The Bar and Spiral Structure Legacy (BeSSeL) Survey: Mapping the Milky Way with VLBI Astrometry

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Astrometric Very Long Baseline Interferometry (VLBI) observations of maser sources in the Milky Way are used to map the spiral structure of our Galaxy and to determine fundamental parameters such as the rotation velocity ($\Theta_0$) and curve and the distance to the Galactic center ($R_0$). Here, we present an update on our first results, implementing a recent change in the knowledge about the Solar motion. It seems unavoidable that the IAU recommended values for $R_0$ and $\Theta_0$ need a substantial revision. In particular the combination of 8.5 kpc and 220 km s$^{-1}$ can be ruled out with high confidence. Combining the maser data with the distance to the Galactic center from stellar orbits and the proper motion of Sgr A* gives best values of $R_0 = 8.3 \pm 0.23$ kpc and $\Theta_0 = 239 \pm 7$ km s$^{-1}$, for Solar motions of $V_\odot = 12.23$ and 5.25 km s$^{-1}$, respectively. Finally, we give an outlook to future observations in the Bar and Spiral Structure Legacy (BeSSeL) Survey.

1 Introduction

The Milky Way is a barred spiral galaxy, as seen from observations of CO and HI gas (e.g. Burton 1988; Dame et al. 2001), and star counts (e.g. Benjamin et al. 2005). However, our location in the Galaxy makes it difficult to determine the number and positions of spiral arms, the length and position of the central bar, and the rotation curve. As a result, even the most fundamental parameters of the Milky Way, such as the distance to the Galactic center $R_0$ and the rotation speed $\Theta_0$ are still not known with high accuracy. However, these values are not only important for Galactic astronomy, but also for a wide range of different fields. This includes the interpretation of the proper motions of the Magellanic Clouds (Besla et al. 2010; Diaz & Bekki 2011; Peebles 2010; Ružička et al. 2010; Shattow & Loeb 2009) and galaxies in the Andromeda subgroup (Brunthaler et al. 2005, 2007; van der Marel & Guhathakurta 2008), the motion of the Sun relative to the cosmic microwave background (e.g. Loeb & Narayan 2008), and even on the interpretation of dark matter direct detection experiments (Foot 2010; McCabe 2010).

In recent years, many large scale surveys have covered the Galactic Plane in all wave bands from radio to gamma rays. However, almost all of these surveys are all only two dimensional, and using them to construct a three dimensional model of the Milky Way is not trivial, mainly due to large uncertainties in distance measurements (Georgelin & Georgelin 1976; Hou et al. 2009). These also affect the interpretation of these surveys since most astrophysical quantities, such as linear size, mass, and luminosities, strongly depend on the distance to the object.

2 Galactic distances

In Galactic astronomy, the kinematic distance is very commonly used. Here, a distance is deduced from a measured line-of-sight velocity, a rotation model of Milky Way, and the assumption that the object has no peculiar motion. Apart from a distance ambiguity in the inner Galaxy (near and far
kinematic distance), errors in the rotation model and peculiar motions can lead to very large errors in the kinematic distance. One extreme example is the star forming region G9.62+0.20. It is located at a distance 5.2 ± 0.6 kpc [Sanna et al. 2009], while the near and far kinematic distances place the source at 0.5 and 16 kpc, respectively. This source shows a very large peculiar motion which may be induced by the central bar and is responsible for the large error in the kinematic distance.

