Why Galaxies Care About AGB Stars:
A Continuing Challenge through Cosmic Time
Proceedings IAU Symposium No. 343, 2019
F. Kerschbaum, M. Groenewegen & H. Olofsson, eds.

doi:10.1017/S1743921318005690

LSST: making movies of AGB stars

Željko Ivezić, Krzysztof Suberlak and Owen M. Boberg

Department of Astronomy, University of Washington,
Box 351580, Seattle, WA 98195-1580, USA
email: `ivezic@astro.washington.edu`

Abstract. LSST (www.lsst.org) will be a large, wide-field ground-based system designed to obtain repeated images covering the sky visible from Cerro Pachón in northern Chile. The telescope will have an 8.4m (6.5m effective) primary mirror, a 9.6 sq.deg. field of view, and a 3.2 Gigapixel camera. In a continuous observing campaign, LSST will cover the entire observable sky every three nights to a depth of $V \sim 25$ per visit (using 30-second exposures and *ugrizy* filter set), with exquisitely accurate astrometry and photometry. Close to a half of the sky will be visited about 800 times during the nominal 10-year survey. The project is in the construction phase with first light expected in 2020 and the beginning of regular survey operations by 2022. We describe how these data will impact AGB star research and discuss how the system could be further optimized by utilizing narrow-band TiO and CN filters.

Keyword. surveys

---

1. Introduction

The progenitors of stars on the asymptotic giant branch (AGB) are red giants; their progeny are planetary nebulae and white dwarfs. AGB stars have a strong impact on the galactic environment; stellar winds blown during this evolutionary phase are an important component of mass return into the interstellar medium and may account for a significant fraction of interstellar dust (for a recent review, see Höfner & Olofsson 2018). These dusty winds reprocess the stellar radiation, shifting the spectral shape towards the IR. Dusty AGB stars are observable in our Galaxy and in its close satellites, most notably the Magellanic Clouds. In addition to its obvious significance for the theory of stellar evolution, the study of AGB winds has important implications for the structure and evolution of galaxies (Girardi & Marigo 2007; Marston *et al.* 2009). In our own Galaxy, its estimated 200,000 AGB stars are good tracers of dominant components, including the bulge (Whitelock & Feast 2000; Jackson, Ivezić & Knapp 2002). AGB stars also have a great potential as distance indicators (Rejkuba 2004).

The last decade has seen fascinating observational progress in optical and infrared imaging surveys. Modern large sky surveys are having a major impact on AGB star research: well-defined statistical samples allow the use of AGB stars as stellar population tracers both in our and other galaxies. In the infrared, the recent Wide-field Infrared Survey Explorer All-sky Survey (WISE; launched in 2010) improved sensitivity by up to three orders of magnitude compared to IRAS, and detected about 560 million objects (Wright *et al.* 2010). In the optical, the "gold standard" SDSS dataset is currently being greatly extended by ongoing ground-based surveys such as Pan-STARRS (Kaiser *et al.* 2010) and the Dark Energy Survey (Flaugher 2008), and most recently by Gaia's Data Release 2.

Optical variability greatly helps with the identification of AGB stars, as well as providing constraints on the physics of AGB phenomenon (via light curve shapes, amplitudes

