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THE FIRST HYPERVELOCITY STAR FROM THE LAMOST SURVEY

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ABSTRACT

We report the first hypervelocity star (HVS) discovered from the LAMOST spectroscopic survey. It is a B-type star with a heliocentric radial velocity about $620\,\mathrm{km\,s^{-1}}$, which projects to a Galactocentric radial velocity component of $\sim 477\,\mathrm{km\,s^{-1}}$. With a heliocentric distance of ∼13 kpc and an apparent magnitude of ∼13 mag, it is the nearest and brightest HVS currently known. With a mass of $\sim 9M_\odot$, it is very similar to HVS HE 0437-5439 in its stellar properties; the two stars are the most massive HVSs known so far. The star is clustered on the sky with many other known HVSs, with the position suggesting a possible connection to Galactic center structures. With the current poorly-determined proper motion, a Galactic center origin of this HVS remains consistent with the data at the 2–3σ level. We discuss the potential of the LAMOST survey to discover a large statistical sample of HVSs of different types.

Subject headings: Galaxy: center — Galaxy: halo — Galaxy: kinematics and dynamics — stars: early-type — stars: individual (J091206.52+091621.8)

1. INTRODUCTION

Hypervelocity stars (HVSs) are stars with velocities that exceed the escape velocity of the Galaxy. They were first predicted by Hills (1988), as a consequence of the tidal disruption of tight binary stars by the central massive black hole (MBH) of the Galaxy. Since the first discovery of an HVS (Brown et al. 2005), around 20 HVSs have been found (Edelmann et al. 2005; Hirsch et al. 2005; Brown et al. 2006a,b, 2007a,b, 2012). Here we report the discovery of the first HVS in the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) survey.

Besides the Hills mechanism, HVSs may also be produced by the interaction between single stars and an intermediate mass black hole inspiralling towards the central MBH (Yu & Tremaine 2003), tidal disruption of dwarf galaxies (Abadi, Navarro, & Steinmetz 2009), and surviving companion stars in the white dwarf + helium star channel of Type Ia supernovae (Wang & Han 2009).

HVSs provide a unique probe for a wide range of Galactic science (Kenyon et al. 2008), on scales from a few pc (near the central MBH) to $\sim 10^5$ pc (the Galactic halo). The spatial and velocity distributions, as well as the detection frequencies of HVSs, can be used to test the ejection mechanisms. The number density, velocity, and stellar type distributions of HVSs can reveal the environment around the central MBH and the stellar mass distribution near the MBH (e.g., Brown et al. 2006a; Kollmeier & Gould 2007; Lu et al. 2007; Kollmeier et al. 2010). The sky distribution of HVSs suggests a connection to the S stars in the two disks near the central MBH (e.g., Lu et al. 2010), which may provide clues to the MBH growth (Bromley et al. 2012). The trajectories of HVSs can also be used to probe the shape of the dark matter halo of the Galaxy (Gnedin et al. 2005; Yu & Madau 2007).

For all of the above applications, it is desirable to assemble a large, statistical sample of HVSs. The LAMOST survey has this potential, as described below. In this paper, we report the first HVS discovered in the internal Data Release 1 (DR1) of LAMOST. In § 2, we provide a brief description of the data, and then focus on the properties of the HVS and discuss the implications. Finally, in § 3, we summarize the results and forecast the prospects of further HVSs discoveries from the LAMOST survey.

