}\|} \quad (1)$$

$$\mathbf{u} = [u_x, u_y, u_z] \quad (2)$$

$$\mathbf{v} = [v_x, v_y, v_z] \quad (3)$$

$$u_r = \mathbf{a} \cdot \mathbf{u} = a_x u_x + a_y u_y + a_z u_z \quad (4)$$

$$v_r = \mathbf{a} \cdot \mathbf{v} = a_x v_x + a_y v_y + a_z v_z \quad (5)$$

The positive direction is directed from the observer toward the sender.

If  $\|\mathbf{v}\| < c$  and  $\|\mathbf{u}\| < c$ , then Doppler equation [1] can be written as it follows:

$$f' = \frac{c + v_r}{c + u_r} f = \frac{c + \mathbf{a} \cdot \mathbf{v}}{c + \mathbf{a} \cdot \mathbf{u}} f \quad (6)$$

where

$f$  - the frequency of the emitted light  
 $f'$  - the frequency of the observed light  
 $c$  - the speed of light

From the equation (6) it follows that:

$$c + \mathbf{a} \cdot \mathbf{u} = \frac{f}{f'} (c + \mathbf{a} \cdot \mathbf{v}) \quad (7)$$

$$\mathbf{a} \cdot \mathbf{u} = \frac{f - f'}{f'} c + \frac{f}{f'} \mathbf{a} \cdot \mathbf{v} \quad (8)$$

$$a_x u_x + a_y u_y + a_z u_z = \frac{f - f'}{f'} c + \frac{f}{f'} \mathbf{a} \cdot \mathbf{v} \quad (9)$$

## 2. The heliocentric coordinate system as a referential coordinate system

Suppose that the observed star  $Z$  is moving with a uniform, rectilinear space motion noted by  $\mathbf{u}$  regarding the coordinate system ( $K$ ) Fig[2]. We will assume that the observed object belongs to the Milky Way Galaxy. Let us denote by  $\tau_A$  the time when the signal was sent from the point noted by  $Z_1$  and by  $t_A$  the time when the signal is registered at point noted by  $A$ . We assume that  $\tau_A$  and  $t_A$  are expressed in the same units of time. The unit vector of the direction  $AZ_1$  is denoted by  $\hat{\mathbf{a}}$ . In an analogous way, we will define triples  $(\tau_B, t_B, \hat{\mathbf{b}})$  and  $(\tau_C, t_C, \hat{\mathbf{c}})$  for pairs of points  $(B, Z_2)$  and  $(C, Z_3)$ , respectively.

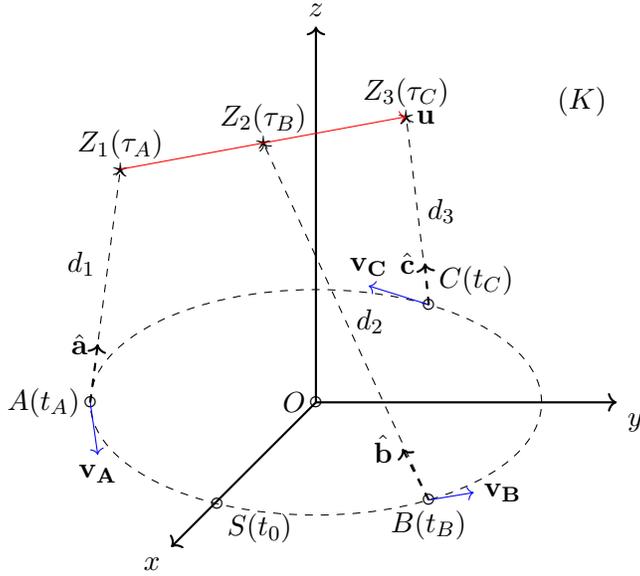


Figure 2: Star  $Z$  moves uniformly regarding the sun.