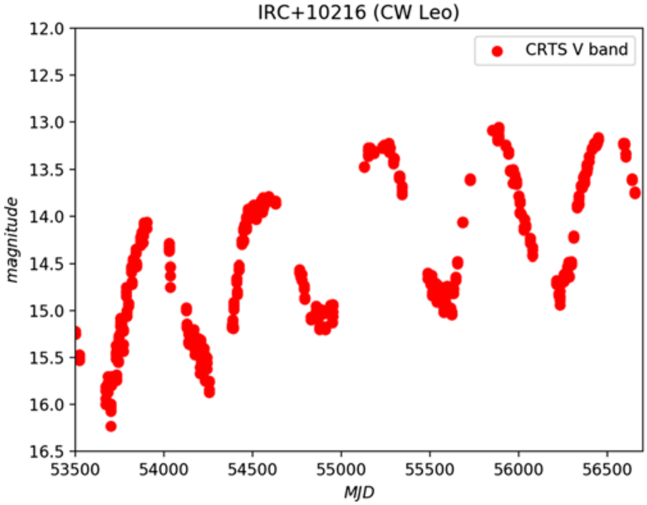

Figure 1. The visual light curve for the carbon-rich AGB star CW Leo (IRC +10 216). It was serendipitously observed by the Catalina Real-time Transient Survey (CRTS, see http://crts.caltech.edu) over 700 times during a period of close to 10 years. LSST will obtain similar light curves in six photometric bandpasses, with comparable signal-to-noise ratios, for close to 100,000 AGB stars.

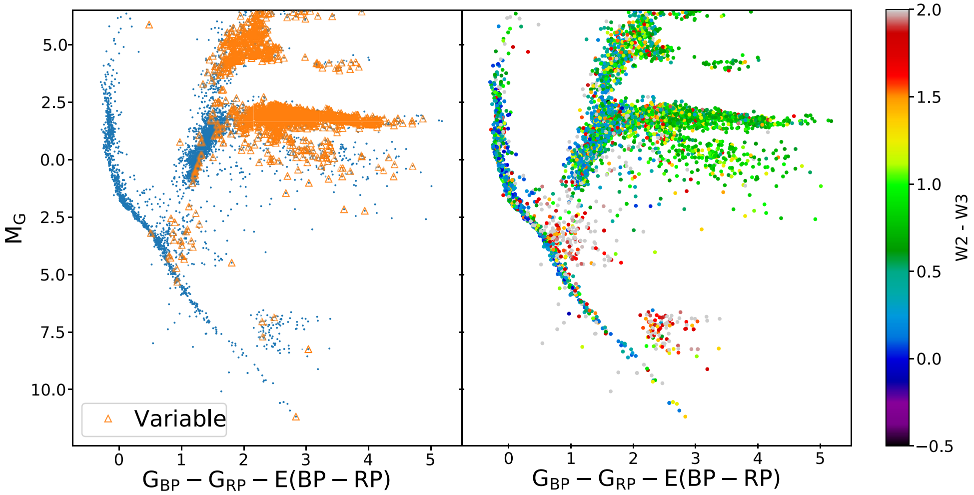

Figure 2. An illustration of the power of combining multiple unbiased surveys using a high-latitude subsample of bright Gaia sources with trigonometric parallaxes. The two panels show the subsample distribution in the Hertzsprung-Russell diagram (absolute Gaia-based magnitude M_{G} vs. reddening-corrected Gaia color). The left panel marks sources where Gaia detected variability, and the right panel is color-coded by the WISE $W2 - W3$ color, which indicates dust presence for positive values. Variable sources with $-2.5 < M_{\mathrm{G}} < 1$ and $W1 - W2 > 0.4$ are likely AGB stars with dusty envelopes.

and periods; see e.g., Wood 2015). With modern sky surveys, light curves for detected AGB stars come for “free”. For example, the Catalina Real-time Transient Survey (CRTS, see http://crts.caltech.edu) alone has provided over 700 photometric measurements spanning ~9 years (see Figure 1) for the famous AGB star CW Leo (IRC10+216).

Particularly clean (low contamination) stellar population samples can be constructed by combining several unbiased surveys. Figure 2 illustrates how a combination of optical