Certainly, the trigonometric parallax is the most fundamental method, since it is based on pure geometry without any astrophysical assumptions except the well known orbit of the Earth about the Sun. However, the measurement of an accurate trigonometric parallax requires extremely high astrometric precision. Friedrich Wilhelm Bessel was able to measure the first stellar parallax of the star 61 Cygni [Bessel 1838a,b]. A huge step forward came with the ESA's Hipparcos satellite [Perryman et al. 1997]. It provided astrometric accuracies of the order of 1 milliarcsecond, which allows distance estimates in the Solar neighborhood out to 100 pc with 10% accuracy, i.e. a very small portion of the Milky Way. Following the footsteps of Hipparcos, ESA's new Gaia mission [Perryman et al. 2001] will be launched in late 2012 to provide astrometry of up to 1 billion stars in the Milky Way with parallax accuracies up to 7 μas if it achieves specifications, a factor 100 better than Hipparcos. Although Gaia will revolutionize our view of the Milky Way, the strong extinction by gas and dust in the Galactic plane and in particular the spiral arms will prevent Gaia from making significant progress on the spiral structure of the Milky Way. Since radio waves are not affected by interstellar extinction, radio astronomy can come to the rescue and fill the gaps.

3 VLBI Astrometry

Recently developed calibration techniques for Very Long Baseline Interferometry (VLBI) have improved the accuracy of astrometric VLBI observations significantly. When these techniques are applied to VLBI networks like the NRAO Very Long Baseline Array (VLBA) in the US, the European VLBI Network (EVN) in Europe and China, or the VLBI Exploration of Radio Astrometry (VERA) array in Japan, it is now possible to measure parallaxes of radio sources with accuracies of the order of 10 μas, comparable to the expected accuracy of Gaia.

Possible target objects for VLBI astrometry are either radio continuum sources or strong maser emission. Most radio stars are relatively weak, and the sensitivity of current instruments limits the detection to sources within a few hundred parsec [e.g. Loinard et al. 2007; Menten et al. 2007; Torres et al. 2007]. However, sensitivity upgrades of existing VLBI instruments [e.g. Ulvestad et al. 2010] and eventually the Square Kilometer Array [Fomalont & Reid 2004] will extend the accessible range to even weaker and more distant sources.

| Source          | Parallax [μas] | Reference |
|-----------------|---------------|-----------|
| W3(OH)          | 512 ± 10      | Xu et al. [2006] |
| Orion Nebula    | 2425 ± 35     | Menten et al. [2007] |
| S 269           | 189 ± 16      | Honma et al. [2007] |
| VY CMa          | 876 ± 76      | Choi et al. [2008] |
| NGC 281         | 355 ± 30      | Sato et al. [2008] |
| S 252           | 476 ± 6       | Reid et al. [2009a] |
| G232.6+1.0      | 596 ± 35      | Reid et al. [2009a] |
| Cep A           | 1430 ± 80     | Moscadelli et al. [2009] |
| NGC 7538        | 378 ± 17      | Moscadelli et al. [2009] |
| W51 IRS2        | 195 ± 71      | Xu et al. [2009] |
| G59.7+0.1       | 463 ± 20      | Xu et al. [2009] |
| G35.2-0.7       | 456 ± 45      | Zhang et al. [2009] |
| G35.2-1.7       | 306 ± 45      | Zhang et al. [2009] |
| G23.0-0.4       | 218 ± 17      | Brunthaler et al. [2009] |
| G23.4-0.2       | 170 ± 32      | Brunthaler et al. [2009] |
| G23.6-0.1       | 313 ± 39      | Bartkiewicz et al. [2008] |
| WB 89-437       | 167 ± 6       | Hachisuka et al. [2009] |
| IRAS00420+5530  | 470 ± 20      | Moellenbrock et al. [2009] |

Table 1 List of 18 sources which were used to fit a new model of the Galaxy in Reid et al. [2009b].

Molecules with maser lines suitable for astrometry are hydroxyl (OH), methanol (CH$_3$OH), water (H$_2$O), and silicon monoxide (SiO). Since OH masers at a low frequency of 1.6 GHz are strongly affected by interstellar scattering and ionospheric effects, they are not the optimal targets for VLBI astrometry. SiO masers at 43 GHz are less affected by scattering and the ionosphere, but these observations are more vulnerable to tropospheric phase errors and require excellent weather conditions. Nevertheless, both masers have been used to measure accurate distances to evolved stars [e.g. Choi et al. 2008; van Langevelde et al. 2000].