Coordinate system  $(K)$  is heliocentric ecliptic coordinate system. Coordinate axes are determined in accordance with the *ICRS* standard. Referring to Fig[2] we have that:

$$d_1 = \|\mathbf{AZ}_1\| \quad (10)$$

$$d_2 = \|\mathbf{BZ}_2\| \quad (11)$$

$$d_3 = \|\mathbf{CZ}_3\| \quad (12)$$

$$\mathbf{A} = \mathbf{OA} = [A_x, A_y, A_z] \quad (13)$$

$$\mathbf{B} = \mathbf{OB} = [B_x, B_y, B_z] \quad (14)$$

$$\mathbf{C} = \mathbf{OC} = [C_x, C_y, C_z] \quad (15)$$

$$\hat{\mathbf{a}} = [a_x, a_y, a_z] = \frac{\mathbf{AZ}_1}{\|\mathbf{AZ}_1\|} \quad (16)$$

$$\hat{\mathbf{b}} = [b_x, b_y, b_z] = \frac{\mathbf{BZ}_2}{\|\mathbf{BZ}_2\|} \quad (17)$$

$$\hat{\mathbf{c}} = [c_x, c_y, c_z] = \frac{\mathbf{CZ}_3}{\|\mathbf{CZ}_3\|} \quad (18)$$

### 3. The coordinate system that is stationary with respect to the Galactic Center

By definition, the origin of the *ICRS* coordinate system is at the *barycenter* of the Solar System. This means that in our calculations the velocity, denoted by  $\mathbf{V}$ , at which the solar system is moving relative to the Galactic Center has been omitted. In order to include the velocity  $\mathbf{V}$  in our calculations, we will assume that the origin of the referential coordinate system, denoted by  $(K')$ , is stationary in relation to the Galactic Center. At one moment, which we can mark as some initial time  $T_0$ , the coordinate system  $(K')$  is identical to  $(K)$ , after which  $(K')$  remains fixed in relation to the Galactic Center, while  $(K)$  together with the Solar system, continues to move at velocity  $\mathbf{V}$  in relation to the Galactic Center. We do not yet know the true value of the  $\mathbf{V}$ , but we can take any  $\mathbf{V}$  so that the inequality (20) holds:

$$\mathbf{V} = [V_x, V_y, V_z] \quad (19)$$

$$\|\mathbf{V}\| < M \quad (20)$$

where  $M$  is some previously given positive number

Let's us denote with  $A'$ ,  $B'$  and  $C'$  the points from the coordinate system ( $K'$ ) that correspond to the points  $A$ ,  $B$  and  $C$  from the coordinate system ( $K$ ).

$$\mathbf{A}' = [A'_x, A'_y, A'_z] = \mathbf{A} + t_A \mathbf{V} \quad (21)$$

$$\mathbf{B}' = [B'_x, B'_y, B'_z] = \mathbf{B} + t_B \mathbf{V} \quad (22)$$

$$\mathbf{C}' = [C'_x, C'_y, C'_z] = \mathbf{C} + t_C \mathbf{V} \quad (23)$$

Let us denote by  $\mathbf{v}'_A$ ,  $\mathbf{v}'_B$  and  $\mathbf{v}'_C$  the velocities with which the points  $A'$ ,  $B'$  and  $C'$  move in relation to the coordinate system ( $K'$ ).

$$\mathbf{v}'_A = \mathbf{v}_A + \mathbf{V} \quad (24)$$

$$\mathbf{v}'_B = \mathbf{v}_B + \mathbf{V} \quad (25)$$

$$\mathbf{v}'_C = \mathbf{v}_C + \mathbf{V} \quad (26)$$

Let  $f$  denotes the frequency of the emitted light at points  $Z_1, Z_2$  and  $Z_3$  respectively. Let  $f_A, f_B$  and  $f_C$  denote the frequencies of the observed light at points  $A', B'$  and  $C'$  respectively. Let  $\mathbf{v}'_A, \mathbf{v}'_B$  and  $\mathbf{v}'_C$  denote the velocities of the observed light at points  $A', B'$  and  $C'$  respectively regarding to the coordinate system ( $K'$ ).

