Using *Kepler* to Probe Long-Period Variables and Galactic Evolution

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Abstract Continued periodic monitoring of the original *Kepler* field, or monitoring a new field in a different part of the Milky Way Disk, would provide an unbiased census of long-period variables (LPVs) in the Galactic Disk. While other variability surveys of the Magellanic Clouds and the Galactic Bulge (e.g. OGLE and MACHO) have enabled accurate counts and characterizations of LPVs in those environments, no such sample exists for the Disk, despite the fact that this is where most of the stars in our Galaxy reside. The material shed by these stars, enriched by the nucleosynthetic products created deep within each star's core, will be recycled into the interstellar medium to form the next generation of stars and planets, thus changing the chemical composition of the Galaxy over time. Although the two-wheel mission is expected to have degraded sensitivity and a smeared point spread function, with this project as part of the extended mission, *Kepler* is still fully capable of providing important information on the life cycle of stars, the enrichment of the interstellar medium, and the chemical evolution of galaxies.

During its primary mission, *Kepler* downloaded a complete image of the 115 square degree field-of-view every 30 days (*Kepler* Archive Manual 2012). While these data have largely been used as an engineering and calibration resource, they represent an unprecedented, temporally resolved view of a piece of the Milky Way Galaxy. Our current understanding of late stellar evolution in the Galactic Disk has been hampered by terribly biased samples. Surprisingly, the *Kepler* full field images (FFIs), which provide a steady, unblinking view of one field in the Galactic Disk, have yet to be exploited to address this issue. We are currently undertaking a project to study long period variables (LPVs) and their role in stellar and galactic evolution, using a variety of ground- and space-based telescopes at a range of wavelengths. In its new two-wheel mission, *Kepler* can play a vital role in creating the much needed, unbiased database of LPVs in the Milky Way Disk for this and numerous future projects.

We suggest that, in addition to the new primary science that will be investigated during its two-wheel operations, *Kepler* continue to regularly generate full field images (FFIs), preferably toward the original field but certainly toward a field in the Galactic Disk, during the extended mission. In addition to the scientific arguments outlined below, these observations would also provide continuity in engineering and calibration data that *Kepler* used during its previous planet-finding mission with such excellent results.

The nominal cadence of the full downloads of photometry from the original *Kepler* field, every $\sim$30 days, is ideal for the study of evolved stars, all of which undergo a phase as long-period variables (LPVs) as they end their lives, ejecting their envelopes while on the asymptotic giant branch (AGB; e.g. Habing 1996). LPVs pass through multiple pulsation modes (e.g. Wood & Sebo 1996), with periods ranging from roughly 50 to 1000 days (e.g. Samus et al. 2012), and amplitudes varying from the precision limit of available photometry to several magnitudes. They are the signposts of Galactic enrichment, as stars on the AGB pulsate, turn themselves inside out, and eject dust and freshly generated nuclear fusion products back into the interstellar medium (e.g. Habing 1996; Lattanzio & Wood 2004).

However, fundamental questions about the details of how stars die remain unanswered. At what rate do stars lose mass as they evolve along the AGB? How does this influence their lifetime on the AGB? What is the link between pulsation mode, period and amplitude, and dust production? Do pulsations or radiation pressure on newly generated dust drive the mass loss? How do these processes depend on the initial mass and metallicity of the star?

The answers to all of these questions are vital to quantifying how much stars enrich the interstellar medium with the dredged-up heavy elements from their interiors and with the dust grains created in their atmospheres. Further, without solid knowledge of AGB evolution, models of the chemical enrichment of galaxies can produce wildy different results depending on how they treat these processes (e.g. Conroy & Gunn 2010; Noël et al. 2013). Thus, understanding AGB stars is important not just from the perspective of stellar evolution, but for the fundamental role they play in the evolution of galaxies.

In the past decade, optical photometric surveys have made tremendous strides in identifying LPV populations in systems with metallicities different from the Milky Way Disk. In particular, the MACHO and OGLE surveys (Alcock et al. 1992, 1995; Udalski et al. 1997), while designed to detect microlensing events, have left us with nearly complete samples of LPVs in the Large and Small Magellanic Clouds (LMC and SMC) and the Galactic Bulge (e.g. Soszyński et al. 2009, 2011, 2013). Infrared surveys have supplied complementary information, particularly on the more dusty, embedded AGB stars, in parts of these fields, including several *Spitzer* surveys (e.g. Meixner et al. 2006 for the LMC; Bolatto et al. 2007, Gordon et al. 2011, for the SMC; and Uttenthaler et al. 2010 for the Bulge), as well as the all-sky WISE (Wright et al. 2010) and 2MASS surveys (Cutri et al. 2003; Skrutskie et al 2006). The microlensing surveys have sampled only a limited piece of the Galaxy, though, and such a high cadence is not absolutely needed for finding and characterizing LPVs. The infrared surveys, on the other hand, are sensitive to more dusty, embedded AGB stars, but the pulsation amplitudes drop with increasing wavelength and these surveys are too sparsely sampled temporally to easily find LPVs by themselves.