The most suitable targets are methanol (6.7 and 12.2 GHz) and water (22 GHz) masers. They are very strong and are found in high mass star forming regions (HMSFRs) mainly in the spiral arms of the Galaxy. The catalog of 6.7 GHz methanol masers by Pestalozzi et al. [2005] lists more than 500 sources, and many more were found recently with Arecibo [Pandian et al. 2007], Effelsberg [Xu et al. 2008], and in particular in the methanol multi beam survey on the Parkes telescope [Caswell et al. 2010; Green et al. 2010]. Water masers can be even stronger and Valdettaro et al. [2011] list more than 1000 sources in the Galaxy.

Parallaxes using the 6.7 GHz methanol transition have been reported so far only with the EVN [Rygl et al. 2010a,b], while the VLBA can currently observe only the 12.2 GHz methanol and 22 GHz water maser lines. One example is the distance to W3(OH), a high mass star forming region in the Perseus spiral arm of the Milky Way. Two independent parallax measurements with the VLBA of bright methanol [Xu et al. 2006] and water [Hachisuka et al. 2006] masers yielded consistent distance estimates of 1.95 ± 0.04 and 2.04 ± 0.07 kpc.

Another example that demonstrates the high quality of VLBI parallax measurements is the Orion Nebula. Four
independent measurements with two different instruments give, within their joint errors, consistent results. Sandstrom et al. (2007) observed one radio star with the VLBA and obtained a distance of \(389.74 \pm 2\) pc, while Hirota et al. (2007) used VERA to measure the parallax of water masers in the nebula \(437 \pm 19\) pc. The most accurate measurements of \(414 \pm 7\) pc (Menten et al. 2007; VLBA, 4 radio stars) and \(418 \pm 6\) pc (Kim et al. 2008; VERA, SiO maser) also agree with each other and with the modeling of the orbit of the binary \(\Theta^1\) Ori C from near-infrared interferometry (Kraus et al. 2007 434±12 pc).

4 A new model for the Milky Way

4.1 Measurements so far

In Reid et al. (2009b), we used 18 sources, with published parallaxes at that time (see Table I and Fig. 1), to analyze the spiral structure and the rotation of the Milky Way. We were already able to locate the Local arm and the Perseus spiral arm from Galactic longitudes \(l = 122^\circ - 190^\circ\). The measured pitch angle of the Perseus spiral arm of \(16^\circ \pm 3^\circ\) favors four rather than two spiral arms for the Galaxy. Furthermore, we find that most of the HMSFRs are closer than their kinematic distance. Note that the same data set has been also analyzed by Bovy et al. (2009), McMillan & Binney (2010), and Bobylev & Bajkova (2010).

4.2 Solar Motion

Astrometric observations not only yield the distance but also the proper motion of a source. Together with the known position and line-of-sight velocity, this gives the full 6 dimensional phase space information for the observed sources. However, all measurements are heliocentric. Therefore, the peculiar motion of the Sun relative to the LSR is needed to convert the measured heliocentric into Galactocentric motions. For over a decade, the values of \(V_\odot = 10.00 \pm 0.36, V_\odot = 5.25 \pm 0.62,\) and \(W_\odot = 7.17 \pm 0.38\) km \(s^{-1}\) for the peculiar motion of the Sun derived from Hipparcos data by Dehnen & Binney (1998) have been widely used. When using this Solar motion, we find that the HMSFRs rotate on average \(15\) km \(s^{-1}\) slower than the Milky Way (Reid et al. 2009b).

This controversial result has sparked new interest in the Solar motion and Binney (2010) argues that this slower rotation is partly induced by an erroneous value of \(V_\odot\). Mignard (2000) and Piskunov et al. (2006) already favored a significantly higher value of \(V_\odot\), in the range of \(\sim 12\) km \(s^{-1}\). This higher value, which is similar to the pre-Hipparcos value (e.g. Mihalas & Binney 1981), has been also found in a number of recent studies (Costado et al. 2011). Francis & Anderson 2009; Schönherr et al. 2010), while the values of \(U_\odot\) and \(W_\odot\) have not changed considerably (see also Fuchs et al. 2009). Although the issue of the \(V_\odot\) component of the Solar motion is probably still not solved, it seems likely that the value of \(V_\odot\) is probably closer to \(12\) km \(s^{-1}\) than to \(5\) km \(s^{-1}\).