2. THE LAMOST SURVEY AND ITS FIRST HVS

2.1. *Data*

LAMOST is a 4m Schmidt telescope (now named the Guo Shoujing Telescope) at the Xinglong Observing Station of the National Astronomical Observatories of China. It is equipped with 4000 optical fibers in the focal plane, taking spectra with resolution $R = \lambda/\Delta\lambda = 1800$. Within the LAMOST spectroscopic survey (Cui et al. 2012; Zhao et al. 2012), the LAMOST Experiment for Galactic Understanding and Exploration (LEGUE; Deng et al. 2012) aims to take ∼8 million stellar spectra for targets covering 16,000 square

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TABLE 1
PROPERTIES OF LAMOST-HVS1

	J091206.52+091621.8
Position ($J2000$)	$(\alpha,\, \delta) = (138^\circ.027199,\, 9^\circ.272725)$ $(l,\, b) = (221^\circ.099564,\, 35^\circ.407261)$
Magnitudes	$g = 12.91 \quad r = 13.22 \quad i = 13.50$ $B = 12.96\ V = 13.06\ J = 13.36$ $H = 13.43\ K = 13.53$
Distance	13.4 ± 2.2 kpc (Heliocentric) 19.4 ± 2.1 kpc (Galactocentric)
Radial Velocity	$v_{r\odot} = 620 \pm 10\,\mathrm{km\,s^{-1}}$ $v_{rf} = 477 \pm 10\,\mathrm{km\,s^{-1}}$
Proper Motion (mas yr^{-1})	$(\mu_\alpha \cos\delta\,, \quad \mu_\delta)$ $(-2.5 \pm 1.9,\ -1.2 \pm 1.9)$ [PPMXL] $(-4.0 \pm 0.7,\ -4.9 \pm 1.2)$ [UCAC4]
Spectral Type	B
$T_{\rm eff}$	$(2.07 \pm 0.12) \times 10^4$K
$\log[g/(\mathrm{cm\,s^{-2}})]$	3.67 ± 0.19
[Fe/H]	-0.13 ± 0.07
Mass	$9.1 \pm 0.7 M_\odot$

degrees of sky over the course of five years. The target-selection criteria required to achieve various science goals can be found in Carlin et al. (2012), Chen et al. (2012), Yang et al. (2012), and Zhang et al. (2012).

The internal DR1 of LAMOST spectra and stellar parameters includes spectra obtained during a Pilot Survey (from October 2011 to June 2012; Luo et al. 2012) and the first year of the regular survey (from September 2012). Most of the observed stars are brighter than $r = 16$. We performed a systematic search for HVSs in the catalog including stars of A-type or earlier, and one of the $\sim 10^5$ stars turned out to be a HVS (hereafter, denoted LAMOST-HVS1).

2.2. *Properties of LAMOST-HVS1*

The star (J091206.52+091621.8; LAMOST-HVS1) has been observed twice by LAMOST, separated by about 70 days (December 23, 2012 and March 5, 2013). It is a bright star with magnitude around 13. The radial velocities at the two epochs from spectral fitting are consistent with each other within the uncertainties, and therefore there is no evidence for it being a close binary system.

The measured heliocentric radial velocity, $v_{r\odot} = 620 \pm 10\,\mathrm{km\,s^{-1}}$, translates to a Galactocentric radial component $v_{rf} = 477 \pm 10\,\mathrm{km\,s^{-1}}$, according to

$$v_{rf} = v_{r\odot} + U_0 \cos l \cos b + (V_{LSR} + V_0) \sin l \cos b + W_0 \sin b, \tag{1}$$

where we adopt $V_{LSR} = 250\,\mathrm{km\,s^{-1}}$ for the velocity of the local standard of rest (LSR) (Reid et al. 2009; McMillan & Binney 2010) and $(U_0, V_0, W_0) = (11.1, 12.24, 7.25)\,\mathrm{km\,s^{-1}}$ for the peculiar motion of the Sun with respect to the LSR (Schönrich et al. 2010). The star has proper motion measurements, $(\mu_\alpha \cos\delta,\, \mu_\delta) = (-2.5 \pm 1.9,\, -1.2 \pm 1.9)\,\mathrm{mas\,yr^{-1}}$ in the PPMXL catalog (Roeser et al. 2010) and $(-4.0 \pm 0.7,\, -4.9 \pm 1.2)\,\mathrm{mas\,yr^{-1}}$ in the UCAC4 catalog (Zacharias et al. 2013). A more accurate determination is clearly desirable.

