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Aberration in proper motions for Galactic stars

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Ref: *Mon. Not. Roy. Astron. Soc. (2013), Vol. 433, 3597–3604*

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Outline

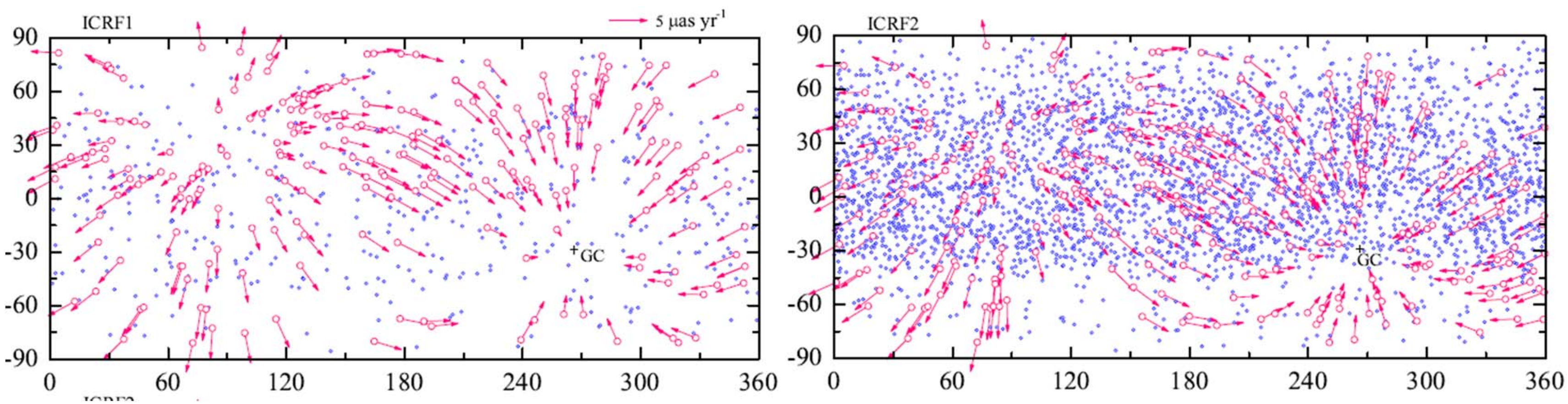
- Acceleration of the SSB and aberration in proper motions
- Theoretical expressions
- More suitable formulas for short periodic stars
- Discussion

Introduction

- Origin: acceleration of the SSB, known as secular/Galactic aberration (drift) for extragalactic sources

- Dipolar proper motions and its impact on ICRF and EOP

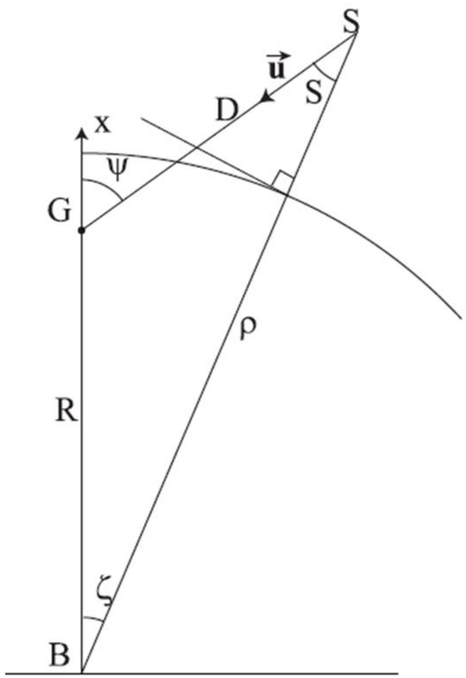
Ref: Liu J.-C., Capitaine N., Lambert S. Malkin Z. Zhu Z. (2012), A&A, 548, A50



- Rotation of the ICRS: $0.1\,\mu\text{as}\,\text{yr}^{-1} < \omega_{x\,y\,z} < 1\,\mu\text{as}\,\text{yr}^{-1}$ depending on the distribution of sources