4.3 Revised values

The analysis in Reid et al. (2009b) was based on the old Hipparcos value of the Solar motion from Dehnen & Binney (1998). Here we give an update using the new values of Schönherr et al. (2010), which are \(U_\odot = 11.10 \pm 1.2, V_\odot = 12.24 \pm 2.1,\) and \(W_\odot = 7.25 \pm 0.6\) km \(s^{-1}\). Using this value, the HMSFRs rotate \(\sim 8 \pm 2\) km \(s^{-1}\) slower than the Milky Way. By fitting our measurements to a model of the Galaxy, we can also estimate the distance to the Galactic center \(R_0\) and the circular rotation speed \(\Theta_0\). Assuming a flat rotation curve, we get values of \(R_0 = 8.4 \pm 0.6\) kpc and \(\Theta_0 = 247 \pm 16\) km \(s^{-1}\). A similar analysis allowing for different rotation curves yields results in the range of \(R_0 = 7.9 - 9\) kpc and \(\Theta_0 = 223 - 280\) km \(s^{-1}\). However, the ratio of these two values is much better constrained with a value of \(\Theta_0/R_0 = 29.4 \pm 0.9\) km \(s^{-1}\) kpc \(^{-1}\). Clearly, the number of sources is currently not large enough to constrain different rotation curves.

The slower average rotation of the HMSFRs together with the higher overall rotation of the Milky Way also explains why most of the kinematic distances are larger than...
the true distances. A description that takes into account these two effects and gives (in general) more accurate kinematic distances, and a more realistic distance uncertainty estimate is also presented in Reich et al. (2009). It should be noted, however, that these revised kinematic distances can be still unreliable, because sources may have very large peculiar motions.

4.4 Independent measurements of $R_0$ and $\Theta_0/R_0$

The distance to the Galactic center $R_0$ has been the target of numerous investigations over the last decades (see Reid 1993 for a review). Most measurements in the range between 7.5 and 8.5 kpc and direct geometric distance estimates are rare. The accurate determination of stellar orbits in the Galactic center yields now consistent values from two groups of $8.4 \pm 0.4$ kpc (Ghez et al. 2008) and $8.33 \pm 0.35$ kpc (Gillessen et al. 2009). A trigonometric parallax to water masers in Sgr B2, a star forming region located within 150 pc from the Galactic center, also yields a consistent value of $R_0 = 7.9^{+1.8}_{-0.7}$ kpc, but with a larger uncertainty (Reid et al. 2009c). Further observations of the water masers in Sgr B2 will improve the accuracy to a value comparable or even better than from the stellar orbits.

The ratio of $\Theta_0$ and $R_0$ is known with better than 1% accuracy from the proper motion of Sgr A* (Reid & Brunthaler 2004). This motion in the Galactic plane of $6.379 \pm 0.026$ mas yr$^{-1}$ is a combination of Galactic rotation and Solar motion, and corresponds to a value for $(\Theta_0 + V_\odot)/R_0$ of $30.24$ km s$^{-1}$ kpc$^{-1}$. Using the Solar motion from Schönrich et al. (2010), and assuming the distance of $8.4$ kpc, yields a value of $\Theta_0/R_0 = 28.79 \pm 0.26$ km s$^{-1}$ kpc$^{-1}$, where the uncertainty is dominated by the uncertainty in the Solar motion. This value depends only weakly on the assumed $R_0$ (in the correction of the Solar motion), and does not change by more than 0.7%, even for extreme values of $R_0$ of 7.5 or 9.5 kpc. This value is perfectly consistent with our results from the independent maser parallaxes but significantly larger ($> 11 \sigma$) than the IAU value of 25.88 from the combination of $R_0 = 8.5$ kpc and $\Theta_0 = 220$ km s$^{-1}$. Hence, one requires an $R_0$ of less than 7.7 kpc to have a rotation velocity of 220 km s$^{-1}$.