Figure 1 shows the low-resolution LAMOST spectrum of the star. The basic stellar atmospheric parameters, listed in Table 1, are obtained by fitting the spectrum with the University of Lyon Spectroscopic analysis Software (ULySS[1]; Koleva et al. 2009). It has effective temperature $T_{\rm eff} \simeq 2 \times 10^4$K, surface gravity $\log[g/(\mathrm{cm\,s^{-2}})] \simeq 3.7$, and slightly sub-solar metallicity, $[\mathrm{Fe/H}] \simeq -0.13$. The presence of strong helium lines indicates that it is an early B-type star.

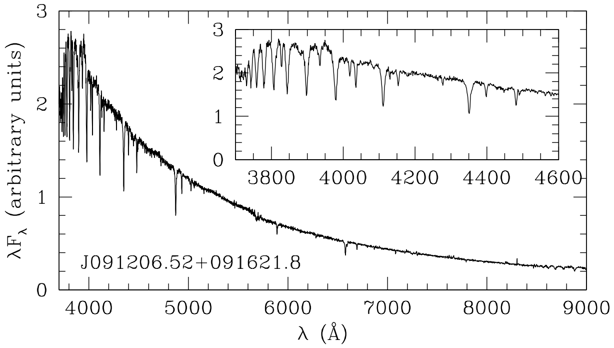

FIG. 1.— Spectrum of LAMOST-HVS1 taken with the Guo Shoujing Telescope. Shown in the inset is a zoomed-in view of the blue end of the spectrum.

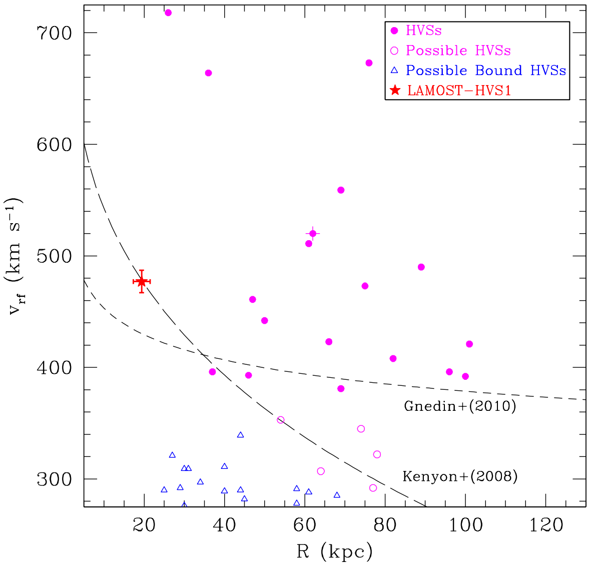

FIG. 2.— Galactocentric radial velocity of known/possible/bound HVSs (Brown et al. 2012) and LAMOST-HVS1 versus the Galactocentric distance. The short and dashed curves are escape velocities from two models of Galactic potential (Kenyon et al. 2008; Gnedin et al. 2010), and the difference illustrates the current uncertainties in the models. The filled circle with a cross is HVS HE 0437-5439, LAMOST-HVS1's near twin (see text).

To determine the distance and mass of LAMOST-HVS1, we make use of the list of masses and luminosities of B-type stars compiled by Hohle, Neuhäuser, & Schutz (2010), based on 2MASS photometry and Hipparcos parallax. By matching the values of temperature and surface gravity to the range derived from spectral fitting of the LAMOST-HVS1, we infer its spectral type to be between B1 and B2.5. While the luminosity class is not well-constrained, it is correlated with the spectral type. For example, the star could be B1I, B2IV, or B2.5V. The degeneracy leads to only a small luminosity variation

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[1] http://ulyss.univ-lyon1.fr/

among such stars, which translates to a relatively well-constrained distance, 13.4 ± 2.2 kpc. With 8 kpc adopted for the Sun's distance to the Galactic center (GC), the Galactocentric distance of LAMOST-HVS1 is calculated to be $R = 19.4 \pm 2.1$ kpc. The mass of LAMOST-HVS1 is inferred to be $9.1 \pm 0.7 M_\odot$.

