Mem. S.A.It. Vol. 85, 699

Memorie della

Gaia & Ultra-Cool Dwarfs: a high-definition picture of the Milky Way

J. Bochanski[1,2]

[1] Haverford College, 370 Lancaster Avenue, Haverford, PA 19041, USA
[2] Rider University, 2083 Lawrenceville Rd, Lawrenceville, NJ 08648, USA
e-mail: jbochanski@rider.edu

Abstract. *Gaia* will produce a parallax catalog containing millions of low–mass stars and thousands of brown dwarfs with distances and radial velocities known to 1% and 10 m s^{-1} precisions. These measurements will enable a wide variety of scientific investigations, including the astrometric detection of Jupiter–mass planets around nearby stars, precise measurements of the Milky Way's structural and kinematic components, discovery and refinement in the nearby stellar moving group census, measuring the density of dark matter within the disk of the Galaxy, a precise measurement of the stellar IMF, and the discovery of thousands of widely separated binary star systems. I discuss the details of some of these studies, and their implications on the understanding of Galactic formation and evolution.

Key words. Stars: low–mass – Stars: brown dwarfs – Galaxy: disk – Galaxy: solar neighborhood – Galaxy: structure

1. Introduction

Gaia promises to revolutionize our understanding of the Milky Way (MW). It will deliver precise parallaxes and proper motions for hundreds of millions of stars, along with radial velocities for stars brighter than $G \approx 17$ (Perryman et al. 2001; de Bruijne 2012). In particular, *Gaia* will produce precise astrometric and kinematic measurements for low–mass stars, the most common star in the Galaxy. Low–mass stars and brown dwarfs, defined in this proceedings as M dwarfs and later, are the most common star in the MW, comprising $\sim 70\%$ of all stars (Reid et al. 2002; Bochanski et al. 2010; Kirkpatrick et al. 2012). Their overwhelming contribution to the stellar population of the MW has made them targets for a bevy of scientific investigations, including studies of the initial mass function, targets in exoplanet searches, and tracers of kinematic populations within the Galaxy. Much of this work has resulted from survey observations, derived from deep, wide-angle surveys such as the Sloan Digital Sky Survey (SDSS; York et al. 2000) and the Two-Micron All Sky Survey (2MASS; Cutri et al. 2003). *Gaia* will produce its own all–sky catalog, building on existing studies and complementing upcoming surveys such as the Large Synoptic Survey Telescope (LSST; Ivezic et al. 2008).

In the following proceedings, I discuss some of the science cases enabled by *Gaia* observations of low–mass stars and brown dwarfs. These include the astrometric discovery of planets around low–mass stars, the volume–limited census of nearby stars and brown dwarfs and measurement of the low–mass initial mass function, the identification of nearby moving groups, and measuring the local dark matter density contribution. All of these scientific investigations are critically dependent on the precise parallaxes and motions that will be measured by *Gaia*. *Gaia*'s end of mission parallax standard error is expected to be $\sim 10\ \mu$as for bright stars ($6 < G < 12$), and rise to a few 100 μas from $12 < G < 20$ mag. Proper motions will be $\sim 2\times$ more precise than parallaxes at the end of the mission. However, the details of these expected yields vary on the absolute magnitude and color of the star being observed, with redder stars having lower precision than the brighter, bluer stars. Using the PyGaia package[1], I computed the approximate distance limits for K, M and L dwarfs where *Gaia* will deliver parallaxes better than 1% precision. These limits are shown in Figure 1, and frame the following discussion. Late–type low–mass stars (M5 and later) will have precise astrometric solutions out to $\sim$ 100 pc, making them ideal targets for exoplanet searches and tracers of nearby kinematic structures. Intrinsically brighter low–mass stars will have precise parallaxes out to ~ 1000 pc, making them ideal for measuring the bulk structural properties of the MW, including the disk scale height and length, along with the dark matter density near the Sun. Of note is the lack of L and T dwarfs in Figure 1. Brown dwarfs are so intrinsically faint in the optical that only the brightest within 10 pc will produce 1% precision parallaxes. Alternative methods for measuring precise parallaxes of brown dwarfs should be pursued to complement the overwhelming catalog of low–mass stars *Gaia* is expected to produce.

