Connection between the Physics of Stars, Galaxies and the Universe
FAME and NASA Research Themes
Capabilities at the SMEX, MIDEX, and DISCOVERY Class Level

Rob P. Olling[1,2]
[1]US Naval Observatory, [2]USRA

ABSTRACT

Galactic and stellar studies can make substantial contributions to the resolution of many fundamental problems in modern astronomy such as those outlined in the NASA themes: 1) "The Evolution of Solar-type Stars and Implied Effects on Terrestrial Planets (SEC)," 2) "The Formation and Evolution of Galaxies (ORIGINS)," 3) "The Evolution of Stars and Galaxies (SEU)," and 4) "The Search for Near-Earth Asteroids (SSES)." Currently, these promises are not realized due to the scarcity of precise data that measure the phase-space positions, chemical composition and ages of diverse stellar populations in the greater solar neighborhood (GSN; with distance $d \lesssim 3$ kpc). Here we outline in some detail the relations between Galactic and stellar studies, extragalactic physics and the NASA research themes. We show that studies of stars (*astro*physics) are an indispensable ingredient for the advancement of our understanding of phenomena beyond our own Milky Way.

We will outline the effects of three types of astrometric missions: 1) the current, MIDEX-sized FAME realization ("FAME/M"), 2) a smaller, SMEX-sized instrument ("FAME/S") in LEO and 3) a more powerful DISCOVERY-class implementation ("FAME/D"). The salient features are: FAME/S has 4 astrometric and 1 photometric CCD, FAME/M has 12 CCDs (2 photometric), and FAME/D is equipped with 24 CCDs (12 astrometric, 4 event detection, and 8 photometric). FAME/S will have an astrometric accuracy of order 130 μas, roughly 2.5 times worse than FAME/M ($\sim$50 μas), while FAME/D will achieve FAME/M-like astrometry but will also generate a multi-band photometric catalog at the milli-magnitude level, as well as search for fast-moving near-Earth asteroids.

An astrometric satellite such as FAME/M/D will determine the distances of about 584,000 stars closer than 100 parsec with an accuracy of 0.5%. Virtually all of these stars are brighter than V=13, and thus suitable for high-resolution, ground-based, follow-up spectroscopy. Contained in this sample are $\sim$5,000 A-type, $\sim$38,000 F-type, $\sim$124,000 G-type and $\sim$171,000 K-type stars. Among the "0.5%-sample", there are about 4% thick disk stars (23,000) and 0.1% halo stars (584). Such incredible distance/luminosity opens the way to age-date individual stars. Since the luminosity of G-type stars evolves at an approximate rate of 10% per Gyr, a 1% luminosity (0.5% distance) calibration corresponds to a age-resolution of about 100 Myr. Earlier (later) type stars evolve faster (slower), yielding increased (decreased) age resolution. However, such dating techniques require knowledge of the metallicity of the stars, which can be provided by either

FAME/D or by ground-based follow up (for FAME/M). Thus, the 0.5% FAME/M/D catalog can be used to recover the history of the Milky Way in exquisite detail in many areas such as star formation, chemical enrichment, dynamics, et cetera.

At a distance of 100 pc, FAME's 1σ proper motion accuracy of 50 μarcsec/yr corresponds to a linear velocity of *24 meters per second,* so that virtually all binaries among the "0.5%-sample" will be uncovered. In combination with accurate follow-up spectroscopy (e.g., USNO's FTS), precision mass determination will be possible for up to several hundred thousand stars: an increase by *four orders of magnitude* over the current status. All fundamental stellar parameters (radius, mass, gravity, surface temperatures, Helium content, metallicity and age) can be determined at the several-percent level for the circa 1% of stars that are in detached eclipsing binaries. From this list of 5,840 stars with 0.5% astrometry, one can select the most interesting ones for follow-up, such as the ∼6 halo stars, the 234 thick-disk stars and a sample of thin-disk stars that spans the age of the Galactic disk.

Due to it's rapid spin, scanning law and photometric precision, FAME/M/D is also very good at detecting apparent variability among stars (one detection per day, on average). Especially eclipses and transits lasting several hours will be characterized very well by FAME. Such events are very robustly measured. We estimate that FAME/M/D will detect roughly 430 "hot-Jupiter" systems like HD 209458-b among stars brighter than V=12.