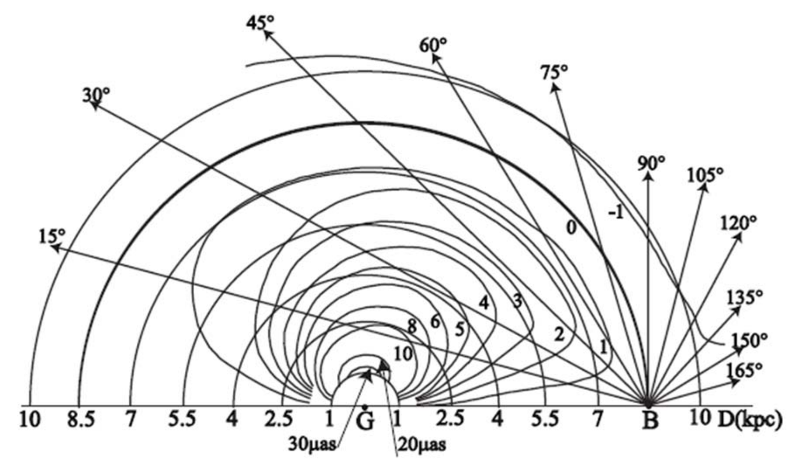
- J. Kovalevsky, *Aberration in proper motions*, 2003, A&A, 404, 743
  - Sec. 7. Time dependent aberration of stars in the Galaxy

- Basic assumption: central Newtonian force toward the GC



Apparent proper motions of stars

$$\Delta\mu_s = \frac{-V_c^2 R \sin\zeta}{c(R^2+\rho^2-2R\rho\cos\zeta)}$$



Theoretical Expressions

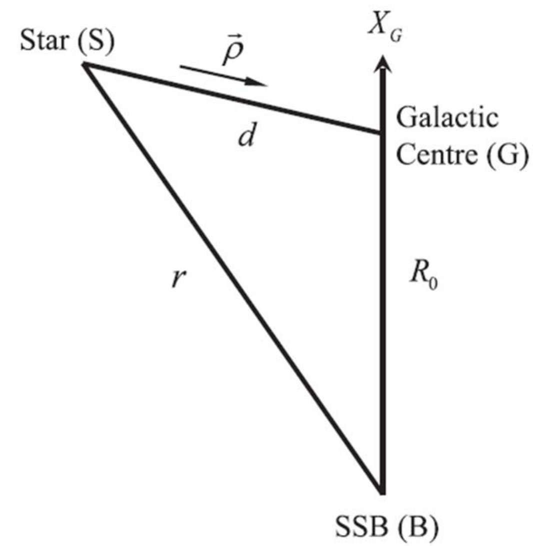
Planetary aberration in positions

$$\Delta \boldsymbol{p}^{\mathrm{PL}} = \frac{1}{c}\boldsymbol{p} \times \left[\left(\boldsymbol{v}^{\mathrm{E}} - \boldsymbol{v}^{\mathrm{PL}}\right) \times \boldsymbol{p}\right]$$

Higher hierarchy reference system

Aberration in proper motions

$$\Delta \dot{\boldsymbol{p}}^{\mathrm{S}} = \frac{1}{c}\boldsymbol{p} \times \left[\left(\boldsymbol{a}^{\mathrm{B}} - \boldsymbol{a}^{\mathrm{S}}\right) \times \boldsymbol{p}\right]$$



Galactic aberration constant for the SSB

$$A^{\mathrm{B}} = \frac{a^{\mathrm{B}}}{c} = \frac{V_0^2}{cR_0} \simeq 5\ \mu\mathrm{as\,yr}^{-1}$$

Session 1 poster by Z. Malkin.