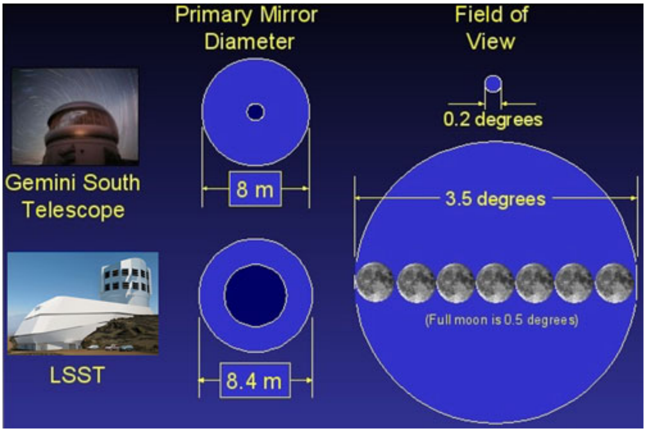

Figure 3. The speed at which a system can survey a given sky area to a given flux limit is determined by the so-called étendue (or grasp): the product of the primary mirror size and the field-of-view. The figure compares the primary mirror size and the field-of-view for LSST and Gemini South telescopes. The system étendue is much larger for LSST. Figure courtesy of Chuck Claver.

variability and red infrared colors efficiently selects dusty AGB stars. The ongoing Zwicky Transient Facility (ZTF; Bellm & Kulkarni 2017) is expected to obtain 300-epoch optical photometry over three quarters of the sky, including the Galactic plane, within next three years. The depth of the ZTF data will be comparable to Gaia's depth ($V \sim G \sim 20.5$). Because dusty AGB stars are heavily extincted at optical wavelengths, and thus can be much fainter, a much deeper optical time-domain survey can open a huge parameter space for studying AGB stars. LSST will be such a survey, extending the depth reached by time-domain ZTF and Gaia surveys by about 4 magnitudes.

2. Brief overview of LSST

The Large Synoptic Survey Telescope (LSST; for an overview see Ivezić *et al.* 2008) is the most ambitious survey currently being constructed or planned in the visible band. The LSST survey power is due to its large étendue (see Figure 3). LSST will extend the faint limit of the SDSS by about 5 magnitudes and will have unique survey capabilities for faint time domain science.

The LSST design is driven by four main science themes: probing dark energy and dark matter, taking an inventory of the Solar System, exploring the transient optical sky, and mapping the Milky Way (for a detailed discussion see the LSST Science Book, LSST Science Collaboration 2009). LSST will be a large, wide-field ground-based system designed to obtain multiple images covering the sky that is visible from Cerro Pachón in Northern Chile. The system design, with an 8.4m (6.5m effective) primary mirror (Gressler *et al.* 2018), a 9.6 deg^2 field of view, and a 3.2 Gigapixel camera (Kahn *et al.* 2010), will enable about 10,000 deg^2 of sky to be covered using pairs of 15-second exposures in two photometric bands every three nights on average, with typical 5σ depth for point sources of $r \sim 24.5$. The system is designed to yield high image quality as well as superb astrometric and photometric accuracy. The LSST camera provides a 3.2 Gigapixel flat focal plane array, tiled by 189 4K×4K CCD science sensors with 10 μm pixels (see Figure 4).

The construction phase of LSST, funded by the U.S. National Science Foundation and Department of Energy, started in 2016 and is progressing according to the planned schedule (for an illustration of the current status, see Figure 5). First light for LSST is