FAME/D would also be good at detecting fast-moving nearby bright ($V\lesssim17$) near-Earth asteroids. Apparent motions between 12 and 8,300 milli-arcseconds/second (0.09 and 60 $\mathrm{km\,s^{-1}}$ at 0.01 AU) can be detected with some clever even-detection software.

Thus, FAME-like astro/photometric and temporal data can be used to accurately determine: 1) "The Evolution of Solar-type Stars and Implied Effects on Terrestrial Planets," with a resolution of 100 Myr; 2) "The Formation and Evolution of Galaxies." For the three components of the Milky Way (halo, thick disk and thin disk) we derive almost trivially: 2A) the star formation history, 2B) the metallicity evolution, 2C) the evolution of the spectral-energy distribution; 3) "The Evolution of Stars (and Galaxies)" will be tested in excruciating detail with the 584k or so "precision" stars, and 4) the frequency of "... Near-Earth Asteroids."

1. Introduction

The scientific return of a FAME-like ("FAME") astrometric mission has been well documented by the FAME science team (FAME 2000-2002), and include the definitive calibration of: 1) the absolute luminosities of the standard candles, 2) solar neighborhood stars from all populations, 3) the frequency of companions ($M \gtrsim 80 M_{Jupiter}$) of solar-type stars., 4) stellar variability, 5) the binarity frequency. Stellar evolution and structure will be checked in great detail in nearby star clusters and visual astrometric binaries. Also, distances and proper motions allow, for the first time, a detailed study of the ages and kinematics of the youngest know stars in star forming regions. Further, the survey nature of "FAME" ensures that a large number of stars become available to probe the potential of the Milky Way in both the radial and vertical directions (rotation curve and disk mass). Given its wide and profound ramifications, it comes as no surprise that a "FAME" mission is well received in broad segments of the astronomical community. We found already ten papers on FAME-enabled science in the *refereed* literature.

However, a detailed study of the Galaxy has even wider implications due to the intimate relations between, on the one hand, the properties of the greater Solar neighborhood (GSN; $d \lesssim$ 3kpc), and, on the other hand, galactic structure & dynamics, galaxy formation and evolution. That is to say, many fields of extra-galactic research have a "high-resolution" equivalent in our own Galaxy. The Milky Way galaxy *should* be an important and precise benchmark in many areas of astronomical research. However, many fundamental parameters of stars and the Galaxy are currently ill-determined.

We argue that NASA should kick-start detailed studies of the Galaxy and its contents via the "FAME" mission of $(\frac{1}{2} — 1)\ 10^8$ stars. The "FAME" astrometric mission, with enhanced photometric capabilities (FAME/D) will provide the data that allow us to "do cosmology in our own back yard," and hence provide valuable sanity checks (local calibrations) for the high-redshift studies that are possible with the HST and NGST observatories.

Near-Earth objects (NEO) can be fairly easily detected by a FAME/D mission that runs in even-detection, rather than input-catalog mode. FAME/D's observing strategy of many ($\sim$18) events in a short period (2 hr), repeated about every ten days is particularly well-suited to detect Fast-moving, nearby NEOs.

2. FAME/S, FAME/M and FAME/D: Capabilities Outlined

2.1. FAME/M

The FAME/M mission comprises a Geosynchronous orbit, a 40 minute spin period, and a 20 day precession period. The sky will be covered about once per day during a five year mission. The focal plane is filled with 12 CCDs (2kx4k) operated in time-delayed integration mode. Two of the CCDs have photometric filters (SDSS r' & i'), 10 are astrometric (550-850 nm).

2.2. FAME/D

A more mature astro-photometric mission such as FAME/D would have the same orbital and spin characteristics as FAME/M, but be equipped with twice the number of CCDs. In this case, 12 CCDs would run in astrometric mode, 4 CCDs in event-detection mode (EDM), and 8 CCDs will be devoted to intermediate-band photometry. The 4 EDM chips would be unfiltered to achieve maximum electron count to allow event detection in 2-dimensional rasters (more noisy).

A reasonable choice for the division of the photometric CCDs would be to devote 1.5 CCDs for SDSS u', 1.5 for F411, 1.5 for Mg b, 1 for g', 1 for i', and 1.5 for pseudo SDSS z' (=pz' = Ca II = Pachen Jump) (SDSS r' can be recovered from the astrometric band and i'). The bands with the smallest bandwidth and/or total throughput have more CCD area allocated so as to increase the number of detections and hence the final S/N ratio. The focal plane layout has the 4 EDM chips first in line, and one set of 3 photometric CCDs (u', g', pz') behind each other so as to obtain semi-simultaneous multi-color photometry as the stars transits the 4 photometric chips sequentially.