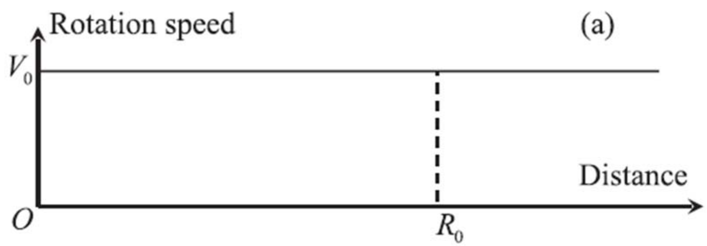
and define: $\gamma = \dfrac{a^{\mathrm{S}}}{a^{\mathrm{B}}}$

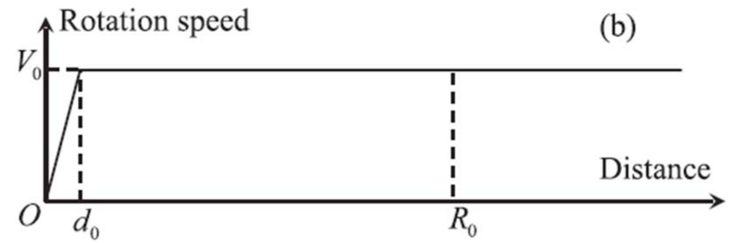
Apparent proper motions in Galactic longitude and latitude

$$\Delta\mu_\ell \cos b = \Delta \dot{\boldsymbol{p}}^{\mathrm{S}} \cdot \boldsymbol{e}_\ell = \frac{1}{c}\boldsymbol{p} \times \left[\left(\boldsymbol{a}^{\mathrm{B}} - \boldsymbol{a}^{\mathrm{S}}\right) \times \boldsymbol{p}\right] \cdot \boldsymbol{e}_\ell = -A^B\left(1 - \gamma\frac{R_0}{d}\right)\sin\ell$$

$$\Delta\mu_b = \Delta \dot{\boldsymbol{p}}^{\mathrm{S}} \cdot \boldsymbol{e}_b = \frac{1}{c}\boldsymbol{p} \times \left[\left(\boldsymbol{a}^{\mathrm{B}} - \boldsymbol{a}^{\mathrm{S}}\right) \times \boldsymbol{p}\right] \cdot \boldsymbol{e}_b, = -A^B\left(1 - \gamma\frac{R_0}{d}\right)\cos\ell\sin b$$

Simplified rotation curve of the Galactic disk





$$\gamma = \frac{R_0}{d} \longrightarrow \begin{cases} \Delta\mu_\ell \cos b = -A^{\mathrm{B}} \left[1 - \left(\frac{R_0}{d}\right)^2\right] \sin \ell \\ \Delta\mu_b = -A^{\mathrm{B}} \left[1 - \left(\frac{R_0}{d}\right)^2\right] \cos \ell \sin b. \end{cases}$$

$$\gamma = \frac{R_0 d}{d_0^2} \longrightarrow \begin{cases} \Delta\mu_\ell \cos b = -A^{\mathrm{B}} \left[1 - \left(\frac{R_0}{d_0}\right)^2\right] \sin \ell \\ \Delta\mu_b = -A^{\mathrm{B}} \left[1 - \left(\frac{R_0}{d_0}\right)^2\right] \cos \ell \sin b \end{cases}$$

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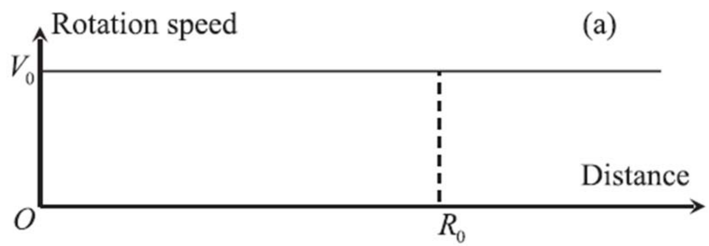