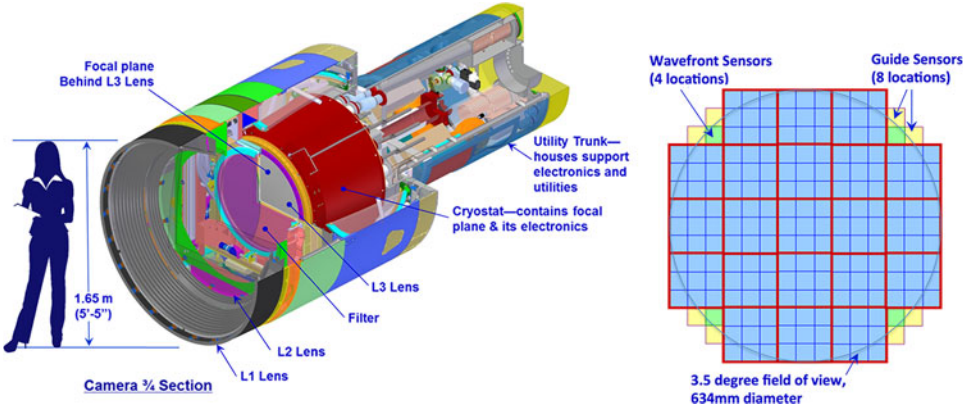

Figure 4. The left panel shows a cutaway view of LSST camera. Not shown are the shutter, which is positioned between the filter and lens L3, and the filter exchange system. The right panel shows the LSST Camera focal plane array. Each cyan square represents one 4K× 4K pixel sensor. Nine sensors are assembled into a raft; the 21 rafts are outlined in red. There are 189 science sensors, for a total of 3.2 Gigapixels. Also shown are the four corner rafts, where the guide sensors and wavefront sensors are located. Adapted from Ivezić *et al.* (2008).

Figure 5. The figure shows a photograph of the LSST summit at sunset, from the direction of Gemini South, at the time of this Symposium (August 2018). First light for LSST is expected in 2020 with a 144 Mpix engineering camera, and with the full 3.2 Gpix camera in 2021. The small dome on the left is an auxiliary telescope that will be used for photometric calibration. For more photographs, see https://www.lsst.org/gallery/image-gallery. Credit: LSST and Gianluca Lombardi.

expected in early 2020 with a small commissioning camera (144 Mpix), with the full 3.2 Gpix camera integrated by the end of 2020.

2.1. *Baseline LSST surveys*

The survey area will be included within 30,000 deg^2 with $\delta < +34.5°$, and will be imaged multiple times in six bands, *ugrizy*, covering the wavelength range 320–1050 nm. About 90% of the observing time will be devoted to a deep-wide-fast survey mode which will observe an 18,000 deg^2 region over 800 times (summed over all six bands) during the anticipated 10 years of operations, and yield a coadded map to $r \sim 27.5$ ("the main survey"). These data will result in databases containing about 20 billion galaxies and a similar number of stars, and will serve the majority of science programs. The remaining 10% of the observing time will be allocated to special programs such as a Very Deep and

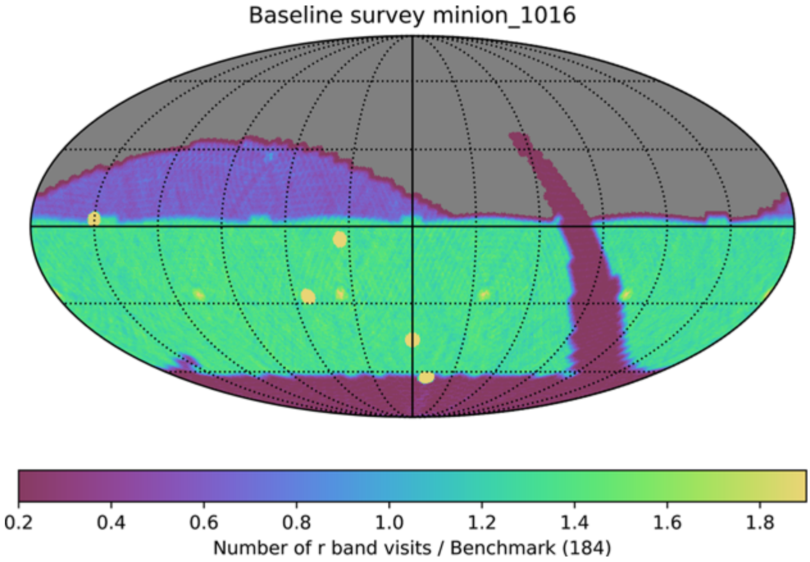

Figure 6. The distribution of the r band visits on the sky for a simulated realization of the baseline cadence (Delgado *et al.* 2014; Jones *et al.* 2014). The sky is shown in the equal-area Mollweide projection in equatorial coordinates (the vernal equinoctial point is in the center, and the right ascension is increasing from right to left). The number of visits for a 10-year survey, normalized to the survey design value of 184, is color-coded according to the legend. The three regions with smaller number of visits than the main survey ("mini-surveys") are the Galactic plane (arc on the right), the region around the South Celestial Pole (bottom), and the so-called "northern Ecliptic region" (upper left; added in order to increase completeness for moving objects). Deep drilling fields, with a much higher number of visits than the main survey, are also visible as small circles (the color scale is saturated; typically, deep drilling fields will be observed more than a thousand times per band). The fields were dithered on sub-field scales and pixels with angular resolution of ∼30 arcmin were used to evaluate and display the coverage. Adapted from Ivezić *et al.* (2008).