2. Detecting exoplanets

The astrometry produced from *Gaia* observations will not only measure parallaxes and proper motions for all stars with $G < 20$, but it will also produce a catalog of astrometric binary systems (Perryman et al. 2001). The astrometric deviation of a companion varies with the mass and semi-major axis of the companion, and is inversely proportional to the distance of the system and mass of the primary. Thus, for nearby systems with close secondaries, the least massive companions will be detected. This case was explored in Sozzetti et al. (2014), which discussed the possibility of detecting Jupiter–mass planets with periods of 0.2-6.0 years around M dwarfs within 30 pc. Sozzetti et al. (2014) demonstrated that planetary detection efficiency fell with distance, from $\sim 90\%$ within 10 pc, to $\sim 60\%$ at 30 pc. They also showed that the least massive primaries ($\sim 0.1 M_{\odot}$) will have astrometric planets detected with an efficiency $\sim 85\%$. Assuming current estimates for the fraction of planets around M dwarfs, Sozzetti et al. (2014) estimated $\sim$ 100 giant planets will be discovered by *Gaia* within 30 pc. By expanding the sample to M dwarfs within 100 pc, they predicted $\sim$ 2600 detections of planets, with $\sim$ 500 orbits being measured. While not the primary mission of Gaia, its ability to astrometrically detect planets around M dwarfs will probe phase space that is currently unexplored, namely planets with large masses and semi–major axes.

3. The solar neighborhood

While *Gaia* will deliver the highest precision astrometry and radial velocities for stars within $\sim$ 25 pc, the "extended" solar neighborhood, ranging out to 100 pc, will show the greatest improvement over current measurements. Currently, $\lesssim$ 3,000 low–mass stars and brown dwarfs have well–measured parallaxes ($\sigma_{\pi} <$ 5%) within this volume (see Table 1). This is critically important for two specific studies: 1) measuring the stellar initial mass function (IMF; Bochanski et al. 2010; Reid et al. 2002; Chabrier 2003) and 2) mapping the MW's disk and halo (Jurić et al. 2008; Ivezić et al. 2008; Bochanski et al. 2010).

Historically, measurements of the low–mass stellar IMF have relied on a few thousand nearby stars with well–measured parallaxes (i.e., Reid et al. 2002). Using nearby stars

[1] The PyGaia package, authored by Anthony Brown, is available at `https://github.com/agabrown/PyGaia`.

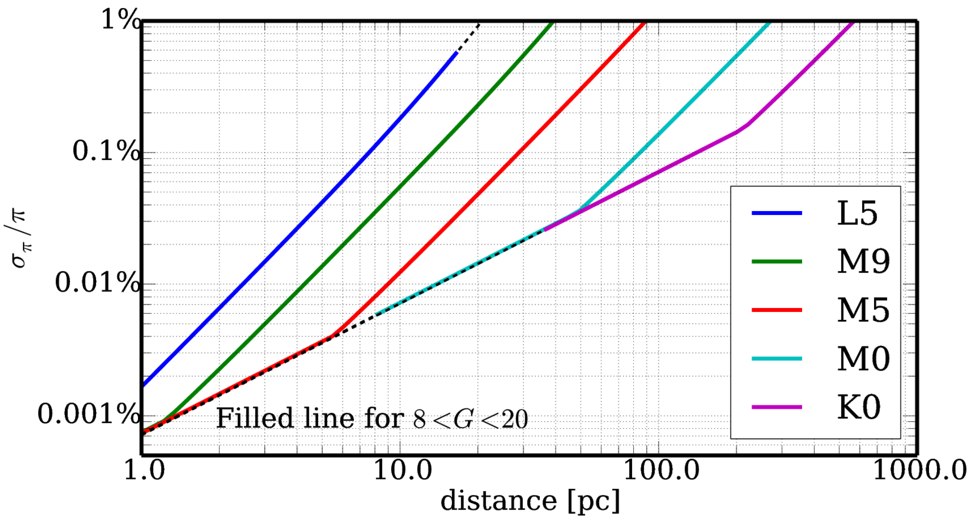

Fig. 1. Expected parallax precisions as a function of distance for K0, M0, M5, M9 and L5 dwarfs, with colors given in the legend. The filled–in colored lines denote distances stars of this spectral type would have $8 < G < 20$. Note that M dwarfs from $\sim 1 - 300$ pc will have distances with precisions better than 1%. This figure was calculated using the PyGaia software package.