2.2.1. NEO detection

The idea of event triggering is not well developed at this time. So as to detect fast-moving NEOs (FAME's only NEO niche) we need to be able to cut out large rasters around objects that are not known stars or known Solar system objects. Most of those objects are faint, so we need to find a way to detect the faint fast-moving objects while leaving the "stationary" faint stars untouched. So I envisage having two catalogs on board with fairly coarse position accuracy and no proper motion: 1) the traditional FAME input catalog, 2) a catalog with fainter objects. When an object is detected it is checked against the positions and magnitudes of these known objects: IF bright, THEN to download buffer. IF faint THEN check to see if it is in the faint catalog, IF yes, THEN "merge_data_with_existing_data" ELSE object is "new," so cut out large raster for next CCDs (as it might move at a level of arcseconds/second).

Three comments: 1) the "merge_data_with_existing_data" step could produce a catalog of faint objects that have only course positional and photometric information (much like Tycho), 2) the positional check can be of order several arcseconds, 3) the motion of NEOs may be preferentially in the cross-scan direction, so even a large CS motion of 2 arcsec/sec would hardly change the S/N ratio.

2.3. FAME/S

A FAME/S type mission could be in a low-Earth polar, sun-synchronous, orbit at an altitude around 900 kilometer to reduce launch costs. The instrument would be 3-axes stabilized to always point away from the Earth (and approximately 90 degrees away from the Sun). Thus, the sky would be scanned at the orbital period (around 100 minutes). The data will be continuously recorded, and downloaded during passes over the ground station (twice per day, 15 minutes per pass). With 5 CCDs (41% of FAME/M) and a 2.5 times slower scan rate, such a FAME/S mission produces 6 times less data than FAME/M. The 2-hour's worth of solid-state memory on FAME/M corresponds to 12^{hr} for FAME/S: large enough to retain all data for the bi-daily downlink sessions of 15 minutes duration (assuming one fully-steerable ground station). Such scheme also assumes a datarate of

5.3 Mbit/second during two 10 minute periods per day[1].

property	FAME/S	FAME/M	FAME/D
Funding Level	SMEX	MIDEX	DISCOVERY
Orbit	Sun-synchronous LEO	GEO	GEO
Orbital Period	$\sim 100^{min}$	24^{hr}	24^{hr}
Visibility	twice 15^{min}/day	24^{hr}/day	24^{hr}/day
Ground Station	Fully Steerable	Minimum Steering	Minimum Steering
Downlink rate	5.3 Mbit/sec twice 10 min/day	440 kbit/sec, 24^{hr}/day	440 kbit/sec, 24^{hr}/day
Bus	3-axes stabilized	spin-stabilized	spin-stabilized
Scan-rate	3.6^o/min.	9^o/min.	9^o/min.
Aperture	twice 23x23 cm	twice 40x9 cm	twice 53x13 cm
Focal Length	10.5 meter	10.5 meter	15 meter
# of CCDs	5	12	24
astrometric	4	10	12
photometric	1	2	8
trigerring	-	-	4
pixelsize	15μm	15μm	15μm
pixel scale	0.206 arcsec/pix	0.206 arcsec/pix	0.206 arcsec/pix
CCD operation	Stare or TDI	TDI	TDI
Integration time	5.58^{sec}	2.23^{sec}	1.56^{sec}
Astrometric band	550-850 nm	550-850 nm	550-850 nm
Event Trigger	-	-	400-990 nm
$\#\nu_{550-850}$(V=9;A0V)	186,000	186,000	374,000
$\#\nu_{SDSS}$(V=9;A0V)	80,000	80,000	80,000
$\#\nu_{400-900}$(V=9;A0V)	-	-	736,000

3. The Benefits of an Astrometric/Photometric Survey Mission
A Discovery Class Astro-Photometric Explorer (FAME/D)

The survey nature of “FAME” ensures that a large number of stars become available for a variety of studies such as:

1. A definite calibration of the absolute luminosities of standard candles (Cepheids, RR Lyrae): the zero-point of the extra-galactic distance scale.
2. The luminosity calibration of $\sim 10^6$ solar neighborhood stars

---

[1] FAME/M’ datarate is about 822 stars/second, or 35.5 10^6 stars/12^{hr}. In the FAME/S scheme about 6 10^6 would be downloaded in (say) a 10 minute window, or 9864 stars/second. This leads to a downlink rate 12 times larger than in FAME/M, or 12*(440 kb/sec)=5.3 Mbit/sec. Such a data rate should be easily achievable, even with the FAME/M omni antenna since the power levels reaching the ground station are about 1,300 times higher.