Fast time-domain survey. For an illustration of the current baseline survey sky coverage, see Figure 6.

3. Anticipated Impact of LSST on AGB star research

During the 10-year survey beginning in 2022, the LSST will cover about half of the sky, with each sky location observed over 800 times in six broad-band filters. These imaging data will be superior to optical survey data currently available (for a comparison of SDSS and LSST-like images, see Figure 7).

The LSST data will be used for finding AGB stars by several complementary methods:

(*a*) **Optical identifications of IR counterparts.** If, for example, the dust-enshrouded C star IRC +10 216 were 40 kpc away, it would have $i = 27$, $z = 25$ and $y = 23$ (based on SDSS observations), which is brighter than LSST faint limits in these bands. Therefore, even stars with exceedingly thick dust shells and barely detected by IRAS will be detectable in the i, z, and y bands by LSST throughout the Galaxy.

(*b*) **Search for spatially-resolved envelopes.** As demonstrated by SDSS observations of IRC +10 216, LSST will be able to detect and *resolve* an IRC +10 216-like envelope at a distance of 15 kpc! Stars with resolved envelopes will be especially useful for refining selection criteria based on other methods (such as color and variability).

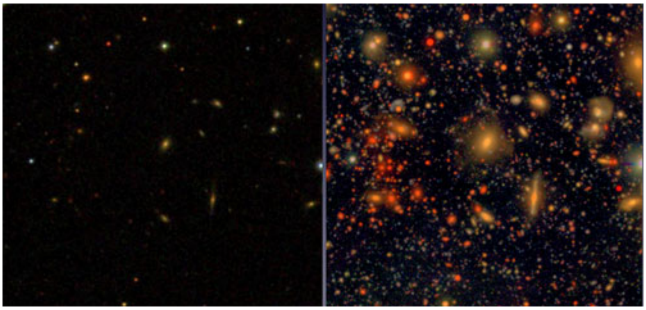

Figure 7. A comparison of an SDSS image (left, 3.5×3.5 arcmin^2 *gri* composite) showing a relatively random piece of high Galactic latitude sky with a similar *gri* composite image of the same field obtained by the Hyper Suprime Cam survey (HSC, right). The HSC image is about 4-5 mag deeper than the SDSS image and comparable to the anticipated LSST 10-year coadded data). Courtesy of Robert Lupton.

(*c*) **Color selection.** The extremely red optical colors of dusty AGB stars are very distinctive; color-selected LSST samples will be able to trace structure throughout the Local Group and beyond.

(*d*) **Variability.** Thanks to their particularly large light curve amplitudes (several magnitudes), and over 800 observations during 10-year survey, variability will be a powerful detection method for AGB stars (n.b., LSST will detect over one hundred million variable stars).

It is evident that LSST, although driven by different science goals, will be a powerful machine for discovering and characterizing AGB stars. This ability could be further enhanced by utilizing narrow-band filters.

4. Specialized narrow-band filters

According to their photospheric chemical composition, AGB stars can be divided into oxygen-rich (O-rich) and carbon-rich (C-rich) stars; O-rich stars are associated with silicate-rich dust chemistry and C-rich stars with carbonaceous dust grains. The C-to-O stellar count ratio is an important distinguishing characteristic of stellar populations; for example, it is more than two orders of magnitude higher in the Galactic center than in the Large Magellanic Cloud (Nikutta *et al.* 2014). Hence, it is highly desirable for a survey to be able to classify stars into O and C classes.