4.5 Conclusion and best values for $R_0$ and $\Theta_0$

The measured maser parallaxes, and the combination of the stellar orbits with the proper motion of Sgr A* provide independent and consistent evidence for a higher rotation velocity of the Milky Way. Therefore, it seems unavoidable that the IAU recommended values for $R_0$ and $\Theta_0$ need a substantial revision. In particular the combination of 8.5 kpc and 220 km s$^{-1}$ can be ruled out with high confidence.

The weighted average of the four direct measurements for $R_0$ of $8.4 \pm 0.4$ kpc (Ghez et al. 2008), $8.33 \pm 0.35$ kpc (Gillessen et al. 2009), $7.9^{+1.8}_{-0.7}$ kpc (Reid et al. 2009c), and $8.4 \pm 0.6$ kpc (Reid et al. 2009b) gives best value of

$$R_0 = 8.3 \pm 0.23 \text{ kpc}.$$  

This translates then into a rotation speed of

$$\Theta_0 = \Theta_0/R_0 \times R_0 = 28.79 \text{ km s}^{-1} \text{ kpc}^{-1} \times 8.3 \text{ kpc} = 239 \pm 7 \text{ km s}^{-1}.$$  

These values are almost identical to values presented by McMillan (2011) and marginally consistent with the rotation speed of $224 \pm 13$ km s$^{-1}$ provided by Koposov et al. (2010) from modelling the stellar stream GD-1. For the old Solar motion of $V_\odot = 5.25$ km s$^{-1}$, $\Theta_0$ would increase to $246 \pm 7$ km s$^{-1}$. The uncertainties are formal uncertainties and are dominated by the uncertainty in $R_0$. The true uncertainties are probably a factor of $\sqrt{2}$ larger, since the two stellar orbit distances may have similar systematic errors (they are independent measurements with different instruments, but of the same source).

A higher value of $\Theta_0$ is also supported by the observation of a retrograde-rotating and metal-poor component in the stellar halo of the Milky Way by Deason et al. (2010) when assuming a value of $\Theta_0 = 220$ km s$^{-1}$. A value of $\Theta_0 \sim 240$ km s$^{-1}$ would explain this apparent retrograde rotation.

5 The Bar and Spiral Structure Legacy Survey

Motivated by these very encouraging results from only 18 sources, we have started a much larger project, the Bar and Spiral Structure Legacy (BeSSeL) Survey, a VLBA Key science project. The goal of BeSSeL, named in honor of Friedrich Wilhelm Bessel who measured the first stellar parallax, is to measure accurate distances and proper motions of up to 400 high mass star forming regions in the Milky Way between 2010 and 2015. This will result in a catalog of accurate distances to most Galactic high mass star forming regions visible from the northern hemisphere and very accurate measurements of fundamental parameters such as the distance to the Galactic center ($R_0$), the rotation velocity of the Milky Way ($\Theta_0$), and the rotation curve of the Milky Way. Additionally, maps of the maser distribution from the first epoch of each source will be published on the BeSSeL website shortly after the observations.

