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ORIGINAL ARTICLE

Recent advances in the determination of some Galactic constants in the Milky Way

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Abstract Here we statistically evaluate recent advances in determining the Sun-Galactic Center distance (R_{sun}) as well as recent measures of the orbital velocity around the Galactic Center (V_{lsr}), and the angular rotation parameters of various objects. Recent statistical results point to $R_{sun} = 8.0 \pm 0.2$ kpc, $V_{lsr} = 230 \pm 3$ km/s, and angular rotation at the Sun (ω) near 29 ± 1 km/s/kpc for the gas and stars at the Local Standard of Rest, and near 23 ± 2 km/s/kpc for the spiral pattern itself.

This angular difference is similar to what had been predicted by density wave models, along with the observation that the galactic longitude of each spiral arm tracer (dust, cold CO) for each spiral arm becomes reversed across the Galactic Meridian (Vallée in Astrophys. J. 821:53, 2016b).

Keywords Galactic structure · Galactic constants · Galactic disk · Statistics

1 Introduction

The value of the distance of the Sun to the Galactic Center, R_{sun}, is one of the fundamental parameters of our Milky Way disk galaxy. Similarly, the value of the circular orbital velocity V_{lsr}, for the Local Standard of Rest at radius R_{sun} around the Galactic Center, is another fundamental parameter. In 1985, the IAU recommended the use of $R_{sun} = 8.5$ kpc and $V_{lsr} = 220$ km/s. Recent measurements of R_{sun} and V_{lsr} deviate somewhat from this IAU recommendation.

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Section 2 makes a table of recent measurements of two galactic constants, namely the distance of the Sun to the Galactic Center, and the orbital circular velocity near the Sun around the Galactic Center. Section 3 deals with current angular rotation rates for various galactic features, while Sect. 4 concludes.

2 Galactic constants R_{sun} and V_{lsr}

Table 1 shows about forty *very recent* measurements of R_{sun} and/or V_{lsr}, as published from mid-2012 to early-2017. Each different type of measurement (column 3) comes with its own assumptions, and each assumption comes with its own error.

As shown statistically in the last rows of Table 1, one finds here that the median and unweighted mean for R_{sun} are close to 8.0 ± 0.2 kpc, while the median and mean for V_{lsr} are close to 230 ± 3 km/s. Next, we show a weighting using the original authors' own error bars, without personally interjecting an opinion, Thus we then chose a weight (inversely proportional to the stated error) for each published data, giving a mean for R_{sun} of 8.0 ± 0.2 kpc, and for V_{lsr} of 228 ± 2 km/s.

All recent reviews since 2010 gave values for R_{sun} below the IAU-recommended value of 8.5 kpc. Each review covers a different time period (none included published data since early 2016) and each weights different methods differently (some earlier published results here were not included in some reviews). Malkin (2013) found a weighted mean value of 8.0 ± 0.4 kpc. Gillessen et al. (2013—their Fig. 2) showed a median near 8.1 ± 0.3 kpc. Bland-Hawthorn and Gerhard (2016) had an unweighted arithmetic mean of 8.0 ± 0.4 kpc (their Table 3) and a weighted mean of 8.2 ± 0.1 kpc (their Fig. 4a). De Grijs and Bono (2016) yielded $R_{sun} = 8.3 \pm 0.4$ kpc.