At infrared wavelengths, the predominant dust type is relatively easily determined thanks to the prominent silicate dust feature at 10 μm. At optical wavelengths, it is harder to separate the two classes. The current LSST baseline design includes six broadband filters. The system throughput as a function of wavelength for these bandpasses is shown in Figure 8. The ability of LSST to characterize AGB stars (i.e., to separate C from O type stars) could be further enhanced by adding narrow-band filters. For example, the so-called TiO (7780 Å) and CN (8120 Å) filters, see Figure 9, introduced by Wing (1971) have been successfully used by a number of groups (Cook, Aaronson & Norris 1986; Kerschbaum *et al.* 2004; Battinelli & Demers 2005, and references therein) for the identification and characterization of late-type stars in external Local Group galaxies.

The LSST Science Requirements Document (Ivezić & The LSST Science Collaboration 2011) allows for about 10% of the observing time (300 nights) to be allocated to specialized programs. If only 2 nights (<0.1% of the total observing time) were allocated to a narrow-band survey, it would be possible to cover about 10,000 sq.deg. of sky in each band. Such a time allocation would match the cost of procuring the filters (of the order

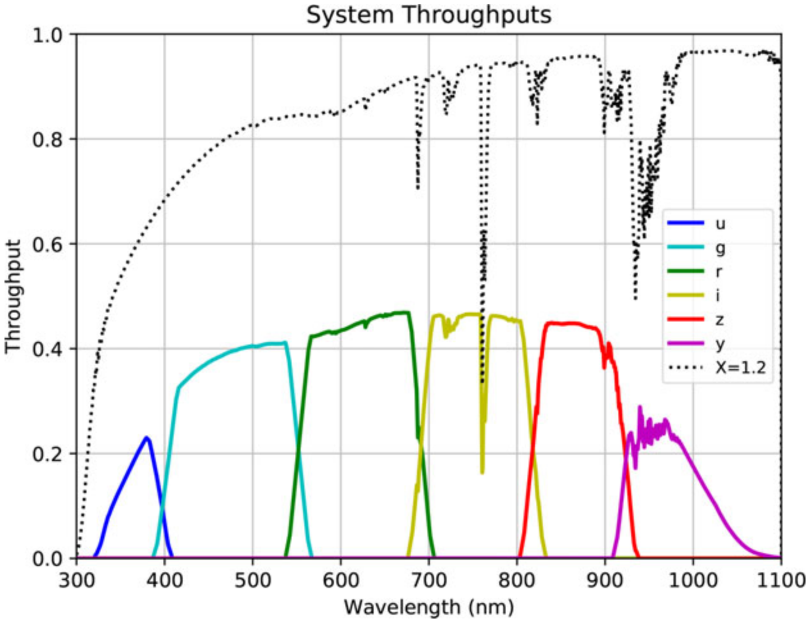

Figure 8. The LSST bandpasses. The vertical axis shows the total throughput. The computation includes the atmospheric transmission (assuming an airmass of 1.2, dotted line), optics, and the detector sensitivity. Adapted from Ivezić *et al.* (2008).

$1M) to the cost of the LSST system itself (about 400,000 USD per observing night). Given that such data would be useful for extra-galactic astronomy and cosmology, too (C. Stubbs, priv. comm.), it is plausible that more than 2 observing nights could be negotiated for this program.

Assuming 150 Å wide filters, the faint limits would be at about apparent magnitudes 22-22.5. This is about 0.5-1 mag shallower than e.g. a study of And II by Kerschbaum *et al.* (2004), but the surveyed area would be over 1,000,000 times larger! Furthermore, it is noteworthy that the deep and exceedingly accurate broad-band photometry will come for "free" and will include many epochs which can be used to reject foreground Galactic M dwarfs by variability. The same data would enable efficient calibration of the narrow-band survey.

This program may represent an exciting opportunity for the AGB star community. In order to execute such a program, this community may wish to organize a working group which would have three main goals: fundraising for the filter procurement, securing an allocation of observing time from the LSST, and the timely analysis of narrow-band survey data.