Interestingly, LAMOST-HVS1 appears to be almost a twin to HE 0437-5439 (a.k.a HVS 3; e.g., Edelmann et al. 2005; Bonanos et al. 2008; Przybilla et al. 2008), which is also a $\sim 9 M_\odot$ B-type star, with similar temperature and surface gravity. Together, the two make the most massive HVSs discovered so far, and the much smaller distance makes LAMOST-HVS1 the brightest HVS.

With the velocity and distance determined, Figure 2 places LAMOST-HVS1 in the v_{rf}–R plane, and compares it to the known HVSs, as well as possible HVSs and possible bound HVSs, as listed in Brown et al. (2012). Clearly, LAMOST-HVS1 is the nearest HVS discovered so far. Following Brown et al. (2012), we also plot two curves (long and short dashed) of escape velocities, based on the Galactic potential models of Kenyon et al. (2008) and Gnedin et al. (2010), respectively. At $R \sim 20$ kpc, the velocity $v_{rf} = 477\,\mathrm{km\,s^{-1}}$ of LAMOST-HVS1 is above the escape velocity in the Gnedin et al. (2010) model and falls almost on top of the model curve from Kenyon et al. (2008), establishing its identity as an HVS.

2.3. *Galactic Center Origin?*

We now explore to what extent the data constrain the origin of LAMOST-HVS1.

Lu et al. (2010) and Zhang et al. (2013) demonstrate that, under the tidal-disruption scenario, the spatial distribution of HVSs can track that of the progenitors. Lu et al. (2010) indeed find that most of the discovered HVSs, if viewed from the GC, show spatial distributions near the great circles connecting to the planes of the clockwise-rotating young stellar (CWS) disk and the northern arm of the mini-spiral or the outer wrapped part of the CWS disk, supporting the GC origin of HVSs.

Following Lu et al. (2010), the top panel of Figure 3 shows the sky distribution of the known and possible HVSs and the position of LAMOST-HVS1, *as viewed from the GC*. The great circles correspond to different stellar structures in the GC: the CWS, the outer wrap of the CWS (Outer-CWS), the Northern arm (North-arm), and the counter-clockwise stellar disk (CCWS). Interestingly, LAMOST-HVS1 falls into the clustered region defined by most other known HVSs. It is closest to the Outer-CWS great circle and also close to the one for the North-arm. This seems to support its GC origin, and suggests that its progenitors were associated with the CWS or North-arm.

In the top panel of Figure 3, LAMOST-HVS1's twin, HE 0437-5439, lies near the CCWS circle. But it is also possible to connect to the Outer-CWS, similar to LAMOST-HVS1. HE 0437-5439 has been proposed to have been produced from the Large Magellanic Cloud (Edelmann et al. 2005; Bonanos et al. 2008; Przybilla et al. 2008), but with well-measured proper motion Brown et al. (2010) conclude that it is more likely a compact binary ejected from the GC, which later evolved into a blue straggler.

The proper motion of LAMOST-HVS1 is not well-measured. We perform a Monte Carlo simulation, by accounting for the uncertainties in the proper motion (for both the PPMXL and the UCAC4 value), distance, and radial velocity (all assumed to be Gaussian), in order to consider the implications of the velocity vector for the origin of LAMOST-HVS1. Obviously, the uncertainties are dominated by those in the proper motion.

