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NAVAL CENTER FOR SPACE TECHNOLOGY

Full-Sky Astrometric Mapping Explorer (FAME)
Detailed Science Requirements Document (SRD)

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1. SCOPE

1.1 Identification

This document applies to the Full-Sky Astrometric Mapping Explorer (FAME) Observatory.

1.2 Purpose

This document establishes the scientific requirements for the FAME observatory. These requirements are the basis for the more detailed requirements to be included in the specifications for the individual elements of the FAME observatory, which include, but are not limited to the spacecraft bus, the instrument payload, ascent support equipment (ASE), and related ground elements.

1.3 System Overview

The FAME observatory will provide the positions, proper motions, parallaxes, and photometry of nearly all stars as faint as 15th visual magnitude with accuracies of 50 microarcseconds (µas) at 9th visual magnitude and 500 milliarcseconds (mas) at 15th visual magnitude. Stars will be observed with the Sloan Digital Sky Survey g', r', i', and z' filters for photometric magnitudes with millimagnitudes (mmag) accuracies. This is accomplished by a scanning survey instrument with a mission life of 2.5 years and an extended mission to 5 years.

1.4 Document Overview

This Detailed Science Requirements Document (SRD) establishes the top-level scientific performance requirements for the FAME program.

- Section 1.0, *Scope:* Purpose and contents of this document, and an overview of the FAME program.
- Section 2.0, *Requirements:* The performance and science requirements of the FAME mission, including requirements, goals, and minimum (floor) science mission.
- Section 3.0, *Supporting Notes:* Additional description of FAME measurements and science goals.

2. REQUIREMENTS

2.1 Performance Requirements

FAME will create a catalog of star positions based on a 2 1/2 year mission with:

1. A measured position, parallax, and proper motion of stars between 5th to 9th visual magnitude to 50 microarcseconds, 50 microarcseconds, and 70 microarcseconds per year respectively. For stars fainter than 9th visual magnitude the mission Astrometric accuracy shall degrade no more rapidly than implied by the photon statistics, i.e., no more rapidly than the inverse square root of the apparent brightness. At 15th visual magnitude, the mission astrometric accuracy shall be no worse than 500 microarcseconds.
2. Photometric magnitudes for all stars in the wide band astrometric bandpass as well as the Sloan g', r', i', and z' filters. The accuracy of individual observation magnitudes will be from millimagnitudes at 9th magnitude to four hundredths magnitude at 15th magnitude. The mission magnitude accuracies will be tenths of a millimagnitude at 9th magnitude and five millimagnitudes at 15th magnitude.
3. The above accuracy specifications apply to 90% of the unconfused sources at a given magnitude, with the other 10% not exceeding twice the accuracy specification. The coverage is for > 98% of the sky to take into account areas of crowding. Stars within this near full-sky coverage are selected for measurement (data rate limited) based on planned scientific programs.

2.2 Science Objectives

FAME will provide:

1. Calibration of the luminosities of the "standard candles" (the galactic Cepheid variables and the RR Lyrae stars) that are fundamental in defining the distance scale to nearby galaxies and clusters of galaxies.
2. Calibration of the luminosities of solar-neighborhood stars, including Population I and II stars, thus enabling diverse studies of stellar evolution and other interesting science. In the case of Population II subdwarfs, this will allow the determination of the distances and ages of galactic and extragalactic globular clusters with unprecedented accuracy.
3. Definitive determination of the frequency of solar-type stars orbited by brown dwarf companions in the mass range of 10 to 80 M_{jup} with orbital periods up to a little longer than the duration of the mission. This will include an exploration of the transition region between giant planets and brown dwarfs, which appears to be in the range of 10 to 30 M_{jup}.
4. Proper motions and distances for individual stars in star forming regions and young clusters for determinations of membership, ages and kinematics.
5. A study of kinematic properties of the survey of 40 million stars within 2.5 kpc of the Sun, and in particular, an assessment of the abundance and distribution of dark matter in the galactic disk with much greater sensitivity and completeness than previously possible.

2.3 Requirements, Goals, Floor

2.3.1 Astrometry

The FAME position and parallax accuracy requirements, goals, and floor for the 2 1/2 year mission in μas are listed in Table 2-1.

Table 2-1. FAME Requirements, Goals and Floor for the 2 1/2 Year Mission (Astronomy)

		Requirement	Goal	Floor
Standard candles:	9 mag	50	50	200
	12 mag	100	100	400
	15 mag	500	500	1000
Solar Neighborhood Stars:	9 mag	50		200
	15 mag	500		2000
Brown Dwarfs:	9 mag	50	25	100
	15 mag	500	250	1000
Star forming region:	9 mag	50	25	500
	12 mag	125		500
	15 mag	500		1000
Reference Frame:	9 mag	50	20	500
	15 mag	500	250	1000
Stellar Astrophysics:				
White Dwarfs:	12 mag	100	60	500
	15 mag	500	300	2000
Planetary Nebulae:	12 mag	100	60	500
	15 mag	500	300	1000
Subdwarf O/B Stars:	12 mag	100	60	200
	13 mag	150	75	300
HB Stars:	12 mag	100	60	300
Galactic Structure:	9 mag	50		
	12 mag	100		400
	15 mag	500		2000
Relativity:	9 mag	1000	500	2000
Solar System:	9 mag	2000	1000	10000

2.3.2 Photometry

The FAME accuracy requirements, goals, and floor for the 2 1/2 year mission in millimagnitudes (mmag) are listed in Table 2-2..

This gives the minimum photometric requirements that are needed for astrometry. Accurate astrometry requires knowledge of the colors of the stars to determine the point spread function and achieve the most accurate centering. In principle, photometry of adequate precision could be obtained from the ground. In practice, the organizational effort, cost, and schedule requirements would be nearly impossible. With FAME required photometry can be obtained to meet the mission requirements and, because FAME makes so many measurements of each star, the photometric product is suburb and enables new science. Much of the interest is in the area of variability, so requirements are given both in terms of individual observations and the values based on all observations from the mission. Values given below are for apparent visual magnitudes (V), unless otherwise specified. In the discussion below, absolute magnitudes (Mv) will be used in some cases.

Table 2-2. FAME Requirements, Goals and Floor in mmag for the 2 1/2 Year Mission (Photometry)

			Requirement	Goal	Floor
Standard candles (nonvariable stars, per mission):		12 mag	2		
	g', r', i'	9 mag	0.5	0.2	5
	g', r', i'	12 mag	2	0.8	5
	g', r', i'	15 mag	8	3	10
Solar Neighborhood stars:		9 mag			
		15 mag			
Brown Dwarfs (astrometric, per observation)		9 mag	3	1	4
		12 mag	12		
Star forming region					
(per observation)		9 mag	3	1	3
		12 mag	12	4	12
(per observation all filters)		9 mag	10		
		12 mag	10		
		15 mag	30		
Reference Frame:		9 mag			
Photometry:					
(per observations)		9 mag	3	1	10
(per mission)	g', r', i'	9 mag	0.5	0.2	5
(per mission)	g', r', i'	15 mag	10		
Stellar Astrophysics:					
Solar-type stars (per observation):		9 mag	3	1	20
		12 mag	12	4	20
Radial Pulsators (per observation):		9 mag	3	1	30
		12 mag	12	4	30
Non-radial Pulsators (per observation):		9 mag	3	1	10
		12 mag	10	4	10
(per mission):		9 mag	0.5	0.2	5
		12 mag	2	0.8	10
		15 mag	8	3	10
Interstellar matter (per mission)		12 mag	2	1	20
Galactic Structure (per mission):		9 mag			
		12 mag			
		15 mag			
	g', r', i'	9 mag	0.5	0.2	5
	g', r', i'	12 mag	2	0.8	10
	g', r', i'	15 mag	8	3	10
Relativity:					
Solar System:					

Note: Requirement is the specification to which the instrument and spacecraft are designed.
Goal is what is desired if this can be achieved within budget and schedule.
Floor is the value at which it is not worth doing the mission for this scientific purpose.