From (9) it follows that:

$$a_x u_x + a_y u_y + a_z u_z = \frac{f - f_A}{f_A} c + \frac{f}{f_A} \hat{\mathbf{a}} \cdot \mathbf{v}'_A \quad (27)$$

$$b_x u_x + b_y u_y + b_z u_z = \frac{f - f_B}{f_B} c + \frac{f}{f_B} \hat{\mathbf{b}} \cdot \mathbf{v}'_B \quad (28)$$

$$c_x u_x + c_y u_y + c_z u_z = \frac{f - f_C}{f_C} c + \frac{f}{f_C} \hat{\mathbf{c}} \cdot \mathbf{v}'_C \quad (29)$$

We have obtained a linear system of three equations with three unknowns  $u_x, u_y$  and  $u_z$ .

$$U = \begin{vmatrix} a_x & b_x & c_x \\ a_y & b_y & c_y \\ a_z & b_z & c_z \end{vmatrix} \quad (30)$$

$$U_x = cU'_x + U''_x = \begin{vmatrix} \frac{f-f_A}{f_A} c + \frac{f}{f_A} \hat{\mathbf{a}} \cdot \mathbf{v}'_A & b_x & c_x \\ \frac{f-f_B}{f_B} c + \frac{f}{f_B} \hat{\mathbf{b}} \cdot \mathbf{v}'_B & b_y & c_y \\ \frac{f-f_C}{f_C} c + \frac{f}{f_C} \hat{\mathbf{c}} \cdot \mathbf{v}'_C & b_z & c_z \end{vmatrix} = c \begin{vmatrix} \frac{f-f_A}{f_A} & b_x & c_x \\ \frac{f-f_B}{f_B} & b_y & c_y \\ \frac{f-f_C}{f_C} & b_z & c_z \end{vmatrix} + \begin{vmatrix} \frac{f}{f_A} \hat{\mathbf{a}} \cdot \mathbf{v}'_A & b_x & c_x \\ \frac{f}{f_B} \hat{\mathbf{b}} \cdot \mathbf{v}'_B & b_y & c_y \\ \frac{f}{f_C} \hat{\mathbf{c}} \cdot \mathbf{v}'_C & b_z & c_z \end{vmatrix} \quad (31)$$

$$U_y = cU'_y + U''_y = \begin{vmatrix} a_x & \frac{f-f_A}{f_A} c + \frac{f}{f_A} \hat{\mathbf{a}} \cdot \mathbf{v}'_A & c_x \\ a_y & \frac{f-f_B}{f_B} c + \frac{f}{f_B} \hat{\mathbf{b}} \cdot \mathbf{v}'_B & c_y \\ a_z & \frac{f-f_C}{f_C} c + \frac{f}{f_C} \hat{\mathbf{c}} \cdot \mathbf{v}'_C & c_z \end{vmatrix} = c \begin{vmatrix} a_x & \frac{f-f_A}{f_A} & c_x \\ a_y & \frac{f-f_B}{f_B} & c_y \\ a_z & \frac{f-f_C}{f_C} & c_z \end{vmatrix} + \begin{vmatrix} a_x & \frac{f}{f_A} \hat{\mathbf{a}} \cdot \mathbf{v}'_A & c_x \\ a_y & \frac{f}{f_B} \hat{\mathbf{b}} \cdot \mathbf{v}'_B & c_y \\ a_z & \frac{f}{f_C} \hat{\mathbf{c}} \cdot \mathbf{v}'_C & c_z \end{vmatrix} \quad (32)$$