1 http://www.mpi-fb.mpg.de/staff/abrunthaler/BeSSeL/index.shtml
The BeSSeL Survey will first target 12.2 GHz methanol and 22 GHz water masers. Once the VLBA is equipped with new receivers that also cover the 6.7 GHz methanol maser line (presumably in 2012) these masers will be also observed. In early 2010, preparatory surveys started with the Very Large Array to obtain accurate positions of the target water masers, and with the VLBA to search for extragalactic background sources near the target maser sources (Immer et al. 2011). The first parallax observations started in March 2010, and first results are expected in mid 2011 (see Fig. 2). In parallel, the VERA array will observe additional H$_2$O and SiO masers throughout the Galaxy. Combined with complementary efforts in the southern hemisphere with the Australian Long Baseline Array, this will result into a detailed and accurate map of the spiral structure of the Milky Way. The superior sensitivity and the large field-of-view of the Square Kilometer Array, which will also cover the 6.7 GHz methanol maser line, will reach even higher astrometric accuracies for methanol masers, radio continuum stars, and pulsars. This will result in a very detailed map of the spiral structure in the southern hemisphere.

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References

Bartkiewicz A., Brunthaler A., Szymczak M., van Langevelde H. J., Reid M. J., 2008, A&A , 490, 787
Benjamin R. A., Churchwell E., Babler B. L., et al., 2005, ApJ , 630, L149
Besla G., Kallivayalil N., Hernquist L., et al., 2010, ApJ , 721, L97
Bessel F. W., 1838a, Astronomische Nachrichten, 16, 65
Bessel F. W., 1838b, MNRAS , 4, 152
Binney J., 2010, MNRAS , 401, 2318
Bobylev V. V., Bajkova A. T., 2010, MNRAS , 408, 1788
Bovy J., Hogg D. W., Rix H., 2009, ApJ , 704, 1704
Brunthaler A., Reid M. J., Falcke H., Greenhill L. J., Henkel C., 2005, Science, 307, 1440
Brunthaler A., Reid M. J., Falcke H., Henkel C., Menten K. M., 2007, A&A , 462, 101
Brunthaler A., Reid M. J., Menten K. M., et al., 2009, ApJ , 693, 424
Burton W. B., 1988, Kellermann, K. I. & Verschuur, G. L. (ed.), The structure of our Galaxy derived from observations of neutral hydrogen. Springer-Verlag, p. 295
Caswell J. L., Fuller G. A., Green J. A., et al., 2010, MNRAS , 404, 1029
Choi Y. K., Hirota T., Honma M., et al., 2008, PASJ , 60, 1007
Coşkunoğlu B., Ak S., Bilir S., et al., 2011, MNRAS , 43
Dame T. M., Hartmann D., Thaddeus P., 2001, ApJ , 547, 792
Deason A. J., Belokurov V., Evans N. W., 2010, ApJ , submitted
Dehnen W., Binney J. J., 1998, MNRAS , 298, 387
Diaz J., Bekki K., 2011, ArXiv e-prints
Fomalont E., Reid M., 2004, New Astronomy Review, 48, 1473
Foot R., 2010, PhRvD , 82, 095001
Francis C., Anderson E., 2009, NewA , 14, 615
Fuchs B., Dettbarn C., Rix H., et al., 2009, AJ , 137, 4149
Georgelin Y. M., Georgelin Y. P., 1976, A&A , 49, 57
Ghez A. M., Salim S., Weinberg N. N., et al., 2008, ApJ , 689, 1044
Gillessen S., Eisenhauer F., Trippe S., et al., 2009, ApJ , 692, 1075
Green J. A., Caswell J. L., Fuller G. A., et al., 2010, MNRAS , 409, 913
Hachisu K., Brunthaler A., Menten K. M., et al., 2009, ApJ , 696, 1981