3. The determination of the frequency of all companions more massive than 80 Jupiter masses (M_J) of solar-type stars within 100 pc
4. A search for 1 $M_{Jupiter}$ objects around the nearest 375 Sun-like stars within 25 pc
5. The *one million* stars brighter than $V \approx 11$ should yield roughly 430 "hot-Jupiters," via the detection of planetary transits
6. An inventory of the occurrence of stellar variability at the several mmag level
7. A statistical study of order hundred thousand G-type stars for which relative ages will be known to $\sim$ 100 Myr.
8. The determination of the stellar binarity/multiplet frequency
9. Stellar structure and evolution will be checked in great detail in nearby star clusters, detached eclipsing binaries and some wide visual astrometric binaries
10. The evolution of the Metallicity and Helium content of the ISM of the Milky Way will be measured at $\sim$ 100 Myr intervals (via star clusters and binaries)
11. A detailed study of the ages and kinematics of the youngest know stars in star forming regions
12. The determination of the 3D distribution of extinction in the greater solar neighborhood
13. The star formation history of the Milky Way's thin disk, thick disk and stellar halo
14. The determination of the potential of the Milky Way in both the radial, azimuthal and vertical directions (rotation curve, velocity field, and disk mass).
15. Many fields of extra-galactic research have a "high-resolution" equivalent in our own Galaxy. The Milky Way galaxy *should* be an important and precise benchmark in many areas of astronomical research.

A basic requirement for many of the topics enumerated above is that additional data is available for the target stars. For example, the calibration of absolute luminosities of stars (e.g., the Cepheid PL relation) requires precise and accurate estimates of the amount of interstellar extinction (A_V) as well as the ratio of selective to total extinction (R_V). With the aid of stellar evolution models, and if one can also determine the effective temperature (T_{eff}), the metallicity ($[Fe/H]$), and surface gravity [$\log(g)$], one can determine the ages of *individual* stars. This is currently only possible for a couple of thousand of bright stars with accurate narrow-band photometry in systems such as Strömgren, Walraven or Geneva.

The astrophysical possibilities are enormous once we are able to determine the ages of a large and unbiased sample of stars: individual stellar ages are the holy grail of astrophysics. Several have been enumerate above. For example, the star-formation history of the Milky Way can be unraveled in all it's details by just counting stars as a function of age (for stars with a main-sequence lifetime larger than the Galaxy). In similar fashion will we be able to determine the history of metal-enrichment. One could check whether the initial mass function has currently the same slope/cutoff as it did billions of years ago. One can study the very details of the evolution of the kinematics of the Galaxy as a function of time, and possibly uncover minor merger events from the fossil kinematic record.

Closer to home, one could use such a data base to identify Solar-type stars of a given age. We expect to be able to date 124,000 individual G-type stars within 100 parsec to roughly 100 Myr. If we assume a disk age of 10 Gyr and a constant star formation rate, each of the one-hundred age bins will contain roughly 1,240 G-type stars. These groups of stars can be analyzed in the context of "The Evolution of Solar-type Stars and Implied Effects on Terrestrial Planets (SEC)." For example, one can select only those stars that have Solar metallicity, and study their properties as a function of age (forwards and backwards).

Such data will allow for fairly determination of the fundamental parameters of stars $[T_{eff}, [Fe/H], \log{(g)}]$ and the intervening interstellar medium (A_V and R_V).

