

THE GAIA-LSST SYNERGY

Željko Ivezić¹, Steven M. Kahn² and Patricia Eliason³

Abstract. We discuss the synergy of Gaia and the Large Synoptic Survey Telescope (LSST) in the context of Milky Way studies. LSST can be thought of as Gaia's deep complement because the two surveys will deliver trigonometric parallax, proper-motion, and photometric measurements with similar uncertainties at Gaia's faint end at $r = 20$, and LSST will extend these measurements to a limit about five magnitudes fainter. We also point out that users of Gaia data will have developed data analysis skills required to benefit from LSST data, and provide detailed information about how international participants can join LSST.

1 Introduction

Studies of stellar populations, understood to mean collections of stars with common spatial, kinematic, chemical, and/or age distributions, have been reinvigorated during the past decade by the advent of large-area sky surveys such as the Sloan Digital Sky Survey and the Two-Micron All Sky Survey (for a recent review, see Ivezić, Beers & Jurić 2012, hereafter IBJ2012). The quest for more precise and time-resolved data over large sky areas continues with the advent of Gaia and LSST.

Gaia is an ESA Cornerstone space mission that will survey the sky to a magnitude limit of $r \sim 20$ and obtain astrometric and three-band photometric measurements for about 1 billion sources, as well as radial-velocity and chemical-composition measurements for about 100 million brightest stars (Perryman et al. 2001). The LSST will be a wide-field ground-based optical imaging system with an 8.4m primary mirror, a 9.6 deg² field of view, and a 3.2 Gigapixel camera. LSST

¹ LSST Project Scientist, University of Washington, Seattle, WA 98155; LSST Project Office, 933 N. Cherry Avenue, Tucson, AZ 85721

² LSST Director, Kavli Institute for Particle Astrophysics and Cosmology, SLAC National Accelerator Laboratory, Stanford University, Stanford, CA 94025; LSST Project Office, 933 N. Cherry Avenue, Tucson, AZ 85721

³ Executive Officer for LSST Corporation, 933 N. Cherry Avenue, Tucson, AZ 85721

will deliver a six-band survey of about 18,000 deg² of the sky visible from Cerro Pachon in Chile to a depth of $r = 27.5$. Over 800 observations of each position (summed over all six bands) that will be obtained during the 10-year survey will enable unprecedented time-domain studies of the faint optical sky. This massive dataset will include photometric and astrometric data for about 20 billion Milky Way stars. For a more detailed discussion, including optical design, the filter complement, the focal plane layout, and special science programs, please see the LSST overview paper (Ivezic et al. 2008) and the LSST Science Book (Abell et al. 2009).

Within the context of Milky Way studies, Gaia and LSST datasets will be highly complementary and synergistic, as discussed in the next section. In addition to scientific connections, the data analysis skills developed by users of Gaia data will carry over to the LSST era – it is likely that Gaia users will be among the most efficient and productive users of LSST data. We discuss possibilities for international participation in LSST in the following two sections and summarize our conclusions in the last section.

2 The Gaia-LSST Synergy

In the context of Gaia, the LSST can be thought of as its deep complement (for a detailed discussion, we refer the reader to IBJ2012). Gaia will provide an all-sky catalog with unsurpassed trigonometric parallax, proper-motion, and photometric measurements to $r \sim 20$, for about 1 billion stars. The LSST will extend the static map to $r \sim 27$ over half of the sky, detecting about 20 billion stars. A detailed comparison of LSST and Gaia measurement uncertainties is given in Figure 1. The LSST will obtain photometric, proper-motion and trigonometric parallax measurements of comparable accuracy to those of Gaia at Gaia’s faint limit and smoothly extend Gaia’s uncertainty versus magnitude curves deeper by about 5 mag. Because of Gaia’s superb astrometric and photometric quality and the LSST’s significantly deeper reach, the two surveys are highly complementary – Gaia will map the Milky Way’s disk with unprecedented detail, and the LSST will extend this map all the way to the edge of the known halo and beyond.

For example, stars just below the main-sequence turn-off, with $M_r = 4.5$, will be detected by Gaia to a distance limit of ~ 10 kpc ($r < 20$), and to ~ 100 kpc with LSST’s single-epoch data ($r < 24.5$). For intrinsically faint stars, such as late M dwarfs, L/T dwarfs, and white dwarfs, the deeper limit of LSST will enable detection and characterization of the halo populations (for illustration, see Figure 23 in IBJ2012). A star with $M_r = 15$ will be detectable to a distance limit of 100 pc with Gaia and ~ 800 pc with LSST, hence the LSST samples will be about 100 times larger. In addition, for a substantial fraction of red stars with $r > 20$, LSST will provide trigonometric parallax measurements accurate to better than 10%. Therefore, despite the unprecedented performance of Gaia for $r < 20$, LSST will enable major discoveries with its deep $r > 20$ sky coverage. At the same time, and in addition to its own discoveries, Gaia will provide excellent astrometric and photometric calibration samples for LSST.