Table 1 Recent measures of global parameters of the Milky Way since mid-2012

R_{sun} (kpc)	V_{lsr}[a] (km/s)	Data used	References
8.0 ± 0.8	218 ± 6	3365 stars	Bovy et al. (2012—tab. 2)
7.7 ± 0.4	–	S0 around Gal. Cntr.	Morris et al. (2012—sect. 5)
8.0 ± 0.4	–	VLBI astrometry	Honma et al. (2012—tab. 7)
8.3 ± 0.4	238 ± 9	SLOAN stars	Schonrich (2012—sect. 4.3)
7.6 ± 0.3	217 ± 11	Cepheids near Sun	Bobylev (2013—tab. 3)
8.2 ± 0.8	–	O-B5 stars	Zhu and Shen (2013—tab. 1)
8.0 ± 0.7	–	Open clusters	Zhu and Shen (2013—tab. 1)
8.0 ± 0.8	–	Classical cepheids	Zhu and Shen (2013—tab. 1)
–	239 ± 16	73 masers	Bobylev and Bajkova (2013—sect. 4)
–	234 ± 5	58 masers	Bajkova and Bobylev (2013—sect. 5)
–	205 ± 15	4400 C stars	Battinelli et al. (2013—fig. 3)
8.5 ± 0.4	–	nuclear star cluster, S2	Do et al. (2013—sect. 6)
8.3 ± 0.2	–	RR Lyrae stars	Dékány et al. (2013—sect. 4)
7.6 ± 0.6	–	Type II Cepheids	Matsunaga et al. (2013—fig. 10)
8.2 ± 0.2	–	Red Giant clumps	Cao et al. (2013—tab. 4)
8.3 ± 0.2	240 ± 8	80 masers	Reid et al. (2014—sect. 4.4)
6.7 ± 0.4	203 ± 12	OB stars	Branham (2014—tab. 3)
7.5 ± 0.3	–	red clump stars	Francis and Anderson (2014—sect. 7)
7.4 ± 0.3	–	154 globular clusters	Francis and Anderson (2014—sect. 3)
–	233 ± 2	RAVE stars	Sharma et al. (2014—table 11)
8.3 ± 0.3	233 ± 13	Palomar 5 glob. clusters	Kupper et al. (2015—Sect. 4.1.1)
7.7 ± 0.1	–	36061 A-F stars	Branham (2015—Sect. 5)
8.3 ± 0.1	–	nuclear star cluster	Chatzopoulos et al. (2015—sect. 4.2)
8.3 ± 0.4	–	RR Lyrae stars	Pietrukowicz et al. (2015—sect. 4.2)
8.0 ± 0.3	–	93 masers	Bajkova and Bobylev (2015—sect. 4)
–	230 ± 10	119 masers	Bobylev and Bajkova (2015a—fig. 1)
–	234 ± 14	120 spectr. binaries	Bobylev and Bajkova (2015b- fig. 2)
–	225 ± 10	open clusters, OB assoc.	Melnik et al. (2016—fig. 10)
–	228 ± 14	GMC, CO $J = 1$–0 gas	McGaugh (2016—table 1)
8.9 ± 0.4	–	4883 MIRA stars	Catchpole et al. (2016—sect. 7)
–	210 ± 10	thin disk stars	Rojas-Ariagada et al. (2016—Fig. 8)
–	240 ± 6	16000 red clump stars	Huang et al. (2016—Fig. 6)
–	230 ± 12	183000 RAVE4 stars	Bobylev and Bajkova (2016—Sect. 5)
7.9 ± 0.1	–	S0 orbit astrometry	Boehle et al. (2016—Table 4)
–	240 ± 8	HI emission	Reid and Dame (2016—Fig. 4)
–	236 ± 6	Open star clusters	Bobylev et al. (2016—fig. 2)
–	231 ± 6	Cepheids	Bobylev (2017—Fig. 2)
–	219 ± 8	OB stars	Bobylev and Bajkova (2017—Sect. 8)
8.2 ± 0.1	233 ± 3	mass model (main)	McMillan (2017—Table 2)
8.0 ± 0.2	227 ± 4	mass model (alternate)	McMillan (2017—Table 6)
7.6 ± 0.1	–	GKM stars	Branham (2017—Table 3)
8.4 ± 0.1	243 ± 10	131 masers	Rastorguev et al. (2017—tab. 1)
8.0	232	Median value (all data)	
8.0 ± 0.2	229 ± 3	Mean value (unweighted; all data), and standard dev. of the mean	
8.0 ± 0.2	228 ± 2	Mean value (weighted; all data), and standard dev. of the mean	
8.0	230	Adopted here (within one s.d.m. of mean value)	

[a]Local Standard of Rest—the kinematic circular rotation value near the Sun, excluding the Sun's peculiar velocity

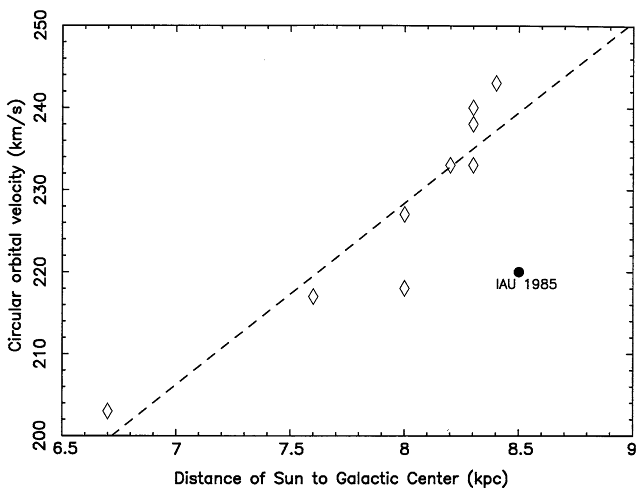

Fig. 1 Plot of nine observations that measured both the solar distance to the Galactic center (*horizontal*) and the LSR circular orbital rotation velocity (*vertical*), as taken from Table 1. The *dashed line* is a weighted fit to the nine data in this figure