Table 1. Low–Mass Stars and Brown Dwarfs with Trigonometric Parallaxes

Spectral Type	Current Number with π	Expected Number after *Gaia*
Early M (M0-M5)	$\sim 1000^a$	1,000,000s
Late M (M6-M9)	$\sim 1500^b$	100,000s
L & T	$\sim 400^c$	$\sim 1,000^d$

a - Sources for parallaxes include: Jao et al. (2011); Reid et al. (2002); Henry et al. (2006); Lépine et al. (2009); Dahn et al. (2002); Vrba et al. (2004); Smart et al. (2010); Monet et al. (1992); Perryman et al. (1997); van Leeuwen (2007) and references therein.
b - Sources for parallaxes include: Dittmann et al. (2014) and references therein.
c - Sources for parallaxes include: Tinney et al. (2003); Marocco et al. (2010); Faherty et al. (2012); Dahn et al. (2002); Vrba et al. (2004); Dupuy & Liu (2012); Andrei et al. (2011); Manjavacas et al. (2013) and references therein.
d - Kirkpatrick, this issue

is advantageous for a number of reasons. First, calculating space densities is very simple, simply count the number of stars within a well–defined volume. This is possible since the distance to all stars (or systems of stars) is well known due to their parallax. This avoids extrapolations from color–magnitude diagrams, which are sensitive to metallicity and magnetic activity (Reid 1997; Bochanski et al. 2013) and nearby binary systems can be resolved and counted separately. The primary disadvantage to computing the IMF in this fashion is the small number of stars available, particularly at spectral types of M6 and later. For most previous studies, only a few tens to hundreds of stars were found in these regimes, making

Poisson noise significant in the smallest mass bins. *Gaia* will deliver precise photometry at distances $\gtrsim 3\times$ larger than current limits, resulting in nearly an order of magnitude more low–mass stars, and a decrease in Poisson uncertainty by $\sim$ 30%. This will result in the definitive measurement of the stellar low–mass IMF in the solar neighborhood.

Gaia parallaxes of low–mass stars and brown dwarfs will also redefine existing color–absolute magnitude relations (CMRs). Widely–used CMRs (i.e., Jurić et al. 2008; Bochanski et al. 2010) are based on nearby stars, which are preferentially solar–metallicity and field age ($\lesssim$ 5 Gyr). When applied to more distant stellar photometry, such as the thick disk or halo population, these CMRs yield biased, overestimated distances. While models may address this problem, modern isochrones fail to match the observed nearby-CMR (Baraffe et al. 1998; Bochanski et al. 2010). Thus, well–measured parallaxes to low–mass stars and brown dwarfs beyond 25 pc will result in the first comprehensive color–absolute-magnitude–metallicity relations. Furthermore, *Gaia* parallaxes will be available for most low–mass stars with existing SDSS photometry. Combining these two datasets will result in more precise measurements of the MW's structural components, such as the disk scale height and scale length, and will also confirm or negate more subtle signals, such as the north–south stellar density asymmetry (Yanny & Gardner 2013).

4. The Galactic neighborhood

Finally, extending beyond 100 pc to a few kpc, *Gaia* parallaxes can be applied to stars in the "Galactic neighborhood". At these distances, two fundamental questions that can be addressed with *Gaia* observations: 1) Locating kinematic substructure and identifying dominant energy and angular momentum mechanisms within the disk, and 2) measuring the local mass density and the contribution due to dark matter.

The presence for kinematic substructure in the disk of the MW has been known for decades, and has been well–studied using Hipparcos and RAVE observations (Eggen & Sandage 1959; Dehnen & Binney 1998; Antoja et al. 2012). There are various formation mechanisms that can cause kinematic clumping, such as heating from the Galactic bar, spiral arms, the disruption of former star formation sites, or recent accretion events of satellites or star clusters. Recently, Antoja et al. (2012) demonstrated the utility of wavelet transform analysis on RAVE observations for identifying kinematic substructure. This statistical method will be well–matched to the millions of low–mass stars and brown dwarfs visible with *Gaia*. After identifying nearby substructures, *Gaia* observations can be used to identify the dominant migration mechanisms within the disk. Scattering off of molecular clouds (Spitzer & Schwarzschild 1953), spiral arm heating (Sellwood & Binney 2002) and minor mergers (Toth & Ostriker 1992; Villalobos & Helmi 2008) all predict slightly different age–velocity dispersion relations. By identifying which mechanisms are the most dominant for nearby stars, *Gaia* kinematic observations can be employed as age indicators.

In addition to studying age–velocity dispersion relations, *Gaia* observations can be used to constrain the local mass density and Galactic potential. Building on the works of Oort (1932, 1960) and Kuijken & Gilmore (1989), Zhang et al. (2013) used SDSS observations of 9000 K dwarfs within $\sim$ 1.5 kpc to measure the vertical density and velocity dispersion profiles for three populations with different metallicities. (Zhang et al. 2013) derived the local Galactic potential from these observations, and compared the visible stellar and gas mass density to the total mass density to derive the local contribution due to dark matter. This technique will be immediately applicable to *Gaia* observations of low–mass stars and brown dwarfs, and will permit this analysis to be extended beyond the solar neighborhood.