5. Opportunities for International Participation in LSST

LSST was designed to be a public project, with full access to all data and data products† open to the entire U.S. and Chileans scientific communities and the public at large. Unlimited immediate access to LSST Data Releases will also be granted to international partners who signed Memoranda of Understanding or Memoranda of Agreement with LSST. For other users of LSST data, there will be a 2-year delay‡. LSST is currently

---

† The baseline definition of LSST Data Products is available in Jurić *et al.* (2017).

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

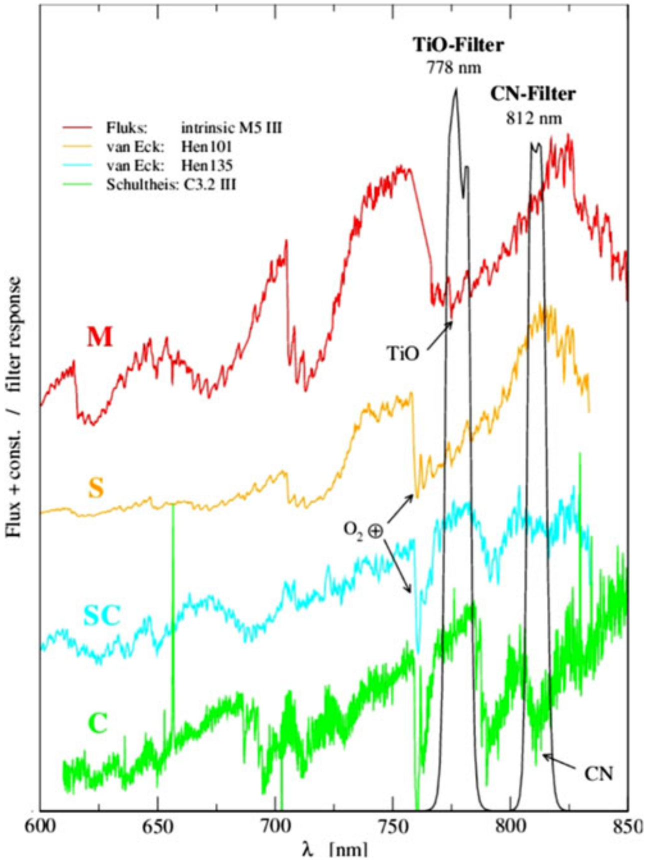

Figure 9. An illustration of the power of TiO (7780 Å) and CN (8120 Å) filters to distinguish stellar spectral features for late-type stars: O-rich (M-type) stars have much redder CN-to-TiO colors than C-type stars. Adapted from Kerschbaum *et al.* (2004).

seeking additional international partners and we encourage the interested colleagues to contact the LSST Corporation. For details about application process for International Affiliates, please see Section 3 in Ivezić, Kahn & Eliason (2014).

6. Conclusions

We are witnessing rapid progress in the availability of large and sensitive sky surveys at all wavelengths. As in many other fields, modern sky surveys are having a major impact on AGB star research: well-defined statistical samples allow the use of AGB stars as stellar population tracers both in our and other galaxies.

LSST, although driven by different science goals, will be a powerful machine for discovering and characterizing AGB stars. As an optical time-domain survey, LSST will be used for finding AGB stars by several complementary methods: as optical identifications of IR counterparts, by searching for spatially-resolved envelopes, by red optical color selection, and by variability.

The ability of LSST to find and classify AGB stars could be further enhanced with narrow-band filters, in particular by utilizing narrow-band TiO and CN filters. In order to make such a narrow-band filter survey a reality, the AGB stars community would have to organize a working group with three main goals in mind: fundraising for the filter procurement, securing an allocation of observing time from the LSST, and the timely analysis of narrow-band survey data. Colleagues interested in this program should contact the first author.