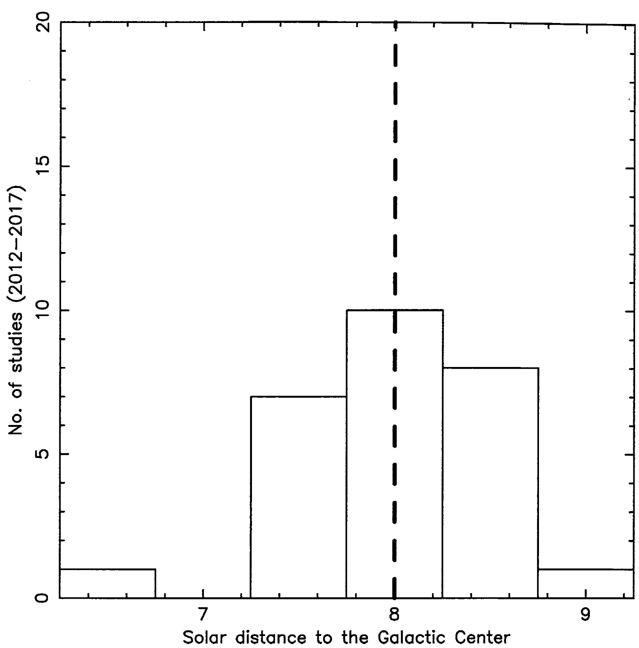

Fig. 2 Histogram of the 27 data in Table 1 on R_{sun}. Here the spread in recent measurements is from 6 to 9 kpc (x-axis), with a peak near 8 kpc

Most measurements in Table 1 are for either R_{sun} or V_{lsr}, but rarely together.

Figure 1 shows a plot of these 9 cases of dual measurements, and the weighted fit of a line shown dashed. These dual measurements gave an increasing V_{lsr} with an increase in R_{sun}, with the Sun's distance at 8.0 kpc and the LSR's velocity at 230 km/s.

Figure 2 shows a histogram of the 27 most recent observational determinations of R_{sun} from Table 1, showing a spread of about 3 kpc and a peak near 8 kpc.

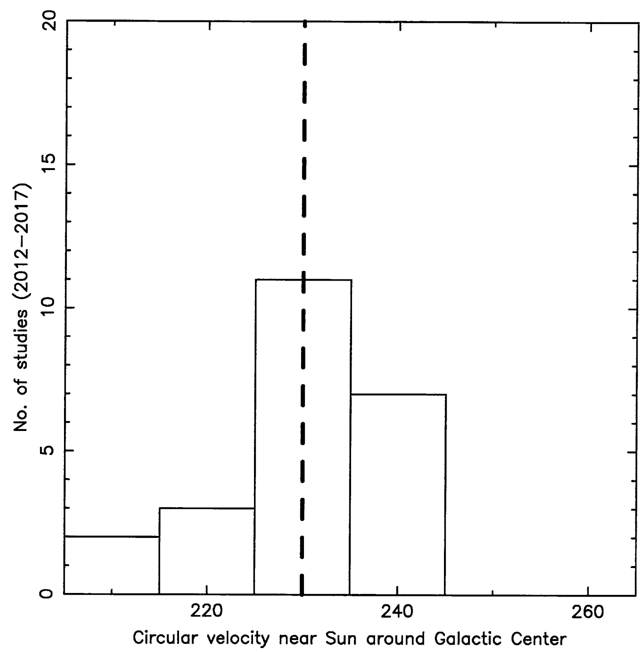

Fig. 3 Histogram of the 24 data in Table 1 on V_{lsr}. Here the spread in recent measurements is from 205 to 245 km/s (x-axis), with a peak near 230 km/s

Figure 3 shows a histogram of the 24 most recent observational determinations of V_{lsr} from Table 1, showing a spread of about 40 km/s and a peak near 230 km/s.