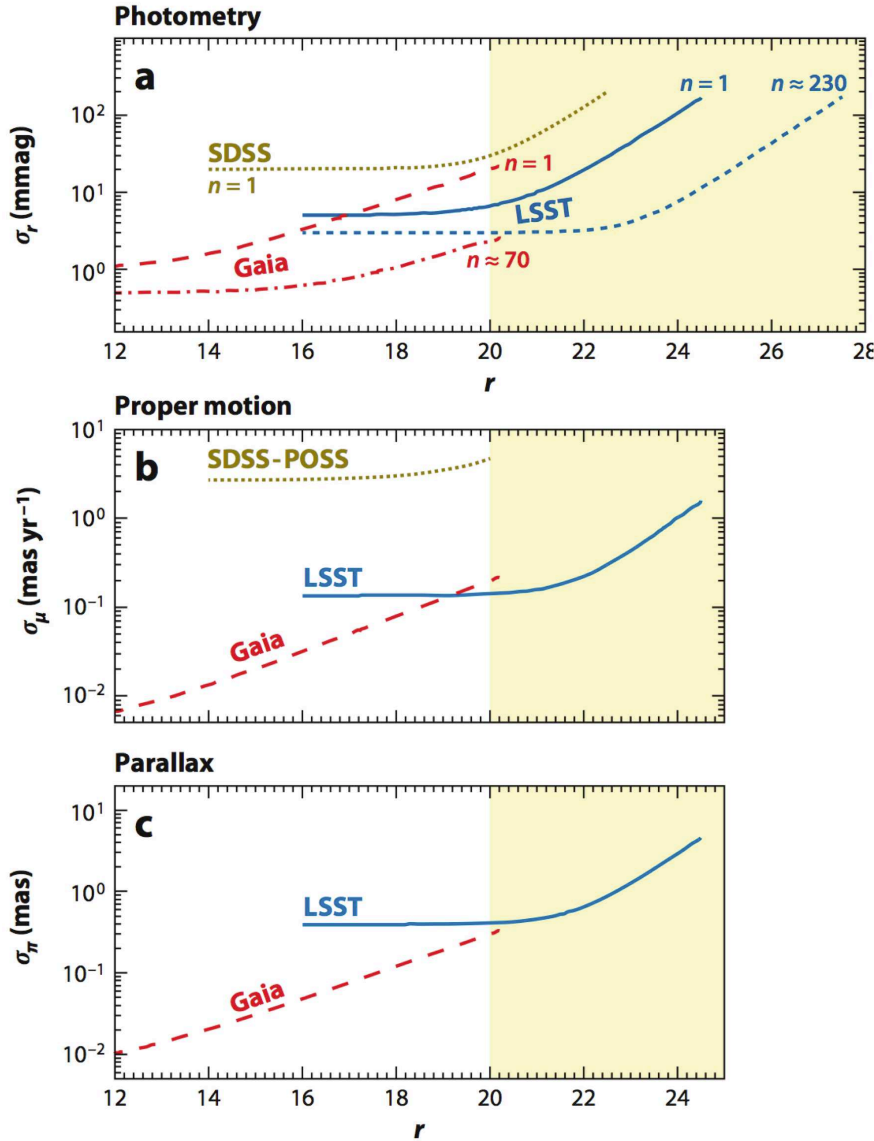


Fig. 1. A comparison of the photometric, proper-motion, and trigonometric parallax measurement uncertainties for SDSS, Gaia, and LSST, as a function of apparent magnitude r , for a G2V star. In the top panel, the curve marked “SDSS” corresponds to a single SDSS observation. The red curves correspond to Gaia; the long-dashed curve shows a single-transit accuracy, while the dot-dashed curve shows the end-of-mission accuracy (assuming 70 transits). The blue curves correspond to LSST; the solid curve shows a single-visit accuracy, while the short-dashed curve shows the accuracy for co-added data (assuming 230 visits in the r band). Adapted from Ivezić, Beers & Jurić (2012).