$$U_z = cU'_z + U''_z = \begin{vmatrix} a_x & b_x & \frac{f-f_A}{f_A}c + \frac{f}{f_A}\hat{\mathbf{a}} \cdot \mathbf{v}'_{\mathbf{A}} \\ a_y & b_y & \frac{f-f_B}{f_B}c + \frac{f}{f_B}\hat{\mathbf{b}} \cdot \mathbf{v}'_{\mathbf{B}} \\ a_z & b_z & \frac{f-f_C}{f_C}c + \frac{f}{f_C}\hat{\mathbf{c}} \cdot \mathbf{v}'_{\mathbf{C}} \end{vmatrix} = c \begin{vmatrix} a_x & b_x & \frac{f-f_A}{f_A} \\ a_y & b_y & \frac{f-f_B}{f_B} \\ a_z & b_z & \frac{f-f_C}{f_C} \end{vmatrix} + \begin{vmatrix} a_x & b_x & \frac{f}{f_A}\hat{\mathbf{a}} \cdot \mathbf{v}'_{\mathbf{A}} \\ a_y & b_y & \frac{f}{f_B}\hat{\mathbf{b}} \cdot \mathbf{v}'_{\mathbf{B}} \\ a_z & b_z & \frac{f}{f_C}\hat{\mathbf{c}} \cdot \mathbf{v}'_{\mathbf{C}} \end{vmatrix} \quad (33)$$

$$u_x = \frac{U_x}{U} = \frac{cU'_x + U''_x}{U} \quad (34)$$

$$u_y = \frac{U_y}{U} = \frac{cU'_y + U''_y}{U} \quad (35)$$

$$u_z = \frac{U_z}{U} = \frac{cU'_z + U''_z}{U} \quad (36)$$

In order to calculate the three unknowns  $u_x$ ,  $u_y$  and  $u_z$ , we first need to determine the speed of light  $c$ . We have the following equations:

$$t_{AB} = t_B - t_A \quad (37)$$

$$\mathbf{A}'\mathbf{B}' = [B'_x - A'_x, B'_y - A'_y, B'_z - A'_z] \quad (38)$$

$$\mathbf{A}'\mathbf{B}' = \mathbf{AB} + t_{AB}\mathbf{V} = [(B_x - A_x) + t_{AB}V_x, (B_y - A_y) + t_{AB}V_y, (B_z - A_z) + t_{AB}V_z] \quad (39)$$

$$\mathbf{Z}_1\mathbf{Z}_2 = -d_1\hat{\mathbf{a}} + \mathbf{A}'\mathbf{B}' + d_2\hat{\mathbf{b}} \quad (40)$$

$$\Delta\tau = \tau_B - \tau_A \quad (41)$$

$$\mathbf{Z}_1\mathbf{Z}_2 = \Delta\tau\mathbf{u} \quad (42)$$

$$d_1\hat{\mathbf{a}} - d_2\hat{\mathbf{b}} + \Delta\tau\mathbf{u} = \mathbf{A}'\mathbf{B}' \quad (43)$$

$$d_1a_x - d_2b_x + \Delta\tau u_x = B'_x - A'_x \quad (44)$$

$$d_1a_y - d_2b_y + \Delta\tau u_y = B'_y - A'_y \quad (45)$$

$$d_1a_z - d_2b_z + \Delta\tau u_z = B'_z - A'_z \quad (46)$$

We have obtained a linear system of three equations with three unknowns  $d_1$ ,  $d_2$  and  $\tau$ .

$$abD = (c)abD' + abD'' = \begin{vmatrix} a_x & -b_x & u_x \\ a_y & -b_y & u_y \\ a_z & -b_z & u_z \end{vmatrix} = \begin{vmatrix} a_x & -b_x & \frac{cU'_x + U''_x}{U} \\ a_y & -b_y & \frac{cU'_y + U''_y}{U} \\ a_z & -b_z & \frac{cU'_z + U''_z}{U} \end{vmatrix} = c \begin{vmatrix} a_x & -b_x & \frac{U'_x}{U} \\ a_y & -b_y & \frac{U'_y}{U} \\ a_z & -b_z & \frac{U'_z}{U} \end{vmatrix} + \begin{vmatrix} a_x & -b_x & \frac{U''_x}{U} \\ a_y & -b_y & \frac{U''_y}{U} \\ a_z & -b_z & \frac{U''_z}{U} \end{vmatrix} \quad (47)$$