$\geq$ 6 band photometric system is incorporated, then a fairly accurate determination of the stellar parameters for the majority of stars can be accomplished temperature (T_{eff}), gravity $[log(g)]$, metallicity ($[Fe/H]$), mass (M) and age (τ). From the ground, such info is virtually impossible to obtain for a significant fraction of "FAME" stars due to the huge number of stars involved and the required stringent accuracies. from the ground

4. Brown Dwarfs & Planets

Several thousand nearby G-type have been targeted in radial velocity surveys, and found over four dozen sub-stellar companions with minimum masses between 0.15 MJup to 80 MJup. The 80 MJup limits is roughly the sub-stellar limit: heavier objects are stars, lighter objects are planets. It is suggested that the frequency of brown dwarfs (low-mass stars) declines substantially near the sub-stellar limit, while the frequency of gas-giant planets rises toward lower masses (Mazeh et al. 1998). Also, wide binary stars appear to be equally hospitable to the formation of gas giant planets as are single stars. These results are still uncertain because of the small number of systems available for analysis and because of the sin(i) ambiguity inherent in radial velocity detections.

One of the most interesting aspect of FAME mission is that it will *survey* all nearby stars for low-mass companions. This will be done astrometrically as well as photometrically.

For example, for the case of of G-type primaries (sun-like stars), FAME could derive orbits for companions with masses down to 8 M_J around 24,000 stars within 100 pc, 4 M_J around 3,000 stars within 50 pc, and 2 M_J for 375 stars within 25 pc. These numbers are based on the results from simulations carried out for the GAIA mission (Casertano 1998), adapted to the FAME mission requirement of 50 μas astrometric accuracy. The great advantage of astrometric planet detection is that the *orbits*, and hence the sub-stellar masses can be determined directly, as compare to radial velocity surveys that are sensitive to $M_p \sin i$ only.

4.1. Planetary Transits

When a star transits FAME's focal plane (FP), it is detected by 1—3 CCDs, separated by 2.2 seconds. Below V=11, the photometric accuracy of FAME's astrometric bandpass is better than 5 mmag (0.005 mag) *per CCD crossing.* About nine minutes and 40 minutes later, the star transits the focal plane again. These time separations are set by the optical design and the spin-rate. The precession rate determines how often these sequences repeat.

On average, each batch of observations comprise 12 focal plane crossings and ~24 observations per batch. The observing batches last (2±1) hours and are separated by 10^{+30}_{-9} days, depending on the location on the celestial sphere. In total, during a 5 year mission, 2000 observations in (77±31) observing batches will cover each point on the sky. Thus,

1. each FP transit (FPT) has ~ 3 independent detections
2. Batches of FPTs comprise ~ 6 FP transits during 2±1 hours
3. (77±31) batches are separated by 10^{+30}_{-9} days

Given an edge-on observing geometry, the probability of detecting a hot-Jupiter in transit equals the ratio of the transit time (T_{trans}) to the orbital period (T_{orb}). For Sun-like main-sequence stars, one can estimate that this probability reduces to $P_{transit,seen,once} \approx 0.077 T_{orb}^{-2/3}$, where T_{orb} is measured in days. After a five year mission, with about 77 visits in random orbital phases, the total detection probability is: $P_{trans,mission} = 1 - (1 - P_{transit,seen,once})^{77}$. For orbital periods of 1, 2, 7, 14, 30, 365 days, we arrive at detection probabilities of 100%, 98%, 81%, 64%, 46%, and 11%, if the system is edge-on.

After factoring in the geometric detection probabilities and the total number of stars, we conclude that a FAME-like mission would detect of order 430 "hot Jupiters" in transit, or about 30% more than the estimated number for the "Kepler" mission. However, the FAME detections would occur around much brighter stars ($V \lesssim 11$), and are thus much more suitable for follow-up observations with instruments such as SIM or TPF.

The length of an observing batch of two hours, more-or-less covers the planetary transit in systems like HD 209458. The probability for multiple detections is also fairly large. Three transit events would be observed in $\gtrsim 53\%$ ($\gtrsim 9.7\%$) of systems with periods less than 7 (30) days, or in ~155 (~13) systems.

5. Astrometry & Photometry: A Powerful Astrophysical Tool

m

The combination of accurate FAME astrometry and medium-band photometry opens up many fields of Galactic and stellar physics where theory is ahead of observational tests. It will also become possible to estimate the formation history of (the chemical elements of) the Galaxy. So as to meaningfully test theories of stellar structure and evolution, the errors on stellar temperature, radius (R) and mass (M) should be smaller than several percent, while errors in metallicity should be smaller than 25% (Andersen 1991).