3 Opportunities for International Participation in LSST

LSST was designed to be a public project, with full access to all data and data products¹ open to the entire U.S. scientific community, as well as the public at large. Because the observatory will be sited in Chile, the Chilean astronomical community fully participates in the Project, with equal status and data access as their colleagues from the U.S. In addition, a limited number of French scientists (from laboratories associated with the Institut national de physique nucléaire et de physique des particules - IN2P3) have been granted access in view of French contributions to the development of the LSST camera².

Unlimited immediate access to LSST Data Releases will also be granted to international partners who signed Memoranda of Understanding (MOUs) or Memoranda of Agreement (MOAs) with LSST. For other users of LSST data, there will be a 2-year delay³. Here we briefly overview background on LSST funding and provide detailed information about how international participants can sign MOUs and thus secure immediate access to Data Releases (and obtain an opportunity to join LSST science collaborations, see below).

3.1 LSST Construction Funding

The LSST construction funding is primarily coming from two U.S. federal agencies: the National Science Foundation (NSF) and the Department of Energy (DOE). The NSF contribution is funded under the Major Research Equipment and Facility Construction (MREFC) line (total not to exceed cost is \$473M) and it supports the telescope and site facility construction, the data management system, and the education and public outreach components. This is funded through a cooperative agreement with the Association of Universities for Research in Astronomy (AURA), which also manages the National Optical Astronomy Observatory (NOAO), the Space Telescope Science Institute (STScI), and other facilities. The DOE contribution is funded as a Major Item of Equipment (MIE) through the Office of High Energy Physics in the Office of Science, and it supports the camera fabrication (total not to exceed cost is \$168M). SLAC National Accelerator Laboratory is the lead DOE laboratory for the fabrication of LSST camera.

LSST Corporation has also received substantial support from private donors (about \$40M), which enabled early development of the primary/tertiary mirror, the secondary mirror blank, preliminary site preparation, as well as early sensor studies and some data management activities. Key donors include the Lisa and Charles Simonyi Fund for Arts and Sciences, Bill Gates, Richard Caris, the W.M.

¹LSST Data Products are defined in a living document available as <http://ls.st/dpdd>

²The LSST construction proposals have been submitted and approved by the two U.S. federal agencies, and the appropriate funding profiles have been defined to complete the Project (see §3.1). The LSST Project is therefore no longer considering in-kind contributions to the LSST construction.

³The transient stream, based on image difference analysis, will be available to everyone in the world within 60 seconds from closing the shutter.

Keck Foundation, Research Corporation for Science Advancement, Wayne Rosing and Dorothy Largay, Eric and Wendy Schmidt, and Edgar Smith.

3.2 *LSST Operations Funding*

The NSF MREFC and DOE MIE funds only cover project construction and fabrication costs. The money allocated cannot be used for operations or for the conduct of science with the facility. Instead, operations funding comes from the Astronomical Sciences division budget at NSF, and from Cosmic Frontier research funding in the Office of High Energy Physics at DOE. In both cases, there is significant competition with other projects for those resources.

The current estimate for the annual operations costs of LSST is \sim \$37M/yr in 2013 US\$. This estimate includes mountain and base facility operations, as well as the costs associated with the data processing and data access. It does not include costs for “doing science” with LSST data. Those funds will come from the grants programs at the two agencies.

The expected support for the LSST operations by NSF and DOE, compared to the above estimate, will fall short by about \$10M/yr (again in 2013 US\$). *LSST is currently seeking international partners to support this cost differential.*

3.3 *International Support for LSST Operations*

LSST is seeking international partners to support about a quarter of the operations costs, in the amount of \$10M/yr, with expected start of operations in 2021. With an anticipated number of interested Principal Investigators (PI) set to 500, the cost per PI is \$200,000 integrated over ten years (plus a much smaller amount to offset data distribution costs, see below). Here “a single PI” assumes a senior researcher plus two postdocs and two graduate students. This contribution can be paid in full or in up to ten yearly installments of \$20K, with the payments starting any time between now and 2019. Contributions received prior to the start of operations will be placed in escrow in a U.S. bank. If for any reason the project does not proceed into operations as planned, that money would then be returned to its original contributors. All of the figures above are in 2013 US\$, and must be appropriately escalated to the time of payment. International partner institutions will sign MOUs with the LSST Corporation.

3.4 *The Roles of LSST Corporation*

LSST Corporation (LSSTC) was formed in 2003 as a non-profit organization to further the development of the LSST Concept. With the onset of construction, LSSTC will be primarily concerned with enabling LSST science (by hosting workshops, conducting training programs, and supporting student and postdoctoral fellowships as prioritized by its member institutions).