3. FAME SUPPORTING NOTES

3.1 Distance Scale

3.1.1 Cephids and Interstellar Reddening and Absorption

The Galactic Population I Cepheid variables have been used for many years to establish the zero-point in the Cosmological Distance Scale. However, due to the inaccuracy of the distance determinations it has been impossible to derive an accurate distance scale from the Galactic Cepheids and investigators have turned to the Magellanic Clouds, which they have adopted as a reference point. It has become apparent, however, that metallicity differences between the Magellanic Clouds, the Galaxy and distant galaxies introduce a source of systematic error into the calibrations, so it is important to use the high parallax accuracy of FAME to reintroduce the Galactic Cepheids as the first step in the Cosmological Distance Scale. FAME will be able to measure accurate parallaxes to 70 Galactic Cepheids and determine the zero-point of the Cosmological Distance Scale to an accuracy of 0.01 mag. A weakness of the FAME zero point will be that it will only include 16 Cepheids with periods greater than 10 days, which is the important overlap with the extragalactic Cepheids. If one ignores all external information on the slope of the PL relation, the zero-point error will be increased to 0.02 mag.

The dominant source of error in the FAME absolute magnitude calibrations of Cepheids and the Open Clusters will be uncertainty in the interstellar absorption, since these Population I objects lie in the Galactic plane and are often heavily obscured. We use two methods to estimate the uncertainty in the absorption estimates. First, we use the data of Feast & Catchpole (1997) and Feast & Whitelock (1997) who have obtained a calibration of the Period-Luminosity-Color relation for 223 Galactic Cepheids based on ground-based photometry and Hipparcos parallaxes. Feast & Whitelock (1997) list the observed [<B>-<V>] and E(B-V) values for each star, from which we obtain the "intrinsic" [<B>0-<V>0] values. Laney & Stobie (1994) provide a relation between the intrinsic color of a Cepheid and the logarithm of its Period, and from the difference between the observed and predicted intrinsic color, we estimate the error of the observed value assuming initially that the predicted value is without error. The rms of the difference is 0.07 mag. However, since the width of the Cepheid instability strip is ~0.2 mag, most of this scatter is due to real deviations from the period-color relation and not errors in the extinction estimates. We estimate the extinction error to be quadrature difference of these two effects, 0.04 mag. Second, we compare the independent reddening estimates done by Fernie (1990) and Dean, Warren, & Cousins (1978) and find an rms difference of 0.03 mag, in good agreement with the first estimate. We combine the two to obtain σ [E(B-V)]=0.035 or σ [Av]=0.1 mag.

Because Cepheids are confined to the Galactic plane, their number grows as distance squared. It is then straightforward to show that the error in the zero-point determination is approximately given by:

$$\sigma(\text{zero}-\text{point}) = \frac{\sigma[\text{Av}]}{\sqrt{\text{Neq} * \ln(\text{Dcut}/\text{Deq})^2}}$$

where Deq=1 kpc is the Cepheid distance at which the fractional parallax errors are equal to [ln(10)/2.5]* σ [Av], Neq is the number of Cepheids within this distance, and Dcut ~ 2.5 kpc is the distance at which Cepheids reach V~9 (and hence the fractional parallax errors increase as the square of the distance, rather than linearly). Cepheids beyond this distance do not contribute significantly to the zero point determination. Considering all Cepheids, Neq=70. Considering only those with periods greater than 10 days, Neq=16.

From this formula, one can construct the following table:

σπ (V=9) (μas)	σ (zero-point) (all Cepheids) (magnitudes)	σ (zero-point) (Period > 10 days) (magnitudes)
50	0.008	0.017
100	0.013	0.027
200	0.022	0.046

For Cepheids, the critical magnitude range for performance is V<9. A descoping of FAME by a factor of two would significantly reduce the precision, and by a factor of four would seriously reduce it. It would still be worth doing the mission at $\sigma\pi$ (V=9) = 200 μas, but not much beyond this.

3.1.2 RR Lyrae Distance Scales

3.1.2.1 Parallaxes

We rely here mainly on parallaxes of relatively nearby (and intrinsically bright) RR Lyraes. Therefore, we are sensitive mainly to the mission precision at the bright end. Specifically, there are 73 RR Lyraes for which the nominal mission characteristics would yield <10% parallaxes. [It does not do much good to get much better than 10% because of intrinsic scatter, and the stars for which we get much worse than 10% are not useful because 1) they contribute very little statistically even if they did not suffer from systematics, and 2) one must worry about systematics at a low and undetectable level.]

The mean RR Lyrae absolute magnitude can be measured to 0.022 mags from these 73 stars. If the mission were degraded by a factor of two, the same 73 stars would yield 0.031 mags. Another factor of two would degrade the result to 0.04 mags. If the errors increased beyond that, the mission would not be worth doing. The 10% parallax measurement limit (i.e., the 73rd star) has V=12, so it is at V=12 that the FAME precisions are important for RR Lyrae parallaxes.

3.1.2.2 Statistical Parallax

Here, what is required is only that FAME achieve proper motion precisions of 20 km/s at 3 kpc, i.e., 1.4 mas/yr at V=13. This is about an order of magnitude worse than the nominal FAME precision. So the mission could basically fail for all other applications and still be a resounding success here.

3.1.3 Subdwarf Distance Scale

As will be outlined below, <10% parallaxes are required for this application, and it is not useful to drive parallax errors much below 3%. With the nominal FAME precisions, there are about 700 known stars [Fe/H] < -1.5 for which FAME could get 10% parallaxes. The great majority of these are relatively blue (0.4<B-V<0.8) and hence intrinsically bright (5<Mv<7). If FAME were degraded the number of such stars would fall approximately inversely as the precision cubed. This would be bad but tolerable for a factor of 2 degradation, but would be terrible for a factor 4. One major problem as the number of stars falls is that the sampling of the 2-D space of subdwarfs (B-V,[Fe/H]) becomes worse. It would then be difficult to determine whether the theoretical tracks are correct simply because they would be so poorly sampled. One happy note: faint subdwarfs (Mv>7) that are so rare in the known sample, are all quite close and so will have small parallax errors even if the mission is degraded. Thus, as the sample size falls from degradation, it will lose mainly from the well-sampled color range.

3.1.3.1 Open Clusters and the Distance Scale

Open star clusters have historically played a major role in establishing distances in the Galaxy, using the main sequence fitting technique. Open clusters are also particularly important in setting the zero-point for the Cepheid period-color-luminosity relation because some contain Cepheid variables.

In the Hyades cluster, close enough to apply the moving cluster technique, the main sequence has historically been used to define a standard zero-age main sequence (ZAMS), whose position served to determine the distance moduli of more distant clusters. Main sequence fitting, now understood to require corrections for differences in [Fe/H] among clusters, still plays an important role in establishing the Galactic, and extragalactic, distance scale. Thanks to Hipparcos, the once controversial distances to the Hyades and several nearby clusters have been accurately determined.

However, a controversy has arisen regarding the distance to the Pleiades, Praesepe, and Coma clusters, whose main sequence fitting distances disagree with their Hipparcos distances. Pinsonneault et al. (1998), using theoretical isochrones based on the best physics then available, and including corrections for differences in [Fe/H] between clusters, concludes that agreement between their models and the Hipparcos data cannot be achieved without adopting an anomalously large helium abundance for the Pleiades. They reject this solution and raise the possibility of systematic errors in the Hipparcos data larger than the quoted errors (see also Narayanan & Gould 1999).

Otherwise, they argue that taken at face value, the Hipparcos result raises the possibility that something important is missing in standard stellar models.

FAME observations provide a unique opportunity to resolve the issue of possible systematic errors in the Hipparcos data. Either the outcome will be the confirmation of the Hipparcos open cluster distances, or the determination of new, more reliable, distances, free of the Hipparcos systematic errors.

3.1.3.2 Open Cluster Membership

We must ensure that the targets selected to determine the distances of the Open Clusters are members of the cluster. The most effective way to do that is to determine the probability of membership using proper motions. At magnitude 15, the accuracy of the FAME proper motions is 0.5 mas/yr, which is much better than the 1.0 mas/yr that is normally required for reliable proper-motion membership determinations. We need to ensure that complete samples of stars in the vicinity of each Open Cluster are included in the FAME Input Catalog so that we will be able to derive the probabilities of membership for the Open Clusters within 1000 pc of the sun.

3.1.3.3 Correlated Systematic Errors

We have assumed so far that there are no systematic errors that would dominate the quoted accidental errors. This issue is of considerable interest when we consider averaging the parallaxes of several stars that are members of a star cluster to obtain a more accurate mean parallax of the cluster, or for a member Cepheid. However, if the parallax errors are correlated on an angular length scale comparable to the cluster dimensions, then the mean parallax of several cluster members may not result in a more accurate cluster parallax. Such effects have been reported for the Hipparcos parallaxes in the region of the Pleiades and Hyades clusters by Narayanan and Gould (1999a, b) and Pinsoneault, et al. (1998). The half-amplitude of the parallax zero-point errors is about 1-2 mas on an angular scale of 1-2 degrees. Since the average Hipparcos accidental parallax error is about 1.0 mas, little is gained by averaging more than two or three members to obtain a mean cluster parallax. Since FAME has a scanning law similar to that of Hipparcos, and a reduction scheme necessarily similar to that of Hipparcos, it is probable that it will also have systematic errors in proportion to its mean accidental measurement error that are similar. On the other hand, the ratio of FAME systematic to accidental errors should be somewhat smaller than those of Hipparcos due to the much higher density of stars observed by FAME, 1000 versus 2.5 stars per square degree. We must be very careful about assuming that any number of stars on a small angular scale can be averaged to derive a mean distance with greater accuracy than the unit accuracy. This effect will be important for the parallaxes, but not for the determination of membership based on proper motions.