3 Galactic angular rotation parameter

As gas and stars follow their orbit around the Galactic Center, the quantitative value of the angular rotation of the Local Standard of Rest [LSR] can be obtained from the mean values in Table 1, along with the orbital period around the Galactic Center.

Using 8.0 and 230 km/s for the LSR's constants, the ratio $V_{lsr}/R_{lsr} = \omega$, and ω is the angular orbital rotation around the Galactic Center. Here $\omega = 28.8$ km/s/kpc. This angular rotation value is close to that found earlier by Nagayama et al. (2011).

In a flat rotation curve, the Oort's constant $A = +0.5$ V/R $= +14.40$ km/s/kpc, and the Oort's constant $B = -0.5$ V/R $= -14.40$ km/s/kpc, while the angular rotation $= A - B = 28.8$ km/s/kpc.

Table 2 assembles some data on these angular rotations and rotation periods, as published recently.

Figure 4 shows a diagram of most features mentioned in Table 2. The 'spiral pattern' sits on top of the observed locations of arms (stars and gas); this pattern goes around the Milky Way at a slightly slower speed than that of the orbiting gas and stars (which cross the spiral pattern). There is a smaller angular velocity for the spiral arm pattern (23 km/s/kpc) than for the gas and stars (29 km/s/kpc).

Table 2 Recent studies of the angular rotation of some features of the Milky Way

Feature	R Gal. radius (kpc)	Ref. [a]	ω ang. vel. (km/s/kpc)	Ref. [a,b]	V circ. vel. (km/s)	Ref. [a,b]	P orbital period (Myr)	Ref. [a,b]
LSR[c]	8.0	Table 1	28.8	Eq. 1	230	Table 1	220	Eq. 2
	–	set	28.7	N11	230	Eq. 1	219	Eq. 2
Spiral pattern	8.0	set	25	D15; G11	200	Eq. 1	250	Eq. 2
	–	–	23	L16, J15	184	Eq. 1	273	Eq. 2
	–	–	20	K16	160	Eq. 1	314	Eq. 2
Hot Halo gas	8.0	set	23	Eq. 1	183	H16	275	Eq. 2
Boxy bulge bar	2.1	V16a	30	R08	63	Eq. 1	209	Eq. 2
	–	–	40	Q15	84	Eq. 1	157	Eq. 2
Thin long bar	4.2	V16a	59	G11	248	Eq. 1	106	Eq. 2
	–	–	33	L16a	139	Eq. 1	190	Eq. 2

[a]Literature cited: D15 = Dambis et al. (2015); G11 = Gerhard (2011—Sect. 4); H16 = Hodges-Kluck et al. 2016; J15 = Junqueira et al. (2015—tab. 4); K16 = Koda et al. (2016—Tab. 2); L16 = Li et al. (2016—sect. 2.2.3); L16a = Li et al. (2016—sect. 4.5); N11 = Nagayama et al. (2011—fig. 6b); Q15 = Qin et al. (2015—Sect. 2); R08 = Rodriguez-Fernandez and Combes (2008—Sect. 6.1); V16a = Vallée (2016a—tab. 3)

[b]Equation 1: $R_{(\mathrm{kpc})} \cdot \omega_{(\mathrm{km/s/kpc})} \approx V_{(\mathrm{km/s})}$
Equation 2: $2 \cdot \pi \cdot R_{(\mathrm{pc})} \approx V_{(\mathrm{km/s})} \cdot P_{(\mathrm{Myr})}$
with: $1\ \mathrm{Myr} = 3.16 \times 10^{13}$ s
and: $1\ \mathrm{pc} = 3.09 \times 10^{13}$ km

[c]LSR = Local Standard of Rest, surrounding the Sun's position in the Milky Way disk