Per agreement with the federal funding agencies, LSSTC is also the vehicle through which international partner institutions will contribute to operations funding. LSSTC is currently negotiating MOUs with such organizations to solidify

these commitments. Due to the deadline for submitting a proposal for operations to the funding agencies, *this process needs to be completed by early 2016*.

Once an agreement with LSSTC is signed (or that it is clear that it will be signed), investigators from a foreign institution will be welcomed into the LSST community, including full access to LSST websites, simulations, software, etc.

In cases of sizable institutional participation in LSST, foreign institutes might also consider applying to join LSSTC as a member institution and thus participate in LSSTC governance. Membership will entitle that institution to have a representative attend LSSTC Board meetings (monthly telecons and two face-to-face meetings per year). Attendance at those meetings gives the members institutions a significant role in the oversight of the project, and particularly over science planning associated with the project.

LSSTC will have a significant annual budget that can be used during the construction phase “for the scientific optimization” of LSST. The details are still being worked out, but expected activities include workshops on selected LSST-related science topics, training programs for students and postdocs to familiarize them with LSST software and data analysis tools, fellowships in LSST science, and sponsoring scholarly reports on LSST scientific topics.

Application for membership is via a letter explaining the interests of and capabilities of the institute staff in LSST science, and a commitment to the initial and annual payments (an initial fee of \$75K, and an annual dues payment of \$25K).

3.5 The Cost of Accessing LSST Data

At present, the construction of two LSST data access centers, one at the National Center for Supercomputing Applications in Illinois and one in La Serena in Chile, is planned. These have been sized to handle the expected number (and spectrum) of scientific queries from the U.S. and Chilean communities. With user base enlarged with international partners, there is need to expand these facilities (with costs incurred by new partners), or have international partners build their own data access centers to serve their own communities. At this time, the approximate cost estimates are as follows: \$1,500 per year per PI for U.S.-based data access and about \$3.5M to set up an independent data access center from scratch (using software provided by LSST).

4 The Benefits of Participation in LSST

Although the current call for international partners of LSST is motivated by the immediate need to close the operations budget, the LSST Project is fundamentally looking for partners, rather than selling data. LSST will be a world unique scientific facility and the scientific exploitation of LSST data will certainly benefit from greater international participation. New international collaborators will bring creative ideas for innovative investigations with LSST, access to corollary facilities that can enhance the science of LSST, and key skills to collaborations that are preparing for some of the more challenging LSST analyses. For example,

it is highly likely that Gaia users will be among the most efficient and productive users of LSST data because they will have developed data analysis skills required to handle a billion-star Gaia survey.

Preparing for LSST science is a major effort over the next few years. Waiting for operations to begin before getting engaged will probably not be a successful path to scientific leadership in LSST science. To facilitate preparation for LSST science, joining one or more of the existing science collaborations is probably the best route to engagement as there is no substitute for direct communication between scientists, and we expect international collaborators to get engaged early.

4.1 LSST Science Collaborations

A set of LSST science collaborations was formed by the Project in 2006 with the intent to provide a forum to engage the community in interacting with the project team (e.g. to discuss science opportunities and challenges in each of the main science areas that LSST will address). These collaborations played an essential part in producing the LSST Science Book in 2009, which was instrumental for LSST achieving the top ranking for ground-based astronomical projects by the U.S. Decadal Survey Committee in 2010.

At this stage, the LSST Project no longer takes any oversight role for the collaborations – they are free to set their own policies for admission, governance, publication, etc. The only constraint is that their members must have direct access to LSST data. Once an MOU with LSSTC is signed by international partners, they will be welcomed into the LSST community, including full access to LSST websites, simulations, software, science collaborations, etc.

We emphasize that there is no requirement against the formation of new collaborations in new areas, or even multiple competing collaborations in the same areas. It is left to the community to figure out how best to work with one another in preparing for LSST science.

5 Conclusions

Within the context of Milky Way studies, Gaia and LSST datasets will be highly complementary and synergistic. In addition to scientific connections, it is likely that Gaia users will be among the most efficient and productive users of LSST data because they will have already developed data analysis skills required to handle a billion-star Gaia survey. LSST is currently seeking international partners and we encourage the interested colleagues to contact the LSST Corporation.

References

- Abell, P.A., Allison, J., Anderson, S.F., et al. 2009, arXiv:0912.0201
- Ivezić, Ž., Tyson, J.A., Abel, B., et al. 2008, arXiv:0805.2366
- Ivezić, Ž., Beers, T.C. & Jurić, M. 2012, *ARA&A*, 50, 251
- Perryman, M.A.C., de Boer, K.S., Gilmore, G., et al. 2001, *A&A*, 369, 339