$$abD_1 = (c)abD'_1 + abD''_1 = \begin{vmatrix} B'_x - A'_x & -b_x & u_x \\ B'_y - A'_y & -b_y & u_y \\ B'_z - A'_z & -b_z & u_z \end{vmatrix} = c \begin{vmatrix} B'_x - A'_x & -b_x & \frac{U'_x}{U} \\ B'_y - A'_y & -b_y & \frac{U'_y}{U} \\ B'_z - A'_z & -b_z & \frac{U'_z}{U} \end{vmatrix} + \begin{vmatrix} B'_x - A'_x & -b_x & \frac{U''_x}{U} \\ B'_y - A'_y & -b_y & \frac{U''_y}{U} \\ B'_z - A'_z & -b_z & \frac{U''_z}{U} \end{vmatrix} \quad (48)$$

$$AB_d1 = \frac{(c)abD'_1 + abD''_1}{(c)abD' + abD''} \quad (49)$$

$$abD_2 = (c)abD'_2 + abD''_2 = \begin{vmatrix} a_x & B'_x - A'_x & u_x \\ a_y & B'_y - A'_y & u_y \\ a_z & B'_z - A'_z & u_z \end{vmatrix} = c \begin{vmatrix} a_x & B'_x - A'_x & \frac{U'_x}{U} \\ a_y & B'_y - A'_y & \frac{U'_y}{U} \\ a_z & B'_z - A'_z & \frac{U'_z}{U} \end{vmatrix} + \begin{vmatrix} a_x & B'_x - A'_x & \frac{U''_x}{U} \\ a_y & B'_y - A'_y & \frac{U''_y}{U} \\ a_z & B'_z - A'_z & \frac{U''_z}{U} \end{vmatrix} \quad (50)$$

$$AB\_d_2 = \frac{(c) abD'_2 + abD''_2}{(c) abD' + abD''} \quad (51)$$

$$abD_\tau = \begin{vmatrix} ax & -b_x & B'_x - A'_x \\ ay & -b_y & B'_y - A'_y \\ az & -b_z & B'_z - A'_z \end{vmatrix} \quad (52)$$

$$\Delta\tau_{ab} = \frac{abD_\tau}{(c) abD' + abD''} \quad (53)$$

In a similar way for the direction  $\mathbf{A}'\mathbf{C}'$  we will get the following equations:

$$d_1 a_x - d_3 c_x + \Delta\tau u_x = C'_x - A'_x \quad (54)$$

$$d_1 a_y - d_3 c_y + \Delta\tau u_y = C'_y - A'_y \quad (55)$$

$$d_1 a_z - d_3 c_z + \Delta\tau u_z = C'_z - A'_z \quad (56)$$

$$acD = (c) acD' + acD'' = \begin{vmatrix} a_x & -c_x & u_x \\ a_y & -c_y & u_y \\ a_z & -c_z & u_z \end{vmatrix} = \begin{vmatrix} a_x & -c_x & \frac{cU'_x + U''_x}{U} \\ a_y & -c_y & \frac{cU'_y + U''_y}{U} \\ a_z & -c_z & \frac{cU'_z + U''_z}{U} \end{vmatrix} = c \begin{vmatrix} a_x & -c_x & \frac{U'_x}{U} \\ a_y & -c_y & \frac{U'_y}{U} \\ a_z & -c_z & \frac{U'_z}{U} \end{vmatrix} + \begin{vmatrix} a_x & -c_x & \frac{U''_x}{U} \\ a_y & -c_y & \frac{U''_y}{U} \\ a_z & -c_z & \frac{U''_z}{U} \end{vmatrix} \quad (57)$$