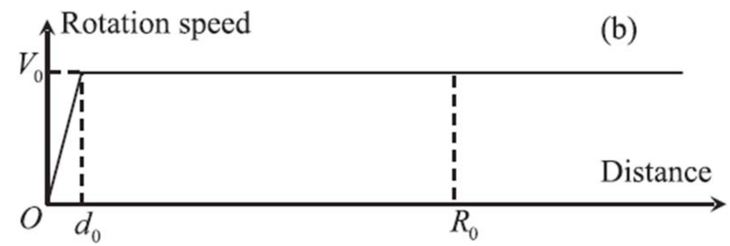

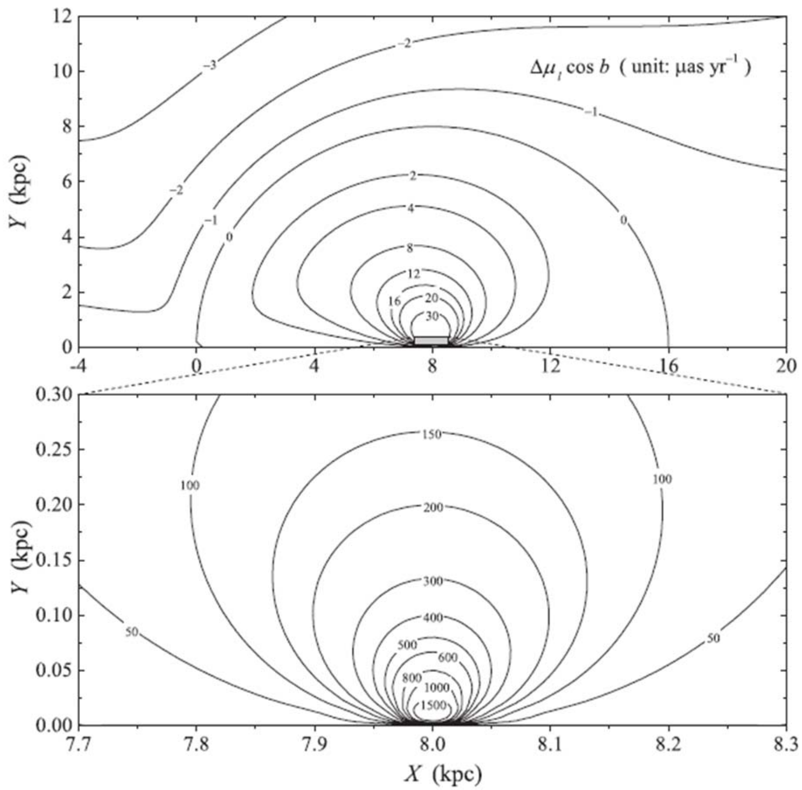

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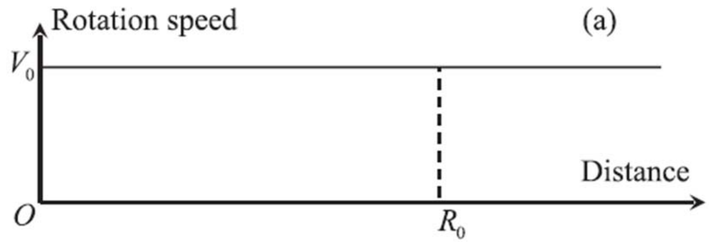
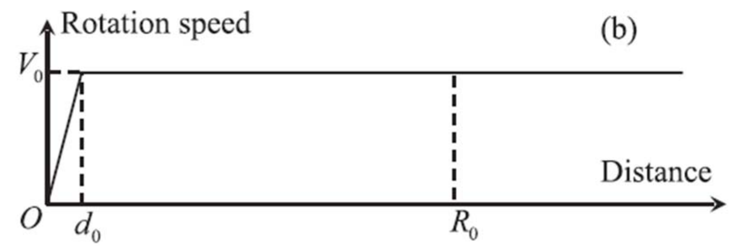
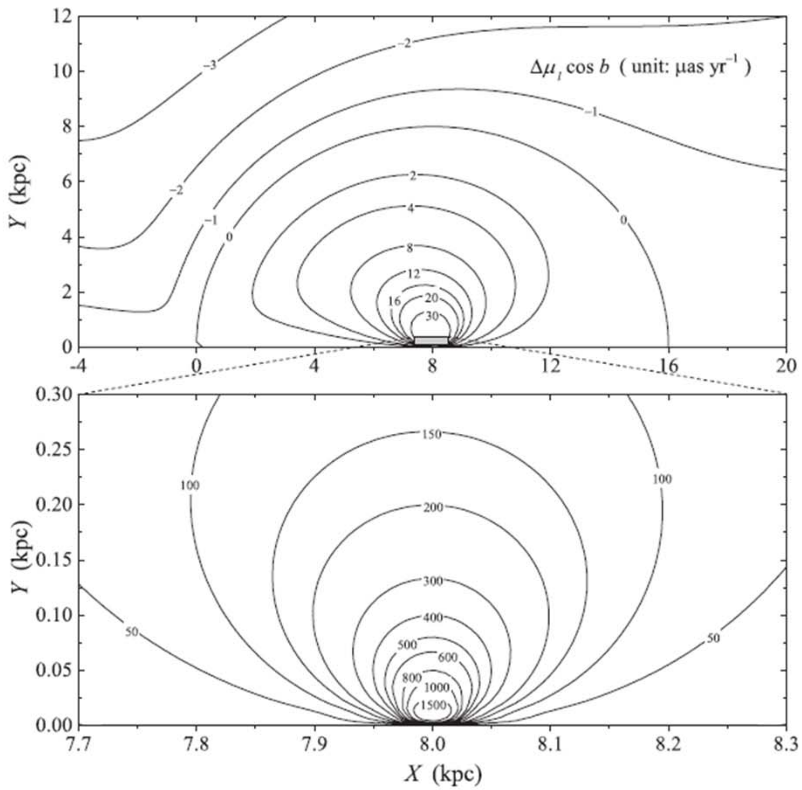
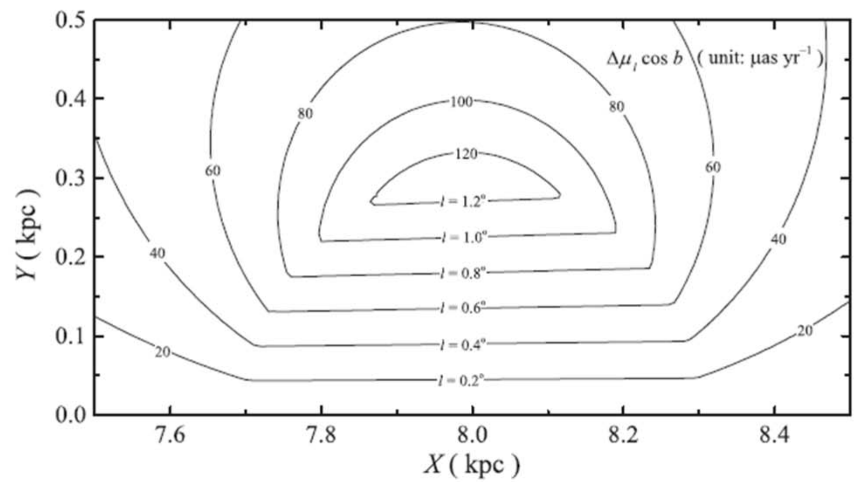






$$\gamma = \frac{R_0 d}{d_0^2} \longrightarrow \begin{cases} \Delta\mu_\ell \cos b = -A^{\mathrm{B}} \left[1 - \left(\frac{R_0}{d_0}\right)^2\right] \sin \ell \\ \Delta\mu_b = -A^{\mathrm{B}} \left[1 - \left(\frac{R_0}{d_0}\right)^2\right] \cos \ell \sin b \end{cases}$$



The light travel time issue

- Approximation in the basic equation $\Delta \dot{\boldsymbol{p}}^{\mathrm{S}} = \frac{1}{c}\boldsymbol{p} \times \left[\left(\boldsymbol{a}^{\mathrm{B}} - \boldsymbol{a}^{\mathrm{S}}\right) \times \boldsymbol{p}\right]$ (*)
- How to deal with non-rectilinear acceleration during the light travel time from the star to the observer?

Define the ratio of the orbital period and the light time τ.