Our understanding of late stellar evolution in the Galactic Disk remains hampered by terribly biased samples, despite the progress in other environments. While the General Catalog of Variable Stars (GCVS, Samus et al. 2012) is a good resource for bright variable stars, it suffers from being a compilation of numerous individual studies, each with its own goals and biases. Only ∼75% of the Miras and semi-regular variables (SRVs) have periods, for instance. Comparison of the period distributions in the GCVS and those from the unbiased OGLE samples show significant differences in both their Mira and SRV populations. Also, the relative numbers of Miras and SRVs differ substantially. These may reflect real differences in the sample populations, given their different ages and metallicities, but uncorrected observational biases certainly contribute. The extent to which those differences are intrinsic and which are due to biases simply cannot be determined with the current samples of Disk LPVs from the GCVS.

Kepler can be the solution, providing us with a long-term, stable view of a particular field in the Milky Way Disk. Once the LPVs have been identified, a multitude of resources from other missions and at other wavelengths can be brought to bear to fully characterize them. A number of questions do need to be considered, though, due to the new constraints *Kepler* will be operating under.

Which field should be monitored? Should the original *Kepler* field continue to be the target of regular FFIs, or should a new field be chosen?

The *Kepler* field is steadily becoming the most studied field in Galactic astronomy at a wide range of wavelengths. For example, J. P. Lloyd at Cornell has obtained multiple epochs covering the entire *Kepler* field over a 40-day baseline in the UV field with 300 orbits of GALEX. A. Krauss will be obtaining high-resolution H-band spectra of 100,000 sources in the *Kepler* field using APOGEE at the SDSS telescope. These spectra will help distinguish giants and dwarfs, although one must keep in mind that by our estimates, 1.6 million sources could be catalogued using the *Kepler* data. Based on results from the ASAS survey for optical variables, Pigulski et al. (2009) found at least 950 variable stars in the *Kepler* field. Those data however, had a baseline of only 500 days and thus are insensitive to the LPVs with the longest periods. The longer periods, >400 days, are exactly where the Mira period distribution in the GCVS is most discrepant from the unbiased OGLE surveys in the LMC, SMC, and Bulge. The current database of *Kepler* FFIs covers a baseline of over 1500 days, just enough to cover a single cycle of the longest Mira periods, which can be over 1300 days. Thus, continued monitoring of the original field will enable us to better find and characterize those LPVs with the longest periods. Further, since dust production is strongly correlated with period, such stars will significantly contribute to Galactic enrichment, so having an unbiased census of them is vital. Additionally, by continuing to monitor the stars in this field, any changes to the stars around which planets and planetary candidates have been found would also be discovered.

On the other hand, one might argue that the existing 1500-day database is adequate, and a different direction, sampling a different part of the Galactic Disk, should be chosen for the long-term monitoring. This would give an unbiased sample of a second set of Disk stars and allow us to build a more complete picture of the evolved stars, particularly the LPVs, in the Galaxy. Fields that are worth considering include the North and South Ecliptic Poles, noted in the Call for White Papers as having favorable locations for spacecraft pointing. Scientifically, these fields have been observed repeatedly by the infrared space telescopes *WISE* and *Spitzer* (e.g. Jarrett et al. 2011), as well as by their ground-based support teams. Thus, these fields have substantial, complementary data that would provide important information about the dust production of the LPVs we anticipate discovering, as well as their luminosities, as the spectral energy distributions of AGB stars often peaks in the IR. They might be too far off the Galactic plane, though, to contain sufficient stars in the Disk population we are most interested in. Alternatively, a Disk field visible in the southern hemisphere could leverage observations from several near-IR surveys, such as VISTA/VHS (McMahon et al. in prep.) and DENIS (DENIS Consortium 2005), as well as UKIDSS (Lawrence et al. 2007) and 2MASS. Arguments could undoubtedly be made for additional fields in the Milky Way Disk, such as toward the outer Galaxy, to sample lower metallicity stars, or perpendicular to known spiral arms, where the lower stellar density means the smeared point spread function in the two-wheel mode will cause fewer problems in the data analysis of the FFIs. The specific field chosen is not particularly important, as long as it contains a large number of Disk stars for monitoring. Thus, a field that supports both the science goals presented here and those of the other projects being pursued during the extended mission would be ideal.

What cadence should be used? Maintaining the current ∼30-day cadence would provide a uniform data set that is well-suited to the periods of LPVs. More frequent FFIs might be desirable, though, from an engineering stand-point, as the spacecraft continues to age. In that case, a somewhat more uneven candence might be desirable, such as [0, 7, 30, 37, ...] days, in order to mitigate period aliasing.

What integration time should be used? As with the cadence and field questions, the 30-minute observation would nominally provide continuity with the existing FFI data. However, the anticipated pointing drift described in the Call for White Papers is ∼0.9 arcsec/minute, or nearly 30" in a 30-minute observation. Depending on the field chosen for monitoring, source confusion could be a significant issue. Shorter integration times would, of course, be less sensitive, but would result in less source blending.

Despite these challenges, we believe on-going production of FFIs by *Kepler* would supply a very useful database with which we can create unbiased samples of Galactic LPVs. We are entering a new era in astronomy, with growing awareness of the importance of the temporal domain. It is for this reason that so many resources are being directed to the LSST, but we don't have to wait for its completion to tackle temporal astronomy ourselves. We have outlined in this brief discussion how continued temporal monitoring of the *Kepler* field or another field in the Galactic Disk could lead to significant progress in the study of late stellar evolution and stellar death, providing a well characterized sample in the Galactic Disk to compare with samples in other environments (LMC, SMC, and Bulge). The suggested monitoring will also benefit anyone interested in slow variations or changes in the photometric behavior of stars in the Galactic Disk.

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