$$acD_1 = (c) acD'_1 + acD''_1 = \begin{vmatrix} C'_x - A'_x & -c_x & u_x \\ C'_y - A'_y & -c_y & u_y \\ C'_z - A'_z & -c_z & u_z \end{vmatrix} = c \begin{vmatrix} C'_x - A'_x & -c_x & \frac{U'_x}{U} \\ C'_y - A'_y & -c_y & \frac{U'_y}{U} \\ C'_z - A'_z & -c_z & \frac{U'_z}{U} \end{vmatrix} + \begin{vmatrix} C'_x - A'_x & -c_x & \frac{U''_x}{U} \\ C'_y - A'_y & -c_y & \frac{U''_y}{U} \\ C'_z - A'_z & -c_z & \frac{U''_z}{U} \end{vmatrix} \quad (58)$$

$$AC\_d_1 = \frac{(c) acD'_1 + acD''_1}{(c) acD' + acD''} \quad (59)$$

$$acD_3 = (c) acD'_3 + acD''_3 = \begin{vmatrix} a_x & C'_x - A'_x & u_x \\ a_y & C'_y - A'_y & u_y \\ a_z & C'_z - A'_z & u_z \end{vmatrix} = c \begin{vmatrix} a_x & C'_x - A'_x & \frac{U'_x}{U} \\ a_y & C'_y - A'_y & \frac{U'_y}{U} \\ a_z & C'_z - A'_z & \frac{U'_z}{U} \end{vmatrix} + \begin{vmatrix} a_x & C'_x - A'_x & \frac{U''_x}{U} \\ a_y & C'_y - A'_y & \frac{U''_y}{U} \\ a_z & C'_z - A'_z & \frac{U''_z}{U} \end{vmatrix} \quad (60)$$

$$AC\_d_3 = \frac{(c) acD'_3 + acD''_3}{(c) acD' + acD''} \quad (61)$$

$$acD_\tau = \begin{vmatrix} ax & -c_x & C'_x - A'_x \\ ay & -c_y & C'_y - A'_y \\ az & -c_z & C'_z - A'_z \end{vmatrix} \quad (62)$$

$$\Delta\tau_{ac} = \frac{acD_\tau}{(c) acD' + acD''} \quad (63)$$

For the direction  $\mathbf{B}'\mathbf{C}'$  we will get the following equations:

$$d_2 b_x - d_3 c_x + \Delta \tau u_x = C'_x - B'_x \quad (64)$$

$$d_2 b_y - d_3 c_y + \Delta \tau u_y = C'_y - B'_y \quad (65)$$

$$d_2 b_z - d_3 c_z + \Delta \tau u_z = C'_z - B'_z \quad (66)$$

$$bcD = (c) bcD' + bcD'' = \begin{vmatrix} b_x & -c_x & u_x \\ b_y & -c_y & u_y \\ b_z & -c_z & u_z \end{vmatrix} = \begin{vmatrix} b_x & -c_x & \frac{cU'_x + U''_x}{U} \\ b_y & -c_y & \frac{cU'_y + U''_y}{U} \\ b_z & -c_z & \frac{cU'_z + U''_z}{U} \end{vmatrix} = c \begin{vmatrix} b_x & -c_x & \frac{U'_x}{U} \\ b_y & -c_y & \frac{U'_y}{U} \\ b_z & -c_z & \frac{U'_z}{U} \end{vmatrix} + \begin{vmatrix} b_x & -c_x & \frac{U''_x}{U} \\ b_y & -c_y & \frac{U''_y}{U} \\ b_z & -c_z & \frac{U''_z}{U} \end{vmatrix} \quad (67)$$