Descoping of the astrometric accuracy by a factor of two will have a small effect on the determination of membership, but a major effect on the distance determination of the clusters. On the other hand, if the correlated systematic errors can be controlled, then the average of four times more stars in a cluster will compensate for the reduced accuracy. A reduction in the magnitude limit of FAME would have a major impact, as that would considerably reduce the number of star clusters within the reach of FAME.

3.2 Luminosity Calibration of Solar Neighborhood Stars

The calibration of stellar luminosities in the solar neighborhood, including both Population I and II stars, will be improved by FAME. With an accuracy some 20 times better than Hipparcos, it will be possible to calibrate the luminosity axis of the HR diagram for nearly all types of stars and enable diverse studies of stellar evolution and other interesting science. In the case of the Population II subdwarfs, this will enable the determination of the distances and ages of galactic and extragalactic globular clusters with unprecedented accuracy.

FAME will determine the mean absolute magnitude of the bright massive supergiants of Mv = -5 to an accuracy of 0.02 mag. The FAME parallax error budget of 50 μas for stars brighter than 10th magnitude yields a proportional parallax accuracy ($\delta\pi/\pi$) of 0.05, or a distance modulus accuracy of 0.11 mag. at a distance of 1000 pc. For these bright stars, the standard luminosity function predicts between 30 (assuming they are concentrated towards the disk) and 230 (spherical volume) of these stars within a volume of radius of 1000 pc and height +/- 100 pc for the cylindrical case. Even in the restricted cylindrical case, the accuracy of the mean absolute magnitude is an unprecedented 0.02 mag.

For the fainter stars in the HR Diagram, the luminosity function increases rapidly and there will be 300,000 stars brighter than tenth apparent magnitude with Mv < 0. These stars will have individual absolute magnitudes determined to < 0.11 mag. With this level of accuracy for large numbers of stars, it will be possible to calibrate the mean absolute magnitudes of small groupings of stars throughout the upper part of the HR diagram. Beyond V = 10, the accuracy of the FAME parallaxes decreases to about 500μas at V = 15. The standard luminosity function predicts that there will 40 stars of Mv = 15 within a volume of radius 10 pc. Nearly all of these faint stars have had their luminosities adequately calibrated from modern ground-based parallaxes, so FAME will have its greatest impact on the calibration of stars with Mv brighter than 5.

Methods, such as that developed by Lutz and Kelker, have been developed to correct for systematic errors in luminosity calibrations due to the bias introduced when selecting stars with parallaxes larger than some given value. However, an accurate knowledge of the true, and unknown, spatial distribution of the sample is necessary for its implementation. Indirect methods relying on the distribution of proper motions of the sample stars can be used to infer the true parallax distribution. However, FAME's large sample of accurate parallaxes will put us in the unique position of being able to independently determine the required corrections by breaking the sample into discrete parallax groupings.

The number of subdwarfs will be increased by at least a factor of 20 over those used with the Hipparcos data; hence again the accuracies are extremely favorable.

Descoping by a factor of two will still make the calibration of the HR Diagram 10 times better than Hipparcos at all magnitudes.

3.3 Brown Dwarfs and Planets

Radial velocity surveys of several thousand nearby solar-type stars have discovered over four dozen unseen companions with minimum masses below the substellar limit, in the mass range from 0.15 M_{jup} to 80 M_{jup}. Essentially all have orbital periods shorter than 5 years. An analysis of the secondary mass distribution for low-mass companions suggests that the frequency of stellar companions (i.e., brown dwarfs) drops off rapidly near the substellar limit of 80 M_{jup}, while the frequency of gas giant planets rises toward lower masses (Mazeh et al. 1998). The transition region between gas giant planets and brown dwarfs appears to lie in the range of 10 M_{jup} to 30 M_{jup}, although this result is still very preliminary and uncertain because of the small number of systems available for analysis and because of the sin(i) ambiguity inherent in radial velocity detections. Wide binary stars appear to be equally hospitable to the formation of gas giant planets as are single stars.

FAME will provide a definitive determination of the frequency of solar-type stars orbited by brown dwarf companions in the mass range 10 M_{jup} to 80 M_{jup} and with orbital periods up to about twice the duration of the mission (i.e., ten years, with the extended mission). This will include an exploration of the transition region between gas giant planets and brown dwarfs. To be specific, FAME has the sensitivity to derive orbits for companions with masses down to 8 M_{jup} around 24,000 solar-type stars within 100 pc, 4 M_{jup} around 3,000 solar-type stars within 50 pc, and 2 M_{jup} for 375 of the nearest solar-type 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 goal for FAME would be to lower these detection limits by a factor of two, allowing 1 M_{jup} planets to be detected within 25 pc around solar-type stars. The floor for FAME would raise the nominal detection limits by a factor of two.

In addition, FAME will be able to derive orbital inclinations for many of the stellar and substellar companions with spectroscopic orbits, thus eliminating the sin(i) ambiguity in the masses. For the 51 Peg-type systems with hot Jupiters in short-period orbits, FAME will be able to search for additional companions in much wider orbits. The discovery of additional planetary-mass companions would be especially significant, because it would provide evidence for planetary systems (as opposed to just the largest planet) orbiting solar-type stars, as in the case of the Upsilon Andromedae system of three planets (Butler et al. 1999).

The first confirmation of an extrasolar planet by transit photometry of the star HD 209458 (Charbonneau et al. 2000; Henry et al. 2000) emphasizes the possibility that FAME can detect planets photometrically as well as astrometrically. A transit by a Jupiter-size planet (or a brown dwarf star) results in a dimming of the primary star by about 10 mmag. FAME's required photometric accuracy for individual measurements at the 3 mmag level for 9th magnitude stars is sufficient to allow FAME to search for transits by substellar companions. [We exclude 15th magnitude stars, as their expected photometric accuracy of 40 mmag is insufficient for this purpose.] Typical planetary transits last on the order of a few hours. FAME will observe each star roughly 950 times, averaging once a day, but because each star will be observed twice during a 40 minute scan, for three successive scans, each star will have 6 photometric observations over a two hour time period, sufficient to catch at least a portion of a planetary transit. In most cases FAME will not have sufficient temporal coverage to determine an orbital period, but FAME's photometry should provide a powerful survey tool for follow-up ground-based transit searches.

3.4 Star Forming Regions

3.4.1 Present Status

The nearest low-mass star-formation regions (SFRs) in our Galaxy lie at a distance of about 150 pc (e.g., Taurus-Auriga), and the nearest rich SFRs lie at about 450 pc (e.g. Orion). Regions forming truly massive stars are located at about 1 kpc or further (e.g., S106, NGC7538, W3, etc.). The stars in all these SFRs were mostly too faint to be observed by Hipparcos, and even for the brightest members of the nearest SFRs the Hipparcos distance errors amounted to 20 percent or worse. The improved photometric sensitivity and astrometric accuracy of FAME will allow large numbers of pre-main-sequence (PMS) stars in these SFRs to be surveyed efficiently.

Because accurate distances have been determined directly for only a handful of PMS stars, the distances to SFRs and giant molecular clouds (GMCs) are not well determined. As a result we have only a rough idea of how the star-formation regions are laid out in space, and our picture of the three-dimensional structure in SFRs is rather fuzzy.

Because direct distances are not yet available for PMS stars, the usual procedure for identifying members of a SFR relies on circumstantial evidence of extreme youth, such as association with molecular material, excess infrared emission from circumstellar disks, strong lithium absorption, indicators of surface activity (X-ray or radio emission or optical/IR variability), and/or a space motion similar to other nearby young stars. If this evidence supports membership, then the PMS star is assigned the distance adopted for the SFR.

The lack of direct distance determinations means that the luminosities and therefore the ages of individual PMS stars are also poorly determined. Moreover, the evolutionary tracks calculated for PMS stars are not yet well-established, despite a lot of recent work. The net result is that the ages for PMS stars are uncertain by factors of two and more.