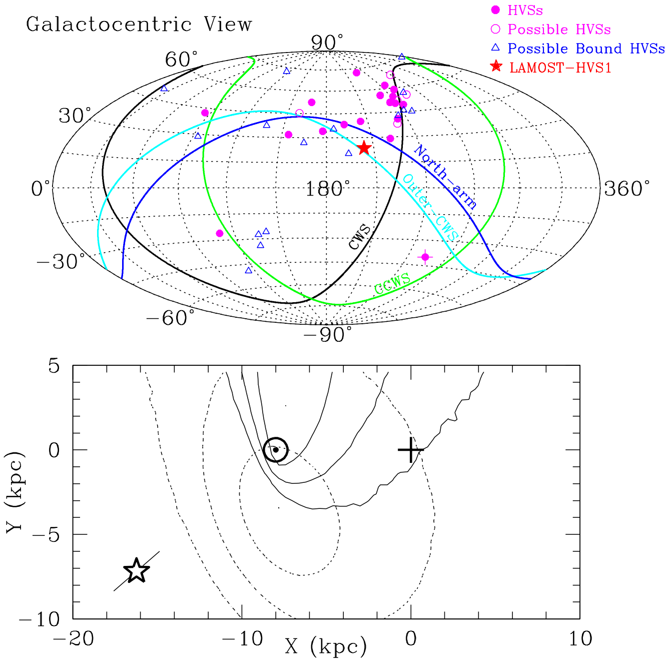

FIG. 3.— *Top:* Galactocentric view of the sky distribution of HVSs in the Galactic coordinate system, and the position of LAMOST-HVS1. The positions of stars are shifted to match what would be seen by an observer at the Galactic center. The great circles correspond to structures of stellar distribution near the massive black hole at the Galactic center (see text). The filled circle with a cross is HE 0437-5439, LAMOST-HVS1's twin (see text). *Bottom:* Distribution of ejection position, if LAMOST-HVS1 originated from the Galactic plane. The contours indicate the 1σ, 2σ, and 3σ ranges (dotted and solid for using PPMXL and UCAC4 proper motions, respectively), and the loose constraint is mainly a consequence of the large uncertainty in the proper motion. The projected position of LAMOST-HVS1 is shown as the star, with the line denoting its 1σ uncertainty. The Sun's position and the Galactic center are marked with a $\odot$ and a cross, respectively.

From the star's current position, we go along the opposite direction of the velocity vector to derive the intercept position in the disk plane. This would be the point of origin for the HVS if it were ejected from the plane and its trajectory were not substantially deflected. The Monte Carlo simulation shows that the most likely intercept is not at the GC (see the bottom panel of Figure 3). The uncertainty is nevertheless large – the GC is within the 2σ (3σ) range of the distribution of the intercept positions with the PPMXL (UCAC4) proper motion adopted. An accurate measurement of the proper motion will be a key to determining the origin of LAMOST-HVS1. If the GC origin holds, the flight time ($\sim$45 Myr) for LAMOST-HVS1 to reach its current position would be comparable to or longer than its lifetime (estimated to be around 30–40 Myr). Therefore it may be either a massive star ejected directly from the GC (with properties in broad agreements with predictions by Zhang et al. 2013), or a blue straggler from similar processes as HE 0437-5439.

Given that LAMOST-HVS1 is the brightest example of

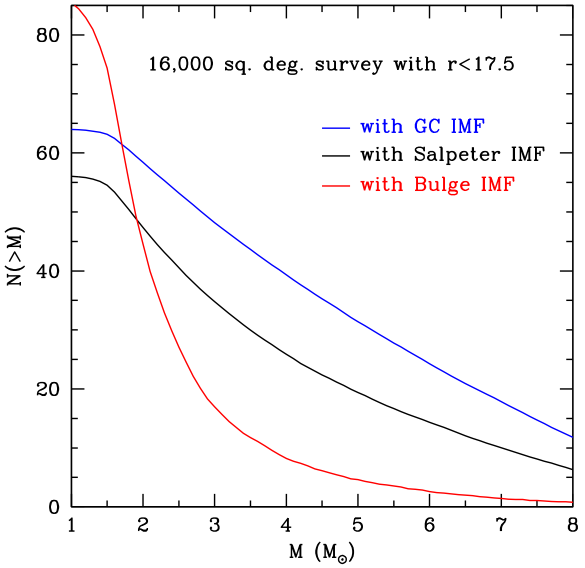

FIG. 4.— Prospect of discovering (unbound) HVSs from the LAMOST survey, based on the plan of a 16,000 square degree survey with a limiting magnitude $r = 17.5$. The curves represent the numbers of HVSs that LAMOST may discover for three cases of the stellar IMF.