$$bcD_2 = (c) bcD'_2 + bcD''_2 = \begin{vmatrix} C'_x - B'_x & -c_x & u_x \\ C'_y - B'_y & -c_y & u_y \\ C'_z - B'_z & -c_z & u_z \end{vmatrix} = c \begin{vmatrix} C'_x - B'_x & -c_x & \frac{U'_x}{U} \\ C'_y - B'_y & -c_y & \frac{U'_y}{U} \\ C'_z - B'_z & -c_z & \frac{U'_z}{U} \end{vmatrix} + \begin{vmatrix} C'_x - B'_x & -c_x & \frac{U''_x}{U} \\ C'_y - B'_y & -c_y & \frac{U''_y}{U} \\ C'_z - B'_z & -c_z & \frac{U''_z}{U} \end{vmatrix} \quad (68)$$

$$BC.d_2 = \frac{(c) bcD'_2 + bcD''_2}{(c) bcD' + bcD''} \quad (69)$$

$$bcD_3 = (c) bcD'_3 + bcD''_3 = \begin{vmatrix} b_x & C'_x - B'_x & u_x \\ b_y & C'_y - B'_y & u_y \\ b_z & C'_z - B'_z & u_z \end{vmatrix} = c \begin{vmatrix} b_x & C'_x - B'_x & \frac{U'_x}{U} \\ b_y & C'_y - B'_y & \frac{U'_y}{U} \\ b_z & C'_z - B'_z & \frac{U'_z}{U} \end{vmatrix} + \begin{vmatrix} b_x & C'_x - B'_x & \frac{U''_x}{U} \\ b_y & C'_y - B'_y & \frac{U''_y}{U} \\ b_z & C'_z - B'_z & \frac{U''_z}{U} \end{vmatrix} \quad (70)$$

$$BC.d_3 = \frac{(c) bcD'_3 + bcD''_3}{(c) bcD' + bcD''} \quad (71)$$

$$bcD_\tau = \begin{vmatrix} b_x & -c_x & C'_x - B'_x \\ b_y & -c_y & C'_y - B'_y \\ b_z & -c_z & C'_z - B'_z \end{vmatrix} \quad (72)$$

$$\Delta\tau_{bc} = \frac{bcD_\tau}{(c) bcD' + bcD''} \quad (73)$$

#### 4. The speed of the light regarding the referential coordinate system

First we will determine which of the two coordinate systems ( $K$ ) or ( $K'$ ) is the referential coordinate system. It follows from equations (49) and (59) that:

$$AB\_d_1 = AC\_d_1 \quad (74)$$

$$\frac{(c) abD'_1 + abD''_1}{(c) abD' + abD''} = \frac{(c) acD'_1 + acD''_1}{(c) acD' + acD''} \quad (75)$$

$$((c) abD'_1 + abD''_1)((c) acD' + acD'') - ((c) acD'_1 + acD''_1)((c) abD' + abD'') = 0 \quad (76)$$

$$\begin{vmatrix} abD'_1 & acD'_1 \\ abD' & acD' \end{vmatrix} c^2 + \left( \begin{vmatrix} abD'_1 & acD'_1 \\ abD'' & acD'' \end{vmatrix} + \begin{vmatrix} abD''_1 & acD''_1 \\ abD' & acD' \end{vmatrix} \right) c + \begin{vmatrix} abD''_1 & acD''_1 \\ abD'' & acD'' \end{vmatrix} = 0 \quad (77)$$

$$A_0 = \begin{vmatrix} abD'_1 & acD'_1 \\ abD' & acD' \end{vmatrix} \quad (78)$$

$$B_0 = \begin{vmatrix} abD'_1 & acD'_1 \\ abD'' & acD'' \end{vmatrix} + \begin{vmatrix} abD''_1 & acD''_1 \\ abD' & acD' \end{vmatrix} \quad (79)$$

$$C_0 = \begin{vmatrix} abD''_1 & acD''_1 \\ abD'' & acD'' \end{vmatrix} \quad (80)$$

$$A_0 c^2 + B_0 c + C_0 = 0 \quad (81)$$

$$c_{1,2} = \frac{-B_0 \pm \sqrt{B_0^2 - 4 A_0 C_0}}{2 A_0} \quad (82)$$

Applying the equations (34),(35) and (36) we can easily calculate the  $u_x$ ,  $u_y$  and  $u_z$ . Applying the equations (49),(51) and (53) we can easily calculate the  $AB\_d_1$ ,  $AB\_d_2$  and  $\Delta\tau_{ab}$ . We will consider only those cases in which  $c_i$ ,  $AB\_d_1$ ,  $AB\_d_2$  and  $\Delta\tau_{ab}$  are greater than zero.