Although radial velocities accurate to 1 or a few km/s have been determined for a few hundred PMS stars, in general the space motions of individual PMS stars have not been determined, and very little is known about the kinematics of SFRs.

3.4.2 The Promise of FAME

Many important aspects of star formation are largely unknown due to the many uncertainties in the distances, memberships, structures, kinematics, ages, and luminosities of young stars in star forming regions and clusters. However, FAME will significantly rectify these uncertainties and will significantly advance our knowledge in several important areas of star formation science.

3.4.2.1 Distances, Memberships, and Kinematics of Star Forming Regions

FAME will determine distances to individual bright stars in the nearest star-formation regions to an accuracy of about 1 percent. Thus, we can use the bright stars to get very accurate distances to the interesting SFRs, their substructures, and young clusters within a few hundred parsecs.

At the nominal limit of 15th magnitude the distances to individual PMS stars in the nearest SFRs will be better than 10 percent. For the many members brighter than this limit, say in the magnitude range 12 to 14, the better astrometric precision will allow a lot of progress in determining whether stars that are grouped together on the sky are physically associated.

Another powerful tool for identifying members of SFRs and young clusters is the space motion of individual stars. The proper motions from FAME will be especially useful, because the velocity dispersion in SFRs and young clusters is on the order of 1 km/s, which corresponds to 200 μas/yr at a distance of 1 kpc. Even with an astrometric performance degraded to 500 μas/yr, the level expected at 15th magnitude, the FAME proper motions will still provide useful information on memberships. If radial velocities can also be measured, e.g., to about 1 km/s using complementary ground-based observations, this will strengthen the membership assignments.

If space motions accurate to 1 km/s can be determined in large numbers, then we can start to study the kinematics of SFRs and their substructures. If the age estimates are good enough, we can trace the motions of individual stars back to the clusters and groups where they formed. The goal here is to understand in detail how PMS stars dissolve into the general field and interstellar medium from the sites of formation.

The velocity dispersion of the gas in GMCs has been determined from observations of the line widths, and ranges from 0.5 to 1.5 km/s, but we don't know whether the recently-formed stars in GMCs share this dispersion. Proper motions from FAME could address this issue, especially if supplemented with radial velocities.

3.4.2.2 Establishing the Zero-Point of Stellar Evolution

The earliest phases of pre-main-sequence stellar evolution (stellar ages less than 3 Myr) are not well understood. However, FAME will determine the distances and hence the luminosities of many very young stars in nearby SFRs, spanning a wide range of masses (B stars in Orion to M stars in Taurus-Auriga and Chamaeleon). When combined with existing optical / IR spectra, these data will define the locus of the stellar birthline (zero-age PMS locus) in the HR diagram. Establishing this birthline is essential for anchoring and advancing both protostellar formation and early stellar evolution. Determining the ages and masses of young stars are key to making these advances.

3.4.2.2.1 Ages

Once memberships have been established, the accurate distances derived from the brighter members can be used to place all the stars down to 15th magnitude accurately on an HR diagram for its SFR or cluster. Then evolutionary models can be used to derive individual age estimates. Of course, this step requires additional photometric and/or spectroscopic information, such as extinction, reddening, and/or effective temperature.

Young PMS clusters are targets of special interest, because they represent groups of stars that formed together out of the same material, and thus are especially useful for testing the theoretical models of stellar evolution. In young clusters FAME can study the formation and early evolution of massive stars, even out to distances as large as 1 kpc. Such studies of very luminous young stars in our own Galaxy would help us understand the star-formation that we observe in other galaxies, where it is much harder to study low-luminosity stars.

3.4.2.2.2 Masses of PMS Stars

Finally, FAME will be able to determine the orbital inclination for selected PMS binaries with spectroscopic orbits, thus contributing to our knowledge of the masses for PMS stars (there are at present only a handful of direct mass determinations for PMS stars less massive than the sun, none of them accurate enough to make definitive tests of the models). FAME should also detect many eclipsing PMS stars, which can then be followed up spectroscopically to provide mass determinations for the double-lined systems. Accurate masses for PMS stars will allow us to carry out fundamental tests of the evolutionary tracks predicted by the theoretical models, assuming that metallicities are available from complementary ground-based observations.

3.4.2.3 Evolution Towards the Main Sequence

FAME is required to make significant progress in understanding the evolution of stars and their planetary systems from early PMS phases towards the main sequence. We now explain how FAME distances, proper motions, and photometry will advance our understanding in these areas.

3.4.2.3.1 Nearby Loose Associations

A recent development that has attracted a lot of interest in the star-formation community is the discovery of a few nearby loose associations of young stars, e.g., the TW Hydrae association at about 50 pc. These poor groups were not previously recognized because they were lost in the maze of field stars. Hipparcos was essential to identifying the half-dozen such associations recently discovered, all within about 100 pc. When combined with indicators of stellar youth (e.g., 2MASS, Sloan, X-ray, and other surveys), the distances and proper motions provided by FAME will allow the identification of additional members for the associations already recognized, and the identification of additional such associations. Even an astrometric performance as poor as 1 mas at V=15 mag could still make an important contribution to the identification of new associations and additional members.

Although these associations tend to be older (3 - 30 Myr) than the traditional SFRs, they have the major appeal that they are nearby and can therefore be studied in more detail, e.g., for the astrometric signature of planetary companions. Identifying these associations is also key for follow-up studies of stellar and planetary system evolution. Very little is known about the stars and planetary systems in this age range since it has been very hard to detect them until Hipparcos and, next, FAME. This is an important stage in the evolution of young stars, because it is the period when stars dissipate their circumstellar disks (perhaps forming planets), decrease their radius (and spin up), and become less active.

3.4.2.3.2 When Do Planets Form?

One of the hottest fields in astronomy is the study of extrasolar planets, and one of the most interesting questions in this field is when do planets form? Although FAME will not have sufficient astrometric accuracy to detect giant planets around PMS stars in the traditional star-formation regions, it can make an important contribution by identifying the optimum young targets for a pointed mission with much higher astrometric accuracy, such as SIM. This is just one of many examples where FAME will be an important precursor mission for SIM and subsequent space missions such as TPF.

3.4.2.3.3 Young Open Clusters

Nearby open clusters and associations such as the Pleiades are home to many stars with common origins, distances, and ages on the order of 100 Myr. Much as with younger PMS regions, FAME distances and photometry will directly provide the luminosities of cluster members which can be translated to masses and ages using models and existing spectra. This will be an iterative process in that the models will be refined to be consistent with the FAME data and the physical characteristics of the clusters (uniform age, metallicity, etc.). When correlated with existing data, derived cluster ages will show how stellar properties (radius, luminosity, effective temperature, rotation, etc.) evolve over time. Derived masses are essential for understanding the mass functions of clusters and how they contribute to the field initial mass function.

Since they have already evolved close to the main sequence, it is important to determine the distances of open clusters to better than 2% to allow the precise determinations of their masses and ages. This can be done for a few hundred members down to V=12 mag in the Pleiades if FAME parallaxes are accurate to 125 μas in this range. A floor level of 500 μas accuracy would also be very useful since the statistics of many stars would improve derived cluster distances. Hipparcos was unable to achieve this accuracy and thus was not useful in addressing these issues of open cluster science.

3.4.2.3.4 Surface Activity and Rotation

FAME will supply photometric measurements good to better than 1% from hundreds of visits to each star. This will allow an assessment of the photometric variability of PMS stars in general, and the determination of photometric rotation periods in particular. As stars evolve towards the main sequence, and even after they have settled onto the main sequence (e.g. in young clusters), their rotation eventually slows down and their chromospheres become less active. However, their rotation velocities and activity levels are expected to increase when they initially evolve from the youngest T Tauri phases. This is because their radii decrease more quickly than the onset of rotational braking (presumably by magnetic coupling). The photometric periods and photometric activity levels provided by FAME should make a major contribution to our understanding of how the rotation and activity of young stars evolve. The members of loose associations, which are midway in age between the SFRs and young open clusters, are likely to play a crucial role in this kind of study.

3.4.2.3.5 Photometric Binaries

The accurate photometry and distances provided by the FAME mission will allow the identification of photometric binaries in clusters, namely those stars that lie above the single-star main sequence on the cluster color-magnitude diagram. This study will contribute to our understanding of the frequency of binaries. Do young clusters show the same result as has been reported for field stars in SFRs, that the frequency of binaries is higher in the youngest populations than for older populations such as the solar neighborhood?