5.1. Content of the FAME/M Catalog

With the aid of star-count models, one can estimate the stellar content of the final FAME/M catalog. Split up by spectral type along the main-sequence, we can determine the distance when such a star reaches FAME's limiting magnitude (V=15). Thus each type of stars samples different volume around the Sun. We present some properties of the expected FAME catalog below, where we assume an average extinction of 1 magnitude per kpc.

Sp.Type	M_V	d_{lim}	Number	$d_{lim;0.5\%}$	$N_{thin\ disk}$	$N_{thick\ disk}$	$N_{spheroid}$
	mag	pc	/1k	pc			
B5V	-1.2	3,487	2,000	100	0.9k	-	-
A5	1.9	1,811	2,800	100	4.6k	-	-
F5V	3.5	1,166	9,600	100	37.6k	1,504	38
G5V	5.1	694	11,200	100	124.1k	4,964	124
K5V	7.4	290	5,600	78	170.7k	6,828	170
M2V	10.0	96	2,000	47	239.8k	9,592	240
KIII	0.6	2,452	6,800	100	6.0k	240	0

5.2. The 5D Classification of Stars

So as to observe five parameters, one needs > 5 independent measurements. Thus, the $4-$band SDSS photometric system that was originally proposed for FAME is not sufficient. Olling (2001,2002) proposed to include a 6 - 8 band filter system for the FAME mission. With such photometric data, the stellar and extinction parameters can be determined to reasonable accuracy. At V=15, we find: 1 - 10% for T_{eff} and R_V, 60 mmag for A_V, and 0.5 dex for $log(g)$ and $[Fe/H]$. The classification accuracy varies across the HR diagram, and is mostly sensitive to T_{eff}. At brighter magnitudes, the classification accuracy improves almost linearly with signal-to-noise ratio.

Optimizing the photometric bands for precise parameter estimation entails several conflicting needs: (A) broad continuum bands are best for T_{eff}, A_V, R_V, (B) narrow bands centered on distinct spectral features [Balmer jump & lines, Mg b, TiO lines, Paschen Jump, etc.] are extra sensitive to $log(g)$ and $[Fe/H]$, and (C) good sensitivity in *all* bands. Similar bands are found in several photometric systems (Strömgren, DDO, Walraven, GAIA, ...). The FAME compromise is to use wide versions of some Strömgren bands, complemented with semi-continuum bands from the SDSS set: g', r', i' and a narrow z'. The exact choice for the location and width of the bands is not so important, as long as the accuracy is of order 1 - 10 mmag. However, a large wavelength range ("NUV" - "NIR") is highly desirable since it increases the lever-arm for T_{eff}, A_V and R_V fitting. Also, the inclusion of one or two bands blue-wards of the Balmer jump would greatly improve the parameter estimation.

Ideally, a FAME-like astrometric mission should have photometric capabilities at the mmag level in *at least photometric six bands.* In the current (canceled) incarnation of the FAME mission, only two photometric CCDs are available. In case a FAME-like mission will be reinstated, we urge the team to add additional photometric CCDs, possibly outside the "astrometric field of view."

5.3. Astrometry & Photometry: Examples

m

We will now present some examples that illustrate that the *combination* of accurate astrometry and photometry yields results that surpass the results from either astrometry or photometry separately: the combination is larger than the sum of the parts.

1) FAME's astrometry can contribute significantly to our understanding of of the evolution –in a statistical sense– of the Sun. "FAME" will determine distances (d) to better than 0.5% (2%) for about 123,000 (750,000) G-type stars out to about 100 (250) pc. Thus, absolute luminosities for 123k G-type stars will be available at the 1% level. Using luminosity (L) as a proxy for age (τ), and an approximate evolution rate of $\Delta L/L \sim 0.1/\mathrm{Gyr}$ (for G-type MS stars), a 1% luminosity "resolution" corresponds to an age resolution of 100 Myr, so that the 10 Gyr of Galactic history is split up in 100 "age" bins. Thus, the individual age bins would contain ~123 G stars each.

Of course, correlation between luminosity and age is not 100%. Other parameters such as extinction (A_V and R_V), mass and radius (gravity), temperature and metallicity also play a role. Those parameters can be determined with the aid of accurate intermediate-band photometry (or follow-up spectroscopy) and models of stellar evolution and atmospheres.