Hachisu K., Brunthaler A., Menten M. K., et al., 2006, ApJ , 645, 337
Hirota T., Bushimata T., Choi Y. K., et al., 2007, PASJ , 59, 897
Honma M., Bushimata T., Choi Y. K., et al., 2007, PASJ , 59, 889
Hou L. G., Han J. L., Shi W. B., 2009, A&A , 499, 473
Immer K., Brunthaler A., Reid M. J., et al., 2011, ApJS , submitted
Kim K. M., Hirota T., Honma M., et al., 2008, PASJ , 60, 991
Koposov S. E., Rix H., Hogg D. W., 2010, ApJ , 712, 260
Kraus S., Balega Y. Y., Berger J., et al., 2007, A&A , 466, 649
Loeb A., Narayan R., 2008, MNRAS , 386, 2221
Loinard L., Torres R. M., Mioduszewski A. J., et al., 2007, ApJ , 671, 546
McCabe C., 2010, PhRvD , 82, 023530
McMillan P. J., 2011, ArXiv e-prints
McMillan P. J., Binney J. J., 2010, MNRAS , 402, 934
Menten K. M., Reid M. J., Forbrich J., Brunthaler A., 2007, A&A , 474, 515
Mignard F., 2000, A&A , 354, 522
Mihalas D., Binney J., 1981, Galactic astronomy: Structure and kinematics /2nd edition/. San Francisco, CA, W. H. Freeman and Co., 1981, 608 p.
Moellenbrock G. A., Claussen M. J., Goss W. M., 2009, ApJ , 694, 192
Moscadelli L., Reid M. J., Menten K. M., et al., 2009, ApJ , 693, 406
Pandian J. D., Goldsmith P. F., Deshpande A. A., 2007, ApJ , 656, 255
Peebles P. J. E., 2010, ArXiv e-prints, arXiv:1009.0496
Perryman M. A. C., de Boer K. S., Gilmore G., et al., 2001, A&A , 369, 339
Perryman M. A. C., Lindegren L., Kovalevsky J., et al., 1997, A&A , 323, L49
Pestalozzi M. R., Minier V., Booth R. S., 2005, A&A , 432, 737
Piskunov A. E., Kharchenko N. V., Röser S., Schilbach E., Scholz R., 2006, A&A , 445, 545
Reid M. J., 1993, ARA&A , 31, 345
Reid M. J., Brunthaler A., 2004, ApJ , 616, 872
Reid M. J., Menten K. M., Brunthaler A., et al., 2009a, ApJ , 693, 397
Reid M. J., Menten K. M., Zheng X. W., et al., 2009b, ApJ , 700, 137
Reid M. J., Menten K. M., Zheng X. W., Brunthaler A., Xu Y., 2009c, ApJ , 705, 1548
Ružička A., Theis C., Palouš J., 2010, ApJ , 725, 369
Rygl K. L. J., Brunthaler A., Menten K. M., et al., 2010a, ArXiv e-prints, arXiv:1011.5042
Rygl K. L. J., Brunthaler A., Reid M. J., et al., 2010b, A&A , 511, A2
Sandstrom K. M., Peek J. E. G., Bower G. C., Bolatto A. D., Plambeck R. L., 2007, ApJ , 667, 1161
Sanna A., Reid M. J., Moscadelli L., et al., 2009, ApJ , 706, 464
Sato M., Hirota T., Honma M., et al., 2008, PASJ , 60, 975
Schönrich R., Binney J., Dehnen W., 2010, MNRAS , 403, 1829
Shattow G., Loeb A., 2009, MNRAS , 392, L21
Torres R. M., Loinard L., Mioduszewski A. J., Rodríguez L. F., 2007, ApJ , 671, 1813
Ulvestad J. S., Romney J. D., Br开花 F. W., et al., 2010, The VLBA: A Telescope Moving Forward, in Bulletin of the American Astronomical Society, Vol. 42, American Astronomical Society Meeting Abstracts 215, p. 442.07
Valdettaro R., Palla F., Brand J., et al., 2001, A&A , 368, 845
van der Marel R. P., Guhathakurta P., 2008, ApJ , 678, 187
van Langevelde H. J., Vlemmings W., Diamond P. J., Baudry A., Beasley A. J., 2000, A&A , 357, 945
Xu Y., Li J. J., Hachisu K., et al., 2008, A&A , 485, 729
Xu Y., Reid M. J., Menten K. M., et al., 2009, ApJ , 693, 413
Xu Y., Reid M. J., Zheng X. W., Menten K. M., 2006, Science, 311, 54
Zhang B., Zheng X. W., Reid M. J., et al., 2009, ApJ , 693, 419