3.5 Reference Frames

The International Celestial Reference System (ICRS) recently adopted by the International Astronomical Union (IAU) employs an International Celestial Reference Frame (ICRF) which is based on the radio positions of extragalactic sources. The extragalactic sources should display no appreciable proper motion at the microarcsecond level due to their distance from the solar system barycenter. Thus, the frame should not display degradation when transformed from epoch to epoch.

The ICRF source positions are obtained by measurements made with Very Long Baseline Interferometry (VLBI) at a wavelength of 3.7 cm. The accuracy of the individual positions of the 212 primary sources making up this frame is of order 300 μas. The accuracy of the positions is limited by the Earth's atmosphere. There are approximately 400 additional sources, which are candidates for inclusion in the frame. The precision of the frame is of order 20 μas.

The optical frame now in use is based on the Hipparcos mission. The individual star positions are accurate to of order 1 mas at epoch 1991.25. The accuracy of these positions is deteriorating at the rate of about 1 mas/year due to the accuracy of the proper motions of the Hipparcos mission. The Hipparcos and its expanded Tycho catalog do not contain any compact extragalactic sources since they are limited to objects brighter than 12^{th} magnitude.

FAME will result in the positions of over a million stars with accuracies in position, parallax, and proper motion of 50 μas, 50 μas, and 70 μas/yr respectively. A FAME reference frame will be established whose precision will be of order 1 μas. In addition FAME will observe over 100 extragalactic sources and stars that display compact radio emission. These measurements will be used to transform the FAME frame onto the ICRF. In addition, the observations of the extragalactic sources will be used to minimize temporal rotations of the FAME frame due to the proper motions of the stars making up the FAME frame. The rotation of the FAME frame should be less than 10 μas/yr. The precision of the FAME frame will lead to it replacing the present ICRF as the international standard. The FAME reference frame will be the source of grid stars for the SIM mission, as it will contain stars at 12th magnitude. The FAME frame will also enable detailed comparison of radio/optical emission mechanisms associated with late type stars, stars with associated maser emission, and compact extragalactic sources.

3.6 Stellar Astrophysics

We now consider how FAME will contribute to improving our understanding of stars that have left the main sequence, particularly white dwarfs, planetary nebulae central stars, subdwarf O/B stars, and Horizontal Branch stars. Most of these old stars are distant, so they drive the FAME astrometric requirements for V=12-15 mag objects. FAME observations of these objects do not require high photometric precision.

3.6.1 White Dwarfs (WDs)

There are now approximately 100 white dwarfs (WDs) with accurate (less than 10% uncertainty) parallax measurements. Many more must be observed with this accuracy to determine the space density, luminosity function, mass spectrum, and production rate of these stars. Determining these values will also illuminate how these objects evolve from hydrogen to helium-dominated atmospheres and will help identify particularly unusual objects.

There are approximately 400 WDs estimated to be brighter than V=15, and most will have distances <250 pc. We require that FAME determine their parallaxes with less than 10% uncertainty, leading to a parallax uncertainty requirement of 0.40 mas at V=15 mag. These photometrically complete FAME observations of WDs will have far greater scientific value than present WD catalogs that, for cool WDs, are based on selection by proper motion and therefore have a kinematic bias. If the parallax accuracy at V=15 is degraded by a factor of 5 (to 2 mas), the hot WDs will no longer be identifiable from their parallaxes, but the ~150 cool WDs with D<50 pc will be—still a useful result, while larger errors will prevent the data being useful. This sets the parallax uncertainty floor. We also list the requirement, goal, and floor accuracies for V=12 mag in section 3, appropriate for relatively close and young dwarfs.

Combined with photometric and spectroscopic data (easily acquired at ground-based observatories), FAME parallax measurements will allow determination of the distances, luminosities, radii, and masses (from their mass-radius relation) of these 400 WDs. Compiling these data will yield adequate statistics to make the determinations listed above.

3.6.2 Planetary Nebulae (PNe)

Only 11 planetary nebulae (PNe) have had the parallaxes to their central stars determined to 3 sigma accuracy. This is inadequate for understanding the nebular physics, space density, and production rate of these objects. The parallaxes of at least as many new PNe must be determined in order to understand these objects better and how they relate to white dwarfs.

There are about 200 central stars of PNe known with V<15. Most are too distant to get a significant parallax measurement with FAME, but distances to PNe are so uncertain that we cannot accurately predict which ones will have a detectable parallax and which will not. We expect that about 20 will have significant (3 σ) detections with the required FAME accuracy of 500 μas at V=15, 10 detections if the accuracy is reduced to 1 mas (floor), and 50 if it is improved to 250 μas (goal). Therefore, we will get useful measurements for any FAME accuracy better than 0.5 mas at V=14 and 1.0 mas at V=15. Some planetary nebulae central stars will be as bright as V=12, and we consider their accuracy requirements in Table 3-1.

3.6.3 Subdwarf (sd) B and Subdwarf O Stars

Many sdO/B stars are on the extended horizontal branch at temperatures 20000-30000K; however, their origin and evolution are not well understood. Fewer than about 10 of these stars have significant (3 sigma) parallax measurements, so observing 100 more would provide a much greater sample so that their space density, luminosity function, and production rate can be established. These determinations will provide major clues to how these objects evolve from the extended Horizontal Branch and how they lose their hydrogen envelopes.

We estimate that the absolute magnitudes of sdO/B stars are Mv ~ 2 and approximately 100 objects will have significant parallax measurements (greater than 3 σ) for V<13 with the baseline requirement (e.g., 150 μas at V=13). Dropping the astrometric accuracy below 300 μas at V=13 (floor) will result in observing too few objects, while improving it to 75 μas at V=13 (goal) will allow significantly more objects to be observed with better distance determinations.

3.6.4 Horizontal-Branch Stars

Significant (3 sigma) distances have been determined for fewer than 10 Horizontal Branch stars, so very little is known about how these stars are distributed in this part of the HR diagram or how they are distributed in the local halo.

However, there are about 1000 Horizontal Branch stars with apparent magnitudes V < 11.5 and distances of 1.5 kpc or less. FAME will determine the distances to all of these objects to accuracies of approximately 10% or better if it meets an astrometric parallax requirement of 100 μas at V=12 mag. Dropping this requirement below 300 μas (floor) will result in accurate distance determinations for too few stars to be worthwhile. Tightening this to 60 μas (goal) will allow better determination of the luminosities and distances for more objects, significantly improving the science yield.

3.7 Galactic Structure

3.7.1 Dark Matter

3.7.1.1 Dwarf Stars

The measurement of local density of dark matter is sensitive to the total number of G-K stars (4<Mv<8) that meet two criteria. First, proper-motion errors must be substantially smaller than their vertical velocity dispersion, i.e., $\sigma(\mu) < (5\ \text{km/s})D = \sim 1$ mas/yr (kpc/D). Second, the fractional parallax errors must be smaller than 25%, i.e., $\sigma(\pi) <$ 250 μas (kpc/D). Clearly, the second requirement places the more stringent requirement on FAME. If FAME accuracies at the bright end are degraded, it will not affect this project. If the precisions are degraded at the faint end (V ~15), we will lose statistics roughly as the cube of the parallax error at V=15. Since the relation is a power law, it is difficult to say exactly where the breakpoint is, but if FAME errors grew from 440 μas, to 1 mas, there would still be very exciting science, while at a few mas, the improvement over present measurements would not be very dramatic. Also, if the FAME magnitude limit were cut below the present limit of V=15 (V=14 near the Galactic plane), the precision of the results would be adversely impacted roughly as $10^{0..3(V-15)}$.

3.7.1.2 K Giants

This measurement will use a large homogeneous sample of K giants that are being acquired by Majewski and for which good classification spectra will be available as well as relatively accurate radial velocities (< 5 km/s). This sample is a natural extension of the work being done for the SIM grid by Majewski and his colleagues. The K-giants have a relatively narrow luminosity function peaking at Mv = 0.8 mag.

The project requires (Bahcall 1984) determining the number versus height above the plane for this sample within a cone of 20 degrees around the two galactic poles. In order to reach a kpc, and to obtain an accurate estimate for the mass volume density near the plane and for the total column density up to 1 kpc above the plane, we need parallaxes accurate to 100 μas at V = 12 mag. With parallaxes of 100 μas at 12th mag, one can do an excellent job on this project. If performance is degraded so that parallax accuracy is 200 μas at V = 12th mag, the project can still be done well. But, a degradation to 500 μas at 12th mag, would make the measurement of questionable value.