known HVSs and its clear similarity to HE 0437-5439, it will be extremely interesting to conduct a more detailed study. If indeed it comes from the GC, and moves along a radial direction, we expect a proper motion around 4–5 mas yr^{-1}, well in reach of current and near-future data. High-resolution spectroscopic study will reveal its chemical abundance pattern and rotation velocity. We plan to perform such follow-up observations and investigations.

3. SUMMARY AND DISCUSSION

We present the first HVS discovered from the LAMOST survey, a B-type star with a mass of $\sim 9 M_\odot$, located at a Galactocentric distance of ∼19 kpc with a Galactocentric radial velocity component of $\sim 477\,\mathrm{km\,s^{-1}}$, based on the measured radial velocity. It is the nearest and brightest, and one of the two most massive HVSs discovered so far.

LAMOST-HVS1 is clustered with most other known HVSs on the sky. Its proximity to the great circles corresponding to stellar structures around the central MBH suggests a GC origin. A more accurate proper motion measurement, achievable in the near future, will pin down its origin.

LAMOST-HVS1 signals the start of the HVS discovery effort from the LAMOST survey. The survey has the potential to discover a large number of HVSs. Figure 4 shows a conservative forecast for the plan of a 16,000 square degree survey with a limiting magnitude of $r = 17.5$ (the final survey may be deeper), following a LEGUE halo target selection with higher priority on bluer stars (Carlin et al. 2012). The forecast assumes a GC origin of HVSs and is anchored by using the space density of HVSs in Brown et al. (2007b). Three cases are considered: a Salpeter initial mass function (IMF; Salpeter 1955), a Galactic bulge IMF (Mezger et al. 1999), and a GC IMF (Lu et al. 2013).

Since the LAMOST survey does not preselect B-type stars as targets for spectroscopic observations to reduce the contamination by the large number of halo stars, it can discover HVSs of various stellar types, from B to G. The total number of HVSs down to $M = 1 M_\odot$ with the above survey parameters is in the range of ∼56–85. In addition, we also expect to find a large number of bound HVSs and possibly binary HVSs. Such a large statistical sample of HVSs of different types would enable a wide range of investigations to elucidate the nature of HVSs, and to constrain Galactic structure.