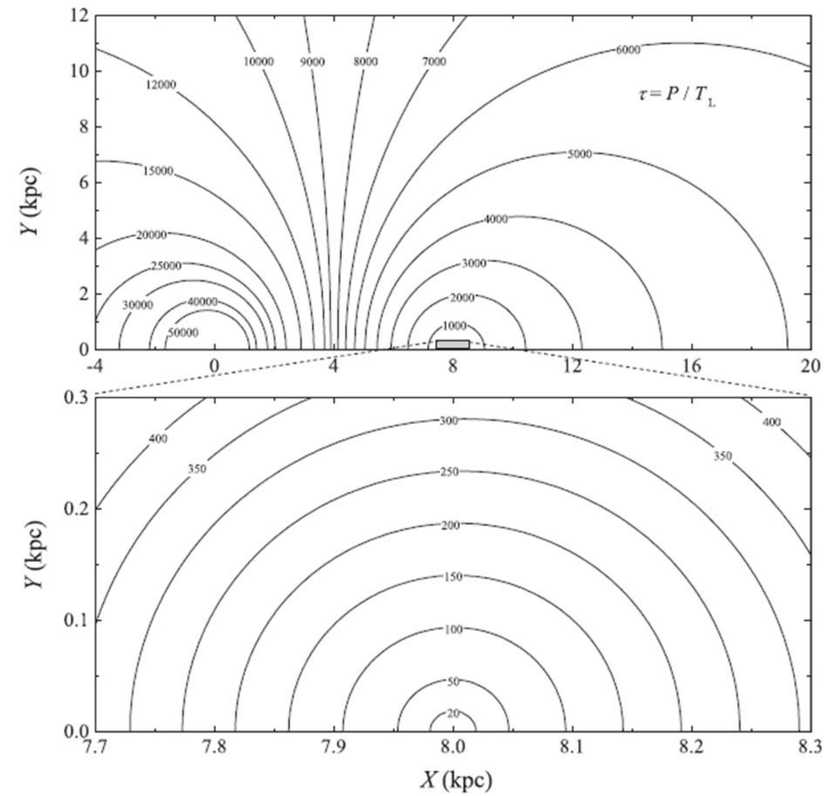
$\tau \gg 1$ means (*) is appropriate.

Flat rotation curve:

$$\tau = \frac{P}{T_{\mathrm{L}}} = 2\pi \left(\frac{d}{r}\right)\left(\frac{c}{V^{\mathrm{S}}}\right)$$

Within the bulge region

$$\tau \simeq 320 \qquad (d < d_0 = 0.3 \text{ kpc})$$

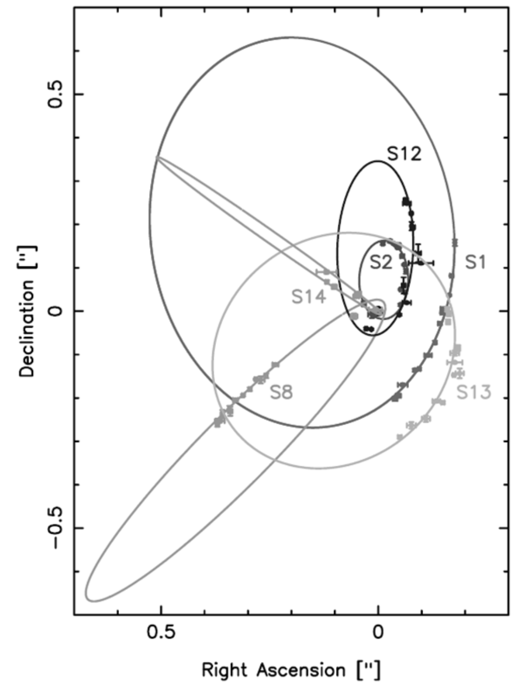


Example: S2 star near the central black hole.

Table A1. Elements of the Keplerian orbit of S0-2.

Element of the orbit	Value	Unit
Central mass	3.3 ± 0.7	$10^6\ M_\odot$
Semimajor axis	4.54 ± 0.27	10^{-3} pc
Separation of pericentre	0.59 ± 0.10	10^{-3} pc
Eccentricity	0.87 ± 0.02	–
Period	15.73 ± 0.74	yr
Pericentre passage	2002.31 ± 0.02	yr
Inclination	45.7 ± 2.60	degree
Angle of line of nodes	44.2 ± 7.0	degree
Angle of node of pericentre	244.7 ± 4.7	degree

Note: The table is grabbed from table 4 of Schödel et al. (2003).