3.7.2 Age of Disk and Halo

3.7.2.1 Age of Disk

The problem is to determine the time of earliest formation of Population I disk stars to age-date the early phases of the formation of the Galaxy. The method is to determine the locus of the faintest G and K subgiant stars in the HR diagram that have passed through the main sequence termination point and are on their way to the base of the giant branch.

The two famous local stars of this type that are within 15 pc are δ Eri, μ Her~A near Mv = 3.7, near the NGC 188 old cluster subgiant branch. The metallicities of δ Eri and μ Her are normal for Population I. Their space motions are clearly old disk.

The HR diagram from Hipparcos for stars with $(\delta \pi /\pi) < 0.1$ shows a ragged lower boundary near Mv = 4.0 which clearly defines the subgiant locus of the oldest stars. However, the number of stars defining this locus is less than 20, and the parallax errors giving $(\delta \pi /\pi)$ near 0.1 are too large to be of use. An error in absolute magnitude of 0.2 mag is an error of 20% in the age.

If we wish the age to be determined to within 2%, the parallax error must be kept to $(\delta \pi /\pi) = 0.01$ (or 0.02 mag in absolute magnitude). This means at 50 μas error for FAME, the distances of the subgiant stars that define the lower envelope must be 200 pc or less. The number of subgiants near Mv = 4.0 within this distance is estimated to be at least 1000 (perhaps as large as 5000) which is excellent for this problem.

If we descope to 100 μas, we reduce the distance to 100 pc and the volume by a factor of 8 to keep the $(\delta \pi /\pi)$ the same at 0.01. The number of subgiants decreases to 120 (or 600), which is still quite adequate. We can relax the $(\delta \pi /\pi)$ to 0.02 to recover the number of 1000, but now with a 4% error in the age, that would still be remarkable. Hence, FAME is ideal for the problem even with 100 μas errors. The apparent magnitudes of the subgiants at 100 pc will be V = 9.0 and V = 10.5 at 200 pc. Descoping to 200 μas will still give an experiment that is 5 times more accurate than Hipparcos in (delta pi/pi) at a given distance and 120 subgiants at (delta pi/pi) = 0.02 which again is 4% in age. The program would still be feasible.

3.7.2.2 Age of the Halo

The best way is still via the absolute magnitude of the globular cluster turnoff of halo clusters. This will be automatically obtained from the field RR Lyrae star parallax calibration that is discussed in section 4.1.2. Ground based color-magnitude diagrams of high precision are available that tie the horizontal branch (residence of the RR Lyrae stars) with the main sequence, solving the problem.

3.7.3 Distance to Interstellar Clouds

3.7.3.1 Technique

An understanding of the physics of interstellar clouds requires, among other things, a knowledge of the radiation field in which a cloud is immersed and a knowledge of the cloud mass. The former depends on the cloud location with respect to the nearby O and B stars. The latter depends on distance from Earth, assuming the angular extent is known (by, for instance, an emission map in H I, CO, or some other feature, or an extinction map) and that column densities are known. Then, the mass depends on the square of the distance, for our purposes. The clouds in question may be 1-10 pc in size, but because the distances are not known, the physical dimensions are also unknown.

The distance to an interstellar cloud can be determined by picking some signature of a given cloud (e.g., Na I absorption, E(B-V)) and searching for the same feature in ever more distant stars, starting near the Sun, until the cloud signature is detected. The distance to the test stars must, of course, be very well known. In the case of the radiation field determination, the distance of nearby O and B stars must be known as well. For a number of problems of interest, FAME can be used to determine all of the needed distances. For the problems discussed here, all the stars of interest are brighter than 11^{th} magnitude. In order to have an adequate density of field stars to locate a cloud to such high precision, it may be necessary to go to 12^{th} magnitude in some cases.

The technique has been applied numerous times, but never to the precision needed for the radiation field determination. Frisch and York (1983) mapped the local interstellar Bubble around the Sun in H I absorption, showing that the elongated feature extends to 400 pc in the third quadrant of Galactic longitude, but lies within 50pc in the direction toward the Galactic center. Frisch, Sembach and York (1990) used the growth of Na I absorption with distance toward Orion stars to locate the front side of Orion's Cloak (Cowie, Songaila and York, 1979) at 200 pc from the Sun.(Orion's Cloak is another large bubble of gas, centered, in this case, on the Trapezium and contained within Barnard's Loop.) Welty et al. (1989) showed that the isolated clouds of CO emission at high latitude (MBM clouds, Magnani, Blitz and Mundy 1985) are in some cases within 100 pc of the Sun, and therefore are not, as had been supposed, of extremely high mass. A number of extinction studies have been used to pin down cloud distances. Of particular interest here is the result by Seidensticker and Schmidt-Kaler (1989) that the Coal Sack nebulae is between 180 and 240 pc (see below.)

3.7.3.2 Radiation Field of Particular Interstellar Clouds

The distance of a cloud from O and B stars must be determined to 10 pc to make any headway in determining the effect of the interstellar radiation field on numerous interstellar parameters. At 500 pc, we need 100 microarcsec parallaxes to say, with high confidence (3 sigma), that a cloud is near a star. Otherwise, one cannot tell if the cloud is immersed in the mean radiation field or in the local field, near a star. For 200 micro arcsec FAME parallax errors, useful work could still be done of great importance. Further degradation would make the program of little interest.

3.7.3.3 Molecular Hydrogen

Molecular hydrogen absorption lines have been detected and analysed in about 100 O and B stars, within 500 pc of the Sun. These stars, observed by *Copernicus* and by *FUSE*, have $0.03<A_V<4.0$. We know much about these particular clouds, empirically, but detailed analysis of the cloud physics and chemistry depends on knowing the radiation field in more detail. One of the clouds for which H2 is now observed is, in fact, the Coal Sack (Rachford et al 2001), where more detailed analysis awaits the outcome of the proposed experiment with FAME.

The excitation of the upper rotational J levels (J>2) varies from 60 ^oK (Snow et al, 2000) to 1000 ^oK (ζ Pup, Morton 1978). It is presumed that the range reflects distances of clouds from stars because pumping of the high J levels of H_2 occurs when the UV photon density is high (Spitzer and Cochran 1973). Proving this simple presumption would be a major step forward and would allow further progress in understanding the creation/destruction of H_2. Some formation mechanisms should leave H_2 in excited rotation states, for instance. With exact knowledge of the radiation field and simple modeling, these effects could be looked for. A direct proof that H_2 is formed on grains may result from this research.

3.7.3.4 Constituents of Interstellar Clouds

The radiation field, along with cloud density, determines the equilibrium ratios of neutral and once-ionized species (e.g., Na^o/Na^+, C^o/C^+, Mg^o/Mg^+). Recent studies have shown that the observed ratios are inconsistent with pure radiative recombination. For an assumed radiation field, the ratios for species give different densities, different by as much as a factor of 10 (Welty et al 1999 a,b). The implication is that the other reactions are dominating the production of the neutrals; one suspected agent is a group of very large molecules (Lepp et al. 1988, Welty and Hobbs 2001). Note that we are talking about molecules with 20-40 atomic nuclei per molecule. Fixing the absolute radiation field and the geometric mean density, given the cloud distances, allows one to decide which species are being under produced and which are being over produced. That decision is a crucial one in the analysis of which large molecules may be present in the diffuse interstellar clouds. It should be pointed out that the other, very circumstantial, evidence for large molecules (>3 atomic nuclei) in diffuse clouds is the presence of hundreds of unidentified absorption lines in absorption spectra of diffuse clouds. These are referred to as the Diffuse Interstellar Bands. Having ruled out other recognized options, researchers suspect that large molecules may be involved (Douglas 1977, Smith, Snow and York 1977, Herbig 1995). Thus, the solution of the electron density mystery noted above may lead directly to solving an 80 year old spectroscopic problem in astronomy, namely, the origin of the diffuse interstellar bands.

3.7.3.5 Stars Inside Interstellar Clouds

It is uncertain how much interstellar material is accreted onto stars. By locating distances of interstellar clouds so precisely that a given star could be known to be inside or outside a cloud, one could make progress. In fact, an entirely new area of research could be created. Obvious candidates for this type of study are white dwarfs, where the accretion may affect surface abundances; field G stars, where the analogs of the heliosphere of the Sun may be suppressed by interaction with a cloud; and stars with detected planetary systems (Talbot and Newman 1977). In the last case, immersion in an interstellar cloud would have dramatic effects on the planetary atmospheres, largely because of the effect of interaction of H_2 in interstellar clouds with ions in the upper atmospheres of the planets.