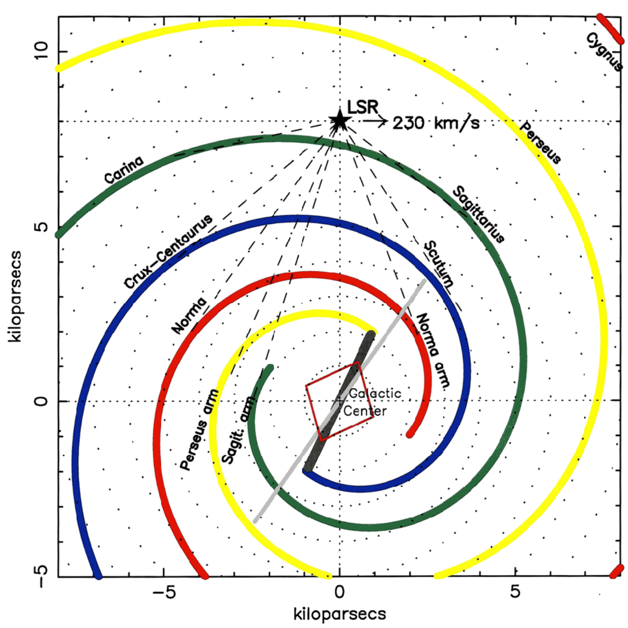

Fig. 4 Diagram of the Milky Way's disk plane, showing some of the various features in Table 2. The Local Standard of Rest [LSR], shown by a *star*, and its direction (*arrow*) and velocity (230 km/s) are indicated. The LSR englobes many local stars, including the Sun, and has an angular velocity near 29 km/s/kpc. The observed spiral arms are shown, located on the theoretical 'spiral pattern', with an angular velocity near 23 km/s/kpc. Near the Galactic Center, the *boxy bulge bar* (*dark gray*) and the *thin long bar* (*light gray*) are shown. The hot halo gas (not shown) stand above and below the disk plane. Observed tangents to the spiral arms are shown as *dashes*. *Circles* at different radii from the Galactic Center are shown as *dots*

The dust lane is located on the inner side of each spiral arm, closest to the Galactic Center. The galactic longitudes of each spiral arm tracer (dust, cold CO) for each spiral arm shows a reversal on both sides of the galactic Meridian (Vallée 2016b), similar to what had been predicted by density wave models.

The angular rotation for the spiral pattern is near ($\approx 23 \pm 2$ km/s/kpc) in the Milky Way Galaxy, which is similar to that found elsewhere in the fairly isolated galaxies NGC 6946 ($\approx$ 22 km/s/kpc) and NGC 2997 ($\approx$ 16 km/s/kpc); it differs from that for the strongly interacting galaxy M51 ($\approx$ 38 km/s/kpc)—for a review see Ghosh and Jog (2016—table 2).

It is more difficult to obtain observational values for the angular rotation and the rotation period of the boxy bulge bar extending to 2.1 kpc, as well as for the thin long bar extending to 4.2 kpc (see Table 3 in Vallée 2016a).

The angular rotations for the spiral arm pattern, and for the two bars, are model-deduced from other observed parameters, thus not directly observed, and not known to better than a few km/s/kpc.

Some models (e.g., Bissantz et al. 2003) required two different angular speeds, one for the bar and another one for the spiral pattern, sufficiently *apart* to prevent a dissolution of the spiral arms. Other models (e.g., Englmaier and Gerhard 1999) have argued that the angular rotation of the spiral pattern ought to be similar to the angular rotation of the short boxy bulge bar, if the two features are *attached*. Given that the difference in Table 2 between these two angular rotations ($\approx$ 12 km/s/kpc) has a quadratically combined error of 12 km/s/kpc, one cannot chose a model in particular (apart or attached).

Some other models (e.g., Li et al. 2016) have argued that the angular rotation of the short boxy bulge bar ($\approx 35 \pm 10$ km/s/kpc) ought to be similar to the angular rotation of the long thin bar ($\approx 46 \pm 15$ km/s/kpc), if the two bars are dynamically *stable*. Recently, Monari et al. (2017) suggested it to be a *loosely* wound spiral structure, with its own rotation. Given that the difference between these two angular rotations ($\approx$11 km/s/kpc) has a quadratically combined error of 18 km/s/kpc, one cannot chose a model in particular (stable or loose).

4 Conclusion

We assembled recent measurements of two basic galactic constants (Table 1). We find R_{sun} close to 8.0 kpc, while V_{lsr} is close to 230 km/s. When both the LSR circular orbital velocity and the distance of the Sun to the Galactic Center are measured in the same experiments, over a wide range of methods, the results display a trend of increasing V_{lsr} with an increase of R_{sun} values (Fig. 1).

Recent studies of the angular rotation rates of some features in the Milky Way (Table 2) are assembled, combining data from Table 1 here and from the literature.

At this time, it is difficult to choose among bar models. More accurate observational data are needed to separate among bar models and spiral pattern.

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