Thus, accurate astrometric data facilitates the determination of the evolution of the G-type stars such as the Sun in a statistical sense. However, it is also evident that the results will significantly improve when the astrometric data is complemented by photometry. Likewise, without the astrometric distance (luminosity) determination, photometric classifications lack a firm zero-point. Other examples of science that is enabled by the joining of astrometry and photometry are:

- An empirical determination of the properties of (G-type) stars such as: rotation, magnetic field strength, variability, planetary frequency, etc. (at ~100 Myr intervals),
- An estimation of the star-formation history of the Milky Way (at the solar circle),
- The formation history of the life-bearing elements, as "frozen in" in the program stars,
- The the pre-Galactic Helium fraction and its subsequent evolution via eclipsing astrometric binaries
- The formation history of most of the Galaxy: thin disk, thick disk, halo
- The dynamical evolution of the solar neighborhood (the age-velocity relation).

2) The most important parameter that determines the internal structure and evolution of a star is its mass. Detached double-lined eclipsing binaries (DEBs) are best suited for accurate (1-2%) mass determinations: 44 such systems (88 stars among which are only *four* main-sequence G stars) were known in 1991 (Andersen). When distances and extinction are determined at the same level, detailed checks on the interior structure and evolution of stars become possible.

The OGLE and HIPPARCOS experiments find that about 0.8% of all stars are DEBs (with periods of about 1 day), so that "FAME" could find 400,000 - 800,000 new DEBs. Roughly

10% of these DEBs will be brighter than V=12. FAME's scanning geometry results in 14±8 eclipses per DEB, in the average. The subset of unequal-mass eclipsing binaries will also show an astrometric wobble that is easily detectable with "FAME." The large number of DEBS will ensure that DEBs will be found among stars of all masses and ages, provided that the particular phase of stellar evolution is long enough to produce 1/0.08=125 objects in the $50 - 100$ million strong "FAME" catalog. Ground-based spectroscopic follow up of the most promising candidates and stellar atmosphere models can be used to arrive at $M, R, log(g), T_{eff}$, and the SED (F_λ). Thus, the addition of spectro-photometric information will turn a "FAME" catalog of DEBs in a highly accurate source of basic astrophysical stellar parameters.

Similar results may be obtained from the large number of expected resolved astrometric binaries. USNO's data base of orbits of resolved binary stars contains about 500 wide ($1 - 15$ arcsec separation) pairs with periods less than 5 years. For these systems, no radial velocity data is required: FAME alone will provide the stellar masses. The USNO data base is rather incomplete and we expect to find many more resolved astrometric binaries in the full "FAME" catalog. FAME's superior astrometric precision is needed to employ this data base because the mass estimates depend on high powers of the angular separation (a) and parallax π and period P ($M_{tot} \propto (a/\pi)^3 P^{-2}$).

Stellar ages need be determined via models of stellar evolution. These models can be tested in environments where two or more stars have "identical" ages such as binaries and clusters. Again, the synergy of *accurate* astrometry and photometry provides new opportunities for additional science:

- the distribution of dust throughout the greater solar neighborhood
- the (radial variation of the) local disk mass
- the Distance to the Galactic center and the Galactic rotation curve
  via calibration of standard candles (RR-Lyrae, Red Clump, etc) and kinematical methods
- the presence of localized "clumps" in the dark matter distribution.
  by comparing large-scale (rotation curve/velocity field) and localized (vertical force) measurements
- constraints on the dynamical evolution of the Milky Way, for example
  from the 5+1D $f(\overline{x}, \mu_l, \mu_b, age)$ *distribution function*

The above examples illustrate how the combination of astrometry and photometry of Galactic stars will contribute very significantly to NASA's SEC, Origins and SEU themes. The discovery of new near-Earth and other solar system objects might be achieved if "FAME" works in "trigger mode," that is to say, employ on-board detection rather than input catalogs.

6. References

Andersen J., 1991, A&AR, 3, 91
Bailer-Jones, C.A.L, 2000, A&A, 357, 197
FAME, 2000-2002, The FAME team. eg., at http://www.usno.navy.mil/FAME/
Gray, R. O., Graham, P. W., Hoyt, S. R., 2001, AJ, 121, 2159

Olling, R.P.,2001, at http://ad.usno.navy.mil/~olling/FAME/rpo_fame.htm
Snider, S., *et al.*, 2001, ApJ, 562, 528