3.7.3.6 Masses and Densities

The molecule H_3^+ has recently been detected in diffuse interstellar clouds (Geballe et al 1999). The column densities are much larger than expected based on current models of diffuse clouds. The very detection of the molecule outside of the darkest molecular clouds was a surprise. Now, knowledge of whether all the interstellar gas is concentrated at one location or, alternatively, spread over many, widely separated, clouds, is important in deciding how far one has to go in modifying existing models of cloud chemistry to explain the observations. For now, the indications are that in at least one striking case, the line of sight to VI Cyg OB2 No. 12, the gas is distributed (McCall et al 1998), deepening the mystery of how H_3^+ can be present at all. The delineation of the material into specific locales on the sightlines in question can be done using the described technique, with FAME. The stars of interest are the same ones to be used in the study of H_2 listed above.

The masses of known clouds clearly depend on the actual distance to the clouds from Earth, which distances can be determined by FAME. Large scale features, such as radio loop I, that appear to be the result of massive flows of interstellar material cannot be analyzed without knowing the gas masses. Having the masses, one can calculate the amount of energy required to create the features and thus decide what caused the ordering of the gas. The Orion Cloak study, mentioned above, as well as the MBM cloud studies, need to redone with this calculation in mind.

The required precision in the distances is not as high as for the radiation field problems described earlier, but parallaxes of <200 microarcseconds will be needed to get accurate masses and densities for the problems listed.

3.7.4 Galactic Kinematics

Many problems in Galactic kinematics can be solved using the FAME proper motion data. Two examples are given here.

1. A mapping of the asymmetric drift velocity (lagging of the halo behind the disk rotation about the Galactic center) as a function of height in the halo can be determined directly, without the need to have radial velocity information, by observing the distribution of proper motion directions at the galactic pole (where you get both the u and v velocities if you know also the distances).

Up to distance of 1000 pc, i.e. $(\delta \pi / \pi) = 0.05$ velocities of 100 km/s translate into the large proper motions of 0.02 arcsec/year, well above the FAME limit. Hence, the asymmetric drift that reaches a maximum of 250 km/sec for population II halo stars can be mapped as a function both of V and height above the plane using direct parallaxes to 1000 pc and photometric parallaxes to 8000 pc for stars, such as RR Lyraes and blue horizontal branch stars at Mv = 0.5 absolute mag. At 8000 pc, a drift velocity of 250 km/sec has a proper motion of 6,600 μas which is more than 10 times above the FAME error of 500 μas at V = 15. Hence, the method is exceedingly powerful even at 15th apparent magnitude.

2. The mystery of why there are no stars leading the sun in the V velocity (toward longitude 90^o) larger than about 70 km/s, whereas the escape velocity from the Galaxy is about 450 km/s. With a rotation velocity of

the sun of 220 km/s there should be stars leading the sun by 230 km/s. Where are they? And what is the solution to the mystery?

The discovery of stars leading the sun is most easily done using proper motions by looking for stars whose proper motion directions are in the +V direction. Radial velocity information is needed except in the directions of the Galactic poles (where the radial velocities are all in the W direction) and in the Galactic plane at longitudes of 0^o and 180^o. FAME will provide a very large data base with which to make a search. There is no restriction on the accuracy because it is the direction of the proper motion vectors that will identify the leading stars. Hence, even a large descope would not compromise the problem.

3.7.4.1 Distance Calibrations with Detached Eclipsing Binaries (DEB)

FAME will measure accurate proper motions and parallaxes for a selected set of about 50 bright (V < 10 mag) detached eclipsing binaries (DEBs). The set of DEBs to be studied by FAME will include early type stars (mostly B-type) to be used in calibrating the distance to the SMC and LMC, as well as later type stars (A-G) to be used in calibrating distances to globular clusters.

Special care will be required in the analysis of the stars in the DEB sample. Only data obtained outside of eclipses should be used in order to assure that unresolved companions do not cause a shift in the centroid position of the light during eclipse. It will be necessary to examine each of the observations of a DEB to check for wobble (which in general will be color dependent) due to the orbital binary motion.

The required groundbased data for precise analysis of the binary system already exists in many cases (see, e. g., the references in the catalog of Hipparcos DEBs, Kruszewski and Semeniuk 1999 as well as in Pojmanski 2000). Ongoing programs to obtain more precise and complete data are being currently acquired (Pojmanski and Paczynski, private communication). These programs will emphasize the selection of binaries of the same spectral type and similar magnitudes for both components.

In order to be useful in determining precise and accurate distances to systems of the greatest interest, the parallaxes of the DEBs must be known to 3% or better. For the DEBs that appear most suitable for this study, that means a parallax accuracy of 100 μas is fine but that a degradation below 300 μas would make the project much less useful.

3.7.5 Stellar Statistics

The FAME catalog will provide a superb and unique resource for modeling the distribution and kinematics of Galactic stars. The catalog will specify precise photometry, colors, positions, proper motions, and parallax measurements (or upper limits). These data will be sufficient to test and revise existing models of the distribution of Galactic stars and will make possible the construction of models that include both number densities of stars of different types in different volumes of the Galaxy as well as their kinematic properties.

The FAME science team will construct exportable software, convenient to use, that will embody a Galactic Model (analogous to the Bahcall-Soneira Galaxy Model). The characteristics of the model will be chosen so as to represent concisely and well, in a statistical sense, the measured stellar data for the FAME catalog. The model will contain, among other things, stellar constituents of a thin disk, and old disk, a spheroidal population, and perhaps a bulge population. Specific ingredients will include luminosity functions, color-magnitude diagrams, scale lengths and scale heights. The properties of the FAME Galactic Model will be useful in guiding follow-up theoretical work and observational studies.

The precision required for carrying out other FAME programs is greater than is required for constructing a useful Galactic Model. Therefore, relaxation of mission requirements is unlikely to affect the value of this project.

3.8 Relativity

One of the few feasible tests of General Relativity is the predicted deflection of the path of light waves by mass. This test provides a measure of the curvature of space time through an estimate of the metric parameter gamma. The most accurate such tests so far performed involved the deflection of the path of microwaves by the Sun. The prediction of General Relativity was found to be correct to within the estimated uncertainty of about 0.02% (unpublished).

No one knows at what level of accuracy General Relativity will break down. We can be sure only that it will break down. However, the a priori probability—whatever that might really mean in this context—must be considered very small that General Relativity would be found wanting at the level of accuracy achievable with FAME. Nonetheless, the measurements should be made, if for no other reason than to check the results for the microwave experiments. The sources of systematic error in these two approaches are very different. A crude error analysis indicates that a 1 sigma uncertainty in the estimate of gamma might be as small as 0.005%. This result depends on many assumptions, including a 45 degree minimum value for the angular separation of the Sun from each target star, a single measurement uncertainty in stellar position of one mas for a ninth magnitude star, no correlation between the estimate of gamma and those of the other unknown parameters of our model, and a mission duration of 2.5 years. To the extent that these assumptions are too conservative, the result will be more accurate (and vice versa).

3.9 Solar System

The observations of solar system objects at μas levels, while interesting and of unprecedented accuracy to date, generally have limited scientific value. The determination of improved ephemerides requires observations over a more extensive time period than the period of observations of FAME. There are a few cases where the observations may be of significance scientifically. One is the determination of masses of asteroids. This is one of the largest sources of uncertainty in the solar system ephemerides. Very precise observations of asteroids over the period that they are experiencing perturbations by each other could lead to more accurate determinations of the mass of the perturbing asteroid. This will require the careful selection of the asteroids, the determination of the correct times for making the observations, and special inclusion of positions into the input catalog. The accuracy achievable based on given observational accuracies is dependent on the circumstances of the encounters.

There is also the possible observation of long period comets to determine the mass of the Kuiper Belt. This will require the selection of an appropriate comet and observations over the lifetime of FAME.

3.10 Photometry/Variability

Photometry with FAME will allow identification of variable stars at an unprecedented level of sensitivity. The accuracy will identify variables with amplitudes of about 10 mmag , and the number of observations (~1000 or more in the astrometric bandpass) will identify stars with infrequent magnitude changes such as flare stars, and stars with brief, or infrequent, eclipses. The observing window function will prevent complete characterization of the variability for many stars (those with multiple periods, for example), but just their identification will allow ground-based followup.