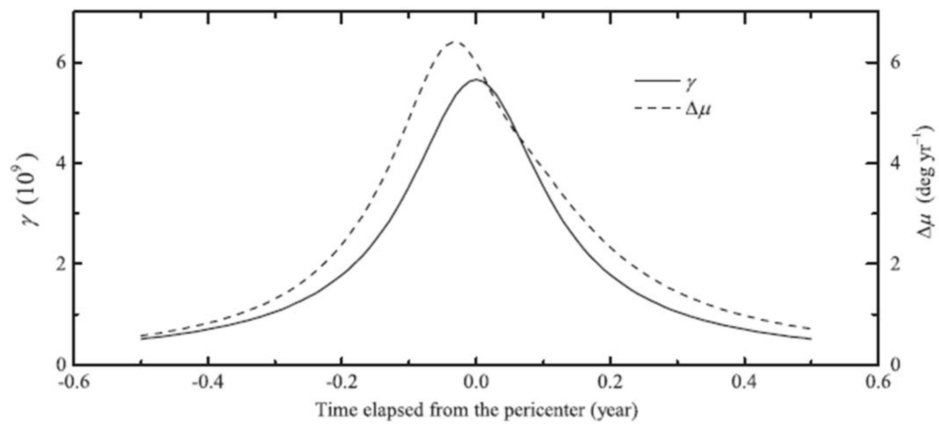
Light time from S2 to the SSB:

$$T_L \simeq 8000\,\mathrm{pc} \times 3.26\ \mathrm{yr\,pc^{-1}} = 26000\,\mathrm{yr},$$

Apparent proper motions:

$$\Delta\mu_\alpha \cos\delta \simeq a^S T_L \frac{\Delta x}{d} \frac{1}{R_0}$$

$$\Delta\mu_\delta \simeq a^S T_L \frac{\Delta y}{d} \frac{1}{R_0}$$



unrealistic large proper motions

A more suitable expression

- The previous equation may be inappropriate for short periodic stars
- Integer multiple of periods: the aberrational effect is zero
- *Define:* $P_{\mathrm{f}} = \text{remainder of } T_{\mathrm{L}} \text{ divided by } P$
- *Effective aberration in proper motions:* $\Delta \dot{\boldsymbol{p}}^{\mathrm{S}} = \frac{1}{c} \boldsymbol{p} \times \left[\left(\boldsymbol{a}^{\mathrm{B}} - \frac{\boldsymbol{v}_2^{\mathrm{S}} - \boldsymbol{v}_1^{\mathrm{S}}}{T_{\mathrm{L}}} \right) \times \boldsymbol{p} \right]$

Apparent proper motions: $\Delta\mu_\alpha \cos\delta = \frac{1}{\kappa} \frac{v_{2,x} - v_{1,x}}{r}, \quad \Delta\mu_\delta = \frac{1}{\kappa} \frac{v_{2,y} - v_{1,y}}{r}$

True proper motions at t_1: $[\Delta\mu_\alpha \cos\delta]_1^{\mathrm{true}} = \frac{1}{\kappa} \frac{v_{1,x}}{r}, \quad [\Delta\mu_\delta]_1^{\mathrm{true}} = \frac{1}{\kappa} \frac{v_{1,y}}{r}$

Observed proper motions at t_1:

$$[\Delta\mu_\alpha \cos\delta]_1^{\rm obs} = \frac{1}{\kappa}\frac{v_{2,x}}{r} = [\Delta\mu_\alpha \cos\delta]_2^{\rm true}$$

$$[\Delta\mu_\delta]_1^{\rm obs} = \frac{1}{\kappa}\frac{v_{2,y}}{r} = [\Delta\mu_\delta]_2^{\rm true}\,.$$

$P_{\rm f} << T_{\rm L}$:

- The effect of aberration will have no effect on the shape of the orbit
- Only change the observed phase of stars on the orbit

Systematic effect on the Gaia stellar reference frame

- Global rotation: larger than the effect of Galactic aberration (μas level)
- Small distortion also exits.
- Important in the GaiaCRF?

Discussion

- Non-disk stars (halo, bulge)
- More realistic model of Galactic kinematics is necessary.
- Observable? (Embedded in stellar proper motions.)
- Kovalevsky (2003): "Applying this correction corresponds to changing from the Barycentric Celestial Reference Frame (BCRS) to a Galactocentric Celestial Reference Frame (GalCRS)."
- The nomenclature issue for relevant effects.

Thank you!

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