5. Conclusions

Gaia observations of low–mass stars and brown dwarfs promise to revolutionize not only our understanding of these objects, but the Galaxy in which they reside. I have demonstrated how these observations can be used to study a variety of interesting astrophysical questions, from planetary to Galactic scales. The common thread between all of these future studies will be the efficient analysis of millions of stars with μas precision astrometric observation. Much like its predecessor Hipparcos, *Gaia* will provide the astronomical community with an extremely valuable and fundamental dataset that will be used by generations of astronomers.

Acknowledgements. I would like to thank the conference organizers and SOC for a productive and fascinating meeting in a wonderful location. I also thank Robyn Sanderson and Jo Bovy for enlightening discussions on Galactic kinematics.

References

Andrei, A. H., Smart, R. L., Penna, J. L., et al. 2011, AJ, 141, 54
Antoja, T., Helmi, A., Bienayme, O., et al. 2012, MNRAS, 426, L1
Baraffe, I., et al. 1998, A&A, 337, 403
Bochanski, J. J., Hawley, S. L., Covey, K. R., et al. 2010, AJ, 139, 2679
Bochanski, J. J., et al. 2013, AJ, 145, 40
Chabrier, G. 2003, PASP, 115, 763
Cutri, R. M. et al. 2003, VizieR Online Data Catalog: II/246
Dahn, C. C. et al. 2002, AJ, 124, 1170
de Bruijne, J. H. J. 2012, Ap&SS, 341, 31
Dehnen, W. & Binney, J. J. 1998, MNRAS, 298, 387
Dittmann, J. A., et al. 2014, ApJ, 784, 156
Dupuy, T. J. & Liu, M. C. 2012, ApJS, 201, 19
Eggen, O. J. & Sandage, A. R. 1959, MNRAS, 119, 255
Faherty, J. K., Burgasser, A. J., Walter, F. M., et al. 2012, ApJ, 752, 56
Henry, T. J., Jao, W.-C., Subasavage, J. P., et al. 2006, AJ, 132, 2360
Ivezic, Z. et al. 2008, arXiv:0805.2366
Ivezić, Z. et al. 2008, ApJ, 684, 287
Jao, W.-C., Henry, T. J., Subasavage, J. P., et al. 2011, AJ, 141, 117
Jurić, M., Ivezić, Ž., Brooks, A., et al. 2008, ApJ, 673, 864
Kirkpatrick, J. D. et al. 2012, ApJ, 753, 156
Kuijken, K. & Gilmore, G. 1989, MNRAS, 239, 571
Lépine, S., et al. 2009, AJ, 137, 4109
Manjavacas, E., et al. 2013, A&A, 560, A52
Marocco, F., Smart, R. L., Jones, H. R. A., et al. 2010, A&A, 524, A38
Monet, D. G., Dahn, C. C., Vrba, F. J., et al. 1992, AJ, 103, 638
Oort, J. H. 1932, Bull. Astron. Inst. Netherlands, 6, 249
Oort, J. H. 1960, Bull. Astron. Inst. Netherlands, 15, 45
Perryman, M. A. C., Lindegren, L., Kovalevsky, J., et al. 1997, A&A, 323, L49
Perryman, M. A. C., de Boer, K. S., Gilmore, G., et al. 2001, AP&SS, 369, 339
Reid, I. N. 1997, AJ, 114, 161
Reid, I. N., Gizis, J. E., & Hawley, S. L. 2002, AJ, 124, 2721
Sellwood, J. A. & Binney, J. J. 2002, MNRAS, 336, 785
Smart, R. L., Ioannidis, G., Jones, H. R. A., Bucciarelli, B., & Lattanzi, M. G. 2010, A&A, 514, A84
Sozzetti, A., Giacobbe, P., Lattanzi, M. G., et al. 2014, MNRAS, 437, 497
Spitzer, Jr., L. & Schwarzschild, M. 1953, ApJ, 118, 106
Tinney, C. G., Burgasser, A. J., & Kirkpatrick, J. D. 2003, AJ, 126, 975
Toth, G. & Ostriker, J. P. 1992, ApJ, 389, 5
van Leeuwen, F. 2007, A&A, 474, 653
Villalobos, Á. & Helmi, A. 2008, MNRAS, 391, 1806
Vrba, F. J. et al. 2004, AJ, 127, 2948
Yanny, B. & Gardner, S. 2013, ApJ, 777, 91
York, D. G. et al. 2000, AJ, 120, 1579
Zhang, L., Rix, H.-W., van de Ven, G., et al. 2013, ApJ, 772, 108