Photometry with the photometric filters on FAME will determine the mean colors of stars with high accuracy. The g’, r’, i’, and z’ filters of the Sloan Digital Sky Survey (York et al. 2000) place constraints on the astrophysical parameters of stars, primarily effective temperature, surface gravity, metallicity, and reddening. When supplemented by ground-based data in the SDSS u’ filter, parameters for many types of stars will be well-determined. With baseline accuracy, the mean magnitudes of stars will be measured with an accuracy better than 1 mmag at V=9 and 10 mmag at V=15. This accuracy is better than is normally attained in ground-based all-sky photometry. It will be sufficient to resolve small deviations from the mean stellar locus (e.g., Newberg et al. 1999) only measurable with high-accuracy data like these. These data will be useful, if not essential, for interpreting all FAME astrometry.

3.10.1 Statistical Parallax Calibration of RR Lyraes

The FAME statistical parallax calibration of RR Lyraes will be based on a sample of approximately 750 stars with V<13. For a large fraction of these, only photographic photometry is presently available which, as Gould & Popowski (1998, *ApJ* 508 844) explicitly showed, is sometimes plagued with severe systematic errors. Hence, obtaining CCD photometry for these stars is critically important. However, if the photometry errors are truly random, even 0.05 mag errors would be quite adequate.

A somewhat more stringent requirement comes from wanting to obtain accurate ephemerides, which in turn are needed so that one can measure the systemic radial velocities from a single (ground-based) spectroscopic measurement. (The alternative is to obtain at least 3 spectroscopic measurements, which would be a huge project for this large sample, although not prohibitive.) For this purpose, 0.05 mag photometry in the astrometric bandpass at each epoch would be adequate. Expressed as a 2.5-year mission average, this would be 0.05 mag/sqrt{N} ~ 0.002 mag, where N = 900 is the number times FAME returns to the same field.

A similar level of photometry is needed to find new RR Lyraes from their light curves, since a non-negligible minority of RR Lyraes at V=13 remain undiscovered.

3.10.2 Trig Parallax Calibration of the Subdwarf Distance Scale

The subdwarf distance scale will be determined from about 200 subdwarfs. The majority will be near the magnitude limit of the subdwarf survey, V=12. In order to relate the parallaxes of FAME subdwarfs to those of comparable stars on the main-sequences of globular clusters, each subdwarf must be assigned an accurate metallicity, temperature, and reddening, which in turn requires a variety of photometric and spectroscopic observations. At present, it is envisaged that the infrared, and narrow-band-optical photometry will be obtained from the ground, but that most of the broad-band optical photometry will obtained from FAME itself. Photometric precision of about 0.005 mag is needed, which is equal to the FAME specifications at V=12.

However, it should be pointed out that if FAME falls short of this requirement, then the photometry can be obtained from the ground. Recall that FAME photometry constitutes only about 25% of the precision photometry needed to properly do this project, and so is more of a bonus than a requirement.

3.10.3 Standard Candles

Accurate mean magnitudes in the SDSS filters will be obtained for Cepheids, RR Lyraes, nonvariable HB stars, stars in open clusters, and main-sequence, metal-poor subdwarfs. Together with the astrometry, these magnitudes and colors will be particularly useful for confirming the Cepheids that are members of open clusters and improving their reddening determinations.

The accuracy will be higher than for most ground-based photometry, due to the high precision and to the absence of systematic zonal errors in the standard stars (see the Hipparcos and Tycho Catalogs, Vol. 3, sections 21.5-21.7 for a discussion of ground-based zonal errors). The FAME baseline accuracy will be greater than necessary for most of these purposes.

3.10.4 Brown Dwarfs and Planets

A transit of a solar type star by a Jupiter-size planet (or a brown dwarf star) results in a dimming of the primary star by about 10 mmag. A transit of a lower mass star having a smaller radius gives a greater variation. Measurement of a transit is necessary to determine the radius and density of a planetary companion.

FAME's baseline photometric accuracy in the astrometric bandpass for individual measurements (3 mmag for V=9, 12 mmag for V=12) is sufficient to allow FAME to search for transits by substellar to sub-Jupiter companions. Typical planetary transits last on the order of a few hours. FAME will observe each star typically 6 times during two consecutive scans lasting 1 hour (and often more during additional scans), and this pattern will be repeated at 10-day intervals. This coverage can catch at least a portion of one or more planetary transits for those planetary systems with high inclinations. Given the large number of stars on the main sequence observed by FAME (roughly 10**6 stars to V=12), many planetary systems may be detected photometrically. Photometric accuracy degraded to 10 mmag will still be useful in detecting those transits with relatively large amplitudes, like the transits of HD 209458.

3.10.5 Variability of Solar-type Stars

FAME can detect solar-like variability in ~40,000 "solar-like" main sequence stars to V=10 with baseline photometric accuracy. The sun shows significant photometric variations on timescales from minutes to decades—dimming by as much 0.2% when large sunspot groups transit the solar disk, brightening by 0.1-0.2% with the "11-year" solar cycle, and perhaps dimming by 0.2-0.6% during the "Maunder minimum" period (1645-1715) of extended inactivity.

Main sequence stars below 1.5 solar masses have convection zones, and so may have magnetic activity cycles similar to the Sun's. Previous studies of small samples (~100 or fewer) of solar-like G and K stars show that variability at the >0.5% level is common (~40%, e.g. Radick et al. 1998). These stars, more variable than the sun, can be studied to V=12 with baseline photometric accuracy, increasing the sample by more than a factor of five. With distances of a few hundred pc, all these stars will have FAME parallaxes to locate them on or above the main sequence. Both younger and older solar-like stars appear to organize their surface magnetic activity into active regions broadly similar to those seen on the Sun; young, active stars may have spot-dominated variability (with flux deficits), in contrast to the faculae-dominated activity (with flux excesses) of older stars, including the Sun (Radick et al. 1998). A statistical study of stellar cycles can give insight into the production of magnetic dynamos and shed light on the incidence of "Maunder-minimum" behavior in stars. It might also identify otherwise solar-like stars less likely to have planets harboring life as we know it due to conditions of extreme variability. Furthermore, periodic starspot transits could bias the search for planets or other companions, and so should be understood for what they are.

With baseline accuracy (3 mmag at V=10 for 1 observation) and typically 6 observations each 10-day semi-precession period, 0.1% variations can be studied for brighter stars on timescales of months or longer, and 0.2% variations at V=12. Yearly variations will be detectable to levels more sensitive by a factor of about four. The photometric filters will give very good mean colors, and (with parallaxes) locate the stars accurately in the color-magnitude diagram. Coverage will be more continuous for a fraction of stars for which the ecliptic latitude is just greater than the Sun angle; this set can be used to look for ~0.1% variations on timescales corresponding to disk transits of spots for V=10 stars. A photometric accuracy degraded to 20 mmag for a single observation would give 1 mmag yearly accuracy, and would still detect cyclic variations of some of the more variable solar analogs.

3.10.6 Stellar Pulsation

Evolved stars in the upper instability strip with radial pulsations (SX Phe, RR Lyr, Type II Cepheids, and RV Tau) have large amplitudes; they will all be identified, and their periods and light curves measured. Variable light curves (e.g., stars with double modes, RR Lyrae with the Blazhko effect, and RV Tau stars) will be easily identified, even with the photometric accuracy degraded to 30 mmag (1 observation) for bright stars. When combined with parallax data and colors from FAME, the boundaries of the instability strip will be accurately defined for SX Phe and RR Lyr stars (several hundred stars each), and short-period Type II Cepheids. Parallaxes for the dozen or two long-period Cepheids and RV Tau stars that are nearby enough will define the P-L relation(s) for all these low-mass stars much more accurately than now.

The identification of low-amplitude non-radial pulsators near the main sequence (delta Sct, lambda Boo, and rotating Ap stars) in order to define the instability strip for these stars requires photometric accuracy <10 mmag (1 observation). This accuracy will be reached at V<12 with baseline accuracy, and will still be useful if reached at V=9-10.

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3.12 Definitions

DEB	Detached Eclipsing Binaries
FAME	Full-sky Astrometric Mapping Explorer
GMC	Giant Molecular Clouds
HR	Hertzsprung Russell Diagram
IAU	International Astronomical Union
ICRF	International Celestial Reference Frame
ICRS	International Celestial Reference System
mas	milliarcseconds
M_{jup}	Mass of Jupiter
Mmag	millimagnitude
Mv	Absolute Magnitude
pc	parsecs

PMS	Pre-Main-Sequence
PNe	Planetary Nebulae
sd	Subdwarf
SFR	Star Forming Region
SIM	Space Interferometry Mission
TPF	Terrestrial Planet Finder
μas	microarcseconds
V	Visual Magnitude
VLBI	Very Long Baseline Interferometry
WDs	White Dwarfs
ZAMS	Zero Age Main Sequence