$$\Delta t_{ab} = t_B - t_A \quad (83)$$

$$\frac{AB\_d_1}{c_{AB}} + \Delta T_{ab}(\mathbf{V}) = \frac{AB\_d_2}{c_{AB}} + \Delta\tau_{ab} \quad (84)$$

$$\Delta T_{ab}(\mathbf{V}) = \frac{AB\_d_2}{c_{AB}} + \Delta\tau_{ab} - \frac{AB\_d_1}{c_{AB}} \quad (85)$$

$$\varepsilon(\mathbf{V}) = |\Delta t_{ab} - \Delta T_{ab}(\mathbf{V})| \quad (86)$$

We will define  $\varepsilon_{ab}$  in the following way:

$$\varepsilon_{ab} = \min\{|\varepsilon(\mathbf{V})|, \|\mathbf{V}\| < M\} \quad (87)$$

If  $\varepsilon_{ab}$  is much smaller compared to  $\Delta t_{ab}$ , then we can determine approximate values for  $\mathbf{V}$  and  $c$ , which we will denote by  $\mathbf{V}_i$  and  $c_i$ . But if this is not the case, then one of the possible reasons why the inequality (87) is not satisfied is that the observed star does not move uniformly in relation to the Sun. Repeating the same procedure for each star, we will get two sequences of numbers which we will denote by  $V$  and  $C$ .

$$V = \{\mathbf{V}_i\}, (i = 1..n) \quad (88)$$

$$C = \{c_i\}, (i = 1..n) \quad (89)$$

We will determine the arithmetic mean  $\mathbf{V}$  and the standard deviation  $\sigma$  for the sequence of numbers  $V$ .

$$\mathbf{V} = \frac{1}{n} \sum_{i=1}^n \mathbf{V}_i \quad (90)$$

$$\sigma = \sqrt{\frac{1}{n} \sum_{i=1}^n (\mathbf{V} - \mathbf{V}_i)^2} \quad (91)$$

If the standard deviation  $\sigma$  is less than some given positive number and  $\|\mathbf{V}\| \gg M_0$  then we will say that  $\mathbf{V}$  is the velocity with which the solar system moves in relation to the Galactic center and the  $(K')$  is referential coordinate system. If  $\|\mathbf{V}\| \ll M_0$  then we will say that the  $(K)$  is referential coordinate system. The  $M_0$  is some positive number.

We will determine the arithmetic mean  $c$  and the standard deviation  $\sigma$  for the sequence of numbers  $C$ .

$$c = \frac{1}{n} \sum_{i=1}^n c_i \quad (92)$$

$$\sigma = \sqrt{\frac{1}{n} \sum_{i=1}^n (c - c_i)^2} \quad (93)$$

If the standard deviation  $\sigma$  is less than some given positive number, then we can conclude that the speed of light is constant.

## 5. Discussion

The author was not able to test this model using real data. But we tested this model by simulating reality using a computer program. If we assume that the unit with which we measure the speed is equal to  $[km/sec]$ , then in order to obtain satisfactory approximate values for  $c$  it is necessary that the increment by which we change the values of the components  $V_x, V_y$  and  $V_z$  is less than 1. Once we have established the value for the velocity  $\mathbf{V}$ , then it is obvious that it is no longer necessary to repeat each step, which simplifies the procedure.

## 6. Conflicts of Interest Statement

The author has no conflicts of interest to disclose.

## References

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