Acknowledgements

We thank Andrew Connolly for careful reading of this manuscript and excellent comments. This material is based upon work supported in part by the National Science Foundation through Cooperative Agreement 1258333 managed by the Association of Universities for Research in Astronomy (AURA), and the Department of Energy under Contract No. DE-AC02-76SF00515 with the SLAC National Accelerator Laboratory. Additional LSST funding comes from private donations, grants to universities, and in-kind support from LSSTC Institutional Members. This work was performed in part at Aspen Center for Physics, which is supported by National Science Foundation grant PHY-1607611.

References

Battinelli, P. & Demers, S. 2005, *A&A*, 442, 159

Bellm, E. & Kulkarni, S. 2017, *Nature Astr.*, 1, 71

Cook, K. H., Aaronson, M. & Norris, J. 1986, *ApJ*, 305, 634

Delgado, F., Saha, A., Chandrasekharan, S., *et al.* 2014, *Proceedings of the SPIE*, Volume 9150, id. 915015

Flaugher, B. 2008, In *A Decade of Dark Energy: Spring Symposium, Proceedings of the conferences held May 5-8, 2008 in Baltimore, Maryland. (USA). Ed. by N. Pirzkal & H. Ferguson.*

Girardi, L. & Marigo, P. 2007, *ASPC*, 378, 7

Gressler, W., Coleman, G., Delgado, F., *et al.* 2018, *Proceedings of the SPIE*, Volume 10700, id. 107002I

Höfner, S. & Olofsson, H. 2018, *A&A*, 26, 1

Ivezić, Ž., Kahn, S.M. & Eliason, P. 2014, *EAS Publications Series*, Volume 67-68, 211 (also arXiv:1502.06555)

Ivezić, Ž., Kahn, S.M., Tyson, J.A., *et al.* 2008, arXiv:0805.2366

Ivezić, Ž. & The LSST Science Collaboration. 2011, LSST Science Requirements Document, LSST Document LPM-17, LSST. https://ls.st/LPM-17

Jackson, T., Ivezić, Ž. & Knapp, G.R. 2002, *MNRAS*, 337, 749

Jones, R.L., Yoachim, P., Chandrasekharan, S., *et al.* 2014, *Proceedings of the SPIE*, Volume 9149, id. 91490B

Jurić, M., Axelrod, T., Becker, A.C., *et al.* 2017, LSST Data Products Definition Document, LSST Document LSE-163, LSST. https://ls.st/LSE-163

Kahn, S.M., Kurita, N., Gilmore, K., *et al.* 2010, *Proceedings of the SPIE*, Volume 7735, id. 77350J

Kaiser, N., Burgett, W., Chambers, K., *et al.* 2010, *Proceedings of the SPIE*, Volume 7733, id. 77330E

Kerschbaum, F., Nowotny, W., Olofsson, H. & Schwarz, H. E. 2004, *A&A*, 427, 613

Marston, C., Strömbäck, G., Thomas, D., Wake, D.A. & Nichol, R.C. 2009, *MNRAS*, 394, 107

Nikutta, R., Hunt-Walker, N., Nenkova, M., Ivezić, Ž & Elitzur, M. 2014, *MNRAS*, 442, 3361

Rejkuba, M. 2004, *A&A*, 413, 903

LSST Science Collaboration 2009, *LSST Science Book*, http://www.lsst.org/lsst/SciBook, arXiv:0912.0201

Whitelock, P.A. & Feast, M.W. 2000, *MNRAS*, 317, 460

Wing, R.F. 1971, *Conference on Late-Type Stars*, ed. G.W. Lockwood & H. M. Dyck, Kitt Peak National Observatory, Contrib. No. 554, p. 145

Wood, P.R. 2015, *MNRAS*, 448, 3829

Wright E. L. *et al.* 2010, *AJ*, 140, 1868

Discussion

Question: What will be the photometric precision of LSST?

Ivezić: Before Gaia, the LSST target for photometric precision was 5 mmag. Now that Gaia is a reality, we may achieve 2-3 mmag photometric precision.

https://doi.org/10.1017/S1743921318005690