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REFERENCES

Abadi, M. G., Navarro, J. F., & Steinmetz, M. 2009, ApJ, 691, L63
Bonanos, A. Z., López-Morales, M., Hunter, I., & Ryans, R. S. I. 2008, ApJ, 675, L77
Bromley, B. C., Kenyon, S. J., Geller, M. J., & Brown, W. R. 2012, arXiv:1203.6685
Brown, W. R., Geller, M. J., Kenyon, S. J., & Kurtz, M. J. 2005, ApJ, 622, L33
Brown, W. R., Geller, M. J., Kenyon, S. J., & Kurtz, M. J. 2006, ApJ, 640, L35
Brown, W. R., Geller, M. J., Kenyon, S. J., & Kurtz, M. J. 2006, ApJ, 647, 303
Brown, W. R., Geller, M. J., Kenyon, S. J., Kurtz, M. J., & Bromley, B. C. 2007, ApJ, 660, 311
Brown, W. R., Geller, M. J., Kenyon, S. J., Kurtz, M. J., & Bromley, B. C. 2007, ApJ, 671, 1708
Brown, W. R., Anderson, J., Gnedin, O. Y., et al. 2010, ApJ, 719, L23
Brown, W. R., Geller, M. J., & Kenyon, S. J. 2012, ApJ, 751, 55
Carlin, J. L., Lépine, S., Newberg, H. J., et al. 2012, Research in Astronomy and Astrophysics, 12, 755
Chen, L., Hou, J.-L., Yu, J.-C., et al. 2012, Research in Astronomy and Astrophysics, 12, 805
Cui, X.-Q., Zhao, Y.-H., Chu, Y.-Q., et al. 2012, Research in Astronomy and Astrophysics, 12, 1197
Deng, L.-C., Newberg, H. J., Liu, C., et al. 2012, Research in Astronomy and Astrophysics, 12, 735
Edelmann, H., Napiwotzki, R., Heber, U., Christlieb, N., & Reimers, D. 2005, ApJ, 634, L181
Gnedin, O. Y., Gould, A., Miralda-Escudé, J., & Zentner, A. R. 2005, ApJ, 634, 344
Gnedin, O. Y., Brown, W. R., Geller, M. J., & Kenyon, S. J. 2010, ApJ, 720, L108
Hills, J. G. 1988, Nature, 331, 687
Hirsch, H. A., Heber, U., O'Toole, S. J., & Bresolin, F. 2005, A&A, 444, L61
Hohle, M. M., Neuhäuser, R., & Schutz, B. F. 2010, Astronomische Nachrichten, 331, 349

Kenyon, S. J., Bromley, B. C., Geller, M. J., & Brown, W. R. 2008, ApJ, 680, 312
Koleva, M., Prugniel, Ph., Bouchard, A., & Wu, Y. 2009, A&A, 501, 1269
Kollmeier, J. A., & Gould, A. 2007, ApJ, 664, 343
Kollmeier, J. A., Gould, A., Rockosi, C., et al. 2010, ApJ, 723, 812
Lu, Y., Yu, Q., & Lin, D. N. C. 2007, ApJ, 666, L89
Lu, Y., Zhang, F., & Yu, Q. 2010, ApJ, 709, 1356
Lu, J. R., Do, T., Ghez, A. M., et al. 2013, ApJ, 764, 155
Luo, A.-L., Zhang, H.-T., Zhao, Y.-H., et al. 2012, Research in Astronomy and Astrophysics, 12, 1243
McMillan, P. J., & Binney, J. J. 2010, MNRAS, 402, 934
Mezger, P. G., Zylka, R., Philipp, S., & Launhardt, R. 1999, A&A, 348, 457
Przybilla, N., Nieva, M. F., Heber, U., et al. 2008, A&A, 480, L37
Reid, M. J., Menten, K. M., Zheng, X. W., et al. 2009, ApJ, 700, 137
Roeser, S., Demleitner, M., & Schilbach, E. 2010, AJ, 139, 2440
Salpeter, E. E. 1955, ApJ, 121, 161
Schönrich, R., Binney, J., & Dehnen, W. 2010, MNRAS, 403, 1829
Wang, B., & Han, Z. 2009, A&A, 508, L27
Yang, F., Carlin, J. L., Liu, C., et al. 2012, Research in Astronomy and Astrophysics, 12, 781
Yu, Q., & Madau, P. 2007, MNRAS, 379, 1293
Yu, Q., & Tremaine, S. 2003, ApJ, 599, 1129
Zacharias, N., Finch, C. T., Girard, T. M., et al. 2013, AJ, 145, 44
Zhang, F., Lu, Y., & Yu, Q. 2013, ApJ, 768, 153
Zhang, Y.-Y., Carlin, J. L., Yang, F., et al. 2012, Research in Astronomy and Astrophysics, 12, 792
Zhao, G., Zhao, Y.-H., Chu, Y.-Q., Jing, Y.-P., & Deng, L.-C. 2012, Research in Astronomy and Astrophysics, 12, 723